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School of Construction Management and Engineering

The development of a novel agent based long term domestic energy stock model

by

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Timothy Lee

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List of Abbreviations

ABM	Agent Based Model
ACE	Association for the Conservation of Energy
ANN	Artificial Neural Network
ASHP	Air Source Heat Pump
AST	Assured Shorthold Tenancy
BAU	Business as Usual
BCIS	Building Cost Information Service
BERR	Department of Business Enterprise and Regulatory Reform
BREDEM	BRE Domestic Energy Model
BREEAM	BRE Environmental Assessment Method
CAS	Complex Adaptive Systems
CCC	Committee on Climate Change
CDEM	Community Domestic Energy Model
CHREM	Canadian Hybrid Residential End-use Energy and Greenhouse Gas Emissions Model
CLG	Department for Communities and Local Government
CREEEM	Canadian Residential Energy End-use and Emission Model
CREEM	Canadian Residential Energy End-use Model
CWI	Cavity Wall Insulation
DECC	Department of Energy and Climate Change

DECM	Domestic Energy and Carbon Model
DEFRA	Department for Environment, Food and Rural Affairs
DG	Double Glazing
DIM	Diffusion of Innovations Model
DOE	Department of Energy
DTI	Department of Trade and Industry
DUKES	Digest of UK Energy Statistics
EE	Element Energy
EHCS	English House Condition Survey
EHS	English Housing Survey
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EST	Energy Saving Trust
FIT	Feed-in Tariff
GDSAP	Green Deal Occupancy Assessment
GSHP	Ground Source Heat Pump
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt-hour
LA	Local Authority
LPG	Liquid Petroleum Gas
LZC	Low and zero carbon
MADM	Multiple Attribute Decision Making

MARKAL	MARKet ALlocation
MASON	Multi-Agent Simulator of Networks
mCHP	micro-Combined Heat and Power
MWh	Megawatt-hour
NPV	Net Present Value
ONS	Office for National Statistics
PCT	Personal Carbon Trading
PV	Photovoltaic
RdSAP	Reduced Data Standard Assessment Procedure
RICS	Royal Institution of Chartered Surveyors
RSL	Registered Social Landlord
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SHW	Solar Hot Water
SVM	Support Vector Machine
SWI	Solid Wall Insulation
UKDCM	United Kingdom Domestic Carbon Model
UNFCC	United Nations Framework Convention on Climate Change
WTP	Willingness to Pay

List of Publications and Presentations

Publications

1. Lee T, Yao R (2013) Incorporating technology buying behaviour into UK-based long term domestic stock models to provide improved policy analysis. *Energy Policy* 52 (363-372). ISSN: 0301-4215
2. Lee T, Yao R (2011) A Prototype Domestic Energy Model using Intelligent Agents, World Sustainable Building Conference, Helsinki.
3. Lee T, Yao R (2010) An Overview of Domestic Energy Models and a New Approach with Agent Based Modelling, 2nd International Conference on Applied Energy, Singapore.
4. Lee T, Yao R (2013) An analysis of UK policies for domestic energy reduction using an agent based tool. Submitted to Energy Policy (Under review). ISSN: 0301-4215

Presentations

1. Lee T, Yao R (2012) Validating a Long Term Domestic Stock Model, 2nd Student Conference on Complexity Science, Gloucester
2. Lee T, Yao R (2011) Agent Based Domestic Energy Modelling, Poster at 'Buildings don't use energy, people do' Conference on Domestic Energy Use and CO_2 Emissions in Existing Buildings, Bath
3. Lee T, Yao R (2010) Domestic Energy Modelling with Intelligent Agents, Presentation at the University of Reading's School of Construction Management and Engineering's annual PhD Conference

Abstract

This research has developed a novel long term domestic energy stock model of owner-occupied dwellings in England. Its primary purpose is to aid policy makers in determining appropriate policy measures to achieve CO_2 emissions reductions in the housing sector.

Current modelling techniques can provide a highly disaggregated technology rich environment, but they do not consider the behaviour required for technological changes to the dwelling stock. Energy efficiency improvements will only occur in the owner-occupied sector of the housing market when owners decide to carry out such improvements. Therefore, a stock model that can simulate this decision making process will be of more use for policy makers in predicting the impact of different measures designed to encourage uptake of suitable technologies.

Agent based modelling has been proposed as a solution to allow the inclusion of individual household decision making into a long term domestic stock model. The agents in the model represent households and have a simple additive weighting decision making algorithm based on discrete choice survey data from the Energy Saving Trust and Element Energy. The model has then been calibrated against historic technology diffusion data.

Sixteen scenarios have been developed and tested in the model. The initial Business as Usual scenarios indicate that current policies are likely to fall well short of the 2050 80% emissions reduction target, although subsequent scenarios indicate that the target is achievable. The results also indicate that care is required when setting subsidy levels when competing technologies are available, as there is the potential to suppress the diffusion of technologies that offer greater potential savings.

The developed model can now be used by policy makers in testing further scenarios, and this novel approach can be applied both regionally and in other countries, subject to the collection of suitable input data.

Chapter 1 Introduction

1.1 Background

The UK has a target to achieve an 80% reduction in CO_{2e} emissions by 2050 from a 1990 base (TSO, 2008). Approximately 30% of UK energy consumption is in the home, and around 80% of this is to provide heating and hot water (DECC, 2011a). Consequently, significant reductions in the domestic sector must involve reductions in hot water and heating demands.

There is a limited range of ways in which this can be achieved, essentially behavioural change, fabric improvements, more efficient heating systems, and energy generating equipment (OFGEM, 2013). Behavioural change could be factors such as people learning how the controls on their heating systems work so that the systems will only produce heat when needed. Fabric improvements will typically be insulation measures – if a dwelling is better insulated it will lose less heat to the outside and will therefore require less heat generation in the first place. In any heating and hot water system there will be some energy loss, so the installation of a more efficient system will be able to reduce such losses. Finally there are various technologies available, eg: solar photovoltaics, that will actually generate energy, and their installation in a dwelling will obviously reduce the total external energy demand of that dwelling.

As well as making improvements to the existing stock there is a separate approach, which is the demolition of existing dwellings and replacing them with more efficient new dwellings. However, annual construction rates are less than 1% and demolition rates are around 0.1-0.2%, therefore the vast majority of the housing stock that will exist in 2050 has already been built (CLG, 2011a). As a result, retrofitting improvements to the existing stock is essential if the 80% reduction target is to be achieved.

Since most of the stock that will exist in 2050 has already been built, improvements to that existing stock become an essential component of achieving the 80% emissions target. The most significant reductions will be as a result of improvements to the stock via a mix of fabric improvements, more efficient heating systems and on-site energy generation. However, all three of these approaches will require the intervention of the owners of those dwellings – ie: changes will not occur until individuals decide to carry them out.

An 80% reduction target is very ambitious and will requiring detailed planning if it is to be achieved. Therefore policy makers need to devise methods designed to encourage the uptake of energy efficiency measures; they then need some way to test and estimate their likely impact. To this end, long term stock transformation models are used that aim to simulate the rate of change that any one policy, or set of policies, might achieve in the overall housing stock by 2050 (or any subsidiary date) . By using such models policy makers can devise alternative sets of policies and input them into a model to estimate the effect they might have in achieving the desired changes to the housing stock (Swan and Ugursal, 2009).

Therefore, policy makers require long term stock transformation models. These models need to provide a reasonable estimate of the likely uptake of various energy saving technologies and the resulting emissions reductions under different scenarios and sets of policy interventions.

There are already many existing long term domestic stock models that are designed to aid policy makers in formulating long term policies to aid stock transformation. However, as will be shown in the following chapter, they suffer from a common weakness in being poor at simulating the decision making of individual homeowners in considering the installation of energy efficient technologies in their homes.

Significant reductions can be achieved by the installation of innovative technologies which are not currently established in the housing sector. Without historical adoption rates it is generally harder for conventional models to predict their future uptake. Instead, to track the adoption of new technologies by individuals, a model needs to simulate the decision making of those individuals who will be deciding whether or not to install innovative energy saving technologies.

Therefore conventional stock models are not ideal for considering policies designed to encourage individuals to invest in energy saving technologies. By incorporating the decision making process into a model, it will be possible for policy makers not only to determine the theoretical impact from any particular technology, but also the practical impact dependent upon the level of support provided to any individual technology. In this way, such a model should be of more practical use in determining the likely impact and cost effectiveness over the long term of varying sets of policies, in order that policy makers can search for cost effective pathways to 2050.

1.2 Aims and Objectives of Research

As established in the previous section, much of the potential reductions in domestic energy demand and emissions will come from technological changes to the building stock: fabric improvements; improved heating systems, and energy generating systems. If these are to be used to attempt to achieve an 80% reduction in emissions by 2050 considerable planning will be required, and housing stock models will be an essential part of the planning and policy preparation process.

Therefore, the main aim of this research is to:

> Develop a novel long term domestic energy stock model capable of simulating individual households' decision making processes.

This will have a particular focus on being able to predict how different policy interventions will impact individuals' decision making, and how that impact will then affect the installation rates of various energy saving technologies. In order to achieve this there are several subsidiary objectives, as follows:

- Carry out a comprehensive literature review
- Identify shortcomings in existing domestic energy models
- Identify suitable methods to address the identified shortcomings

- Produce a long term domestic energy stock model using new modelling methods and techniques
- Test the new long term domestic energy stock model
- Carry out policy and scenario analyses with the new model

Such a model will primarily be of use for policy makers in developing different future scenarios. By making simulated runs of the future of the housing stock it will be possible to analyse the cost effectiveness of different policies, both in isolation and when combined with other policies.

1.3 Thesis Structure

The rest of this thesis is structured in the following manner:

Chapter 2 provides a comprehensive literature review concentrating on the models available and the modelling techniques currently being used for long term domestic energy modelling. This chapter then concludes by identifying shortcomings and weaknesses in the current state of the art models.

Chapter 3 explores the different methods that might be useable in addressing the major weaknesses identified in the previous chapter. It then reviews the extent to which these alternative methods are already being used before recommending the most appropriate method for the development of a new and innovative model.

Chapter 4 is the first of two describing the creation of a new long term domestic energy stock model. This chapter considers the data requirements for the model, discusses potential methods of data collection and then selects the appropriate methods and sources of data.

Chapter 5 is the second chapter describing the mechanics of the new model and concentrates on the development of the algorithms used and the computer programming and testing.

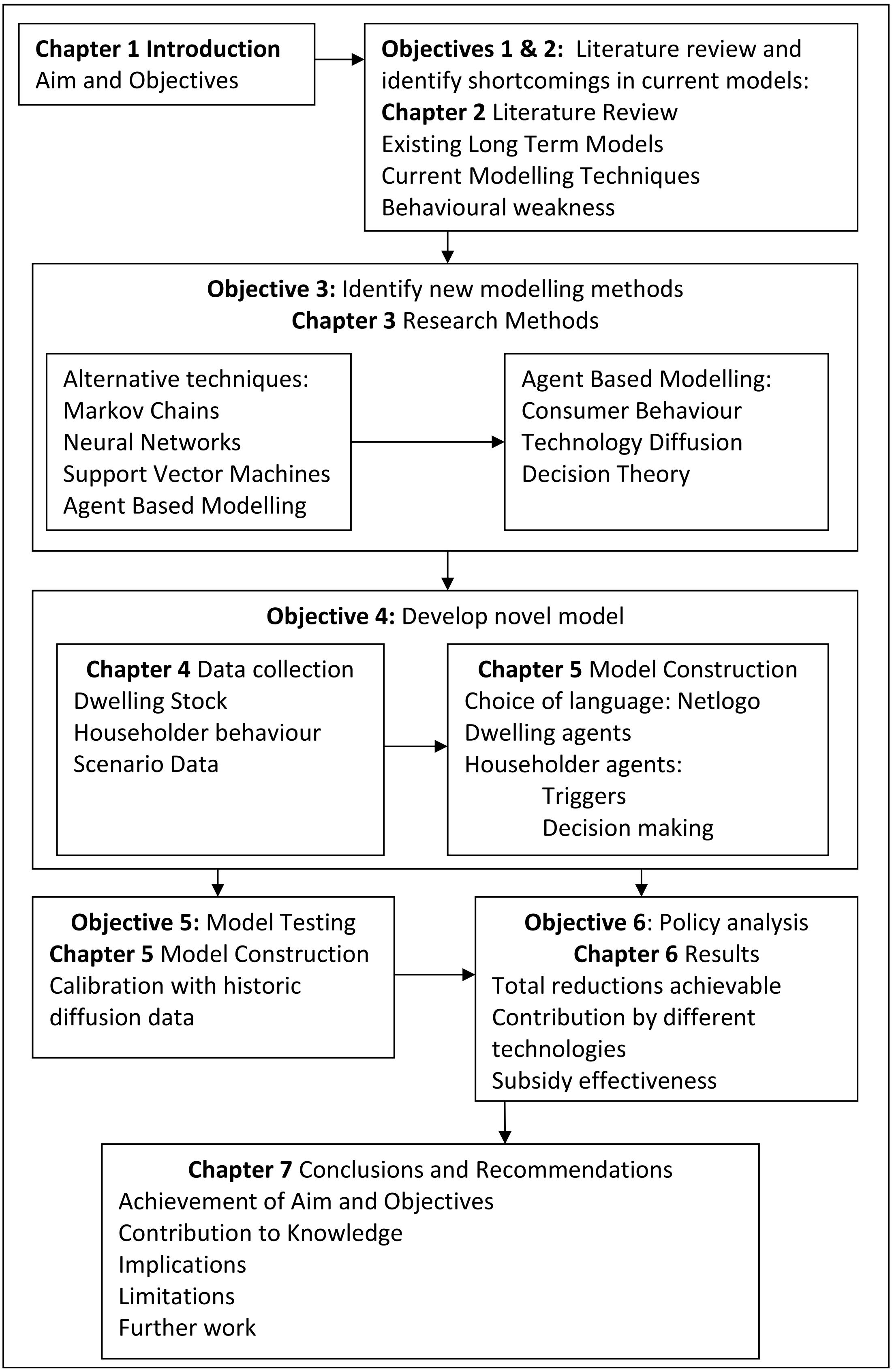
Chapter 6 is the results chapter. This chapter discusses the creation of a number of scenarios and then presents the outputs from those scenarios, together with a discussion of their meaning.

Chapter 7 is the final chapter of the main body of the thesis and provides the conclusions based on the results as well as the limitations and provides recommendations for future work.

The appendices provide the final model's user manual as well as the model's source code.

Figure 1-11 provides a graphical map of the thesis layout:

Figure 1-1 Thesis Map



Chapter 2 Literature Review

2.1 Introduction

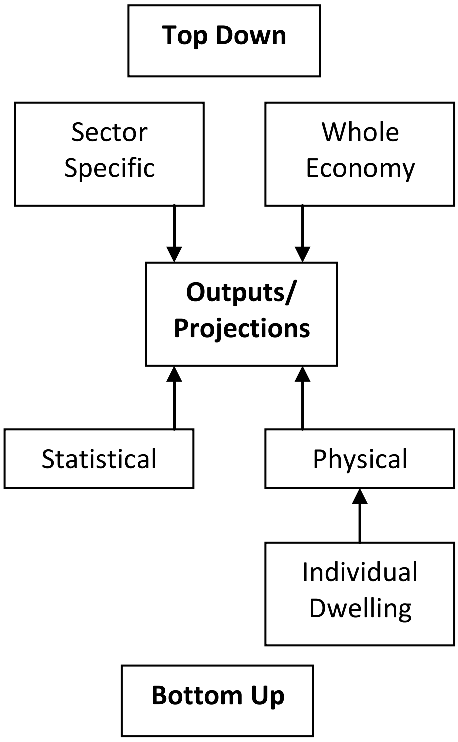
The first section of this literature review provides a general overview of the different types of energy and carbon models that are currently in use. This is followed by a more in-depth section describing and critically analyzing models specifically relating to the domestic energy sector, including a discussion of the respective strengths and weaknesses of the different methods employed by different models. This chapter then concludes by identifying the short-comings that this research is intending to address in the development of a new model.

2.2 Energy Models

There are many different types of energy models available and they have different purposes. Utility companies use almost instantaneous models for demand prediction to maintain the grid supply; building owners require modelling of individual properties. As well as these short term or individual models, there are long term models that are used for analysis over future decades and long term planning and to analyse stock transformation (Swan and Ugursal, 2009). It is this sort that is relevant in considering long term CO_2 planning and the energy demand and supply balance. Even here there is significant variation in both the aims and methods of the various models. However, it should be noted that load profiling models are beginning to be developed to estimate day to day fluctuations in the longer term (typically up to ten years in advance), although they remain focussed on usage and are not aiming to intrinsically model stock changes (Singh, 2012).

There are essentially two broad types of method: either top-down or bottom-up. These types are graphically represented in (Lee and Yao, 2013).

Figure 2-1 Top Down and Bottom Up Model Types



The following subsections describe and discuss the different types, and their uses and methods.

2.2.1 Top Down

The distinction between bottom up and top down models is largely driven by the data sets used. These are either disaggregated micro-level data sets or aggregated macro-level data sets. As would be expected the top down models are high level models using aggregated data and therefore do not include detailed data on the individual constituents of the system being modelled. Different top down models will be analysing different systems and these can generally be divided into two broad categories, either sector specific or whole economy.

2.2.1.1 Whole economy top-down models

These models tend to be interested in the national level and therefore work with econometric aggregated data, eg: economic growth and inflation rates, employment and population projections, etc. At this level such models aim to examine the overall picture rather than the underlying detail, and are typically used for long term large scale planning of the energy supply. A model of this sort will be used to predict future energy demand, the model's outputs can then be used to plan the generating mix to meet the expected demand. Therefore, since this sort of model is only looking at the headline total figures it is not necessary to consider the underlying data at the individual level.

By way of illustration, Fitzgerald's (FitzGerald et al., 2002) model provides a useful example of a whole economy top down energy demand model. With this model they analysed the growth in energy demand from 1960 to 2001. Over this period it was found that non-electricity energy demand had increased at a rate of 1.2% per year whilst electricity energy demand increased at an annual rate of 5%. They also found that the main driver for changes to CO_2 emissions was changes in the electricity generation mix. This model was principally concerned with the price-demand relationship and it found electricity to have a very low price elasticity – ie: significant increases in prices were needed for relatively small reductions in demand. There are a number of potential explanations for this: the first is that electricity is still too cheap a commodity for significant numbers of people to need to respond to price increases. However there could be political implications since the poorest households would be the first to suffer if large price increases were used as a policy tool to curb demand. In addition, from 1960 to 2001 there has been an increase in the use of domestic appliances, and other pieces of technology, that require electricity thus pushing demand. This is then tied in with the lack of substitutability: except for electrically provided heating and hot water there is no alternative method for powering the various electrical devices used in the home, therefore significantly higher price increases are required in order to affect behaviour to reduce usage.

2.2.1.2 Sector specific top-down models

Necessarily the whole economy models discussed in the previous section are low on specific details, some of which will be addressed by sector specific top down modelling. As the name would suggest, sector specific models do not consider the entire economy, but merely a specific subset, eg: transport, industry, buildings, etc.

A typical top-down model for the housing sector will usually make predictions about total energy demand by tracking high level data, such as construction and demolition rates, without relying on detailed analyses of the individual dwellings.

A useful example is provided by the ADEPT model (Summerfield et al., 2010). This is a relatively simple domestic sector top down model illustrating the top down approach, whereby a detailed understanding of the underlying mechanisms driving changes is not required. Instead the model operates using the bare minimum as regards input data. ADEPT was consequently designed to model the delivered energy of the average household, Q_d (MWh), based on data from the Digest of UK Energy Statistics (DUKES) (DECC, 2012a). The DUKES data sets include data on total domestic sector energy use, which can be readily converted to a figure for the theoretical average household. This data was combined with temperature data and price data to produce a simple regression equation:

$$Q_d = B_0 + B_1\theta_e + B_2P_q \qquad [2.1]$$

In this equation B_0 *(MWh)*, B_1 *(MWh/°C)*,B_2 *(MWh)* are the regression coefficients, θ_e is the average external temperature during the heating season and P_q is the energy price index (set in 2005 with a baseline figure of 1). As can be seen then, equation 2.1 estimates energy demand purely based on winter temperatures and energy costs, and as expected θ_e and P_q have a negative correlation with the energy demand Q_d – ie: low temperatures increase heat based energy demand and high prices decrease energy demand.

A model of this sort can be very easily used to make long term annual demand predictions, without recourse to very detailed sets of data. It would not be suitable for shorter term predictions where much greater accuracy is required – in particular for grid supply management. Nor does the model consider the underlying technical changes that would allow any predicted reductions to occur. Therefore it can be seen that different models have their place and purpose. Top down models are useful in projecting overall demand, but since they do not use any data on the technologies being deployed at the individual level, there are limits to their usefulness for policy purposes, as there is no way for these models to describe the underlying processes by which savings might be achieved.

Therefore top-down models tend to have less detailed information. Instead they concentrate more on economic impacts and then predict how those impacts might affect domestic energy demand and usage, whereas the bottom-up models take the disaggregated data and scale it up to consider various impacts and changes.

2.2.2 Bottom up models

In contrast to the top down models previously described, the bottom up approach starts with individual units and then scales up from there to the entire system. Essentially there are two main sub-categories of bottom-up approaches: statistical and physical.

Statistical models operate with a sample of dwellings and find relationships typically between appliance use and energy demand, this will then usually be coupled with further data, such as appliance ownership levels and weather data, in order to produce regression equations (Swan and Ugursal, 2009). Based on the predicted responses for the sample population, scaling up allows an estimation for the entire population under consideration, whether that be local, regional or national. Since these models concentrate on appliance ownership and usage they are generally restricted to relatively short term modelling, as they are more concerned with intraday fluctuations in usage and demand as against modelling long term stock transformation.

That therefore leads to the bottom up physically based models. Physically based stock models are primarily concerned with the physical characteristics of the individual units that make up the dwelling stock. These models carry out a heat balance calculation, or some form of thermodynamic assessment, of individual dwellings to generate a prediction for the energy demand to provide heat for that dwelling. Then scaling up can allow for demand predictions for the entire stock under consideration. By changing the physical components of the modelled dwellings changes to the building stock can be simulated and their effects on energy demand predicted. Therefore physically based stock models are ideally suited for considering long term changes to the housing stock, and predicting the different effects on demand and emissions from varying uptake rates of the various energy efficient technologies that can be installed in the home.

Physically based models therefore require a base set of dwellings that represent the real world stock of interest to the modeller, this sample set can be either real or simulated, and by aggregating and scaling up the individual energy demands projections can be made for the entire stock. Subsequently, by making changes to the initial stock, potential real world changes can be simulated and their effects calculated.

Therefore physical models include a statistical element in the development of their sample set of dwellings, but this is distinct to statistical bottom up models, which, as discussed, are frequently based on regressions.

Since these models are dependent upon a thermodynamic modelling of an individual dwelling it is first necessary to consider how such modelling is carried out.

2.2.3 Individual dwelling models

For a number of years there have already been modelling techniques available for estimating the energy demand from individual dwellings. The primary use for such models has been for regulatory purposes. In the EU, and therefore the UK, the main driver over the last decade has been the Energy Performance of Buildings Directive (EPBD) (EU, 2002). The EPBD lays down a requirement for a standardised assessment of any dwelling when it is constructed, or put up for sale or made available to rent. In the UK there are two statutory tools for complying with the EPBD, the Standard Assessment Procedure (SAP) (BRE, 2011a) for new dwellings and the Reduced data Standard Assessment Procedure (RdSAP) for existing dwellings. As will be seen in the following section, SAP is the primary tool used for dwelling modelling in UK based stock models, so for that reason it is considered in some detail here. Essentially SAP and RdSAP are the same, but RdSAP provides a number of assumed values for existing dwellings, principally based on their age, for construction elements that cannot be measured and where original paperwork is not available (eg: flat roofs where construction elements are not visible and insulation levels cannot be measured and therefore U-values cannot be determined). Therefore SAP (and RdSAP) was principally intended to be a regulatory assessment tool (and to some extent a design tool) as opposed to a predicting tool. For regulatory purposes the output from a SAP calculation is kWh/yr and kgCO_2/yr which are then normalised to provide a per square metre value, which is then converted into a rating on a scale from 1 to 100 (with 1 being very poor and 100 being very good). SAP is largely a development of, and based on, the old BRE Domestic Energy Model (BREDEM) (Anderson et al., 1985, 2002). The inputs to a SAP calculation include a number of components, the more significant ones are detailed in Table 2-1:

Table 2-1 Data requirements for a RdSAP calculation

Size	Area: floor, walls, ceiling, openings Room height
Construction	Age, exposed walls, exposed floors, roofs, doors, windows
Insulation	Exposed walls, exposed floors, roofs, doors, windows
Heating	Fuel type, efficiency, distribution system
Hot water	Fuel type, efficiency
Lighting	No. of incandescent, fluorescent, LED
Renewable technologies	Power of solar hot water and photovoltaic systems, wind turbine dimensions

As can be seen this data collection is relatively detailed about the fabric of a dwelling, its heating and hot water systems, lighting and any renewable technologies. However, it should be noticed that it does not include appliance usage nor cooking (although it does include an estimate of incidental heating gains from such energy demand, as well as metabolic heating gains from the occupants).

One of the intentions of the EPBD was to allow potential occupants of buildings (similar tools to SAP are available for non-residential units) to be able to compare the relative efficiencies of different buildings. They could then use this information as part of their decision making in deciding which building to buy or rent. Since all dwellings have slight variations they make a heterogeneous stock and therefore direct comparison is difficult; therefore, as mentioned earlier, the energy demand is normalized to a per square metre figure, which is then mapped onto a scoring system from 1 to 100. To aid with this standardisation, for easy comparison SAP calculations do not consider the actual usage of the current occupants but instead SAP assumes standardised occupancy patterns. The main elements of these are: the number of assumed occupants, which is set according to floor area, this provides metabolic gains and hot water demand; heating patterns – SAP assumes living rooms are heated to 21°C and bedrooms to 18°C for 9h a day during the week and 16h per day during the weekends. Therefore a SAP assessment will not be a genuine recording of the energy demand of that dwelling with its current occupants. Instead it provides a standardised estimate of energy demand for a theoretical typical household, thus allowing for easier comparison between dwellings. Whilst this reduces the realism at the individual dwelling level, once scaled up to a population for stock modelling purposes these variations should be minimised. It should also be noted that this estimation is restricted to fixed heating (and cooling) hot water and lighting, therefore SAP is capturing in excess of 80% of current domestic energy use. Although it should be noted that in the longer term, if fabric and heating system energy efficiency improvements are carried out, the proportion of energy use captured by SAP will reduce as appliance use becomes more significant due to reductions in the heating load.

The EPBD applies to virtually all buildings (some minor exemptions, eg: unheated buildings), and in the UK a similar tool to SAP has been set up for non-dwellings, the Simplified Building Energy Model (SBEM) (BRE, 2013a), this works in a broadly similar way with details of the structure of the building. However, it is more complex when it comes to usage patterns as it aims to replicate all non-domestic usage. An assessor using SBEM has to identify the different uses for different parts of a building (eg: showers, dance floor, office etc), each different usage comes with its own energy demand assumptions so that again a standardised score for a building can be generated.

As well as statutory tools such as SAP and SBEM, there are other individual dwelling models available, these are usually intended as design tools. Probably the most well known and respected is the Passive House Planning Package (PHPP) (Passive House Institute, 2007). PassivHaus was initially developed as a German standard to recognise and reward energy efficiency in new dwellings, versions of PHPP are now available in many countries. The original tool has now been adjusted to include a refurbishment module, so that it is not purely restricted to the new build sector of the market. The UK version is called PHPP and is used to demonstrate compliance with the PassivHaus standard. In order for a dwelling to achieve the standard the model needs to estimate annual energy demand below certain thresholds, eg: ≤ 15kWh/m^{2}yr heating demand and ≤ 120kWh/m^{2}yr specific primary energy demand. In contrast to SAP the primary energy demand includes appliances, so therefore PassivHaus includes an attempt at estimating appliance usage. However, the main concern in doing so is avoiding overheating, which has been identified as a potential issue with very well insulated dwellings like a PassivHaus. This appliance modelling is therefore primarily checking for incidental gains from inefficient appliances as opposed to detailed modelling of appliance use.

The models considered so far have concentrated purely on the energy side of modelling an individual dwelling. However, there are models that aim to provide a more comprehensive analysis, most noticeably the BRE Environmental Assessment Method (BREEAM) (BRE, 2011b). As well as estimated energy use, BREEAM includes other environmental components in its assessment tool, eg: transport, water, waste, etc., although the energy component is typically SAP based.

As can be seen then, there is a range of models available that concentrate on individual dwellings, although they are primarily concerned with heating and cooling systems and the building fabric. Therefore they largely ignore appliance use and operate with standardised occupancy patterns, as opposed to detailed modelling of varying occupant numbers and behaviours. There are some changes being made to SAP to consider individual usage. These adjustments are being made as a separate module for the Green Deal (a financing scheme for energy efficiency improvements with loan repayments incorporated into the energy bills of a building). This is primarily an occupancy assessment that will make adjustments to the assumed patterns in SAP (BRE, 2013b). The intention is that it should provide a more tailored calculation of energy savings for an individual dwelling (or commercial premises) should energy efficiency measures be installed. Nevertheless, although the standard forms of SAP and RdSAP do not adjust occupancy patterns, they aim for a theoretical 'average' household. Therefore, if aggregated across an entire population the individual differences should balance out and the summation ought to provide a reasonable estimate of total demand and resulting emissions.

Since SAP provides average usage and occupancy patterns (with occupancy levels determined according to dwelling size), when scaled up to the whole population, a SAP based stock model should provide a good estimate of SAP related energy demand. However, in a stock model that includes individual decision making, if SAP energy demand estimates are used to calculate the expected savings from installing a technology, it will only provide savings for the theoretical average user. This will not exactly fit with the extreme ends of the population – ie: it will mis-state the savings for particularly high or low demand households, and therefore may not accurately represent their true decision making process. However, to successfully incorporate such variations into a stock model would require further data sets to enable the development of not only decision making profiles, but associated load profiles for different types of individual households. Furthermore, as discussed in the previous paragraph, the Green Deal is being introduced in 2013, which provides estimated savings on a SAP basis, but adjusted according to individuals' actual energy usage. Therefore, it seems appropriate to keep SAP for use in UK based stock models, as it is well established, and also offers a base point from which future work can be carried out using the Green Deal version of SAP to develop more complex household profiles.

2.2.4 Physical stock-based bottom-up models

Physically based models (alternatively known as engineering models) operate by having a sample set of dwellings which are subjected to a physical assessment using an individual modelling tool of the sort described in the previous section. By making changes to the construction of dwellings in that sample set (eg: adding loft insulation) and then recalculating the estimated energy demand, the effect of the installation of various measures can be determined. Then, by scaling up from the sample set to the whole population of interest to the modeller, projections can be made as to the expected impact from different installation levels for different technologies. Many such models have been developed and are used in many different countries, including the UK, a representative sample of which are reviewed in the following subsections:

2.2.4.1 Johnston

Johnston's (Johnston, 2003) model provides a useful introduction to physically based bottom up stock modelling in the domestic energy sector. As a physical stock based model it relies on having a sample set of reference dwellings in the model that serve to approximate the real world housing stock (in this case UK housing). This model has kept the complexity to a minimum and is virtually as simple as possible with a very low level of disaggregation of the dwelling stock making up its reference dwellings. The stock is split into just two types, based on age band, pre and post-1996 construction. These two types are then used to approximate the entire stock. Both of these types require individual modelling, and in this case the calculations were carried out using a modified form of BREDEM (the pre-cursor to SAP).

The next requirement for the model was to develop scenarios of potential future pathways, this will include assumptions concerning future populations, installation rates of new technologies and future energy demand. The uptake of new technologies – their diffusion or penetration rate – generally takes an S-curve form with a slow introduction then accelerating into a fast uptake period, and finally the uptake rate slows down again as the uninstalled potential diminishes. As this is a stock transformation model with the proportions of dwellings in the two categories changing over time, the diffusion S-curves can primarily be observed via this stock transformation process.

Johnston (2003) produced three main scenarios to represent three alternative future pathways and approaches to future energy demand and emissions. Based on these scenarios the model projected from its initial start date of 1996 to an end date of

2050. The first scenario developed was the Business as Usual (BAU) scenario. The intention behind a BAU scenario is simply to project forward the current state and simulate current trends and patterns forward to 2050 (or any other required date) without any further changes to government policy from the current position. This scenario therefore provides a reference or baseline against which other scenarios, that include policy changes, can be compared, thus the efficacy of different policy measures can be estimated. The model needs to consider: number of households; number of households in each age band; trend rate of, and effect of, improvements to existing housing stock; projections of appliance and lighting use; rise in expected internal temperature vs predicted rise in external temperatures due to global warming. The BAU scenario then predicts a 33% reduction in CO_2 by 2050. However, the use of only two dwelling types limits the depth to which changes to the dwelling stock can be modelled.

Two further scenarios were developed: the Demand-side and Integrated scenarios. These scenarios depend upon making assumptions about the uptake rate of new technologies and demographic changes. In this way a model can be used for policy analysis by applying different assumptions of how the housing market might react to various policy instruments. The Demand scenario assumes a concentration on improvements to reduce demand, and the Integrated scenario adds supply side improvements to the Demand scenario. The Demand scenario assumes new dwellings from 2010 will be built with zero heating requirement, which is in excess of the target that new homes should be zero carbon in use by 2016. After reaching this stage it assumes no further improvement with new homes and instead Building Regulations concentrate on improving the existing stock. The Demand scenario achieves a 50% reduction in energy demand and a 58% reduction in CO_2 emissions. The Integrated scenario adds extra changes to the energy supply with large take-up of more advanced technologies, leading to a predicted reduction of 74% in emissions. Johnston then briefly considered further alternative scenarios, which showed that greater reductions – up to 82% are technically possible. Johnston concludes that reductions of between 60 and 80%, or even more are technically possible, although challenging.

However, there are a number of caveats with this research. The modelling of energy supply changes is necessarily crude as that is a very wide topic in its own right. Grid electricity decarbonisation is essential to achieve an 80% reduction. This impacts on domestic sector modelling, since the grid is currently a more carbon intensive way of satisfying domestic heat requirements than using a domestic gas boiler. However, as the grid supply becomes cleaner, satisfying heat demand via electricity will become environmentally preferable, although economics may still make the gas boiler preferable. This sort of change will also have a significant lag due to the need to overcome the existing installed base of gas boilers. There is therefore a danger of being locked into old technology as and when grid electricity improves.

Nevertheless, this model provides a good introduction to bottom-up stock based models, as it follows the basic operating method of essentially having a starting point and then applying external factors that create a rate of change in the system. Then, by making changes different scenarios can be analysed, and it is in this manner that bottom-up models can be used for policy analysis. So different scenarios can be based on different sets of policies and the respective performance of each set of policies can be measured and compared. However, this does highlight a potential issue with modelling, although there are similar issues with any forecasting method, in that the output is highly dependent on the assumptions as to the factors that will change the system and the resulting rate of change. It also raises the issue of the difficulty in judging the accuracy of different models; however, some assessment can be made by comparison with real world data and by comparison with other models.

2.2.4.2 BREHOMES

The BREHOMES model (Shorrock and Dunster, 1997) is also a bottom-up model, but, in contrast to Johnston's, used much higher levels of input data including a large annual market research survey of around 18,000 homes. BREHOMES also uses other data sources, eg: the English House Condition Survey (EHCS) – a government annual survey that included physical surveys of properties. As a consequence of the large input data sets, BREHOMES differs significantly from Johnston’s in the level of disaggregation as it separates the dwelling stock into 1,000 different categories. This allows for much finer consideration of changes to the housing stock. Also, as it has been compiling data annually it has good historic trend information. In the same way as Johnston's model, each of the model's dwellings is individually modelled to estimate energy demand and emissions, again using a form of BREDEM. Also in the same manner as Johnston's model, BREHOMES provides a default scenario, Reference, to provide a base line against which other options may be compared, the main alternative scenario originally considered was called the Efficiency scenario. This was earlier research – 1997 – than the Johnston work and consequently is not pursuing targets of 60% or more. Therefore the Efficiency scenario is less ambitious and predicts a saving of 13% in 2020 relative to 1995.

This model demonstrates the need for a high level of data to increase the resolution of the model. The extra levels of detail should not only enhance the accuracy of the overall prediction, but should be able to allow for a more accurate prediction of the diffusion trends of individual technologies.

This model also illustrates a potential problem with different models, in particular comparing them. Since they project into the future it is difficult to determine their likely accuracy. One option is to compare outputs from different models, although this is often difficult because they frequently have different start and end dates and will include different scenarios. Furthermore, many models are either proprietary, no longer being developed and no longer available, difficult to use, or do not publish all their assumptions, so it is usually not possible to take the same scenario and run it on several different models for comparison purposes (Lee and Yao, 2013). Newer models tend to have resolved the end date issue, since there is now a general consensus on targets focussing on a 2050 end date, both nationally and internationally. Therefore newer models tend to include projections to 2050, although they may include earlier dates, principally 2020 and 2030, for which there are subsidiary targets and which can act as staging posts on the way to 2050.

2.2.4.3 UKDCM2

The UK Domestic Carbon Model (UKDCM2) (Hinnells et al., 2007) is a newer model than BREHOMES, and it operates with 2050 as its main target data. It then functions in broadly the same manner and is a large scale highly disaggregated model with around 20,000 dwelling types available. As with both Johnston's and BREHOMES, the individual dwelling modelling is carried out using BREDEM. UKDCM was used to produce the Home Truths (Boardman, 2007a) report, which indicated a possible pathway to an 80% reduction. In the same way as the previous modellers Boardman uses a Reference or BAU scenario as a continuation trend of the current rate of progress and also provides alternative scenarios for increased efficiency. These extra scenarios are produced via backcasting, that is a target is set, eg: 60% or 80% CO_2 reduction in 2050, and then the model works backwards from there to determine a possible route to that target. Home Truths provides some policy suggestions to achieve the required levels of improvements for the various scenarios. However, these policies depend upon various levels of compulsion to achieve the necessary uptake rates of technological improvements, which will be difficult for any government to be able to successfully achieve through legislation.

Therefore this shows a weakness in existing bottom up modelling, in that the scenario modelling in Home Truths describes what is technically and theoretically possible with limited consideration of what is genuinely achievable, as it does not consider whether individuals will carry out the required improvements, or the political limitations on mandating changes to people's homes. By way of illustration the 80% pathway requires a large increase in installations of low and zero carbon (LZC) installations, as in Table 2-2 (Boardman, 2007a):

Table 2-2 Low- and zero-carbon installations in existing houses, UK 2005-5050

Year	2005	2011	2050
Total installations	107,200	228,200	25,000,000 (1 per dwelling)

Therefore this pathway requires a massive step change in the rate of installations to over half a million per year (ignoring the further installations required to replace units that fail during the remaining four decades), as against an installation rate of a few tens of thousands per year in the period from 2005-2011.

This therefore demonstrates the usefulness of a highly disaggregated physically based bottom up stock model, in that it has sufficient resolution to allow the tracking of the adoption of different technologies, and the relative effectiveness of different adoption rates. Such a model can also have policy implications in that it is possible to test some policies. However these tend to be policies that mandate a change (eg: banning the sale of non-condensing boilers), as opposed to policies that aim to alter behaviour (eg: a technology subsidy), where changes will be optional rather than compulsory. This is because the traditional physical models, although they model the dwellings well, do not consider the dwelling owners, and include no understanding or simulation of their actions, and improvements to a dwelling will only take place when the owner decides to carry them out. Therefore there is a need to further develop stock based models to be able to not only model an individual dwelling, but also to model that dwelling's owner's decision making behaviour as regards energy efficiency improvements.

2.2.4.4CANADA

In Canada there was the Canadian Residential Energy End-use Model, CREEM (Farahbakhsh et al., 1998), which was later developed into the Canadian Residential Energy End-use and Emission Model, CREEEM (Fung et al., 2000). As the name change indicated the later version includes emissions, whereas the previous version was solely concerned with energy. This is an important addition since different energy production methods produce different levels of emissions, similarly different energy demands can be satisfied in different ways that also affect emission levels. This model was disaggregated and used a representative model of the housing stock. However, it came across one of the major issues with bottom-up modelling, in that it was difficult to develop a sufficiently detailed model of both the housing stock and its usage. The model was developed, however it excluded high rise flats, which account for approximately one third of the Canadian housing stock, obviously limiting the model's usefulness. They report that they excluded flats due to problems with modelling their community heating systems, such systems – combined with the physical properties of flats (reduced external surface area) would suggest that flats are likely to be more efficient than the average of the housing stock. Therefore this model may well have issues in accurately predicting average emission levels. Since then there has been further work on a new Canadian model (Swan et al., 2009), also using a disaggregated housing stock database, but still suffering from the omission of flats. Although this is a significant limitation, it can still be a useful tool, especially if it is used primarily to consider available improvements because improvements are often limited in flats (eg: a mid-floor flat cannot have PV panels on its roof).

As can be seen with the issues faced by the Canadian modellers, obtaining sufficient rigorous data for a comprehensive model can be problematic, and frequently modellers are forced to make assumptions and apply restrictions to the applicability of their models.

2.2.4.5 USA

In the USA there is the Residential Sector Demand Module of the National Energy Modelling System of the Department of Energy (Department of Energy, 2005). As with the other models, this is a disaggregated model, used as an analytical tool to consider legislation, the private sector and technology that affects the residential sector. It provides demand projections on a six stage process:

i. Forecast housing stock levels
ii. Select appropriate technologies to meet various energy demands
iii. Forecast different appliance stock levels
iv. Forecast changes in building shell performance
v. Project levels of distributed energy generation equipment

vi. Calculate energy consumed in meeting the energy demand

This model attempts to predict the choices between different technologies by using technological learning rates, and a learning parameter for the take up of new technology.

Technological learning rates and learning curves are a way to estimate the future cost of a technology, principally based on the initial cost and the number already produced. This is therefore a mathematical way to represent the typical falls in the cost of a technology as the manufacturers learn how to be improve the production process and installers learn how to install it more efficiently. Equation 2.2 shows the simplest form of a learning curve that describes the price of a technology falling over time (Pan and Kohler, 2007):

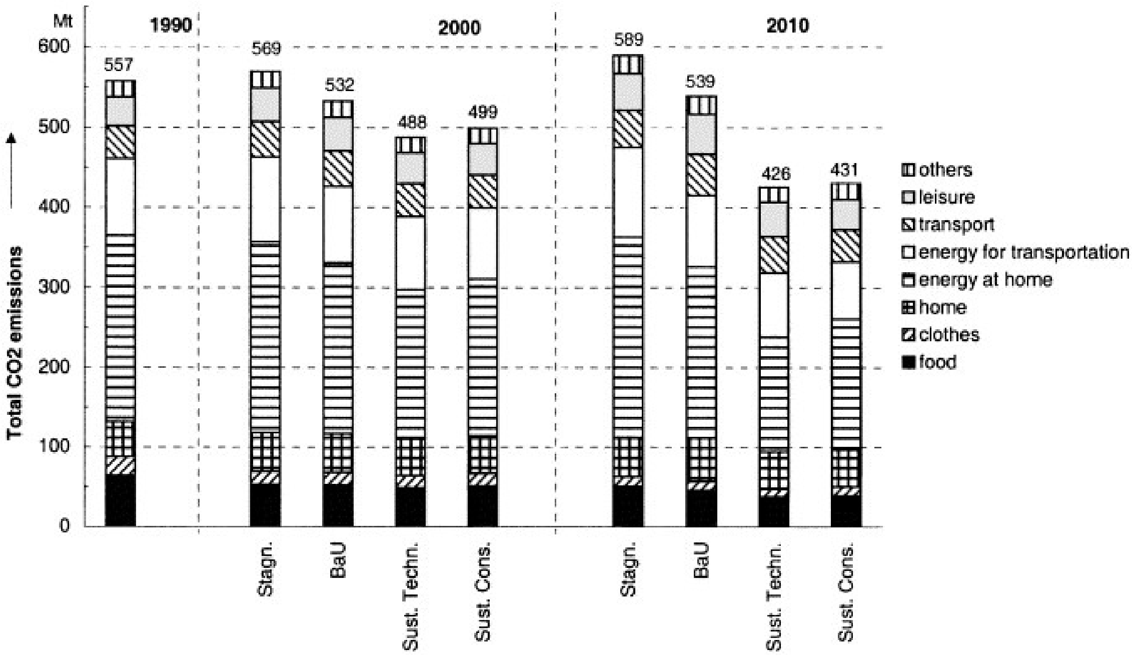
$$C_t = C_0 X_t^{-b} \qquad [2.2]$$

X_t is the total production at time t, b is the learning rate, C_o is the initial production cost and C_t is the cost at time t. Therefore, in long term models equations of this form can be used to estimate the future prices of technologies. However, care needs to be taken as the non-linear form means they are very sensitive to changes in the learning rate (McDonald and Schrattenholzer, 2001). Nevertheless, they allow for the development of future price profiles for different technology types, which can be used in scenario analyses.

2.2.4.6EUROPE

It should be obvious that a realistic model needs to consider the actions of householders, to this end Weber and Perrels (Weber and Perrels, 2000) have analysed lifestyle effects on energy demand. To do this they analysed national household surveys for Germany, Holland and France. However there were difficulties in collating data due to different data sets, time frames and different frequencies of data collection. Consequently there were too many differences to achieve a detailed comparison of the underlying factors on a trans-national basis. Their analysis considered the total energy use of a household rather than that simply used in the home – (ie: including transport, leisure, etc.) they then broke the data down for different household types. They then developed four scenarios for the future economic position and general attitudes towards sustainability to 2010. Although their model found that the more sustainability focussed scenarios provided a greater reduction this was over a relatively short term and did not include detailed disaggregation to consider in depth changes to the fabric of the housing stock. For illustration Figure 2-2 shows their CO_2 results for West Germany (Weber and Perrels, 2000):

Figure 2-2 Development of total CO_2 emissions induced by households in West Germany between 1990 and 2010



As can be seen they attempted to model all energy use attributable to individual households. The four scenarios provided deal with a range of potential pathways, the Stagnation scenario is largely a worse case; the Business as Usual scenario aims to simply be a continuation of existing policies and trends; Sust. Techn. is 'Sustainability through Technological Breakthrough' which assumes technological improvements; and Sust. Cons. is 'Sustainability through Reflective Consumption' which is prepared to sacrifice economic growth.

2.2.5 MARKAL

The previous subsections have described a number of physical bottom up models that are sector specific. A wider scale approach is taken by the wide range of MARKAL (MARKet ALlocation) models used in a number of countries (Zonooz et al., 2009). In the UK MARKAL has been used for projections to 2050 for policy analysis purposes (Skea et al., 2010). MARKAL is a bottom up model, but is whole economy and energy service driven. As service driven it seeks a least-cost optimisation between supply and demand. As a whole economy model separate sectors are treated to some extent like separate modules. The residential sector is represented as a set of energy demands with appliances satisfying those demands and energy sources providing energy to the appliances (Kannan, 2007a). By taking this appliance driven route MARKAL models are less explicit when it comes to the physical characteristics of the dwelling stock than the stock models previously described (Kannan and Strachan, 2009). This short-coming has been acknowledged and in an attempt to address it to some extent, MARKAL takes inputs from other models. In particular, in the UK domestic sector UKDCM outputs are used to enhance the input data (Anandarajah et al., 2009). Since MARKAL relies to some extent on other models then it gains both their strengths and weaknesses along with the extra data provided, in particular MARKAL is not ideally suited to modelling individual decision making behaviour (Kannan, 2007b).

Nevertheless MARKAL models demonstrate that it is possible to combine models for completeness, so that different sectoral modules can be combined into a whole economy model. They also demonstrate the possibility of interacting with other models to gain extra advantages from the specialisation offered by a particular external model. However, this also shows that where an integrated model of this sort is dependent upon other models weaknesses can only be overcome by improving the underlying models and their methods.

2.2.6 Hybrid Models

The previous subsections demonstrate shortcomings in both bottom up and top down modelling techniques, even when a model is restricted to its specialised use, rather than attempting to use it for all situations. MARKAL models, as described above, are one attempt at overcoming some of the shortcomings by providing a less specialised form of bottom up model. However, that still leaves differences between top down and bottom up techniques. Since top down and bottom up models tend to be used in different ways and for different purposes they tend to reach different conclusions, and the difference between them has been referred to as the energy gap (Koopmans and Willem te Velde, 2001). In an attempt to overcome this various attempts have been made to try and reconcile these differences by producing hybrid models.

One of the early attempts to deal with the differences between bottom-up and top-down modelling was in Denmark (Jacobsen, 1998). In this instance he attempts to integrate the two approaches by combining two models, this leads to a hybrid combination. This still depends on projected penetration rates of technologies from the bottom up side, and macro-economic assumptions from the top down side. When discussing the two different types of approaches these are acknowledged as limitations as the two approaches have different cost considerations. In addition, when combining complex models in this way, it is difficult to determine to what extent the in-built errors of each approach may be cancel each other out, or be additive or multiplicative to some degree.

Similar work was carried out in Switzerland (Frei et al., 2003), the authors acknowledge that there will be no 'miracle model' that will be useful in all situations. This therefore supports the continuance of different approaches for different aims, as long as these differences are remembered and models are not mis-used by being applied to problems for which there are better solutions. They also highlight a significant problem in identifying the elasticities that apply to various policy changes – ie: the strength required of a policy measure to achieve a specific level of saving – unsurprisingly empirical evidence for hypothetical policies is not available. This tallies with Fitzgerald's work in Ireland, referred to earlier, where low elasticities were found in the electricity market. In the absence of empirical evidence it is difficult to determine the limit of the low elasticity and therefore the point at which price becomes more significant. This therefore indicates a requirement for more detailed research into the decision making of individuals.

As these different modelling techniques are based on different approaches and different aims they tend to reach differing and sometimes contradictory conclusions. Koopmans & Willem te Velde (Koopmans and Willem te Velde, 2001) found that there were generally two broad types of conclusion from modelling exercises depending on whether a top down or bottom up approach had been applied. The situation they describe has top down modellers finding that energy demand is increasing faster than energy efficiency improvements, and at the same time the bottom up modellers find a large untapped potential for energy efficiency improvements. The difference between the two general approaches is referred to as the energy gap. They put this gap down to the imperfect market – ie: if people were fully aware they may act more rationally and carry out the economically viable improvements indicated by bottom up modelling. Having reached this conclusion they then developed an integrated model. This relies on energy conservation supply curves (CSC), these show price sensitivity, however it essential to find the right discount rate to apply to future savings. When considering the discount rates they report work by Velthuijsen (Velthuijsen, 1995) in which firms were looking for a payback period on investment of 5-6 years, which equates to a discount rate around 15%, which is clearly higher than the market investment rates which were then around 5-8%. However they also report Koomey & Sanstad (Koomey and Sanstad, 1994) finding even higher implicit rates of 25% in reality. These rates are being applied primarily to companies rather than private householders; there is a typical assumption that firms act more financially rationally than private individuals. This suggests the appropriate discount rate that needs to be applied for households is likely to be higher – ie: a shorter payback period is required. In addition their model relies on 40 technical changes across 19 sectors – whilst this allows them to attempt to model the entire economy it means that there is insufficient disaggregation in individual sectors and greater separation would also facilitate the use of different discount rates for each different sector. Again, this suggests it is important to consider economics and behaviour and identifies a need to attempt to collate sufficient data to be confident in the assumptions used in a model.

Drouet et al (Drouet et al., 2005) produced a hybrid model for Swiss housing. They reported that there is limited economic feedback in a traditional bottom up model and this leads to them being prescriptive rather than descriptive – ie: providing a back casting from desired end points, rather than forecasting. Their hybrid system relies on ETEM – a version of MARKAL to provide the economic perspective – however in so doing it assumes perfect information and rational decision making and similar perfect market assumptions (ie: that all actors have access to all the relevant information and use it in an economically rational manner to maximize their economic situation). They then run the top-down and bottom-up segments and feed their results into each other to provide the hybrid result. They then run different scenarios with various carbon taxes designed to achieve a desired reduction (tax levels were set according to the top-down component's calculation of the required tax level to achieve a desired CO_2 reduction, which was varied from scenario to scenario). In doing so they found that the generated carbon reductions were as a result of fuel changes on the supply side rather than technical improvements to properties so there was limited demand reduction.

2.3 Model summaries

As can be seen, the different bottom-up models essentially follow the same structure of requiring high levels of disaggregated data, so that technological changes can be considered together with the rate of uptake of new technologies, thus leading to predictions of future energy demand and emission levels. However, they lag behind the top-down models in being able to consider economic issues. Consequently they are able to quantify the technical potential for improvements but are weak at considering the economic viability of technical measures. This is broadly the conclusion of Swan and Ugursal (Swan and Ugursal, 2009) and Kavgic et al (Kavgic et al., 2010) – that bottom-up models are better for modelling detailed technical changes, but are weak at economic and behavioural factors. There is therefore a clear need for increasing the capability of bottom-up models at responding to economic and behavioural influences. Since there are short comings in existing bottom up modelling, for completeness it is necessary to consider further models to identify the extent to which the lack of decision making has been addressed in the current state of the art, Table 2-3 therefore provides a useful summary of a comprehensive range of UK models together with some additional models from other countries (Lee and Yao, 2013).

Table 2-3 Summary of a representative sample of models

Model Name/ Authors, Country	Summary & Advantages	Disadvantages
BREHOMES (Shorrock and Dunster, 1997), UK	BREDEM based, 1000 dwelling types, weighted stock transformation, scenario analysis to 2020 (later extended to 2050)	No modelling of buying decision making
Johnston (Johnston, 2003) UK	BREDEM based, 2 dwelling types, weighted stock transformation, scenario analysis to 2050, highest possible saving 82%	Disaggregation too low for analysis of technology diffusion, no modelling of buying decision making
UKDCM2 (Hinnells et al., 2007), UK	BREDEM based, 20000 potential dwelling types, weighted stock transformation, scenario analysis to 2050 including 80% reduction	No modelling of buying decision making
DECarb (Natarajan and Levermore, 2007a, 2007b), UK	BREDEM based, 8064 dwelling types per age class with an initial 6 age classes	No modelling of buying decision making
CDEM (Firth et al., 2010), UK	BREDEM based, 47 dwelling archetypes as averages of dwelling stock	Lack of scenario outputs, no modelling of buying decision making
DECM (Cheng and Steemers, 2011), UK	BREDEM/SAP2005 based, 50 initial dwelling types, allows for regional analysis, includes an element of social modelling in predicting energy demand.	No modelling of buying decision making

CREEM (Farahbakhsh et al., 1998), CREEEM (Fung et al., 2000), CHREM (Swan et al., 2011), Canada	Several versions produced. Latest – CHREM: c: 17000 unique house descriptions. Latest version incorporates artificial neural network (ANN) to predict demand	Deals with houses only, not flats. No modelling of buying decision making
Chen et al (Chen et al., 2008), China	Statistical sample led collection of energy use and building characteristic data	Early stages, predictions and policy implications not yet available
Georgopoulou et al (Georgopoulou et al., 2006), Greece	Combined residential and commercial buildings 72 categories and 17 reduction measures. Scenarios based on technically feasible and economically feasible measures	No modelling of buying decision making
Steemers & Yun (Steemers and Yun, 2009), USA	3358 dwelling stock – reduced to 2718 for cooling, includes socio-economic factors when considering heating and appliance use	No modelling of buying decision making
Yucel & Pruyt (Yucel and Pruyt, 2011), The Netherlands	3 dwelling archetypes, 9 household types. Attempts to model typical buying decisions based on economic viability.	Real technologies not used, decision making purely economic, limited stock disaggregation

It is interesting to note that all the UK based models use a form of BREDEM or SAP as their basis for modelling the individual dwellings in their stocks. A SAP based approach is therefore clearly the currently preferred medium for UK stock modelling and its influence is likely to continue with the use of SAP for both satisfying the EPBD requirements and also for Green Deal calculations. Its use as the basis for Green Deal calculations, further supports its use for stock modelling that includes technology purchase decision making, as the running cost savings estimates that will be provided to householders will be based on a SAP calculation. However, SAP itself uses just one occupancy profile, therefore a decision making simulation based on SAP's predicted savings may provide an incorrect result for extreme households whose energy use is a long way from SAP's standard profile. Although using SAP will make it easier for subsequently increasing the resolution of a model by incorporating changes to the SAP profile based on Green Deal version of SAP.

From Table 2-3 it can be seen that work is beginning to be carried out to consider the inclusion of behavioural elements in bottom-up stock modelling. In particular Yucel and Pruyt (Yucel and Pruyt, 2011) included 9 household types with renovation driven improvements based on economic viability. However, this was limited research and more in the form of a prototype as its use of real world data was severely limited with only three dwelling types and simulated as opposed to real improvements available.

Distinct from the bottom up modelling there have been several studies considering relationships between household type and environmental behaviour (Yao and Steemers, 2005; Streimikiene and Volochovic, 2011; Yu et al., 2011). Such research has typically involved producing a small number of distinct profiles of household type that will have distinct behaviour patterns. Although such research is primarily concerned with day to day activity (eg: hours per day at home), as opposed to the one off decision making behaviour involved in considering the purchase and installation of energy efficiency technology. There has also been research to estimate the potential effect from achieving behavioural change with day to day activities (Wilhite and Ling, 1995; Wood and Newborough, 2003; Abrahamse et al., 2007; Ouyang and Hokao, 2009). Such research typically finds there are savings available in the order of 5-10% by achieving more pro-environmental behaviour with day to day activities; this is an empirically based indication of the potential level of savings that might be expected as opposed to a theoretical maximum for behavioural changes. If this indicates the likely extent of demand reduction available from day to day behaviour change, then it emphasises the importance of physical improvements to the dwelling stock. It therefore further highlights the need to understand the decision making processes, and the influences on behaviour, that will affect the installation rates of the different energy efficiency technologies available for the home. In addition, it can be expected that over the long term day to day behavioural changes may begin to impact on one-off decision making by making individuals more environmentally aware (Jackson, 2005).

It can therefore be seen that there are a range of models with different purposes, abilities and limitations, an interesting graphical illustration is made in Figure 2-33 (Hourcade et al., 2006):

Figure 2-3 Three Dimensional Assessment of Energy-Economy Models

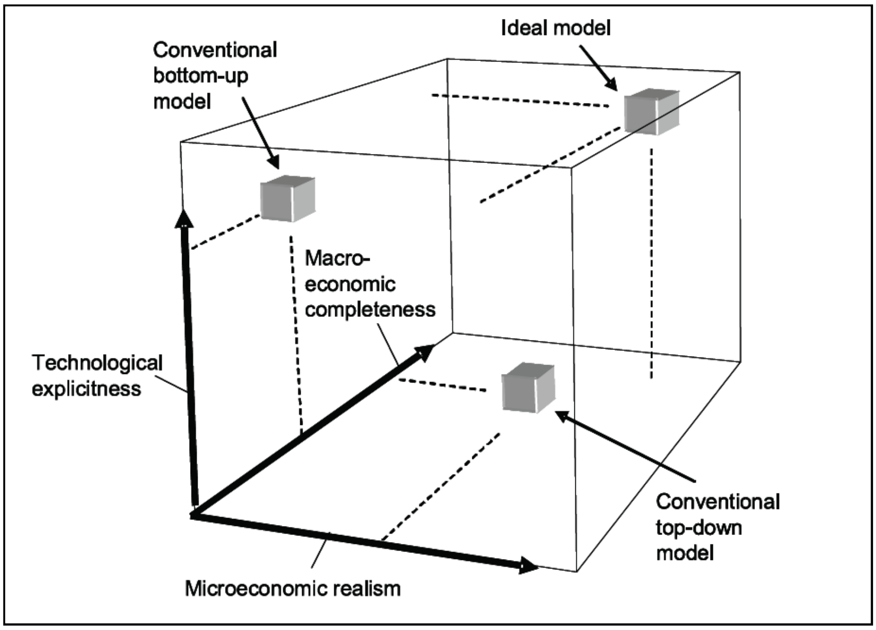


Figure 2-33 (Hourcade et al., 2006) displays the weakness of both top-down and bottom-up modelling types in considering the microeconomic scale. This ought to be an essential component in any type of long term energy modelling, but is of especial importance in the housing sector. This is due to the heterogeneity of the housing stock and the fact that decisions need to be taken by individual households – ie: there are different types of people in different types of houses and those houses will only be improved when people make a decision to carry out an improvement. This heterogeneity of the stock, and the important role of individual households, means that a way needs to be found to incorporate into a technology rich bottom-up model a suitable simulation of the decision making process of individual households, as it affects the thermal properties of the dwelling and its heating demand.

2.4 Chapter summary

This chapter has provided a literature review of energy modelling, and in particular long term domestic energy models and methods. It has identified bottom up stock modelling as the most appropriate method for long term stock transformation analysis. It has also been found that UK based stock models use some version of SAP, or its precursor BREDEM, to model representative dwellings in their models. This has generally been a practical consideration since SAP is well established in the UK, it is relatively straightforward to fit stock energy efficiency data, and it is also practical to use it to model thousands of different dwelling types without an excessive workload.

The major short-coming that has been identified in these stock models is a lack of modelling individual decision making. It is the decision making of individuals that will drive the uptake of energy saving technologies. Consequently stock modelling can be improved if individuals' decision making can be incorporated into a bottom up stock model.

Therefore the main aim of this research is to identify a suitable method to simulate the decision making process and then use that method to develop a novel physically based bottom-up stock model for policy analysis in the UK housing sector.

The next chapter therefore considers consumer behaviour and decision theory and reviews potential methods to incorporate decision making into a stock model.

Chapter 3 Research Methods

3.1 Introduction

As discussed in the previous chapter, physical stock based bottom up models are the most appropriate method for carrying out long term modelling to track changes to the dwelling stock. However these models, while suited to modelling individual dwellings, do not model the individual households and their decision making processes, and it is their decision making that ultimately decides whether or not a particular energy saving technology is installed or not. This chapter therefore begins with an examination of consumer behaviour and technology diffusion, it then identifies potential techniques for being able to incorporate individual decision making into a traditional style stock model.

3.2 Consumer Behaviour

A successful long term domestic energy stock model that aims to incorporate the actions of individual householders necessarily needs to be able to represent some element of individual householder – that is consumer – behaviour.

Consumer behaviour can essentially be broken down into two types – habitual and one off behaviours (Solomon, 2004); although clearly there is a continuum from activities that happen several times a day (eg: turning lights off), through activities that happen approximately weekly (eg: grocery shopping), all the way to activities may happen only once a decade, or even less frequently (eg: moving house). For energy modelling purposes habitual behaviour would be more of interest to load profiling researchers, eg: one type of consumer may use their shower at 7am every day whereas another type might run a bath once a week. As can be seen this sort of behaviour consists of regular and repeated activities that can be used to estimate short term demand. In contrast to this regular behaviour, one off, or very infrequent, purchases will operate in a different way as the habitual norms associated with regular behaviour will be markedly less important when it comes to estimating the effect of the different variables impacting on the decision making process for infrequent behaviour. However, the underlying habitual norms are likely to impact on the attitudes of an individual when considering a one off purchase (Evans et al., 2006).

The main focus of stock transformation models is on changes to the dwelling stock; these arise from one off decisions – the infrequent purchase of energy saving technologies – as opposed to habitual day to day behaviour. Therefore the decision making behind a one-off purchase is more relevant for long term stock modelling than changes to habitual behaviours, although it should be remembered that changes to habitual behaviours (eg: turning the heating thermostat down) do have the potential to provide further savings on top of those that are purely the result of installing new technology.

At its most basic level this can be broken down into a very simple three stage process:

i. need for a new product identified
ii. potential options evaluated
iii. preferred option chosen.

Therefore, in order to simulate this process, it is necessary to gain an understanding of how the need is triggered and how consumers might evaluate different options. The following paragraphs review a number of different texts concerning the factors that influence consumer behaviour, and in particular energy and environmental related behaviours.

In his book, Solomon (Solomon, 2004) discusses consumer behaviour. One of the first points made is that consumers need exposure to information, otherwise they will not be aware of their choices. An important element of the decision making process is the requirement for some form of motivation to create a goal which then requires a drive towards achieving that goal, this leads to a want as a manifestation of a need. It is clear that consumers vary and therefore the outcomes of their decision making will be similarly variable. In order to aid in understanding the differences two high-level personality types are identified: so-called idiocentrics who have an individualist orientation, and allocentrics with a group orientation (from these basic levels rather more personality sub-types can be identified). Together with this, an important aspect of consumer behaviour discussed relates to group influence and opinion leadership. People tend to have a social reference group with which to compare themselves, this can often be an aspirational reference group (effectively keeping up with the Joneses). The group mentality can mean that some consumers tend to follow something of a herd instinct in decision making, and thus their behaviour is influenced by the group.

When consumers are making a decision Solomon identifies the following decision making process: problem recognition; information search; evaluation of alternatives; product choice; outcomes – this is essentially a slightly extended version of the simple three stages previously identified. Three types of decision making are identified: extended problem solving, limited problem solving and habitual decision making; deciding into which category a particular decision falls depends mostly in its regularity, expense and complexity. Irregular energy efficiency purchases will either fall under the extended or limited problem solving categories; the complexity and expense involved will tend to impact on the amount of searching that is carried out when contemplating a new purchase. Also, it can be anticipated that there will be differences between discretionary purchases and items that are needed urgently (eg: the breakdown of the heating system will need to be dealt with more quickly than considering the installation of solar photovoltaics). When selecting amongst alternatives a decision making rule is required; in the vast majority of real world cases this is not explicitly stated but for any modelling exercise rule based heuristics will be required to drive the decision making process.

Solomon provides a brief summary introducing decision making rules stating that there are essentially two broad decision making processes available: compensatory or non-compensatory. With non-compensatory rule sets the choice will usually be either an elimination by aspects rule, where products are eliminated according to missing features until only one remains; or it may be a choice of the product that is the best at a particular feature. In comparison compensatory rule sets allow the decision maker to include all the product’s attributes but to give different weightings to each element to find an optimum solution.

Frank (Frank, 2009) considers consumer behaviour from a microeconomics perspective. He begins by considering a simple cost/benefit analysis, this states that if the benefit of *x* is greater than the cost of *x* then the logical solution is to do *x*. However, it can be difficult to determine the total benefit value and the total costs. Implicit costs often get ignored, for instance in doing *x* not only is there the explicit cost/benefit of doing *x*, but there is also the hidden cost/benefit of therefore not doing *y*, or indeed doing nothing at all. In calculating the total cost there is the question as to whether or not to include sunk costs (especially in cases where plant has already been purchased), this can have a significant impact on the decision making process. Quantification of benefit by consumers is frequently an issue, ie: people are able to say that *x* is better than *y* but are unable to put a value on the difference. There are then income and substitution effects due to price changes; so, as the price of one product increases an alternative product may become more attractive. A number of elements are then identified as determinants of price elasticity: the availability of substitutable products; the share of the budget taken by the good; the direction of income effect; and time, time needs to be included because some measures to deal with price changes take time to take effect. Consideration of price elasticity can become important in forecasting economic trends, in that a tipping point may be reached for a particular product beyond which its demand may begin to change dramatically.

3.2.1 Energy efficiency related consumer behaviour research

Moving on from the general consumer texts there has been work concentrating on energy related behaviour. In Australia there has been behavioural research (Randolph and Troy, 2007) to consider changes that people might carry out. Amongst their survey findings 70% of respondents said they intended to do something about energy efficiency in the next 12 months, which rather begs the questions as to why they didn’t do something in the previous 12 months and will they have actually done something in

12 months' time? The actions that were being taken were not significant ones but fairly small ones such as turning down heating and lighting, as opposed to any installations of technology or insulation. Further results from this research indicated that energy price rises of at least 25-50% would be needed to begin to encourage energy savings. The research also recommended increased education, information and encouragement, together with a clear lead and example from the government.

In Belgium there was quite extensive research carried out into the socio-technical factors affecting residential energy use (Bartiaux et al., 2006). Their starting point was that residential energy use has been steadily increasing in the preceding decades and that behavioural change is needed to achieve significant change and improvement. They had three data collection methods: the first was a simple telephone survey; the second consisted of a quick energy scan, an energy diary, complete energy assessment and recommendations; whilst the third method was in depth interviews. Where recommendations were made only 11% had been carried out after one year with a further 23% expected to be carried out in the following year and these tended to be smaller measures, eg: adapted shower heads. This therefore shows, that even with direct and tailored recommendations being made, that there is considerable lethargy when it comes to energy efficiency improvements. Therefore increased knowledge is needed together with a mixture of subsidies and regulations together with governments leading by example.

An interesting project was the Kirklees Warm Zone, which ran from 2007 – 2010 (Edrich et al., 2010; Liddell et al., 2011). Under this scheme a concerted effort was made to contact all the households in the Kirklees area to offer free assessments together with free loft and cavity wall insulation. Clearly this was a heavily subsidised scheme, as it was not only providing the measures for free, but also providing the manpower to visit every property on a ward by ward basis with heavy advertising and information campaigns at the time each council ward was being targeted. There are some telling figures concerning the up-take rates, which are shown in Table 3-1:

Table 3-1 Kirklees Warm Zone Outputs

Item	Total
Households Visited	165,686
Assessments completed	133,746
Referral to insulation contractor[1]	111,394
Dwellings surveyed	94,788
Homes receiving insulation measures	51,155
Households requesting free carbon monoxide alarm	129,986
Households requesting four free low energy light bulbs	111,714

1: Excludes Council owned dwellings dealt with under Decent Homes

It is intriguing to consider the take up rate with this large scale free offer; as can be seen out of the dwellings where an assessment was completed there was a very high take up of a free carbon monoxide detector (97%) and some free light bulbs (84%), which indicates that there was awareness of what the scheme had to offer. However, the take up rate of the free insulation measures was much less (46%), even allowing for dwellings where the measures were not appropriate. This therefore demonstrates that even a free offering is still not good enough for some households, such individuals seem to put a very high value on the disruption associated with technology installation, and therefore shows that an individual based model needs to be able to include individuals who do not act in a purely economically rational manner (ie: they do not seek to maximize their economic position).

Rivers & Jaccard (Rivers and Jaccard, 2005) have considered firms' energy efficiency investment decisions. Although they were considering industry rather than the domestic sector they highlighted a number of factors that are still applicable in the domestic sector. They pointed out that energy efficiency investments are irreversible – ie: once you've made the investment you cannot at a later stage cash the investment in – as a result this will push up the discount rates, since the investment can no longer be liquidated into cash that could be used elsewhere. As technology is more widely adopted the price tends to fall due to technological learning; it can be argued that this can penalise the early adopter who pays more to get the technology early, whereas the later adopter will pay less and may well get a superior version of the technology. Again this may impact on the appropriate discount rate to apply since the advantage to be gained from early adoption is reduced by the lower cost for later adoption.

In order to achieve the targeted large scale reductions in CO_2 emissions, it is self-evident that behavioural change is needed. This is discussed by Jackson (Jackson, 2005) who considers consumer behaviour and behavioural change. He raises a number of issues and suggestions for behavioural change. He points out that there needs to be a mind change such that an ecological position becomes the social norm, and at the same time habitual behaviours need overcoming and changing. He also points out that behaviour is complex and different positions on different things will interact with each other. At the same time there is something of a re-enforcing cycle where behaviour influences attitudes, which then influence behaviour. This cycle then needs to be turned to the energy efficiency advantage, so that it becomes a positive cycle to encourage energy efficiency activities. When considering a change he identifies a number of questions that need to be considered: What is the potential impact of the proposed behavioural change? What are the barriers to change? What resources are needed to overcome the barriers? By analysing these questions it should be easier to formulate a successful policy. He also raises the differences between a one off purchase decision and long term behavioural change – whilst it may be possible to affect the decision on a one off purchase – achieving long term behavioural change needs regular reinforcement of the message to ensure the change is maintained. He points out that in most instances a mixture of information, subsidies and taxes (and as a last resort, compulsion) are needed to encourage behavioural change.

To try and analyse the behavioural and choice perspective Ipsos Mori (Ipsos Mori, 2009) carried out detailed research amongst individuals and in group sessions. Part of this was in the form of locally based public dialogues, giving members of the public an opportunity to air their views. There is a balance to be made between money and the environment, and amongst the public that balance would currently appear to be swayed more towards money than the environment. They found that the environment is typically given a fairly low priority, and there is concern over the cost of improvement measures – especially if loans are involved – it is also likely that the current economic situation has exacerbated this concern. They identified the stages that people go through when considering an action: contemplation, preparation, action, maintenance – followed by further action as stages in improvement. They also highlighted a distinction between upfront costs, actual payback and value added that are all taken into account when considering an energy efficiency investment. A declared unwillingness to spend can be a way of expressing other barriers to change, rather than just the purely economic situation. Some members of their panels wanted government enforcement to ensure action – this also may have been to ensure that everyone participated and contributed rather than just them with others sharing some of the benefit. Panel members were focussed on the costs – especially the initial upfront costs and were therefore pushing for significant grants and subsidies – much higher than those currently being offered. Concerns were also raised that early adopters are penalised as the technology improves and becomes cheaper over time – this is especially the case with products that are expected to last twenty-five years or more. There was a general consensus that if people are left to their own devices little will happen. There were also suggestions for a phased introduction of minimum standards to force improvements bit by bit, similarly an anti-waste campaign could help in establishing an attitude that energy efficiency should be the social norm and that inefficient behaviour should become socially unacceptable.

DEFRA (DEFRA, 2008) devised a framework to encourage environmental behaviour. In this they have three headline behaviour goals: to install insulation; to have better energy management and to install micro-generation technologies. There are campaigns in other areas, which, whilst not directly aimed at domestic use should have a re-affirming affect in achieving an overall mind change to a social norm of pro-environmental behaviour. It then suggests a broad strategy of using the existing limited mandate for change to focus on behaviour and then put products and services at the centre to build collective action and then use that collective action to widen the mandate, thus generating a virtuous re-enforcing circle. They also raise the distinction between habitual behavioural change and change for one off purchases. Following from that there is a section discussing various common motivators and barriers to change, from this they find that there is an expectation for the government to lead, not only by policy but also by example.

Xu et al (Xu et al., 2007) have considered green buying with a network perspective. This adds the dimension of interaction between members of a network in their buying decisions, by adding this element domino effects may come into play (ie: peer pressure). Buying green can be potentially disruptive and innovative to a network. They quote a very good summary of the situation from the Sustainable Consumption Roundtable (Sustainable Development Commission, 2006), “I will if you will.” They therefore find that consumers will if businesses provide cost effective products and the government provides suitable incentives to make the investment and dis-incentives to not investing. In addition government needs to lead by example in its own purchases, as well as providing a regulations and incentive framework for others to use.

Brohmann et al (Brohmann et al., 2009) considered the empirical research available and produced a number of findings. To encourage more sustainable consumption behaviour will require awareness raising and changed social and economic structures. They also point out that from an economic perspective demand for energy is a derived demand – ie: people do not want energy in and of itself, but, in order to provide for some other need. Two types of behaviour are identified: usage, that is day to day; or buying, that is the investment phase. Amongst the research they reviewed they found some evidence that richer households are more energy aware, although it would be difficult to distinguish such a correlation from one between energy awareness and educational level achieved. They also found research that suggests that improved billing information can induce demand reductions of around 10%. There was also research indicating that people installing micro-generation are more likely to alter habits and use or install other energy efficiency measures. However, they acknowledge that this relationship maybe the wrong way round; since micro-generation tends to be less cost effective than insulation, it would make more sense for people to move onto micro-generation after they had invested in insulation, rather than before. There are therefore two instances here where it is difficult to know what the true relationship is that is being observed. From their review they generated five general hypotheses that appear to be applicable to residential energy efficiency: i) sustainable energy use is influenced by income ii) larger houses are more likely to have energy technologies iii) greater information provision, better billing and live running cost information tends to lead to a reduction in expenditure iv) at very high prices people become more responsive to further price rises v) attitudes and preferences are decisive.

Mahapatra and Gustavsson (2008) wanted to analyse the effectiveness of subsidies on the diffusion of new domestic heating systems. In order to do so they took an adopter-centric approach, as this is clearly reliant on the choices of the end user. In this paper they were concerned with Swedish policy to phase out oil fired and resistance (electric) heating. There was a 30% subsidy available for innovative heating systems, and with this in place they found that the diffusion patterns of the different technologies differed. The annual installations of pellet burners increased 100 fold from 1994 to 2006 but that still only took them from 300 to 32,000 installations per year; whereas heat pumps had an increase over the same period from 2,700 to 40,000 per year. This is a rate seven times less than that for the pellet boilers, but the net positions of 32,000 and 40,000 installations a year are broadly comparable, which may indicate that both technologies will end up with a similar market share. Their analysis could have been at the macro-level or at the micro-adopter centred level, which is the route they chose as the cumulative effect of individual decisions whether or not to adopt a new technology is the final determinant of adopter and diffusion rates. To do this they used a Likert scale questionnaire with six sections: A) current system B) different systems and savings available C) rating of different benefits D) rating different systems according to the preferences from section C E) energy and environmental matters F) socio-economic information. They then identified a four stage process for deciding whether to get a new system: 1) Need 2) Plan 3) Collect Information 4) Select. In order for someone to make the change to an innovative heating system, from a conventional type, behavioural change may be needed – and it will certainly need extra thought and investigation (the default position would be that a defective boiler would be replaced with a new equivalent, without considering alternative options). Therefore there needs to be encouragement to consider all the options when replacing the existing system, otherwise there will be a trend to remain with the status quo. Once the innovators and early adopters have adopted a technology it reaches a stage of being self-sustaining. This self-sustaining nature is due to social contagion – ie: discussions between people, so information about the systems diffuses out from the early adopters to their neighbours, effectively the technology diffusion begins to spread out in an epidemic manner. The adopter rates varied, not only for the new technology, but also based on the different existing technologies. This is understandable as there will be particular advantages and disadvantages in moving from one type of technology to another; depending on the existing heating system some new technology may be a better fit and may cause less disruption during installation. The age of respondents was also a significant factor, older householders were less likely to choose an innovative system unless it had a short payback period; the 36-45 year olds were most likely to opt for a new technology. There were also variations with income – there was some indication that higher income households might be more likely to install new technology but the statistical significance of this conclusion was limited. In sourcing information for choosing a new system they found that mass media was useful for general knowledge, but specific recommendations from a respondent's interpersonal network tended to carry more weight. This leads to contagion diffusion spreading out from the innovators and early adopters as already mentioned. Of the factors affecting the choice of system reliability and cost came out highest. Out of those respondents who already had a new heating system, those with heat pumps were most likely to recommend them to others – a higher level of recommendation for a particular technology should give that technology an advantage and lead to accelerated diffusion rates over alternative technologies. In order to maximise the effectiveness of subsidies they need to be targeted according to the specific existing system to be replaced. Installers are an important source of information concerning heating system options, therefore they need training and the ability to discuss and install innovative heating systems. The research also indicated that the initial investment cost was apparently considered less important than the long term running costs, which would appear to contradict some of the research previously discussed, in particular the Ipsos Mori research. In addition environmental concerns did not appear to be a factor in the decision making process; therefore, politicians targeting CO_2 reductions need to consider how to convert their aims into cost effectiveness for the end user.

Eggink (Eggink, 2007) raises some interesting points concerning behaviour and energy usage. One point that is made is that electricity is invisible and therefore any waste is hidden and consequently not obvious – especially to the typical non-expert domestic user. He then describes an experiment that took place in Harvard's Halls of Residence, where energy usage was displayed and there was a competition between Halls to reduce their consumption. In this experiment reductions in usage were achieved of up to 15%, purely through behavioural change. This suggests that education rather than coercion can be a very effective course of action, since this saving was achieved without any technological interventions except for the provision of improved metering information. However, if a law is accepted then it can be very effective, but it needs support and courageous politicians who will be able to steer it through and maintain the policy against any initial backlash. Amongst individuals there is often a perception that the problem is too large for them and instead they want to leave it up to government or big business to sort out; others have a mentality that they will only act if everyone else has to as well; alternatively people can motivate each other into action, as in the Harvard example. He also describes some people who believe 'technology' will save the day, or that 'they' will not let it happen, with no clear idea what that 'technology' might be, or who the mysterious 'they' are; still others are not concerned because to them energy bills are too small, this means that in these cases energy is too cheap for people to be concerned about their usage levels. Therefore there is a challenge in motivating environmental attitudes and behaviours, to this end he provides two lists of various measures. The first set can be expected to decrease motivation and includes: coercion; over-zealous goals; a feeling that the problem is too large; blind faith in technology; increased hassle; a belief that energy is a small cost. Conversely there is his list of positive motivating factors: training and information; peer pressure and team work; measurement and recognition of personal achievement; belief that the organisation is genuinely interested; incentives for good behaviour and consequences for bad behaviour. He then concludes by pointing out that behavioural change needs reminders and reinforcing; in addition commitment is required, together with leadership by example; finally constant vigilance and repetition is required to continually reconfirm the message.

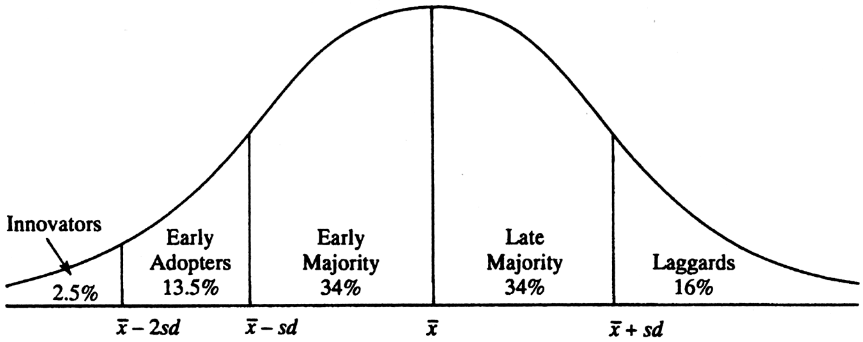
As can be seen there is research attempting to understand attitudes, behaviours and choices, and specifically research looking at consumer behaviour and the diffusion of new energy efficiency technologies. The Mahapatra and Gustavsson (Mahapatra and Gustavsson, 2008) research is of particular interest as it also considers the way people interact in recommending a new technology to others in their social circle. The act of recommending a technology is a very good indicator of the satisfaction level with that particular technology. This is an aspect that is not considered in traditional models, but nevertheless it could have a significant impact on the diffusion of new technologies. It should therefore improve the results from modelling exercises if this information can be incorporated as it can be expected to significantly impact on the relative success of disparate technological solutions.

3.3 Technology Diffusion

The previous section showed that consumer behaviour – in the form of one-off buying decisions – leads to the diffusion of innovations and new technologies into the market. This sub-section therefore provides a brief overview of diffusion.

Rogers' seminal work (Rogers, 2003) provides a comprehensive introduction to the diffusion process. One of the main points identified by Rogers is the heterogeneity of a population when it comes to diffusion of a technology or an innovation. To this end Rogers categorized people's innovativeness, and identified five groups in any population, based on their relative position to the mean theoretical average person, as shown in Figure 3-1(Rogers, 2003):

Figure 3-1 Adopter Categorization on the Basis of Innovativeness



In the case of domestic energy efficiency and long term stock transformation models, the essential component is modelling the adoption of new technologies (or innovations), therefore there is a natural fit with this type of description of a population. If an attempt is being made to model the actions of individuals then, not only does this have parallels with a population distributed around the mean response, but it also allows for a heterogeneous population, which is a strength of an agent based approach to modelling. The important item that needs to be determined is the rate of adoption of particular technologies, Rogers provides three conventional approaches to attempting to determine such a value: firstly, it may be possible to extrapolate from historic adoption rates for similar technologies; some data may be obtainable by describing the features of an innovation to potential adopters and attempting to quantify their responses; or an innovation's acceptability during trial and testing phases can be used to estimate an adoption rate. It is clear that there are weaknesses with any of these approaches, but if the intention is to produce a model that aims to predict the uptake of new technologies, real world data will be limited, and therefore some attempt must be made based on the methods described above.

By reference to a number of previous empirical studies, Rogers (2003) finds that the successful adoption of an innovation typically follows a broadly normal pattern, with an S-curve of adoption, and consequently a broadly normal distribution of individual adopters. If, as Rogers states, '*Adopter distributions follow a bell-shaped curve over time and approach normality*,' then this is a useful approximation when dealing with a heterogeneous population.

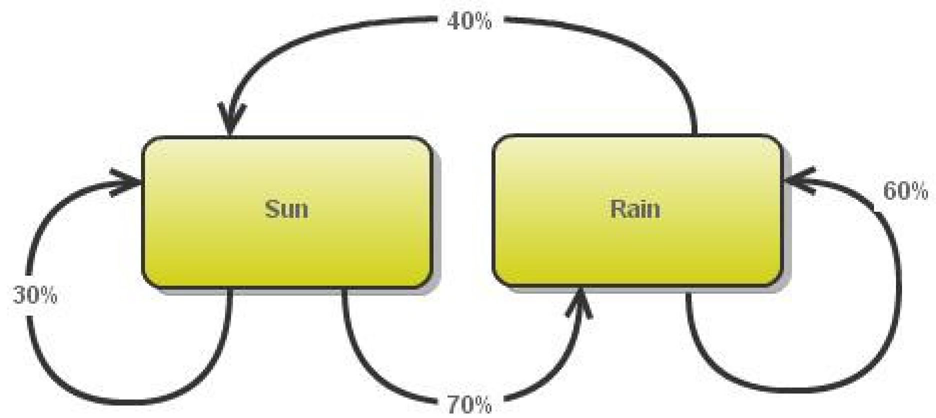
This review of consumer behaviour and technology diffusion has shown that there is a number of basic elements that are required: a trigger, an assessment of options and then a decision and the resulting actions. These are the minimum requirements that are needed for simulating the decision making process of individual homeowners when considering the installation of energy saving measures in their homes. Consequently a technique is required that might be capable of providing such a simulation.

Four possible techniques have been identified, Markov chains, Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and Agent Based Models (ABMs), each of which is briefly reviewed in the following subsections:

3.4 Markov Chains

A Markov chain is used to simulate state transitions, with the transitions dependent upon the relative probabilities of moving from one state to another. In order to operate a Markov chain it is necessary to know all the possible states and the probabilities of moving from one state to another, a simple Markov chain is illustrated in Figure 3-2 (Lee and Yao, 2013):

Figure 3-2 A simple weather Markov chain



This is essentially as simple a scenario as can be, there are only the two states available: sun or rain; if it is sunny today there is a 30% chance it will be sunny tomorrow and a 70% chance it will rain tomorrow; similarly if it is raining today there is a 60% chance it will rain tomorrow and a 40% chance it will be sunny tomorrow. Therefore, in order to determine the probability of a new state the only data that are needed are the current state and the probabilities of changing state (which may include staying with the current state). More formally, in a typical Markov chain the probability of the state at time *t+1* is only dependent upon the state at time *t* (Elaydi, 2005). When it comes to the individual buying decisions of a household the independence from historic states is unlikely to apply – ie: it can be expected that a household's previous experience will impact on its decision making process. Also, a Markov chain assumes a great deal of certainty with constant probabilities of changes of state. However, changes to the probabilities can be expected not only due to changes in a household's experience as previously mentioned, but also over time it can be expected that the likelihood of the installation of a specific technology will increase – at the very least due to rises in fuel prices and falls in installation costs. In addition it can be seen in Figure 3-2 that a return to an earlier state is quite possible in a Markov chain. However, that is not necessarily the case when it comes to improvements to the dwelling stock, eg: cavity wall insulation is virtually a non-reversible improvement. Furthermore, since a Markov chain provides a probability distribution of different states it would be more intuitive to use it at a population level rather than the individual level, since if it were left as a probability distribution at the individual level the end result could be households installing a non-sensible quantity of each technology. Alternatively, if attempting to collapse the probability distribution down to a binary situation (installation or non-installation of each technology) at the individual household level there would be a requirement for very detailed data gathering to compile all the necessary probabilities.

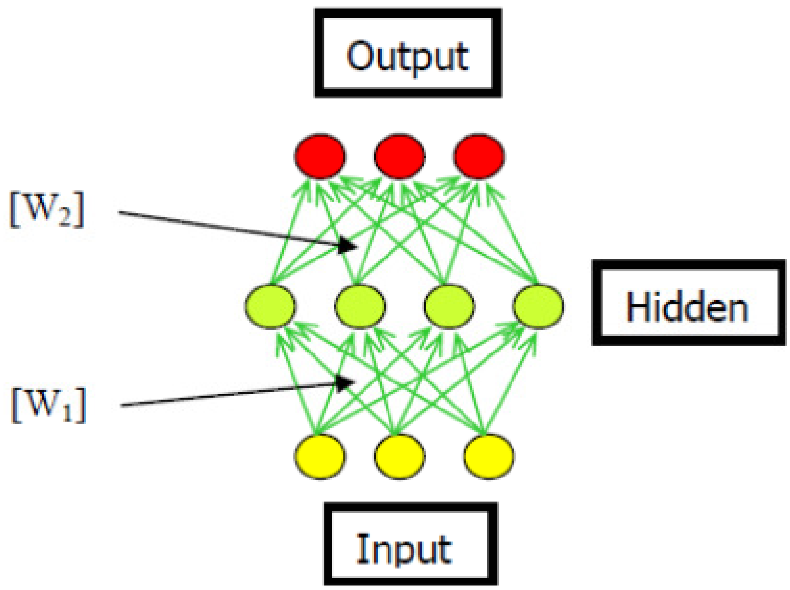
However, Markov chains have been used to some degree in energy modelling, although primarily for short term load modelling which has usually been based on occupancy patterns (eg: (Richardson et al., 2008, 2010; Widén et al., 2009; Ardakanian et al., 2011)). It can be seen that a Markov chain fits more naturally with occupancy patterns, for instance a data set could be compiled with different activities, eg: at home, asleep, away from home, etc., with probabilities for each state transition and energy demands for each different form of occupancy. This is similar to the simple weather pattern previously described and could make a classic Markov chain.

Therefore it can be seen that Markov chains do have their place in energy modelling, but typically with load profiling modelling where there is a fixed set of repeated activities, as opposed to long term stock modelling with one-off and sometimes irreversible decision making.

3.5 Artificial Neural Networks

The next potential method to be considered for incorporating individual household decision making into a stock model is Artificial Neural Networks (ANNs). An ANN has inputs and outputs – these are the two visible layers, between these there will be at least one hidden layer; this layout, with a single hidden layer is shown in Figure 3-3 (Bhatikar et al., 1999):

Figure 3-3 An artificial neural network



As can be seen in Figure 3-3 (Bhatikar et al., 1999) the inputs are mapped into the hidden layer with different weights applied to them, W_1, and then the hidden layer maps onto the output layer with the W_2 weights applied to each factor. A neural network will typically be operated by providing it with an initial data set for which both inputs and outputs are known and the computer can attempt to determine the likely output values based on the inputs. Whilst it is in this training process the weights applied to W_1 and W_2 will be adjusted as the computer 'learns' a way to determine the correct output value. With a complex task there will necessarily be a trade off between accuracy and time spent on the training process and the programmer will need to decide what the acceptable accuracy level is for any particular problem. In adjusting the weights applied to improve the accuracy, an ANN will need to follow some recognised procedure rather than just adjusting at random. Probably the simplest rule, and easiest to understand, is the Widrow-Hoff learning rule, which states: *'when you make a mistake, pay less attention to the input cells that told you to make this mistake, and pay more attention to the input cells that told you not to make this mistake'* (Abdi et al., 1999). Following this rule, an iterative process will take place whereby the weight applied to inputs that suggest the correct output is increased and the weight applied to inputs that suggest an incorrect output are decreased. In this way, by increments, the accuracy of the ANN can be increased, as it learns the relative importance of each of the impact factors. Having been set up with the initial set of training data the model can be validated with a further set of data for which the outputs are known. This can therefore be used as a benchmark to indicate the expected accuracy that will be provided by the ANN once it is finally exposed to new situations for which the outputs are not known (ie: the situations the model has been designed to predict). It can be seen that there is some level of fit between an ANN and an individual household in that the inputs would include data on the household (environmental attitude, previous experience, etc.), information about the dwelling (construction, insulation, etc.), data concerning the technological improvements being considered (cost, saving, disruption, etc.), together with external factors (taxation, advertising, etc.). The output at the individual level would therefore be a prediction as to whether or not that household decided to install a particular technology at that time. This therefore suggests that an ANN approach is quite promising, provided that sufficient training data is available in order to be able to produce a sufficiently robust model capable of dealing with the most likely common combinations of inputs.

Indeed there is already a considerable body of energy modelling research using ANNs. Probably the earliest such research was by Park et al. (Park et al., 1991) where they introduced ANNs for load profiling work, in a similar manner to the energy related use of Markov chains described in the previous subsection. Following on from this there have been many more following a broadly similar path (eg: (Khotanzad et al., 1997; Bakker et al., 2008; Pino et al., 2008). In addition, as discussed in the previous chapter analysing stock models, CHREM (Swan et al., 2011) does use an ANN in a longer term model, developed from work by Aydinalp et al. (Aydinalp et al., 2002) on ANNs. However, in CHREM the ANN is again being used to consider demand modelling, as opposed to using an ANN for studying and predicting the individual household's technology buying decision making process. As well as this demand and load profiling modelling, ANNs have been used in some top-down research (eg: (Ekonomou, 2010; Kankal et al., 2011), in these cases the ANN is essentially being used as an alternative to a regression to provide a prediction of total energy demand based on a limited number of input variables. Therefore it can be seen that ANNs are being used extensively in energy modelling research, but either for load profiling or for general top down modelling.

Due to their set up there is a major limitation with ANNs – this is that they typically operate in a black box manner. During the training stage the model is set up and as the weights are adjusted it is not usually clear exactly what relationship has been identified between the input variables and the outputs. It is possible that the ANN has identified some coincidental relationship that may only apply to the training data, and may not occur in the wider population being studied. In the case of a complex decision making process, with a heterogeneous population where it is not possible to capture and quantify all the input variables, then it would be reasonable to assume a greater likelihood of the ANN identifying some false, or limited, relationship and applying that, in the absence of sufficient data to select a truer relationship that can be applied more generally. Therefore the underlying approach of the ANN of applying different weights to the inputs to determine the output is a potentially worthwhile avenue, but it would be better for the researcher to have greater control in establishing the weights applied and how the input variables are mapped into the outputs and therefore an alternative approach is still required.

3.6 Support Vector Machines

To some extent Support Vector Machines (SVMs) share a number of characteristics with ANNs. SVMs were originally named Support Vector Networks (Cortes and Vapnik, 1995). These were designed for classification problems – in particular splitting a population of inputs into two groups. Essentially this is what is happening with a household's decision making process: there is a set of inputs and these determine a binary output – either the household decides to install the particular technology being considered, or it decides not to. An SVM essentially works by plotting the data in n-dimensional space and then seeks via a learning algorithm for a suitable hyper-plane that separates out the data into two groups based on the outputs. In a simple system it is possible to separate the samples completely, but often there will be a complex data set where no perfect boundary exists, and the learning algorithm needs to find a suitable compromise to achieve as high a level of accuracy as possible, this is referred to as a soft-margin SVM. In practice most real world SVMs will be of this sort – ie: some inputs will be mis-classified (Press et al., 2007). As with ANNs there are data issues with compiling an SVM as sufficient variables need to be included or some false relationship may be found during the learning stage, which is then subsequently applied to the real world data of interest.

SVMs are also beginning to be used in energy modelling research. Once again, like ANNs, SVMs are being used principally for load profiling (eg: (Lai et al., 2008; Li et al., 2009; Kwak et al., 2012)).

SVMs are essentially being used for the same sort of problems as ANNs. They have a number of advantages over ANNs in that the local maxima problem can be overcome and the SVM can be more explicit as to how it is making its classification by providing an equation for the hyper-plane that separates the inputs according to their predicted output. However, they still retain some weaknesses, in that it can be difficult to collate sufficient data for the training process and then it may not be clear if the correct relationship has been identified, in addition the programming load from SVMs tends to be higher making SVMs more complex and slower to run (Zhao and Magoulès, 2012).

3.7 Agent Based Modelling

The fourth potential approach to be analysed is agent based modelling. Agent based modelling is also a relatively new approach to modelling real world situations. An agent based model (ABM) is a, typically computer powered, simulation method; as it is usually computer powered it was only in the 1990s that such models started being used more widely as greater computing power became more available.

As it is a relatively new method there have been several different attempts to define what an agent is, and what agent based modelling is. One of the clearest aims to define the agent that sits at the heart of an ABM and states that an agent is a 'persistent computational entity that can perceive reason act and communicate' (Bergenti et al., 2004). As such, this fairly broad definition indicates that agent based systems are a form of artificial intelligence programming, in that the individual agents are autonomous and simulate an awareness of their surroundings. Therefore individual agents can be considered analogous to small scale Turing machines that can be interrogated and be expected to know about themselves, their environment and their neighbours. (Gilbert, 2008) provides a wider definition than just a description of the individual agent and states that agent based modelling is *'a computational method that enables a researcher to create, analyze, and experiment with models composed of agents that interact within an environment.'*

Gilbert's definition includes an environment which suggests a spatial element, and Bergenti's includes communication, both of these are natural fits with a stock model with individual households, as it is readily possible to imagine a simulation of real world housing with spatially distributed dwellings, with occupants aware of their environment and their neighbours. Indeed one of the founding ABMs was Schelling's segregation model (Schelling, 1969, 1971), this was a very simple model which had a spatially separated grid of autonomous agents. Schelling's agents were split into two types, or populations. The agents were then given a simple rule to measure how 'happy' they were in their current location, based on the number of neighbours they had of the same population as themselves and the number of neighbours from the alternative population. Each turn in the model the agents would stay put if they achieved their threshold happiness level or would move, seeking a more favourable location. Using just this very simple instruction segregation patterns emerged between the two populations that would look very familiar to town and city planners. This is one of the main features of ABMs, by the use of a simple rule of this form for the individual, complex patterns can be observed in the system under investigation. Since the system as a whole is too complex to be completely modelled at the macro level (eg: top-down energy models do not have the low-level detail of a bottom-up energy model), attempting to make predictions purely from the high-level can be difficult. Instead the ABM approach, which concentrates on the actions of the individual, allows for so-called emergent properties to be observed that would not necessarily be possible based on a high level analysis of the system alone. Grimm and Railsback (Grimm and Railsback, 2005) consider this a key advantage of agent based modelling as they describe ABMs as *'models of individual behaviour that are useful for explaining population level phenomena in specific context, with contexts being characterized by the biotic and abiotic environment, sometimes including the individual's own state.'*

A model that is attempting to simulate individual's buying decisions is essentially modelling technology diffusion at a very low level. An agent based approach allows for this to happen, in that explicit adoption rates for a technology are not being produced, but instead, the intention is to model the individual actors, so that overall adoption of different technologies can be estimated under different scenarios. Therefore, an agent based model will simulate the actions of the individuals that will contribute to the adoption of a particular technology and is therefore building an adoption curve from the ground up, as opposed to attempting to apply a specific adoption curve for each technology.

Similarly, there have been many agent based models that have explored issues of diffusion, not only of technology, but also for disease patterns. To this end a popular demonstration is to use the spread of zombies through a population (eg: (McLeod, 2010; Crossley and Amos, 2011)). This is really just a way of introducing epidemic diffusion, but demonstrates that diffusion generally can be modelled with an agent based approach.

Therefore, there would appear to be a natural fit between agent based modelling and physically based bottom-up stock modelling with a heterogeneous population of households. The dwelling stock naturally fits with a spatial environment, and the households would be represented by agents who could be made to be aware of their environment and be able to interact with it – talk to neighbours and carry out improvements to their own dwellings. There is therefore a need to look more closely at an agent approach and the following paragraphs consider the salient points from a number of texts discussing the practicalities of developing an ABM.

Gilbert and Triotzsch (Gilbert and Triotzsch, 2005) provide a useful discussion of computer simulation techniques. They highlight the need to get the right balance between the level of input and quality of output, ie: it is necessary to determine the quality of output that is needed vs the amount of extra input to increase the quality to that level. Depending upon the intended use of the model a good first order approximation may be sufficiently accurate to provide suitable conclusions with a sufficient level of confidence. Essentially a point is reached in any modelling exercise where the effort to improve becomes disproportionate to the level of improvement that can be achieved. One type of computer simulation they consider is micro-analytical simulations, this is essentially bottom-up modelling, with this type of simulation a population can be grown and aged and households can be formed and disbanded, one example quoted considers future nursing home demand. Parallels can be drawn here with long term energy modelling in that a simple top-down style model could be produced that simply assumes a certain percentage of the population over a certain age will require a nursing home. In contrast a micro-analytical, or bottom-up approach, could aim to simulate the aging of individuals, some of whom would go on to demand nursing care. From the individual perspective this is a very simple system (it was not attempting to model detailed behavioural impacts on the likelihood of individual nursing home demand). They then move on to segregation models such as Schelling's as well as migration patterns – by being given similar simple rules the flying patterns of a flock of birds can be readily simulated. At this stage the individuals in the model are simple automata, typically with a single instruction describing movement based on the density of neighbouring agents. In this way the automata in these models have some autonomy over their actions, but the resultant overview is of patterns being created that are similar to those observed in segregated cities or migrating flocks of birds. There are similar cellular automata models, which are used for models of growth and development of cells, again these are fairly simple rules based models, largely determined by the surrounding densities of other agents. Moving on from the simple automata leads to fully fledged agent models, in these the agent becomes more self-controlling than the simple automata, and decides on its own actions based on its perceptions of its environment. These agents need autonomy, social ability, reactivity and proactivity, agents often have some sort of intention, and may also have some knowledge and belief, based on which they may be able to infer something. Agents need rules to specify how all these interactions and choices are to take place, and the model also needs to describe their environment, for instance, this may be a shopping system with a set of shops and buyers, in this instance they describe a system where the agents initially move randomly looking for shops but learn what shops are in which locations and thus establish various shopping behaviours.

Therefore it can be seen that an agent can include an element of learning, often based on its own, or other agents', experiences. This is markedly different from the learning element in an ANN or SVM, where the learning is used to generate a fixed rule set that determines the outcome. Instead, in an agent based system learning will be part of the agent itself, and it can therefore be used to attempt to simulate a real world individual that will learn from experience, but where the past experience that is being learnt from influences future decision making and become part of the system's history.

Gilbert returns to computer modelling in a later text (Gilbert, 2008) but in this case the primary interest is ABMs. He again makes the comparison between micro-simulation (in essence bottom-up modelling) and agent based modelling, whilst the two have many similarities and overlaps, micro-simulation does not have the ability to provide a detailed model of behavioural influences. This is, of course, the major shortcoming in bottom up stock models that was highlighted in the previous chapter. He therefore concludes his comparison of micro-simulation and agent based modelling by identifying agent based modelling as the potentially more powerful and capable modelling method because it can add the extra micro-level dimension of individual behaviour that is missing from pure micro-simulation models. He then lists the following features that are to be found in an agent based model:

i. can be direct correspondence between real world actors and agent models
ii. heterogeneous agents – agent based computation allows for this so can more closely model real world situation
iii. can represent real actors' environment eg: there may be geographical limitations
iv. simulation of agent interactions – eg transfer of data (conversations)
v. bounded rationality: actors not completely or hyper rational so attempts to model same levels of rationality as in real world
vi. can allow for learning and can allow agents to breed and die

In doing this an agent needs to have four important elements: autonomy; social ability; reactivity; proactivity (Wooldridge and Jennings, 1995). However, Gilbert recognises that achieving this in practice can be difficult and instead suggests: perception; performance – motion, communication, action; memory; policy. Clearly, any simulation or model has to include simplifications and omissions and this is acknowledged. Nevertheless, it is readily apparent that the features and elements listed above could easily be used to describe a population of households, interacting with each other, moving home and considering any efficiency improvements. The final part there is the consideration of energy efficiency improvements, which is a form of consumer behaviour, and an agent approach is ideal for simulating consumer behaviour. Gilbert cites Janssen & Jager's work (Janssen and Jager, 1999) which looked at the lock-in of a consumer market, so that it commits to one technology type and this makes it very difficult for an alternative technology to compete (eg: VHS vs Betamax). Again, clearly there are parallels there with domestic energy efficiency – the gas boiler is currently the predominant choice of heating system in the market and any new technology needs to overcome the familiarity advantages that the existing successful technology has already gained.

Axelrod and Tesfatsion (Axelrod and Tesfatsion, 2006) also provide a useful introduction to ABMs and discuss the particular sorts of problems for which they are most suited. They say that ABMs are used in situations where it is necessary to understand how individuals behave and how their individual behaviours combine to produce large scale outcomes, again there are ready parallels with stock modelling. In order to do this it is essential to understand how the agents interact with each other – indeed the modelling of these interactions is one of the main things that sets ABMs apart from more traditional modelling forms. As a result of including these inter-agent relationships the end result can be greater than the sum of its parts. Therefore ABMs are used for studying systems where there are interacting agents and the system exhibits emergent properties – ie: trends arising in the system as a whole due to individual agents' actions and interactions – that cannot be deduced by merely summing agent properties. It also allows agents to be aware of past experiences and for those experiences to influence decisions, this is very difficult to model from a purely mathematical perspective. Therefore the ABM has assumptions, or simplifications, about the agents and their interactions and then runs a computer simulation to model the outcome. There are four types of goals that are generally being considered when using an ABM: empirical, normative, heuristic and methodological. Modellers looking empirically are trying to understand large scale regularities in systems where there is little top down control. Normative studies use the ABM as a laboratory to discover good design, for instance in examining social policies. Others, with a heuristic approach are seeking greater insight about the causal mechanics involved in the social system in question. Finally there are those trying to improve ABMs' methodological approach for two important developments: firstly, for rigorous testing and refinement of theories that are difficult to evaluate with conventional methods; secondly, to gain a deeper understanding of the causal mechanisms in multi-agent systems.

Bergenti et al. (Bergenti et al., 2004) have also discussed ABMs, as mentioned at the beginning of this section, they begin by considering various definitions of an agent which they develop into a, 'persistent computational entity that can perceive, reason, act and communicate.' This definition leaves open matters of intention and rationality or lack thereof – in this way greater flexibility is provided to the modeller. Agents need autonomy – but this needs to be quantified with protocols putting realistic constraints on the autonomy. An important element is the heterogeneity of the agents – this allows not only for different types of actors to be modelled (eg: sellers and buyers) but also the different individuals in each subset of actor type. The other important element of agents is communication – their ability to pass knowledge back and forth allows for modelling of social interactions which can influence individual behaviour, which can then lead to an effect on the overall system being modelled. Finally, in considering the abilities and awareness given to agents in a model they can be likened to Turing machines operating in the universe of their model. Again this indicates a good match with modelling of individual households interacting with each other and with their environment (improving their homes).

Therefore it can be seen that an agent based approach has many advantages in that it is designed for modelling a population of disparate individuals existing in some form of spatial universe, and is set up to facilitate heterogeneity amongst the population of individual agents in the model so that a complex population can be modelled as well as a simple population of homogeneous automata. Having identified agent based modelling as a promising avenue for including the individuals' technology buying processes into a bottom-up stock model it is necessary to consider the extent to which agents have already been used in energy and environmental research.

3.7.1 Existing energy and environment related ABMs

As discussed in the previous section multi-agent systems, or agent based modelling is still a relatively new technique, but it is beginning to be applied in the energy sector, largely because of the advantage of being able to include individual behavioural choices in the models. This section therefore describes some of the models that have been developed to date.

Kempener (Kempener, 2009) produced a model to consider personal carbon trading as a potential policy tool. Initially he identifies a set of potential barriers to energy efficiency measures in general and personal carbon trading (PCT) specifically, these are: the up front costs of new technology; hidden costs; split incentives; psychological; information asymmetry; and regulatory barriers. As can be seen these are the typical set of objections and barriers that might be expected for any new form of government intervention. For PCT to work, and to simplify the system for modelling purposes, he laid down five requirements: the individuals know their emissions and the marginal abatement cost for reducing them; they can assign an economic value to emitting activities; they can compare the economic values of doing an activity with not doing an activity and selling their allowance instead; there is a large market of buyers and sellers; the price is to be determined by the intersection of the supply and demand curves. These assumptions are similar to those that would describe a perfect market. For the purposes of his model the population was broken down into five agent types according to wealth; in addition there are three measures made available to agents for reducing their emissions: cavity wall insulation, solar hot water and solar photo-voltaics. In each year of the simulation the agents are instructed to plan month by month and there is no carry over of carbon allowances into the following year. In making their decisions the agents have to decide if they want to take a holiday and if so whether that is domestic or overseas, and can also decide if they want to invest in the three available abatement technologies. As well as the breakdown of agents by income there was another criterion used: the agents were economically focussed – where maximum money was their primary concern; environmentally focussed – where reduced emissions was their primary concern; or socially focussed where their goal was to maximise holidays. Different scenarios were then run with a different mix of households between these three aims. Each simulation run represented 10 years and over that period the carbon credits were reduced at a rate of 10% per annum. In carrying out this analysis perhaps the most interesting finding was that the agents appeared not to consider marginal abatement costs but instead acted opportunistically. The research also found that at the end of each year not all credits were used, this therefore means that credits did not diffuse successfully through the market, but that also means that the emissions were always less than the cap. Clearly, an annual reduction of 10% is rather extreme, and in all scenarios this led to an almost universal adoption of the abatement measures available, but still in all scenarios at the end of the 10 years over 80% of agents were experiencing several months of the year with no gas and electricity. So, although this research found that PCT would reduce emissions (as it would be bound to do as it simply applies a blanket ban on emissions above the cap), by the end of the simulated period some of the reductions were only possible because the vast majority had to experience months without energy. As already mentioned, the finding that opportunistic behaviour in response to market moves was relevant to decision making rather than the supplied marginal abatement costs is potentially of more interest, and would suggest a lack of economic rationality even with a very simple instruction set.

Another ABM for energy modelling was developed by Wittmann (Wittmann, 2007). His model was developed for the purpose of analysing cities, and is a generic model, and as such does not use real city data but instead is provided as a proof of concept. In his agent system the agents can supply and/or demand energy; this not only allows for a consideration of the domestic user having micro-generation at home and selling back to the grid, but can also be used to consider the position of commercial energy firms. In discussing the apparent lack of rationality in the domestic sector, he highlights the point that most members of the public are in-expert: for instance, given a boiler life cycle around 15 years a private household rarely faces a replacement decision and therefore has no experience or previous knowledge to use in making a decision. Compared with the domestic lack of expertise, commercial actors are generally expected to act from a financially rational perspective, as they will usually be seeking to use shareholders' funds in the most efficient and productive manner. The agents in the model were split into different types in an attempt to model a real population. The different agent types were then given different rule sets for searching for new technology, eg: some would search amongst all options; some only from conventional solutions; and some would just seek a direct replacement for what they already had. The agent basis of the model also allows for innovators and market leaders to adopt early and then communicate their choice to other agents. In using this model as a proof of concept Wittmann analysed the diffusion of technologies and found patterns that look similar to those produced in conventional models. He therefore argues that this demonstrates the validity of agent based modelling for considering city energy usage and technology diffusion.

Another prototype model was developed by Hodge et al. (Hodge et al., 2008). Their model is from a different perspective as they are applying the agent system to the generating capacity to provide analyses of the adoption of new generating technologies. To this end they have six agent classes: raw material agents, producer agents, consumer agents, research agents, government agents, environment agents. The main interactions they have between agents are the buying and selling of energy technology products. With these agent classes specified they are then applied to Indiana's energy system. From this basic framework the model has been adapted and provided with alternative data sets in order to analyse the Californian energy market (Hodge et al., 2011). This therefore highlights an advantage of agent based modelling, in that it is possible to start with a generic model with a lack of real world data, move to a specific model to consider a particular problem and then it can be possible (subject to the availability of data) to make adjustments to the model to consider a different system – in this case a move from Indiana to California.

Ma (Ma, 2006) has also produced an exploratory model. As an exploratory model it does not use real data and technologies but instead has Existing, Incremental, and Revolutionary as three technology types which all have the potential to satisfy the energy demand. This model is more concerned with modelling these competing technologies and does not give detailed consideration to the end users, instead it simply operates on an assumption that demand increases with time. In running the simulations Ma found that a carbon tax could accelerate the rate of adoption of the newer technologies, as it could alter the market position so that the in-built advantage for established technologies is reduced. As the research was concerned with the technologies the time to reach the break even point was also considered. It was found that the break even time is more sensitive to the learning rate than to the initial cost. However, if the learning rate is low then the initial cost becomes a more significant factor; this is understandable since it essentially points out that with a low learning rate the cost decreases more slowly so a technology with a high initial price will stay with relatively high prices for a longer period.

Schwarz (Schwarz, 2007) used an agent based system to model the diffusion of environmental innovations. By looking at previous research a number of results were raised that needed to be considered for developing her model: different types of people have different levels of innovativeness; communication channels are important; individuals' innovativeness characteristics affect their technology adoption decisions. For her model she sought to generate an empirically driven model, which in this instance was considering German water usage, and four technologies were chosen for inclusion in the model. From a combination of a questionnaire and telephone interviews, five different lifestyle groups were identified with differences in innovativeness levels between them. In this instance it was found that inter-agent communication in social networks was of low importance for water technology diffusion; however, contradictorily, it was noticed that agents tended to imitate their peers, but it is possible that some of this effect was due to there only being four technologies available. Nevertheless this research demonstrated that it is possible to use empirical data in an agent based model; indeed, apart from initial exploratory and proof of concept models, it could be argued that it is essential.

A particularly interesting model is that of Faber et al (2008, 2010). They used an ABM to model take up of micro-Combined Heat and Power (mCHP) against an existing base of condensing boilers. This was effectively an innovation diffusion model with the model's agents representing home owners facing a choice of replacement heating system. In their model the typical S-curve of new technology diffusion was observed, and they analysed the effect of different forms of subsidy on the rate of diffusion. By making many runs of the simulation model they could consider different types of subsidy and apply limits to the amounts spent on subsidy to try and find an optimal solution for CO_2 saving per amount of subsidy. This therefore demonstrated the use that an ABM could be put to in considering policy measures to encourage the uptake of low and zero carbon technology in the domestic sector. However, this model was short on disaggregation of different housing types, which would affect the attractiveness of mCHP. To partially consider this situation they also carried out some runs with housing that had improved insulation, and in these runs the savings from mCHP were reduced to such an extent that the technology was not widely adopted for over 100 years. This model therefore demonstrated a use for policy makers but also a need to introduce disaggregation to an ABM.

This section has considered a number of agent based models that have been used in the energy sector. Most of these models aim to simulate the actions of individuals and a number of them are models of technology adoption and diffusion (eg: (Wittmann, 2007; Faber et al., 2010) etc.). An important point to note is that most of these models are exploratory or prototypes of some sort and are typically dependent on assumed, or greatly simplified, data as opposed to detailed real world data sets. In order for a comprehensive bottom up model to be developed then sufficient data will need to be accessed, not only to describe the dwelling stock, but in particular to describe the individual agents that will be simulating real world households.

It can also be seen that an agent based approach is a broad framework that provides a facility for modelling individuals of many different types. As such, an agent approach can deal with a wide range of complexity in the individual agents, from the very simple to quite complex representations of real world actors. Therefore, specifying an agent approach does not define how the rules for the agents will be set. In other words an agent based model still requires a method to describe the rules, or heuristics, that will control what the individual agents will do in the model. Theoretically, it could be possible to integrate the previous techniques – Markov chains, ANNs and SVMs into an ABM by using them at an individual level. However, that would import their respective weaknesses and would multiply the data gathering requirements as sufficient data would be needed to construct the rules for each different agent type.

In the case of a Markov chain this would require sufficient data to identify all the probabilities of state changes for each distinct type of agent; and for ANNs and SVMs would require sufficient data sets for the training of each different agent. Any such approach would therefore severely limit the heterogeneity of the agents, and a good level of heterogeneity will aid in making the model more realistic. Therefore, with an agent based approach consideration needs to be given to the agents' actions, as that will aid in determining the appropriate method to define the rules that will control how each agent will act and react to its situation. In an agent based bottom-up stock model the environment will be the dwelling stock and the agents will represent individual households. These household agents will be subjected to stimulus triggers that will prompt them to consider whether to carry out energy efficiency improvements. Therefore, the essential component that needs to be included within the agents themselves is a method of carrying out a decision making exercise, consequently the following section explores decision theory in order to identify a suitable method for use to drive the householder agents in a domestic stock ABM.

3.8 Decision Theory

An agent based model needs a rule set, or set of heuristics, for the individual agents to describe how they will act. In particular an agent based domestic energy model aims to represent the decision making of real world householders when it comes to their choice of energy efficient technologies to be installed in their homes. Therefore the central component of the agent's rule set needs to be a decision making process. Therefore it is necessary to consider decision theory, and in particular consumer decision or choice theory. By suitable application of the available theories to the available data it can be possible to simulate decision making at the individual level. This makes it possible to project the uptake rates of various green technologies and make long term predictions about the dwelling stock, its energy demand and related carbon emissions under various different scenarios.

When choices are being made by an individual they are making a decision as to which of a number of options is their favourite. Choice theory assumes that such an individual in choosing their preferred option will seek to obtain the most benefit for themselves (Simon, 1959), they are therefore seeking to maximise their utility from that choice. Therefore, if it is possible to estimate the utility an individual might ascribe to different choices it becomes possible to predict which choice they would make when faced with a given situation.

In order to attempt to determine utility, observations need to be made. There are two main approaches to observing the decision making process – either by observing, or recording, details of real world decisions, or by exposing decision makers to simulated choice exercises. These two distinct approaches are revealed preference – records of real world choices and stated preference – decision makers' stated choice in a simulated decision making situation (Adamowicz et al., 1994).

Clearly each of these approaches has its advantages and disadvantages. Revealed preference has the obvious advantage that it is a genuine choice that actually took place and will have had some impact on the decision maker. However, in this situation it is usually impossible to determine exactly what other options were being considered, and there may not be as much information available about the decision maker. In addition, it is usually the case that only a single decision event is available for each decision maker being observed. In contrast, the main disadvantage of stated preference is that it is only a stated preference – ie: what the decision maker claims they would have done, this is therefore open to bias as there will be differences between the simulated environment and the real world decision making process. Nevertheless, despite this obvious weakness, stated preference can be a useful tool as it can allow for an individual decision maker to provide a number of decisions and the choice of options available can be more carefully controlled making it easier to quantify results.

Given data, whether it be from revealed or stated preference, or a mixture of the two, that data will need to be analysed if it is to be used to enable predictions or modelling of the outcome of future decision making. Therefore a method is needed to determine which of a number of options will be preferred, this leads to a consideration of the underlying decision making process. As previously discussed, a decision maker is assumed to act in their own best interest, ie: they will seek to maximise their benefit, or utility, from any decision making process. Consequently there are many theories (Yoon and Hwang, 1995) that have been developed that attempt to describe the underlying process of how the preferred option is selected, or at least, how that process can be successfully simulated.

Almost every product is likely to have some level of complexity to it, and the benefits that it provides, such that there will be more than one attribute that that needs to be considered; for instance, in a typical consumer choice situation there are likely to be consumer products where there will be, at the very least, a difference in price and a perceived difference in quality. Therefore an individual decision maker will use some (often subconscious) process to weigh up the respective benefits provided by each good to determine which one they will favour.

This means that the majority of decision making will require an assessment of multiple attributes, the over-arching name for this is Multiple Attribute Decision Making (MADM) (Yoon and Hwang, 1995). The basic principle of an MADM is that the various attributes of the available options can be measured and weighted in some way so that the option that provides the most benefit can be determined.

As briefly mentioned earlier, there are two main approaches that can be applied in evaluating the respective merits of different choices, compensatory and non-compensatory. With a non-compensatory method a weakness in one attribute cannot be made up for by extra strength in another attribute, whereas in a compensatory method it can be.

3.8.1 Non-compensatory methods

The non-compensatory are the simpler methods to consider as it is not necessary to consider the respective weights that should be applied to each attribute.

Lexicographic sequential elimination removes options one at a time by comparing each option's respective strengths in each particular attribute. In contrast elimination by aspects eliminates options according to the order of aspects that would eliminate the most options each time until only one remains (Tversky, 1972). Further adaptations have been made to the underlying procedure, for instance there are semi-ordered methods that only eliminate options if they are significantly weaker at a particular attribute than the strongest at that stage (Manzini and Mariotti, 2012).

Very similar to these two methods are two further non-compensatory methods, maximin and maximax. Maximin chooses the option that has the strongest worst attribute, whereas maximax chooses whichever option has the strongest attribute. As opposed to the sequential elimination methods above, these two methods do not require a ranking of attributes. Therefore there are four general non-compensatory approaches that can be used depending on the exact circumstances of the decision making process under consideration.

3.8.2 Compensatory methods

However, many decisions are more complex than can be catered for by a non-compensatory method, and this leads to compensatory methods, whereby a strength in one attribute can make up for a weakness in another attribute. With the non-compensatory methods previously described, whilst it was generally necessary to determine a ranking of attributes and a strength for each choice in each attribute, there was no need to have strengths comparable across attributes. This extra dimension is required for compensatory methods so the relative importance of each attribute needs to be included in any compensatory decision making methods.

Determining the relative importance of the various attributes can be a challenge for a number of reasons. Firstly, the mix of attributes will be such that the utility coming from each different attribute is in a form that is difficult to compare; for instance there may be an ease of use attribute, eg: a gas boiler requires less intervention than a solid fuel boiler that needs fuel adding from time to time, and another attribute may be the anticipated reduction in energy use, so trying to normalise those two features so they are comparable can be a challenge. Furthermore, it is not possible to examine a decision maker at the subconscious level and determine exactly which attributes are being considered and exactly what level of importance is attached to each one. Indeed choice theories do not attempt to truly replicate the decision making process but aim to provide a useable method that will provide a reasonable estimate of the likely outcome of any decision process.

It is therefore necessary to find a method to essentially normalise the different attributes so that their respective weights can be compared in the model version of the decision making process. Since the choice of energy saving technologies is a purchase decision it is simplest to use an economic normalisation process, ie: use the attributes to alter the price of the technology being considered. Therefore, this then becomes an estimate of the willingness to pay for different items. Willingness to pay is usually estimated from discrete choice experiments with a stated preference (Carlsson and Martinsson, 2001). As previously discussed such experimentation usually exposes participants to repeated simulated decisions with the features included in each choice being varied so that the results can be regressed to estimate the value being ascribed to each attribute.

Willingness to pay is clearly highly related to hedonic valuation (Lancaster, 1966; Rosen, 1974; Kuminoff et al., 2010). Under hedonic theory consumers do not buy a product purely for the sake of owning that product, but for the benefit derived from the various features provided by that good. Therefore the utility ascribed to each feature needs to be established and then valued. By modelling a good in this way the utility ascribed to individual features of a product can be estimated and can then be converted into a monetary value. This allows for utility maximisation through a valuation process.

Clearly, individuals will have their own unique personal values, and different people will have different things to be important (Bardi and Schwartz, 2003). Nevertheless, discrete choice surveys analysing the decision making of individuals aim to ascribe weights to the specific individual features of a choice option, as opposed to evaluating the underlying more generic values of the individual respondents. Therefore, a discrete choice survey, by offering repeated sets of choices can determine the importance an individual gives to a particular feature of a choice option, without an in depth analysis of the individual's more general personal values.

Returning to decision theory, it can be seen that willingness to pay and hedonic valuation are essentially analogous to a compensatory decision making method. Compensatory decision making allows for a weakness in one attribute to be made up for by a strength in another attribute; for example one technology may be initially more expensive but it may have lower running costs and provide greater efficiency savings. Therefore a compensatory method allows those two features to be weighed off against each other so that the decision maker can decide which of those two technologies they prefer for their own particular circumstances. There are broadly two main compensatory methods, the weighted product method and simple additive weighting, as shown in equations 3.1 and 3.2 (Zhou et al., 2006).

$$V(A_i) = \prod_{j=1}^{n} x_{ij}^{w_j} \quad i = 1, 2, 3 \ \dots m \qquad [3.1] \ \mathit{Weighted\ Product}$$

$$V(A_i) = \sum_{j=1}^{n} w_j v_j(x_{ij}) \quad i = 1,2,3 \ \dots m \qquad [3.2] \ \mathit{Simple\ Additive}$$

In the equations $V(A_i)$ is the value ascribed to alternative *i*, *x* is each attribute, *w* is the weight given to each attribute and *v* is the value given to each attribute. As can be seen the weighted product method is more complex as its product layout means that one low scoring attribute will be of more significance than under the simple additive weighting, which is merely a sum of the individual values. Therefore there are close parallels between simple additive weighting, willingness to pay and hedonic valuation, as they all attempt to put a value on the constituent components and sum those constituents to determine the overall value and therefore utility.

An alternative approach to the numerically based compensatory methods is fuzzy logic decision making (Yoon and Hwang, 1995). Fuzzy logic is most suitable for qualitative data, typically a linguistic assessment, eg: very important, important, not important, etc. However, discrete choice surveys, via a regression analysis, provide quantitive data for the weights being applied to the different features of a choice option.

This would therefore suggest that for the household agents in the model a simple additive weighting decision making algorithm would be an appropriate method to use for the underlying heuristics that will drive the agents' purchasing behaviour. To further check that this is an appropriate method and a possible approach for driving the agents it is as well to check how the rule sets for agents in other models are compiled; consequently the following paragraphs review some further research with a particular focus on the setup of the agents in the particular models reviewed.

3.8.2.1ABMs with a compensatory decision making algorithm

Schwarz & Ernst's model (Schwarz and Ernst, 2009) concerning water saving technology adoption has already been referred to, but this provides a useful starting point as this was empirically based research; this empirical data took the form of a questionnaire from which five agent types were identified. Each agent then had an algorithm to run that allowed for the comparison of different options based on producing a utility value for each of the four technologies available. This was essentially a simple additive weighting function applying appropriate weights to the different impacts, and then selecting the option calculated to provide the highest utility. This model therefore demonstrates that this approach is possible albeit at a relatively simply level with only four technologies and five agent types, and increases to both of these will require larger datasets.

Tran (Tran, 2012a, 2012b) used an agent approach to look at purchasers of new cars, and in particular to gauge the effect of networks, or inter-agent communication, on the diffusion of new technologies. In this case Tran was looking at the diffusion of innovative fuel types for new cars (electric, gas, etc) and produced six vehicles types as amalgams of real world cars with price, performance and other factors determined solely by fuel type. For the agent population, consumer survey data were used to produce two agent types: early adopters and mass market. Therefore, similarly to Schwarz & Ernst's model, considerable simplifications were carried out to reduce the number of technologies and the heterogeneity of the population. In addition, as the primary focus was to look at the effect of networks, the extent of inter-agent communication was changed from simulation to simulation and was therefore limited in its empirical base. Based on the consumer survey that was used to produce the two agent types the sensitivity of each agent was determined to each of the factors of the different vehicle choices available (eg: price, performance, etc.), these were then used to provide utility values for each individual for each component. Then the probabilities were combined to provide a probability logit function for each individual for each technology option. Such an approach is less intuitive and requires rather more computing power than using a simple additive weighting approach and allowing the agent to select the option with the highest overall utility value from the summations.

There has also been some interesting Swiss research (de Haan et al., 2009; Mueller and de Haan, 2009) using an agent approach to simulate car purchasing and the individual consumer's choice and decision making process. This was a large scale, empirically backed, model with 2089 car types and an agent population of 100,000. Since there is a large number of choices it is not reasonable to assume that the agents would consider every single car type when making a purchase decision, therefore there was a preliminary filter applied to reduce the choice set, eg: car class size – an agent representing a family wanting a large family car is not going to consider the range of sports cars on the market. Again utility values, based on the importance individual agents attach to the various car attributes, are calculated and these are used to determine the agents' choice of new car. This model therefore shows that it is possible to operate an agent based model with a complex data set and maintain much of the heterogeneity that will allow for micro-level simulation of not only the stock, but also the individual actors and their decision making process.

3.9 Chapter summary

In this chapter various aspects of consumer behaviour have been considered, and the relevant element has been identified – one-off purchase behaviour.

This was followed by a review of four potential techniques to incorporate decision making into a stock model: Markov chains, artificial neural networks, support vector machines, and agent based models. Of the four, agent based modelling was found to be the most appropriate as it has a natural fit with a set of spatially distributing heterogeneous actors (individual households in different dwellings making their own decisions).

An agent approach is essentially an open framework that leaves open the question of the algorithm that drives the individual agents' actions. The main action of these agents, in representing individual households, is to carry out a decision making exercise when triggered. Therefore decision theory was reviewed in order to identify a suitable method. This decision making process will be to weigh up the perceived benefit of a range of options and then to select their favoured choice. Having discussed both compensatory and non-compensatory methods, simple additive weighting was chosen as a suitable compensatory method for the individual householder agents to carry out their decision making process.

Therefore, the new model to be developed will be an agent based model driven by a simple additive weighting choice mechanism.

Consequently, the next chapter goes on to consider the data collection requirements to construct this model.

Chapter 4 Data Collection

The construction of an agent based long term domestic energy stock model is necessarily data intensive as numerous large data sets are required. Essentially there are three distinct sets of data that are required for the model: firstly housing stock data, which are to be used to prepare the dwelling stock for the model; secondly householder data, these are required to prepare a reasonable simulation of individual households' actions; finally, data are needed to produce scenarios for the model to analyse based on potential sets of policy interventions and predictions of long term demographic changes, etc. The rest of this chapter is arranged to consider each of these three elements in turn.

4.1 Housing Stock Data

As discussed in the second chapter there are a number of existing UK based stock models, these can therefore be used to provide a good indication of the level of data gathering that is required. The Johnston (Johnston, 2003), CDEM (Firth et al., 2010), and DECM (Cheng and Steemers, 2011) models all use 50 or fewer initial dwelling types, whereas the BREHOMES (Shorrock and Dunster, 1997), UKDCM2 (Hinnells et al., 2007) and DECarb (Natarajan and Levermore, 2007a) models all use at least 1,000 different dwelling types. All of these models use a form of BREDEM (Anderson et al., 1985) (Anderson et al., 2002) or SAP (BRE, 2011a) to model the individual dwellings, it is therefore worth considering the main elements of a dwelling that are included in a SAP calculation. The following seven main components were identified in Table 2-1: size, construction, insulation, heating, hot water, lighting, renewable technologies. With just 2 options per component that generates 128 dwelling types (2^7) and 3 per component increases that to 2,187 (3^7). Therefore it can be seen that if any great level of detail is to be achieved in the model the number of dwelling types will need to be in the thousands. Due to the dimensionality of this, it would be quite easy to develop a model with more dwelling types than there are actual dwellings in the UK, therefore care needs to be taken to strike an appropriate balance between the level of detail required and producing a model of a manageable and realistic size.

Having determined the appropriate order of magnitude for the model to be some thousands of dwelling types, it was necessary to consider the ways to gather that data. Theoretically there are two applicable approaches to data collection, either primary or secondary data collection. In order to produce an Energy Performance Certificate (EPC) approximately two hours in total is required to allow for travel to and from a dwelling, time on site taking measurements, and time in the office inputting the data and generating the certificate, based on the reduced data SAP (RdSAP); a broadly similar time would therefore be required for collecting data for this model. This would therefore be upwards of 10,000 man hours simply on this element of data gathering, without considering the time needed to arrange those visits and to ensure they were a good statistical match for the general dwelling stock. Since primary data gathering is not practical for the dwelling stock data secondary data need to be secured.

At the same time as considering the secondary data sources, consideration needs to be given to the extent of the model. The UK is split into four main geographic regions: England, Scotland, Wales and Northern Ireland, approximately 84% of the UK population lives in England (ONS, 2009); care needs to be taken with government data sets as some cover England, some England and Wales, some Great Britain and some the entire United Kingdom. In cases where a data set covers only England, there are usually broadly comparable, although not necessarily identical, data sets for the other three parts of the United Kingdom. Therefore, this model is being restricted to England.

Consideration also needs to be given to the types of households and dwelling ownership structures. In the UK (and England) the dwelling stock can essentially be separated into three sectors: owner-occupied, the private rental sector, and social landlords. Table 4-1 shows the relative distributions of the dwelling stock between these three sectors for both the UK as a whole and for England in particular (CLG, 2011b).

Table 4-1 Dwelling stock by tenure: United Kingdom and England, 2008

	Owner Occupied	Private Rented	Social Landlord	Total
England	15,029,000 67.1%	3,443,000 15.4%	3,926,000 17.5%	22,398,000
United Kingdom	18,118,000 67.3%	3,938,000 14.6%	4,855,000 18.0%	26,911,000

As can be seen over two thirds of dwellings are owner-occupied, with social and private landlords taking up the remainder of the stock. Social landlords are governmental, or quasi-governmental, bodies – typically local authorities or housing associations – and they generally provide housing for those who are unable to secure housing in the private sector, and consequently most social tenants will be in receipt of some form of government support. The energy efficiency of the public sector stock will largely be determined by government policy. Indeed the social landlord sector of the market is probably the most straightforward for government intervention, since the government is already heavily involved as a landlord. Therefore any requirements that are laid down are typically non-political and are generally considered to be for the public benefit, as any minimum standards being applied will be for the benefit of the more disadvantaged sectors of society. In recent years the main policy affecting energy efficiency in social housing has been the Decent Homes standard. Under Decent Homes minimum standards were set for various aspects of social housing, including thermal performance. The original intention was that all social housing would comply with these standards by the end of 2010; this target was not quite achieved, although it is estimated that there was 92% compliance leaving around 305,000 so-called 'non-decent' with a revised target for 100% compliance by 2018-2019 (Bennington et al., 2010). Therefore, in the social housing sector energy efficiency improvements to the dwelling stock are already largely driven by government and there is no significant opportunity for tenants to carry out improvements, essentially all they can do is make requests of their social housing provider, who may well already be operating some scheduled improvement scheme for their stock. As a result there would appear to be limited benefit from attempting to model the decision making behaviour in this sector of the market.

In contrast, the private rented sector is rather more variable than the social housing sector. Since the late 1990s English tenancies have been Assured Shorthold Tenancies (ASTs) – these typically provide an initial term of six months and then allow for termination by the landlord on giving two months' notice, or one months' notice by the tenant. Therefore most tenants are now on ASTs, and as this is a fairly short term contract they have limited security and limited rights – in particular they do not have the right to carry out improvements to their home – if they did so they could receive notice soon afterwards or be made to remove anything they had added so they would be unlikely to recoup the cost. Conversely for the landlord any improvements they make will be for the benefit of the tenant and lead to reductions in their bills, which may not necessarily result in higher rents for the landlord. This is the split incentive problem in that the landlord makes the investment and the tenant gets the benefit. There is also a wide variety of private landlords – they range from large commercial entities that own several thousand dwellings and therefore employ large professional teams to ensure proficient management and maximum return on investment down to private individuals who may only own a few properties, or even the so-called 'accidental' landlord – these are typically people who have been forced to rent out their own property because they could not sell and are then renting elsewhere for either family or work issues and therefore will have little or no expertise and a limited budget to make improvements. This is therefore a complex sector that really needs consideration in its own right due to the unique issues involved.

That leaves the owner-occupied sector – which is by far the largest with approximately two thirds of dwellings. As the name suggests the occupant and the owner are the same person and they therefore have the greatest flexibility as to what, if any, improvements are carried out to their homes (although there will be some limitations, eg: listed buildings – historically important – where the heritage value impacts on the allowable changes; and some long leasehold properties (mostly flats) where ownership is typically for 99 or 125 years and will eventually revert to a freeholder, and in theory the freeholder's permission should be sought before improvements are made, but should not be unreasonably refused). It is therefore this sector of the market that needs to be considered in most depth as this is the one where individual home-owners will be making decisions that affect the energy efficiency of their individual homes. Consequently, this model is being restricted to owner-occupiers in England only.

As already mentioned, a model will be of more use if it achieves a good level of heterogeneity and is capable of tracking the uptake of various different energy efficiency technologies. This therefore requires a model with many different dwelling types and therefore an input data set that is at least as detailed. Such a data set needs to provide sufficient detail on the fabric, heating and hot water systems of individual dwellings, so that it can be used to reasonably accurately estimate energy demand and the resulting emissions for individual dwellings; from there it should then be possible to scale up the results for the entire dwelling stock.

In theory the most complete such database of dwelling information will be the Energy Performance Certificate (EPC) Register (Landmark Information Group, 2012), which to December 2012 has data lodged on some 8.6 million dwellings (although this may include a small number of duplicates where a dwelling has been inspected more than once); unfortunately, this data has yet to be made available to researchers. Therefore, an alternative source needs to be found. The next most comprehensive data set will be from the English Housing Survey (EHS) (CLG, 2010). As the name suggests this is an English based data set and this therefore restricts the model to modelling the English housing stock. The EHS has replaced the English House Condition Survey (EHCS) that operated in earlier years. The EHS carries out a questionnaire survey of over 16,000 households together with a physical survey of around 8,000 dwellings annually. Therefore the physical survey, with an 8,000 dwelling sample size, provides a good snap-shot of the current constitution of the housing stock.

The latest available version of this data-set 2008-9 (CLG, 2011c) has been used as the base from which to construct the housing stock for this model. The data is provided on a two year rolling basis, so the sample is actually 16,150 with surveys having been carried out in the period April 2007 to March 2009. Due to the size of the data in the EHS it is presented in separate files and therefore work needed to be carried out to prepare it before it could be used to generate the housing stock. Since one of the main features of the model is the simulation of the decision making processes of owner-occupiers the first stage was to associate the tenure responses from the questionnaires with the physical survey data. In so doing the number of valid responses was reduced to 15,523. The distribution of responses is as shown in Table 4-2:

Table 4-2 English Housing Survey Tenure Type

Tenure type	Frequency	Percent	Valid Percent	Cumulative Percent
own with mortgage	4100	26.4	26.4	26.4
own outright	3690	23.8	23.8	50.2
privately rent	2337	15.1	15.1	65.2
rent from LA	2792	18.0	18.0	83.2
rent from RSL	2604	16.8	16.8	100.0
Total	15523	100.0	100.0	

As can be seen 50.2% are owner-occupiers and this reduces the sample to 7790. With only 50.2% of the 15,523 being owner-occupiers this is significantly below the expected level (c. 67%) in the broader population. However this was a conscious decision in compiling the EHS – they attempted to survey all tenanted properties and only a representative sample of the owner-occupied dwellings. Nevertheless a sample of 7,790 owner-occupied dwellings is more than enough to provide statistical significance (a sample of 7,790 from a population of 15,029,000 provides a confidence interval of 1.11% at a 95% confidence level)

Therefore this sample of 7,790 dwellings could be used as the base for preparing the owner-occupied dwelling stock for use in the model. The amended data-set was split in to four age bands. The first age band covers all dwellings built before 1945 – in the UK and England this is still a significant proportion of the stock (38%), this age band captures most of the solid wall stock, and dwellings built in this period were generally larger. The second age band is from 1945 – 1964 this period saw a significant level of house building principally due to post-war reconstruction and the cut off date approximately marks the introduction of thermal requirements in the building regulations. The third age band goes up to 1990 and includes tighter building regulations. The final age band is for dwellings built after 1990 with further tightening of building regulations and measurable levels of timber frame dwellings and essentially no solid walls. Having separated the dwelling stock into these four groups it was analysed in SPSS to provide a statistical description of the dwelling stock, as shown in Table 4-3, Table 4-4, Table 4-5 and Table 4-6:

Table 4-3 Pre 1945 Owner-occupied Stock

RdSAP Age band:	B 1900-1929		Floor Area	No. of dwellings	
Type:			Mean m²		%
		Flat	78.7	171	5.68484
		MidSemi	97.5	2288	76.0638
		Detached	169.9	549	18.2513
		Total		3008	
					%
Walls:		Solid		1884	62.633
		Cavity		690	22.9388
		Filled cavity		434	14.4282
Windows		All DG		1628	54.1223
		Partial DG (35%)		1380	45.8777
					%
Heating		Gas cond combi		505	16.7886
		Gas combi		966	32.1144
		Gas regular		1147	38.1316
		Oil + LPG		207	6.88165
		Electric		134	4.45479
		Solid		45	1.49601
		Community		4	0.13298
Roof					
Flats	%	Depth of insulation (mm)		Not flats	
93	54.386	No loft			%
36	21.0526	<100	Set @ 50mm	908	32.0056
28	16.3743	100-200	Set @ 150mm	1357	47.8322
14	8.18713	200 +	Set @ 250mm	572	20.1621

Table 4-4 1945-1964 Owner-occupied Stock

RdSAP Age band:	D 1950-1966		Floor Area	No. of dwellings	
Type			Mean m^2		%
		Flat	60.6	75	5.043712
		MidSemi	86.2	1048	70.47747
		Detached	128.5	364	24.47882
		Total		1487	
					%
Walls:		Solid		144	9.683927
		Cavity		606	40.75319
		Filled cavity		737	49.56288
Windows		All DG		1112	74.78144
		Partial DG (56%)		375	25.21856
					%
Heating		Gas cond combi		258	17.35037
		Gas combi		382	25.68931
		Gas regular		704	47.34364
		Oil + LPG		57	3.833221
		Electric		63	4.236718
		Solid		21	1.412239
		Community		2	0.134499
Roof					
Flats	%	Depth of insulation (mm)		Not flats	
43	57.33333	No loft			%
6	8	<100	Set @ 50mm	387	27.40793
23	30.66667	100-200	Set @ 150mm	685	48.51275
3	4	200 +	Set @ 250mm	340	24.07932

Table 4-5 1965-1990 Owner-occupied Stock

RdSAP Age band:	F 1976-1982		Floor Area	No. of dwellings	
Type			Mean m^2		%
		Flat	61.3	190	7.793273
		MidSemi	80.6	1191	48.85152
		Detached	121.3	1057	43.35521
		Total		2438	
					%
Walls:		Solid		95	3.896637
		Cavity		1158	47.49795
		Filled cavity		1185	48.60541
Windows		All DG		1992	81.70632
		Partial DG (52%)		446	18.29368
					%
Heating		Gas cond combi		376	15.42248
		Gas combi		502	20.59065
		Gas regular		1202	49.30271
		Oil + LPG		138	5.660377
		Electric		196	8.039377
		Solid		15	0.615258
		Community		9	0.369155
Roof					
Flats	%	Depth of insulation (mm)		Not flats	
119	62.63158	No loft			%
25	13.15789	<100	Set @ 50mm	616	27.40214
32	16.84211	100-200	Set @ 150mm	1147	51.02313
14	7.368421	200 +	Set @ 250mm	485	21.57473

Table 4-6 1990+ Owner-occupied Stock

RdSAp Age band:	I 1996-2002		Floor Area	No. of dwellings	
Type			Mean m^2		%
		Flat	49.6	97	11.31855
		MidSemi	79.1	277	32.32205
		Detached	131.1	483	56.35939
		Total		857	
					%
Walls:		Solid		42	4.900817
		Cavity		374	43.64061
		Filled cavity		441	51.45858
Windows		All DG		824	96.14936
		Partial DG (35%)		33	3.850642
					%
Heating		Gas cond combi		146	17.03617
		Gas combi		134	15.63594
		Gas regular		458	53.44224
		Oil + LPG		56	6.534422
		Electric		61	7.117853
		Solid		0	0
		Community		2	0.233372
Roof					
Flats	%	Depth of insulation (mm)		Not flats	
59	60.82474	No loft			%
1	1.030928	<100	Set @ 50mm	32	4.210526
21	21.64948	100-200	Set @ 150mm	430	56.57895
16	16.49485	200 +	Set @ 250mm	298	39.21053

In analyzing the stock data it is very easy to rapidly accumulate a very large number of different dwelling types that need to be modelled. In this simplified analysis of the dwelling stock there are 4 age types (pre-1945, 1945-1964, 1965-1990, 1990+); 3

detachment types (a flat, a detached house, or a midsemi – a combination of a semi-detached and mid terraced); 3 wall types (solid (or timber in the 1990+ age band), cavity, and filled cavity); 2 glazing types (double glazed, partial – with a percentage of double glazing for the partially double glazed set according to age); 7 heating types (gas condensing combination boiler, gas combination boiler, gas regular boiler, oil and LPG, electric heating (Economy 7), solid fuel (an amalgam of the different solid fuels, including biomass), and community heating); and 4 roof types (no roof – another dwelling above, insulation less than 100 mm, 100-200 mm, 200 mm +). Potentially 2,016 different dwelling types solely based on those six characteristics (4 x 3 x 3 x 2 x 7 x 4). An initial reduction was made by considering the loft insulation – in the statistics a number of dwellings have no roof – all the no roof options have been assigned as flats (ie: another dwelling above). This reduced the number of cases to: non-flats: 4 x 2 x 3 x 2 x 7 x 3 = 1008 and flats 4 x 1 x 3 x 2 x 7 x 4 = 672, making a reduced theoretical potential of 1,680 different types of dwelling. However, in the starting stock for the model not all those 1,680 different types need to be represented, eg: in the 1990+ stock there are no instances of solid fuel heating and only 2 with community heating, meaning it would not be possible to have community heating in the timber framed set of dwellings and the filled cavity and the empty cavity, etc. The sample was then weighted to present the different characteristics of the dwelling stock and this resulted in 781 unique dwelling types being represented in the sample of 7,790. The aim of this weighting was to ensure that the technologies represented in the model matched as closely as possible the weightings of the various technologies in the survey data, as presented in Tables 4-3 to 4-6. Table 4-7 provides a comparison of wall types, loft insulation and gas heating, and shows that for each option the model is within 1% of the survey data.

Table 4-7 Comparison of EHS and model initial stock composition

	CWI	Cavity	Solid		No Loft	<100 mm	100-200 mm	>200 mm		Gas Cond	Gas Combi	Gas Reg
Model start	2806	2833	2151		313	2010	3723	1744		1283	1985	3511
EHS 2008	2797	2828	2165		314	2011	3723	1742		1285	1984	3511

When the model is running there are further factors that can be added in to the characteristics of the dwellings, heat pumps (both ground and air), solar hot water, and solar photovoltaics, these can be applied to both new build dwellings and as retrofit improvements to existing dwellings. This increases the theoretical number of dwelling types up to 7,992 (it is assumed that flats without roofs do not have permission for installing solar hot water or solar photovoltaic systems) each of which will need calculations as an agent could make changes to an existing dwelling to change it so that its characteristics matched one of the previously unused dwelling types.

In order to limit the number of dwelling types a conscious decision has been made to exclude certain technologies: micro-wind turbines, micro-hydropower, and micro-combined heat and power (mCHP). The first two are excluded as there are limited sites where they are suitable and are therefore not valid options for the vast majority of dwellings. The third, mCHP, has been excluded since as the thermal performance of the building envelope is improved the advantages of an mCHP system are decreased (incidental electricity generation during the heating cycle) which is expected to lead to reduced uptake (Faber et al., 2010). Recent uptake figures for all three technologies are shown in Table 4-8 (Ofgem, 2012):

Table 4-8 Feed in Tariff Installations in England

Technology	H1 2011	H2 2011	H1 2012
micro-wind	158	92	201
mCHP	133	106	9
micro-hydro	3	6	3

As can be seen these are very low levels, and with a model with 7,790 dwelling representing the entire home-owner stock in England of approximately 15,000,000 dwellings noise in the model will be far larger than any of these installation levels. It is therefore not sensible to attempt to include them at this stage as there is insufficient data available and insufficient resolution to attempt any accurate modelling of their adoption.

Clearly these few characteristics on their own are insufficient to be able to calculate the expected energy demand for a dwelling, therefore a number of assumptions have been made to be able to model the different dwelling types. These assumptions have been predominantly based on the assumptions used by RdSAP to allow for the entry of an existing dwelling into SAP software, which is designed for new build properties where greater technical detail can be included. The main values used are included in Table 4-9 (BRE, 2011a):

Table 4-9 RdSAP assumptions by age band

RdSAP Assumptions		Pre 1945	1945-1964	1965-1990	1990 +
Chimneys		1	1	0	0
No of Doors	Flat	1	1	1	1
	Not Flat	2	2	2	2
Door Area		1.85	1.85	1.85	1.85
Door U Value (W/m^2K)		3	3	3	3
Floor infiltration		0.2	0	0	0
Draught lobby	Flat	Yes	Yes	Yes	Yes
	Not Flat	No	No	No	No
Wall U Value	Solid	2.1	2.1	1	0.45
	Cavity	2.1	1.6	1	0.45
	Filled Cavity	0.5	0.5	0.4	0.45
Loft U Value	< 100 mm	0.68	0.68	0.68	0.68
	100 - 200	0.29	0.29	0.29	0.29
	200 +	0.16	0.16	0.16	0.16
Wall thickness (m)	Solid	0.22	0.22	0.22	0.3
	Cavity	0.25	0.25	0.26	0.3
Floor type		Suspended	Solid	Solid	Solid
Window U Values	Single	4.8	4.8	4.8	4.8
	Double	3.1	3.1	2	2
Window g values	Single	0.85	0.85	0.85	0.85
	Double	0.76	0.76	0.72	0.72
Window area (m^2) [TFA = Total Floor Area)	Flat	0.0801 * TFA + 5.580	0.0341 * TFA + 8.562	0.1199 * TFA + 1.975	0.1148 * TFA + 0.392
	Not Flat	0.1220 * TFA + 6.875	0.1294 * TFA + 5.515	0.1252 * TFA + 5.520	0.1382 * TFA - 0.027
Heat loss perimeter (m)	Flat	15.1	15	14.1	14.1
	MidSemi	16.25	15.56	15.25	14.88
	Det	36.92	31.6	31	32.6

Other data are taken from the SAP documentation for SAP2009, v9.90, in particular from Appendix S, which provides the RdSAP assumptions that are required to be input into a SAP calculation (eg: annual energy demand from a central heating pump) (BRE, 2011a).

4.1.1 SAP Calculations

All the UK stock models discussed in the Literature Review (Chapter 2) use a form of SAP, or its predecessor BREDEM, for physically modelling the energy demand of the housing stock. In addition the Green Deal began at the beginning of 2013, this is a finance and advice scheme for energy efficiency improvements that is based on SAP. Therefore, the intention is that SAP based assessments should inform household's decision making processes when determining the savings to be made from installing a technology, or a set of technologies. However, SAP only has one standardised usage profile, and calculates energy demand on a monthly basis before providing annual outputs. Therefore the calculated savings for the installation of a technology will similarly be provided on an annual basis, both in SAP and in a Green Deal Assessment. However, under the Green Deal the standard usage profiles are amended by actual usage data for the individual household concerned. This means that personalised Green Deal Assessments will include greater variation in the energy demand and running costs. If these variations were to be included in the model it would magnify the size of the model by the number of usage profiles developed, so the model is being restricted to the basic SAP calculation, in particular, SAP2009, v9.90, which was introduced in 2011. This is a practical limitation, and by using the standard average usage profile from SAP extreme households will not be explicitly modelled, where the outcome of their decision making could vary due to their either extremely high or extremely low usage.

In carrying out a SAP calculation the physical characteristics of the dwelling, together with standardised assumptions and occupancy patterns are combined to provide a steady state based estimate of the energy demand for that particular dwelling. A SAP calculation operates via a multi-page worksheet (typically with a computerised front end) as shown in Appendix C, but the following paragraph provides a simplified example of a small element of the SAP calculation to illustrate its operation:

A surveyor assessing a dwelling needs to identify the construction of the dwelling, this includes the construction of the walls, the total area of the walls, and the same for other elements of the building envelope (roof, floor, windows, etc.). Given the construction type of each element (eg: unfilled cavity wall) and age band of the dwelling, SAP will assign a standard U-value (W/m^2K), U_j, which, when combined with the area, A_j for each building element, can determine the fabric heat loss of the dwelling, as shown in equation 4.1:

$$Fabric\ Heat\ Loss\ (W/K)\ = \sum_{j=1}^{n} A_j U_j \qquad [4.1]$$

The fabric heat loss rate is one of a number of components that are used to calculate the net energy requirement to satisfy the heating demand. To the fabric heat loss ventilation losses are added. These are then combined with incidental gains from a number of sources: metabolic, lighting, losses from the hot water system, cooking etc. When all these factors are summed a total heat loss rate is determined (W/K) that is the rate at which the dwelling will lose energy based on the internal-external temperature differential. SAP provides monthly average external temperatures as well as standardised occupancy patterns that dictate the internal temperatures. Therefore by simply multiplying the total heat loss rate by the temperature differentials the net heating demand per month can be calculated. These net figures are then grossed up according to the efficiency of the heating system.

The calculation of the demand for hot water is rather simpler, and is based on an assumed occupancy level, which is determined according to the size of the dwelling. In a similar manner to the heating demand, hot water demand is also calculated on a monthly basis. From the total hot water demand it is possible to determine the net energy required to provide the estimated levels of hot water. In a similar manner to the heating system, further adjustments are made to allow for losses from the system – most notably distribution losses through pipe work and storage losses if the hot water system includes a hot water storage tank. By allowing for these factors an overall net energy demand for hot water can be determined which can then be grossed up according to the efficiency of the hot water system.

SAP also includes some electricity use (apart from electric heating) in the form of a calculation of lighting demand and pumps and motors for heating and hot water systems. Pump requirements are standardised according to the type of heating and hot water systems and for each type provide a single figure in kWh/yr. Lighting demand is calculated according to an assumed demand which is modified by an estimate of the levels of natural lighting available through windows. In order to be able to carry out a full SAP calculation on the model dwellings many assumptions were taken from RdSAP, as detailed in Table 4-99. Such data has been used for the lighting calculations here, eg: calculating the window area for the dwellings according to dwelling age.

In addition, the SAP spreadsheet calculates the energy supplied from any solar hot water or PV systems. For solar hot water RdSAP provides a standardised collector size, and SAP provides standard efficiencies, which have been combined to provide the total hot water energy provided by solar hot water systems. In the case of PV both SAP and RdSAP allow for different sizes of system, therefore variation has been included in the model, with the size of the PV system dependent on the roof area of the dwellings.

Therefore the housing stock data set that was compiled provided sufficient data for each of the 7,992 dwelling types to be input into the SAP worksheet to calculate the outputs for each dwelling. These outputs were in the form of energy in kWh/yr for heating, hot water, cooling and electricity (lighting and electricity required by heating and renewable energy systems). In order to do this an excel spreadsheet was developed that allowed for automation of the input dwelling data as well as automation of the equations required to drive the SAP calculation to generate the required outputs. In addition, over the period from 2008 to 2050 it is reasonable to assume that external temperatures may change. This will impact on heating demand, since if the external temperature rises it will be easier to achieve the desired minimum internal temperatures, which could lead to reduced energy demand. Conversely higher external temperatures may lead to an increase in the potential for internal overheating and thus drive demand for domestic cooling systems, which would increase energy demand. Therefore, each of the 7,992 dwellings was also modelled with 0.1°C increments in temperature up to 4°C higher than the current assumed temperatures in SAP, leading to a total of 327,672 SAP calculations being carried out, although the initial state of the model only uses 781 of these. These temperature changes are applied in a simple manner by just applying the increment equally across all twelve calendar months. This allows for some consideration of temperature changes, but is a simplification as it assumes uniform temperature changes across the year. Many more complex weather scenarios could be imagined, that could lead to very hot summers and very cold winters, which, whilst they might have the same annual average temperature would have noticeably different energy demands.

4.2 Householder Data

Having prepared dwelling stock data based on owner-occupied dwellings in England in 2008, data sources needed to be identified that could be used to describe the occupants of those dwellings, and in particular sources that considered their energy efficiency investment decision making processes. To this end two main data sources were identified, both of these are from research carried out in 2008 – the first by Element Energy was prepared for the Department of Business, Enterprise and Regulatory Reform (BERR) (Element Energy, 2008) and the other by the Energy Saving Trust (EST) on behalf of the Department of Energy and Climate Change (DECC) (Skelton et al., 2009).

As seen in the previous sub-section, the current installation rates of new energy efficiency technologies are very low, such that it is essentially impossible to obtain statistically significant data to describe how the individuals involved carried out their purchase decision making process. In addition, any attempt to extrapolate for the general population from these first installations would be limited as the earliest adopters are likely to have noticeably different weightings in their decision making process than the bulk of the general population. Therefore, both these pieces of research – Element Energy's and EST's – operated in a similar manner by carrying out discrete choice surveys. As discussed in the previous chapter, discrete choice surveys are ideal for discerning how individuals might act when there is little real market data available. However, the caveat needs to remain that the results are only a stated preference and therefore an estimate of how an individual might have acted, as opposed to how they genuinely acted with a real world transaction.

As mentioned above, both of these pieces of research were conducted in 2008 – the same year as the housing stock data, and they were both large scale surveys to achieve statistical significance, with the Element Energy research including 1,171 owner-occupier households in England and EST's research including 2,019. In developing a discrete choice survey the intention is to provide the subjects with choices between two options. This is then repeated a number of times with different options in order to make an estimate of which of the elements of each option are considered most important. The responses can then be used to apply some form of weighting to the value put on each element. Therefore, by determining the expected weights applicable to the different elements of an option, it becomes possible to estimate the value of alternative options by combining the weights applicable to those alternatives.

Element Energy chose to do this via willingness to pay, this is a fairly intuitive approach whereby the repeated discrete choice data are used to estimate a monetary value assignable to the underlying components of a product. This approach therefore assumes that demand for a product is a derived demand for the underlying benefits provided by the product, eg: people do not buy a boiler because they want a boiler, they buy a boiler because they want hot water and heating. Since the choices available for energy efficiency investment in the home are all satisfying the same needs (eg: insulation contributes to thermal comfort; heating systems provide heating and hot water, etc.), different elements need to be valued in order to allow for the comparison of competing products that are aiming to satisfy the same needs. Element

Energy identified a number of elements and put values on them as shown in the Table 4-10 (Element Energy, 2008):

Table 4-10 Element Energy Willingness to Pay Factors

Attribute/ Technology	Primary WTP	Primary s.e	Discretionary WTP	Discretionary s.e
Refuelling/fuel storage	-£1,383	£215		
Garden dug up	-£1,629	£268		
Loss of cupboard space	-£596	£107		
Friend recommendation	+£372	£131	-£212	£147
Plumber	+£690	£142	+£263	£167
Friend and plumber	+£776	£125	+£553	£143
£1 saved on energy bill	+£2.91	£0.30	+£2.95	£0.53
£1 spent on maintenance	-£5.87	£0.60	-£9.21	£1.70
Solar PV			£2,832	£225
Solar Hot Water			£2,903	£235
Micro Wind			£1,288	£223

In their discrete choice survey Element Energy provided respondents with a number of repeated discrete choice questions with two options in each question. Each option contained variations on the features included in Table 4-10, and in this way it was possible to determine the importance the respondents gave to each of the features. The figures are provided as average willingness to pay values together with the standard error bereaved in the sample; for instance, in a primary decision making exercise the average respondent was willing to pay £2.91 for an annual saving of £1 on their energy bill, conversely losing cupboard space reduced the average WTP by £596.

As can be seen, Element Energy identified two distinct types of decision situation. The first, the primary, is for situations where the existing heating system has failed and a replacement is needed – in this decision making situation a decision to install some form of system is compulsory. The alternative, the discretionary buying decision, is, as the name suggests, discretionary and therefore the outcome of this decision making process could be to do nothing – ie: choose not to install one of the technologies.

For the discretionary options they generated a base willingness to pay (WTP) for each of the three technologies considered – solar PV, solar hot water and micro-wind. Adjustments to the base WTP were then made according to the other factors: impact of a recommendation, impact from money saved and an impact from maintenance costs. This adjusted WTP could then be compared with the actual costs of that particular technology to determine whether it would be installed in that particular situation (eg: if a technology cost £3,500 and there was an adjusted willingness to pay up to £4,000 then the technology would be adopted, conversely, if the adjusted willingness to pay was only £3,000 the technology would not be adopted).

In the case of the primary decision a similar procedure is followed, each technology that is being considered has an initial price which is then adjusted according to the factors listed in Table 4-10 and then the option with the cheapest adjusted price is selected as the preferred option. As can be seen in Table 4-10, the Element Energy research identified disruption as a major negative factor, with space for a fuel store (solid fuel or oil systems) or having the garden dug up (ground source heat pumps) being particularly detrimental factors in assessing the willingness to pay for a technology.

There are some interesting differences to the weights being applied under the primary and discretionary buying decisions. Firstly, there is the impact of recommendations – in the discretionary case a recommendation from a friend has an average negative effect, although there is a wide spread to this value, but it does suggest that a friend only recommendation is of limited value for discretionary choices. At the same time the uplift from the plumber's recommendation to a recommendation from both the plumber and a friend is much larger, and significant, whereas the difference for the primary decision is much less and is not significant. The other interesting difference between the two decision situations is with the value put on maintenance costs. The average value of -£9.21 per pound of annual maintenance under the discretionary option is much larger than the -£5.87 for the primary situation or the £2.95 per pound of saving on the energy bill. This therefore has an impact on the discretionary decision making as it heavily penalizes technologies with high maintenance costs, even if they achieve greater savings. It would be reasonable to assume that a rational consumer would put the same value on £1 saved as on £1 spent, but clearly this is not so as there is a factor of approximately 3 difference between the two, this illustrates the economic irrationality of in-expert consumers making one-off buying decisions; ie: households do not act in a purely economically rational manner, which is generally found to be the case in any real world economic decision (Becker, 1962), since economic rationality is a modelling simplification. Nevertheless, where this irrationality can be quantified to some degree it can be modelled, particularly in an agent based environment where heterogeneity naturally leads away from homogenised rational decision making

Unfortunately, the usefulness of the Element Energy research is somewhat limited as these average figures are the only ones that have been made available from the discrete choice survey part of the research. This therefore limits the extent to which a heterogeneous population can be modelled, although the provided standard errors give an indication of the range of responses and can be used to describe a heterogeneous population. As discussed in section 3.3 technology adoption populations tend towards a normal distribution; furthermore, in discussing the data, Element Energy treat this data as normally distributed (Element Energy, 2008)

The Energy Saving Trust carried out a broadly similar exercise, with research that included a discrete choice survey. EST have not made available the raw data but have provided data for each respondent after processing and analysis, this therefore makes this data set much more suitable for describing a heterogeneous population. The data provided are in the form of a table of logit co-efficients for the weighting to be applied to the different factors for each individual respondent. EST combined this data into a tool that would estimate technology take up rates if people were exposed to a particular set of circumstances. In order to facilitate this utility values are used, and to this end a *'NONE'* utility factor for each respondent is also included - this is a utility value assigned to maintaining the status quo. Therefore the EST tool would only predict that an individual would adopt a technology under a given set of circumstances if the utility ascribed to that option exceeded the status quo *NONE* utility. Table 4-111 shows the items included in EST's estimate of an individual's utility (Skelton et al., 2009):

Table 4-11 EST Willingness to Pay Factors

Tech	Internal wall insulation		External wall insulation		Solar hot water		Triple double glazing		
	£20/mth saving	*£40/mth saving*	*£20/mth saving*	*£40/mth saving*	*£20/mth saving*	*£40/mth saving*	*£20/mth saving*	*£40/mth saving*	
Price	£1,000	£2,000	£3,000	£4,000	£5,000	£6,000	£8,000	£10,000	
Incentive	Council rebate		Government environmental award		Stamp duty discount	Council tax rebate		Government grant	No incentive
	£250 pa for 3 years	*£250 pa for 8 years*	*£250 pa for 10 years*	*£125 pa for 10 years*	*£500*	*£300*	*£500*	£500	
Payment method	Personal savings	Loan repaid from energy bill	Mortgage	Government loan		Energy supplier loan		Bank loan	
				0% APR	*2% APR*	*0% APR*	*2% APR*	2% APR	7% APR
Monthly Repayment	£10	£20	£30	£40	£50	£60	£70		

Therefore the utility ascribed to any particular choice is split into five factors: *Tech*, *Price*, *Incentive*, *Payment method*, *Monthly repayment*. Some of the factors are an amalgam of two sub-factors, most notably *Tech*, which is a combination of a technology type and a saving on energy bills, eg: internal wall insulation is available either with a saving of £20 per month, or £40 per month, and the combination counts as one *Tech* option. Therefore there are eight *Tech* options, eight *Price* options, nine *Incentive* options, nine *Payment method* options and seven *Monthly repayment* options, as this is how the EST have presented their data.

In the EST data each respondent has a co-efficient value or weighting for each of these options calculated from their responses to the discrete choice survey. One option from each of the five factors is taken according to the situation being considered. These are then summed, as in a simple additive weighting process, to determine the utility of that particular choice. This utility value is then compared with that respondent's *NONE* value, and by repeating the process across the whole sample population an estimate of the adoption rate of that particular option is produced.

Some of EST's factors are an amalgam of other factors, most notably *Tech*, which is a combination of a technology (eg: internal wall insulation), and a saving on utility bills (either £20 or £40 per month).

Therefore, it can be seen that each of these two data sets have their own strengths and weaknesses. In particular the Element Energy data is readily useable in a technology independent manner, and also includes utility estimates on a per pound basis, allowing for greater flexibility in considering the myriad of different situations encountered in a heterogeneous housing stock. However it has the short-coming of only providing aggregated outputs as opposed to individual level data. Conversely the Energy Saving Trust data provides figures for each survey respondent making it ideal for use in developing a heterogeneous population of agent households, but the factors it uses are themselves composite factors. Therefore neither data set is ideal and the two need to be combined in order to provide the data that will be required to determine the behaviour of the model's agents.

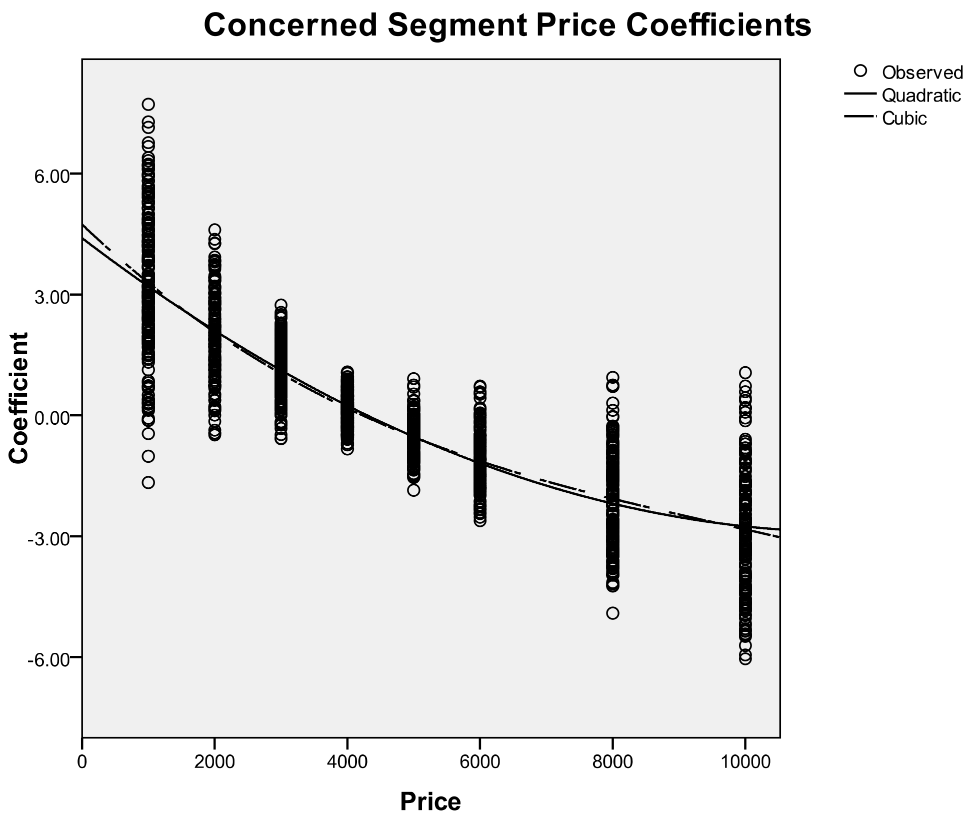
There are methods for attempting to combine logit co-efficients from different studies (eg: (Merkouris, 2004), (Hensher, 1998), (Yuan and Yang, 2004)) However, the main uses are for longitudinal studies with repeated applications of the same questionnaire, for combining stated preference and revealed preference data, or for when there is fuller access to the underlying data. These papers and the methods they describe also work on the basis that all the variables are independent. However, in this instance that is not the case as the final effect is that all the variables impact on the willingness to pay, and price is included as a variable. Unfortunately this means that there appears to be no established method for combining data sources that are as disparate as these two data sets, therefore an alternative approach needs to be considered in order to be able to merge the two data sets together.

The EE data is provided only as average figures for the entire population, whereas the EST data provides values for each respondent, therefore there is potentially more data available in the EST data set and so that will be considered first when merging the data sets. Since a manual approach is required to combine the data sets it is not practical to analyze each respondent's values in turn, so they need to be clustered into manageable sets. Fortunately the EST survey also included questions that allowed the respondents to be classified by DEFRA environmental segment. DEFRA (DEFRA, 2008) carried out a survey to identify different types of people according to their behaviour and environmental attitude, seven classes of people were identified: Positive greens; Waste watchers; Concerned consumers; Sideline supporters; Cautious participants; Stalled starters; and Honestly disengaged. Since each EST respondent was marked with a flag identifying them as belonging to one of these seven classes these were used to separate out the respondents into seven different sets to provide an initial level of heterogeneity in the population. Complete heterogeneity was achieved by dispersing respondents around the centre point for each of the seven clusters.

The EE data is provided in a format that shows the effect on willingness to pay. Since it is possible to create a regression for the effect of price with the EST data, it is proposed that the willingness to pay effects from the EE data are used to alter the price of the technology in the EST model. As previously discussed (Table 4-10), EE provides WTP data for a number of variables, therefore it will be possible to take the starting price for a technology, apply an alteration to the price according to the WTP impact of these variables, and then use the adjusted price as the input to the EST simulator. There is some overlap between the two sets of data and the variables available, therefore care needs to be taken to ensure a variable is not effectively counted twice. This is essentially why the mathematical techniques for combining models assume all the variables are independent.

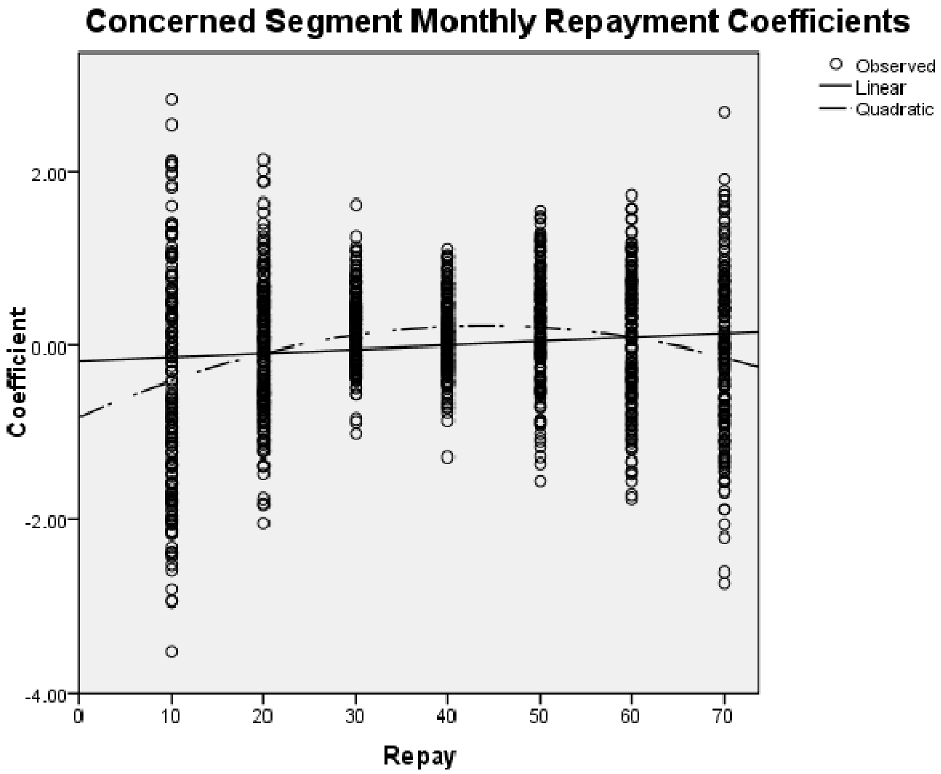
Therefore, for each of the seven clusters the first step was to take the discrete price data, as supplied by the EST and apply regression to convert it into a continuous variable. Figure 4-1 shows the distribution of responses and the regression lines for the Concerned segment of the population (similar graphs were produced for the other six segments).

Figure 4-1 Regression of Price for the Concerned Segment



As can be seen there is a clear trend in this data, in that willingness to pay falls as the price increases, which is as would be expected. Furthermore, the quadratic and cubic regression curves are very similar in the range of the survey responses, a linear regression would have given an R^2 value of 0.739, whilst the quadratic achieves 0.781 and the cubic is marginally better at 0.783. As will be seen in the following chapter the co-efficients for the x^2 term are already in the order of 10^{-8} so the cubic co-efficients are even smaller so the decision has been taken to use the quadratic form for the price regression. A similar exercise is required for each of the seven segments for the monthly repayment figures from the EST data, Figure 4-2 shows again the responses for the Concerned segment (with similar graphs being produced for the other six segments).

Figure 4-2 Regression of Monthly Repayment for the Concerned Segment



In Figure 4-2 it is far from clear what is happening, and the regressions do not pick up on the data very successfully, with a linear regression having an R^2 of 0.011 and the quadratic a little better at 0.061 with the cubic regression marginally improving on this with an R^2 of 0.064. This poor fit is generally due to the very wide spread of responses, although it can be seen that the average at each cost point is fairly flat. Therefore this time, in contrast to the price regression, the cubic regression is to be used for the repayment regression; although this is a marginal decision, and an argument could be made for simply using the mean since even the cubic regression does not provide a great deal of explanatory power. This factor is meant to estimate the impact of varying the rate at which the cost of an improvement technology is repaid by changing the monthly repayment. The wide spread of responses would seem to suggest confusion amongst respondents, as well as different approaches – it might be that some respondents preferred the monthly repayments to be as high as possible with the aim of paying for the technology in as short a time as possible, whilst for others the priority might simply have been to reduce the monthly outgoings, even though that would extend the repayment term.

So far this has allowed for the conversion of the discrete values for price and monthly repayment from the EST data into continuous regression variables such that any desired figures can be used to model the thousands of different potential situations that may occur during a model run. That then leaves three further factors from the EST data: *Tech*, *Incentive* and *Payment* method. As already shown in Table 4-11, these are more problematical as they are amalgams of two separate factors: *Tech* is a combination of technology and reduction in bills; *Incentive* is a combination of the source and size of incentive; and *Payment* is similarly a combination of the source and size of funding. In addition, for each one there are only two numerical values available (either amount of money or interest rate), so with only two data points it is not possible to use this data to provide a regression that can be used to estimate values for intermediate points. The average values for each option for these factors are in a range from -0.95 to +1 therefore the effect of going from one extreme to the other is markedly less than that for the price factor, as can be seen in Figure 4-1, for the Concerned segment its averages vary approximately in the range -3 to +3. Therefore the decision has been made to remove these three factors and replace them with a single value based on the average of the three combined, this therefore simplifies the EST inequality to:

Price + Monthly Repayment + LoanIncentive > None [4.2]

If the inequality is satisfied then the technology is adopted.

With this simplified version it is now possible to include the EE data; so, most of the information that was lost in removing Tech, Incentive and Payment can be re-introduced via the EE data set, and this also avoids double counting of any of the factors. As previously mentioned EE have only provided aggregate figures, so these have had to be used, but with individual agents' values random normally distributed around the mean according to the spreads described in the data. Since the EE data is provided as an effect on the WTP it has been used to adjust the price that is input into the EST inequality.

Therefore these two data sets have been combined to provide a heterogeneous set of data with unique values for each agent that describe the weights each agent will apply to the different factors impacting on a buying decision. Clearly there are some limitations with this: the EE data are not available at the individual level; some assumptions have had to be made in combining the two data sets; and both data sets are based on stated preference from discrete choice surveys, as opposed to revealed preference from real world market transactions. In order to attempt to address some of the inherent errors, during model construction, validation and calibration can be used in order to rescale the factors to improve the model's accuracy, this is to be discussed in the following chapter which deals with the construction of the model.

4.3 Scenario Data

The first two sections of this chapter have discussed the data required for modelling the physical stock and the householder agents. The third set of data that is required is to be used to construct scenarios that can be simulated in the model. Since the model is primarily designed to operate by providing projections from 2008 to 2050 (or any other future date of interest) potential scenarios need to be produced that can be analysed in the model so that predictions can be made as to the likely effects of different factors. Therefore this data comes from numerous different sources. Table 4-122 details the main data sources used for scenario production:

Table 4-12 Data sources for scenario construction

Trigger Points	Trigger points : a convenient truth. Promoting energy efficiency in the home (EST, 2011)
Population	National Population Projections (ONS, 2011)
Construction and Demolition Rates	Net Supply of Housing (CLG, 2011a)
Grid Decarbonisation	Fuel Mix Disclosure Table(DECC, 2012b) The Renewable Energy Review (Committee on Climate Change, 2011) The Carbon Plan (DECC, 2011b)
Subsidy and Incentive Levels	Renewable Heat Incentive Briefing (Friends of the Earth, 2010) Renewable Heat Incentive (DECC, 2011c) Projected Future Feed In Tariffs (Feed-in Tariffs Limited, 2012)
Temperature	UK Climate Projections (Jenkins G et al., 2009)
Inflation and Prices	Fossil Fuel Price Projections (DECC, 2012c) The Growth Potential for Micro-generation in England, Wales and Scotland (Element Energy, 2008) The Property Makeover Price Guide(BCIS, 2008) The Greener Homes Price Guide (BCIS, 2009)

The combination of these data sets allows for the construction of potential scenarios where it is possible to vary any or all of the factors listed to analyze the likely impact of different subsidy levels, or the success or failure of different external policies, or other external factors.

4.4 Chapter summary

In this chapter the identification and acquiring of the necessary data for model construction has been described. This data can be split into three sets: housing stock, householders, and scenario data.

The housing stock data has been taken from the physical surveys in the 2008 English Housing Survey. By combining this data with RdSAP building element assumptions this data has been converted into a format suitable for input into SAP to calculate the theoretical energy demand. The initial housing state of the model (representing 2008) consists of 7,790 dwellings consisting of 781 unique dwelling types, and in total the model allows for 7,992 unique dwelling types, each of which has been modelled in SAP at 41 different temperatures.

The householder data has been taken from discrete choice surveys conducted in 2008 by Element Energy and the Energy Saving Trust. These data sets have been combined and used to provide a simple additive weighting decision making algorithm for each unique householder agent. The initial population of the model is set to 7,790 to match the initial size of the housing stock.

Finally a set of data has been compiled from numerous sources that provides estimated of future demographic changes, economics, and policy measures. These will form the basis of the scenarios that will be analysed with the model.

Having assembled the necessary data sets, the following chapter details its actual development and construction.

Chapter 5 Model Development

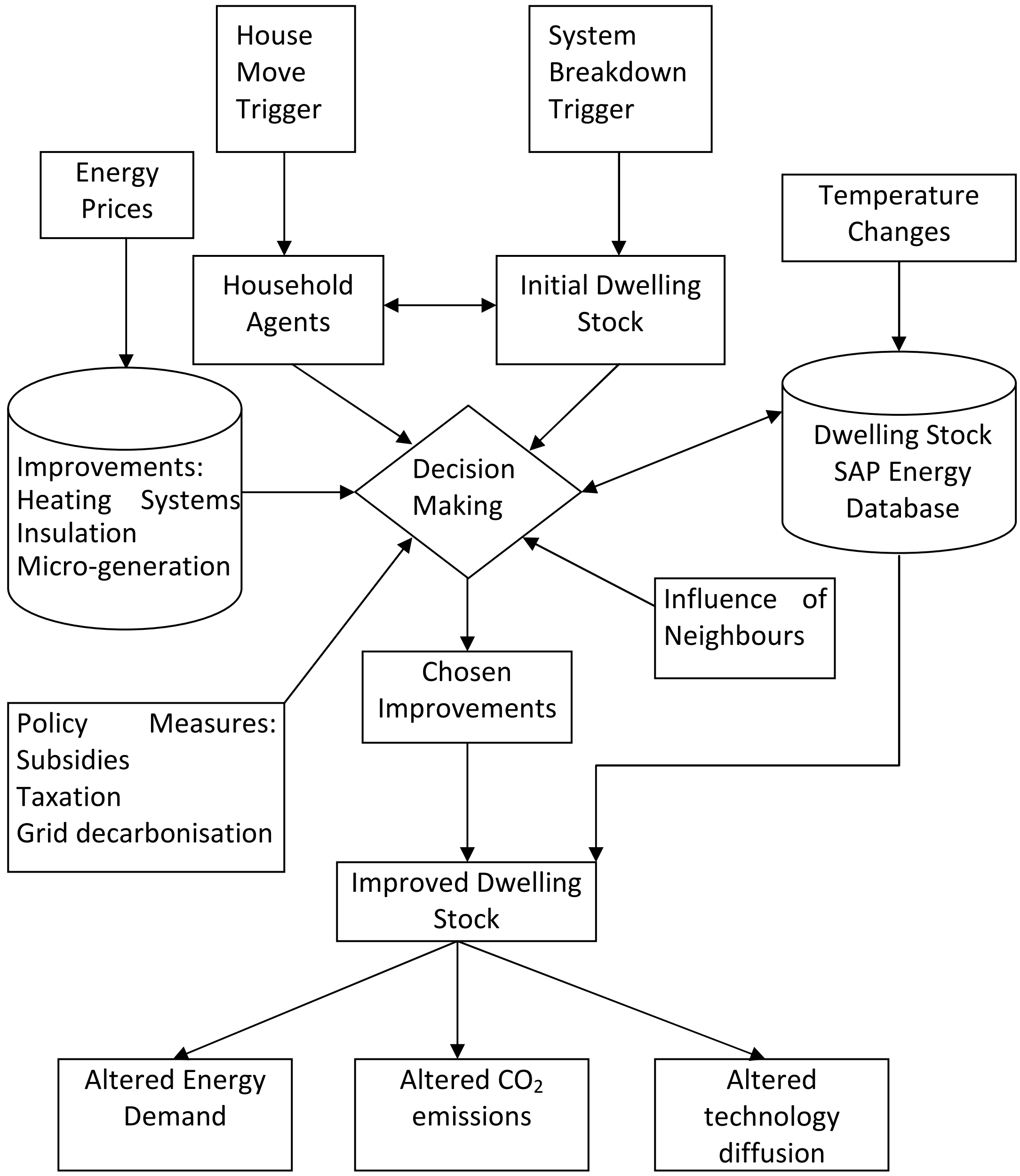
5.1 Introduction

This chapter describes the actual development, construction and testing of the model, and is divided into a number of subsections. The first section provides an overview of how the model is intended to operate. This is followed by a section that describes the NetLogo environment that has been chosen for developing the model; the next subsections describe the actual construction of the model's agents; then there is a description of the user controls that allow for the input of demographic and policy changes; the following section describes the operation of the model; and the final section then explains the testing and calibration of the model.

5.2 Model Framework

Before commencing programming, it is useful to devise a framework, or overview, that details how the model is intended to operate. The flow-chart provided in Figure 5-1 details the basic operation of the model over the course of a single model year and the interaction between the various components, or modules that it will contain.

Figure 5-1 Model overview for 1 model year



From this overview, it is clear that the decision making process is central to this model. Indeed, as detailed in the Literature Review (Chapter 2), the lack of a decision making capability was identified as the main weakness with existing long term domestic energy stock models.

As the figure shows the model essentially has two databases of information that the dwelling agents refer to when making an energy efficiency investment decision. The first of these is a database of the energy demand of the dwelling stock. This database provides the current energy demand, and also provides the energy demand following any potential improvements. The only factor that impacts on this database is the temperature – if external temperatures increase the database adjusts to reduce the energy demand accordingly. The other database available to the decision making householder agents is the set of available technologies, this feeds the available technologies and their running costs into the decision making process.

At the top of the overview are the two triggers for the decision making process. The first of these acts on the households, and is a house-move, which is used as the trigger for all potential improvements. The other trigger acts on the dwelling stock and is the failure of a heating system, which then requires replacement. These triggers are covered in more detail in section 5.4.3.

There are then two further items in the overview that impact on the decision making process. The first of these is policy interventions. In running scenarios through the model it will be possible to adjust the extent of subsidies, taxation, and grid decarbonisation. This allows for their impact on the decision making process to be determined, and therefore the effectiveness of the chosen policies to achieve CO_2 emissions reductions.

The final item that is involved in the decision making process is the effect of neighbours. As previously discussed, recommendations from a household's network can be expected to have an impact on the decision making process when considering a purchase, and, as discussed in the previous chapter Element Energy found that this can have a noticeable impact on willingness to pay.

Therefore, in the decision making process each householder agent, when triggered, evaluates the range of available improvements and then installs those that satisfy their requirements as laid down in the decision making algorithm. This leads to an altered set of dwellings, and therefore changes in the demand for energy, CO_2 emissions, and the penetration levels of the individual technologies. The flow-chart details the model's processes over the course of a single model year, therefore the improved dwelling stock at the bottom becomes the starting point for the next year of a model run. Therefore, over a typical model run from 2008 to 2050 each dwelling agent will undertake a number of decision making exercises, since during that 42 year period the average agent will move house several times and face a number of heating system failures.

As this shows, the main intention of the model is to be able to simulate the decision making of individual households based on various stimuli in order to determine the likely outcome. The model will therefore allow policy makers to alter various factors – principally taxation and subsidy levels as policy interventions, in order to determine their effectiveness in achieving the desired behaviour that will lead to wide scale adoption of energy saving technologies and thus CO_2 emissions reductions.

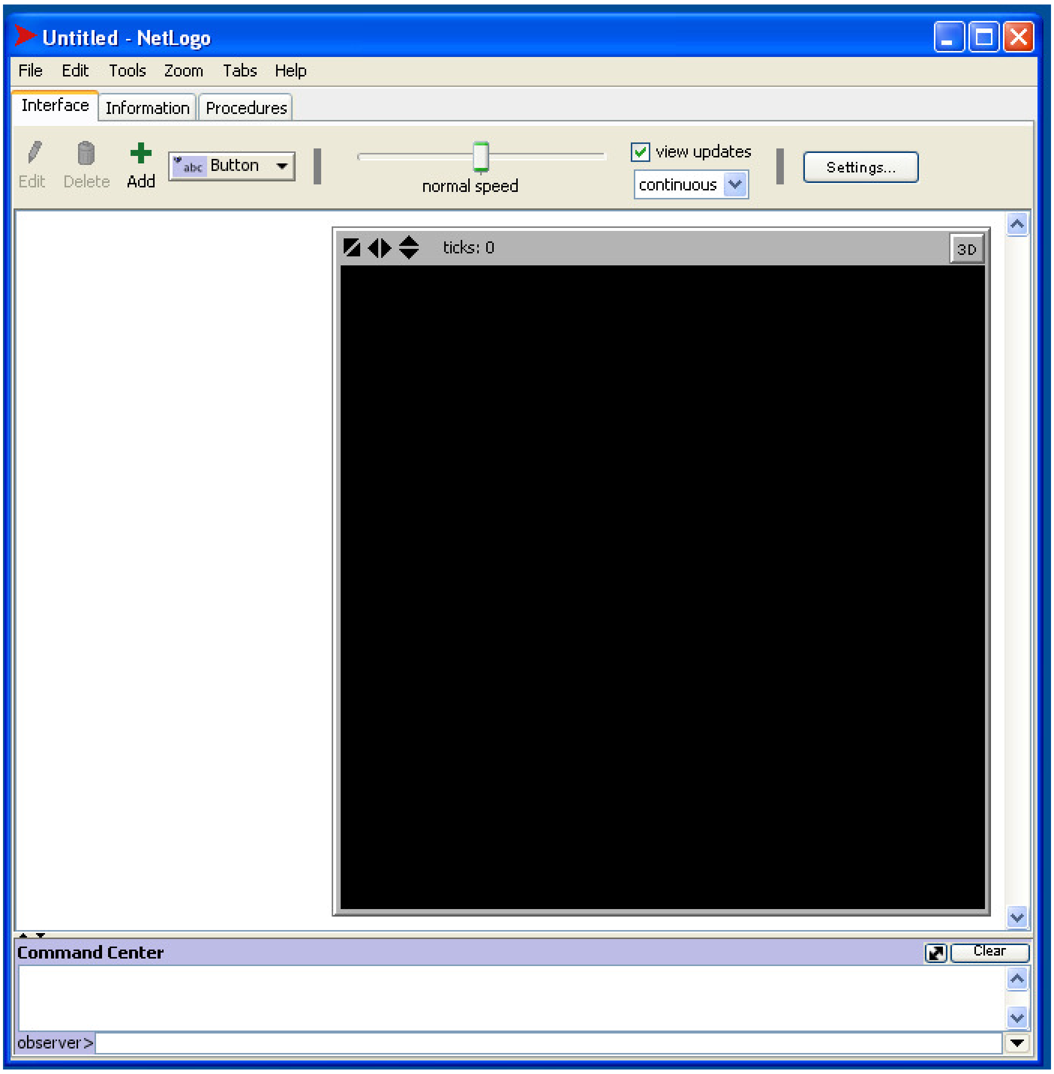
5.3 NetLogo Multi-agent programmable modelling environment

Clearly, before a computer model can be built an appropriate programming language needs to be selected to be used for model development. There are several available languages and programming environments that are available, so an analysis of their respective strengths and weaknesses is required. To this end a very useful review exercise has already been carried out by Railsback (Railsback et al., 2006); he reviews the main five agent based languages: Swarm (Swarm Development Group, 1999), Java Swarm, Repast (North et al., 2006), MASON (Luke et al., 2005), and NetLogo (Wilensky, 1999). Railsback begins by providing a brief overview of the five. Obviously Swarm and Java Swarm are related, with the original Swarm being one of the oldest agent platforms, as the name suggests Swarm was originally designed with swarms in mind with more general tools added later. Repast shares some history with Swarm and is also Java based but does not retain swarms as the key concept. Railsback describes MASON as having been designed in order to minimize run times, but finds it to be the least mature of the platforms. Finally, he describes NetLogo, which is a development from a whole host of Logo languages and therefore shares many programming characteristics with other members of the Logo family. As such NetLogo also has a history of being used as an educational tool, and therefore ease of use is of primary importance. In addition the prime focus of NetLogo is on a spatial grid, which greatly simplifies matters for models consisting of spatially distributed agents. In order to test the five languages, Railsback codes the same model (but with varying numbers of agents) in each of the five different languages. He finds MASON and Repast to be the fastest, then NetLogo and finally Swarm and then Java Swarm both being several times slower than NetLogo with the larger populations where run times were the longest. Finally, in his conclusions Railsback identifies NetLogo as most suitable for starting to use agents and for spatial models with a short time length (the domestic stock model being developed in this research is primarily intended to simulate 42 years, which is essentially 42 time steps in modelling terms). Gilbert (Gilbert, 2008) also discusses the relative strengths and weaknesses of these languages and similarly concludes that NetLogo is the preferred starting point for most agent based researchers, principally as it is the quickest and easiest to learn to use.

NetLogo is an open source and freely available agent based platform maintained by the Center for Connected Learning and Computer-Based Modeling at Northwestern University in Illinois. This means that NetLogo is still being further developed and new versions are periodically released, this model has been developed in version 4.1.3 released in April 2011, although the current version is now 5.0.3 – released in October 2012. Version 4.1.3 is the last iteration of the fourth edition of the software and it could be expected that verification work would have been needed to convert this model to version 5 of NetLogo so the decision was taken to remain with version 4.

Figure 5-2 shows the initial screen presented on opening NetLogo:

Figure 5-2 NetLogo start screen



As can be seen there are three tabs at the top of the page. The first of these, *Interface*, is the one displayed by default, as in Figure 5-2. Once a model is loaded this will consist of buttons and controls for the end user, with the agents displayed in a grid in the black box. The second tab, *Information*, allows the programmer to provide instructions, explanations, or other free text that may be of use or interest to an end user. The final tab, *Procedures*, includes the underlying code that drives the model. At the bottom of the screen is the *Command Center*, this allows the end user to interrogate individual agents, to examine their individual states and to give them extra instructions. There is a number of other features (such as automated running) that will be covered in more detail at the appropriate point, where their usage is being discussed.

5.4 Agent Construction

As discussed in the previous chapter there are two sets of individual entities that are needed to go into this model. The first is the households that will be carrying out decision making processes. The second is the dwelling stock – that is the individual houses that will be occupied by the householder agents and will be subjected to their decision making.

5.4.1 Dwelling agent construction

As changes will be made to the dwellings in the model, a SAP calculation is needed for each potential change. This information will then be used by the householder agents to evaluate the benefit they will receive from each potential option during their decision making. There are two programming approaches to doing this, either a SAP calculation could be carried out each time a householder agent faces a decision making situation, or every possible situation could be processed in SAP beforehand and the model could include a database of each different potential dwelling. In carrying out multiple and repeated simulations with the model there would obviously be many repeated calculations with the first option. This would also slow down the model's operation as thousands of SAP calculations would be required each year in the model. Therefore, as mentioned in the previous chapter, all the possible situations were subjected to a SAP calculation in advance to create a reference database of the different dwelling types. In addition, they were modelled at different external temperatures to allow for scenario simulations that include climate change related temperature increases. The model includes 7,992 dwelling types and 41 temperatures (the initial temperature and then 0.1°C increments up to 4°C) making a total of 327,672 SAP calculations.

The model does not need all the outputs from a SAP calculation, in particular the CO_2 emissions levels, as these will vary according to the carbon intensity of the different fuels. Instead, the outputs required are limited to just four items: annual estimated energy demand in kilowatt hours for heating, hot water, electricity (lighting, pumps, etc), and cooling. By combining these individual figures with the relevant carbon intensities of different energy sources the total CO_2 emissions for that dwelling can be determined. The CO_2 emissions are not taken from the SAP calculations to allow for changes in fuel carbon intensity – in particular to allow for modelling of grid electricity decarbonisation scenarios. The cooling figure is not directly used as the model does not include a simulation of the installation of cooling systems, but the figures are recorded so that estimates can be made of the potential impact on energy demand reductions should cooling systems start to be installed in significant numbers.

Table 5-1 shows a sample of the data derived from the SAP calculations that is included in the reference dwellings:

Table 5-1 First 40 Reference Dwellings at default external temperature

Reference Number	Age	Detachment	Glazing	Wall	Roof	Heating	Solar HW	Solar PV	Heat (kWh)	Water (kWh)	Electric (kWh)	Cooling (kWh)
11111111	1	1	1	1	1	1	1	1	35910	1781	-2237	222
11111112	1	1	1	1	1	1	1	2	35910	1781	798	222
11111121	1	1	1	1	1	1	2	1	35910	2806	-2312	222
11111122	1	1	1	1	1	1	2	2	35910	2806	723	222
11111211	1	1	1	1	1	2	1	1	45257	2134	-2237	153
11111212	1	1	1	1	1	2	1	2	45257	2134	798	153
11111221	1	1	1	1	1	2	2	1	45257	3402	-2312	153
11111222	1	1	1	1	1	2	2	2	45257	3402	723	153
11111311	1	1	1	1	1	3	1	1	59729	12453	-2243	199
11111312	1	1	1	1	1	3	1	2	59729	12453	792	199
11111321	1	1	1	1	1	3	2	1	59729	14200	-2318	199
11111322	1	1	1	1	1	3	2	2	59729	14200	717	199
11111411	1	1	1	1	1	4	1	1	59729	12453	-2143	199
11111412	1	1	1	1	1	4	1	2	59729	12453	892	199
11111421	1	1	1	1	1	4	2	1	59729	14200	-2218	199
11111422	1	1	1	1	1	4	2	2	59729	14200	817	199
11111511	1	1	1	1	1	5	1	1	37987	4386	-2412	257
11111512	1	1	1	1	1	5	1	2	37987	4386	623	257
11111521	1	1	1	1	1	5	2	1	37987	5223	-2487	257
11111522	1	1	1	1	1	5	2	2	37987	5223	548	257
11111611	1	1	1	1	1	6	1	1	70626	12953	-2243	199
11111612	1	1	1	1	1	6	1	2	70626	12953	792	199
11111621	1	1	1	1	1	6	2	1	70626	14626	-2318	199
11111622	1	1	1	1	1	6	2	2	70626	14626	717	199
11111711	1	1	1	1	1	7	1	1	34443	5695	-1881	262
11111712	1	1	1	1	1	7	1	2	34443	5695	1154	262
11111721	1	1	1	1	1	7	2	1	34443	6699	-1945	262
11111722	1	1	1	1	1	7	2	2	34443	6699	1089	262
11111811	1	1	1	1	1	8	1	1	9026	1483	-2282	262
11111812	1	1	1	1	1	8	1	2	9026	1483	753	262
11111821	1	1	1	1	1	8	2	1	9026	1745	-2357	262
11111822	1	1	1	1	1	8	2	2	9026	1745	678	262
11111911	1	1	1	1	1	9	1	1	11554	1898	-2282	262
11111912	1	1	1	1	1	9	1	2	11554	1898	753	262
11111921	1	1	1	1	1	9	2	1	11554	2233	-2357	262
11111922	1	1	1	1	1	9	2	2	11554	2233	678	262
11112111	1	1	1	1	2	1	1	1	36473	1781	-2237	222
11112112	1	1	1	1	2	1	1	2	36473	1781	798	222
11112121	1	1	1	1	2	1	2	1	36473	2805	-2312	222
11112122	1	1	1	1	2	1	2	2	36473	2805	723	222

The final four columns show the estimated heat, hot water, electricity and cooling demand in kilowatt hours per year. The reference number is a concatenation of the code values assigned to the different elements that describe the physical characteristics of the different dwellings, these codes and their meanings are shown in Table 5-2:

Table 5-2 Dwelling physical characteristics and code labels

Age	Detachment	Glazing	Wall	Roof W/m^{2}K	Heating	SHW	PV
1 Pre-1945	1 Detached	1 Full DG	1 Solid	0 None	1 Condensing boiler	1 Yes	1 Yes
2 1945-1964	2 Semi/Mid Terraced	2 Part DG	2 Cavity	1 U=0.16	2 Combi-boiler	2 No	2 No
3 1965-1990	3 Flat		3 Retro-fit CWI	2 U=0.29	3 Regular boiler		
4 1990+				3 U=0.68	4 Oil boiler		
					5 Electric		
					6 Solid fuel		
					7 Community Heating		
					8 GSHP		
					9 ASHP		

By way of example the first reference dwelling, with the code 11111111 is therefore a pre-1945 detached house and is fully double glazed with solid walls, a highly insulated roof, a condensing gas boiler, a solar hot water system and solar photovoltaics. The effect of changing the physical characteristics can be seen simply by looking at the next reference dwelling, 11111112, this is an identical dwelling except without the PV system. Therefore it has the same heating, hot water and cooling demand, but it has a positive demand for electricity, as opposed to dwelling 11111111 with the PV system, which has a negative demand for electricity, meaning that it would be feeding back into the grid.

It should be noted that the reference number and the characteristics listed do not include the temperature element. Instead, since a temperature change will affect all dwellings, each time in the model the temperature is changed the reference dwellings are replaced with a new set that have energy demand figures calculated at the appropriate temperatures. This therefore means that the model only needs to have loaded a reference set of 7,992 dwellings at any one time instead of the complete set of 327,672 again reducing computer load by reducing the number of records to search every time a set of data is needed from a reference dwelling.

These reference dwellings therefore supply the database of the energy demand of every possible dwelling type in the model. They are therefore designed so that they can be called upon by a householder agent to determine the change in energy demand resulting from any particular energy efficiency improvement that is being considered. As well as these reference dwellings, that are used simply to provide an information database, there are the actual dwellings occupied by the householder agents.

As previously mentioned, in chapter 4, the model is being started with an initial population of 7,790 dwellings, based on data from the English Housing Survey (CLG, 2011c). Whilst there are 7,790 dwellings, only 781 unique types are used in the initial stock, with proportions set according to the EHS data.

Table 5-3 shows the data for the last 40 dwellings in the 7,790 starting stock.

Table 5-3 Extract from initial dwelling stock data

Reference Number	Age	Detachment	Glazing	Wall	Roof	Heating	Solar HW	Solar PV	Heat (kWh)	Water (kWh)	Electric (kWh)	Cooling (kWh)
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130322	4	3	1	3	0	3	2	2	4505	4019	378	319
43130422	4	3	1	3	0	4	2	2	4505	4019	478	319
43130522	4	3	1	3	0	5	2	2	3725	2137	248	260
43130522	4	3	1	3	0	5	2	2	3725	2137	248	260
43130522	4	3	1	3	0	5	2	2	3725	2137	248	260
43131222	4	3	1	3	1	2	2	2	8298	2366	423	206
43131322	4	3	1	3	1	3	2	2	7733	3937	378	264
43131322	4	3	1	3	1	3	2	2	7733	3937	378	264
43131322	4	3	1	3	1	3	2	2	7733	3937	378	264
43131422	4	3	1	3	1	4	2	2	7733	3937	478	264
43132122	4	3	1	3	2	1	2	2	5992	2085	423	201
43132122	4	3	1	3	2	1	2	2	5992	2085	423	201
43132122	4	3	1	3	2	1	2	2	5992	2085	423	201
43132222	4	3	1	3	2	2	2	2	6802	2380	423	201
43132222	4	3	1	3	2	2	2	2	6802	2380	423	201
43132322	4	3	1	3	2	3	2	2	6237	3967	378	254
43132322	4	3	1	3	2	3	2	2	6237	3967	378	254
43132322	4	3	1	3	2	3	2	2	6237	3967	378	254
43132422	4	3	1	3	2	4	2	2	6237	3967	478	254
43132522	4	3	1	3	2	5	2	2	5081	2137	248	223
43133222	4	3	1	3	3	2	2	2	6288	2386	423	192
43222322	4	3	2	2	2	3	2	2	7009	3951	382	262
43231122	4	3	2	3	1	1	2	2	7990	2071	427	215
43231222	4	3	2	3	1	2	2	2	9069	2361	427	215

As can be seen in this set of 40 dwellings there are a number of repetitions, for instance there are 17 instances of dwellings with the reference number 43130322 but only one 43130422 (the same dwelling but with an oil boiler instead of a conventional gas boiler). In applying the weightings to make the starting stock a close match to the EHS data some rounding needed to take place, so Table 5-4 shows the distribution of wall, roof and gas heating types in the EHS data and in the model's starting stock, as can be seen the model's distribution closely matches the distribution in the EHS data set.

Table 5-4 Comparison of EHS and model initial stock composition

	CWI	Cavity	Solid		No Loft	<100 mm	100-200 mm	>200 mm		Gas Cond	Gas Combi	Gas Reg
Model start	2806	2833	2151		313	2010	3723	1744		1283	1985	3511
EHS 2008	2797	2828	2165		314	2011	3723	1742		1285	1984	3511

Having developed the reference dwellings and the initial dwelling stock's starting data the next item that needs to be developed is the set of householder agents, which is covered in the next sub-section.

5.4.2 Householder agent construction

The initial dwelling stock has been set at 7,790 dwellings, consequently the initial set of householder agents will be set the same – ie: one household per dwelling. As discussed in the previous chapter, the data to drive the individual agents' decision making process is based on Energy Saving Trust and Element Energy discrete choice surveys of individuals. In reality there is a difference between an individual and a household that will frequently comprise more than one person, and it could therefore be expected that there would be internal discussions within the household, but for this research it is being assumed that the individual data from the surveys represents the responses at the household level. As mentioned in the previous chapter the householder agents are split into seven clusters according to their DEFRA environmental attitude (DEFRA, 2008). Similarly to the dwellings, the householder agents have a code that identifies their cluster membership, these and the initial default distribution are shown in Table 5-5:

Table 5-5 Cluster populations

Cluster Code	Cluster Type	Population Number	Population %
1	Cautious participants	958	12.3
2	Concerned consumers	1519	19.5
3	Honestly disengaged	1628	20.9
4	Positive greens	1909	24.5
5	Sideline supporters	545	7.0
6	Stalled starters	265	3.4
7	Waste watchers	966	12.4

Since there were two different data sources, and only the EST one identified cluster membership only the data coming from EST has been separated out according to cluster membership. These are therefore the regression values for *Price* and *Repayment*, that determine the weight to apply to any particular cost and repayment, as well as the *None* value for maintaining the status quo. In order to generate unique householder agents, although the same regression curves have been used in a specific cluster, the y-axis intercept has been normally varied according to the standard deviation applicable to that clusters' responses. Table 5-6 and Table 5-7 detail these values:

Table 5-6 Cluster price and none co-efficients

Cluster	Price constant	Price std deviation	Price x	Price x2	None	None std deviation
Cautious participants	4.784	1.096	-0.00139	6.254×10^{-8}	4.79	3.820
Concerned consumers	4.400	1.106	-0.00126	5.402×10^{-8}	4.89	3.718
Honestly disengaged	3.978	1.057	-0.00112	$4.702 \text{ X } 10^{-8}$	5.57	3.866
Positive greens	5.001	1.091	-0.00144	6.281×10^{-8}	4.29	3.674
Sideline supporters	5.282	1.103	-0.00153	6.747×10^{-8}	4.99	3.874
Stalled starters	4.089	1.067	-0.00117	5.009×10^{-8}	5.13	4.429
Waste watchers	4.293	1.061	-0.00123	5.347×10^{-8}	5.12	3.957

Table 5-7 Cluster repayment and loanincent co-efficients

Cluster	Repay constant	Repay std deviation	Repay x	Repay x^2	Repay x^3	Loanincent	Loanincent std deviation
Cautious participants	-1.619	0.784	0.108	-0.00207	0.0000127	-1.497	0.904
Concerned consumers	-1.134	0.816	0.0826	-0.00153	0.00000846	-1.134	0.816
Honestly disengaged	-1.206	0.792	0.0862	-0.00165	0.00000946	-1.206	0.792
Positive greens	-1.435	0.824	0.0948	-0.00173	0.00000989	-1.518	0.833
Sideline supporters	-1.081	0.881	0.0605	-0.000812	0.00000254	-1.492	0.913
Stalled starters	-1.275	0.778	0.0784	-0.00142	0.00000891	-1.369	0.884
Waste watchers	-1.238	0.750	0.0834	-0.00151	0.00000835	-1.238	0.750

As discussed in the previous chapter, the EST data consisted of values for *Price*, *Repayment*, *Tech*, *Incentive*, *Payment* and *None*. *Price* and *Repayment* are provided in the regressions as above; *Loanincent* provides a unique value for each agent based around the average sum of the three factors *Tech*, *Incentive* and *Payment* in each cluster; and *None* is based around the cluster average for the utility value of maintaining the status quo and not installing a technology.

Having input the EST data into the householder agents the EE data then need adding to the agents. Individual values are not available from the EE data, so each householder agent has a unique value by random-normally distributing the values around the average for each factor, these values are shown in Table 5-8:

Table 5-8 EE Factors

Factor	Value £	Standard deviation
Fuelstore	1381	215
Garden	1629	268
Cupboard	596	107
Primfriend	372	131
Primsav	2.91	0.3
Primmain	5.87	0.6
Discfriend	553	143
Discsav	2.95	0.53
Discmain	9.21	1.7

All of these factors are used to impact on the price of the technology, so are used before the price is regressed using the regression co-efficients discussed earlier. *Fuelstore* is the impact from needing space to store solid fuel; *Garden* is the impact from needing the garden to be dug up; *Cupboard* is the impact from the loss or gain of cupboard space; *Primfriend* is the impact of a friend's recommendation for a primary decision and *Discfriend* is the same but for a discretionary decision; *Primsav* and *Discsav* are the effect from a saving in bills for primary and discretionary decisions respectively; and *Primmain* and *Discmain* represent the impact of maintenance costs on primary and discretionary decisions.

The original EE data had recommendations as three separate items: a friend's recommendation, a plumber's and a combined recommendation. Attempting to simulate these three options as distinct actions would have greatly complicated the model. Instead, only the combined recommendation has been included, but it is being moderated based on the number of neighbours that already have the particular technology being considered. NetLogo provides a spatial grid for its agents, therefore each grid square has eight neighbouring squares and the model is arranged so that each grid square should contain no more than one dwelling. It would seem reasonable to assume that the greater the number of neighbours with a technology the more likely a particular householder agent is to receive a recommendation or some form of peer pressure that would encourage adoption of that particular measure. Therefore, the decision has been made that an agent, when considering a technology, should count the number of neighbours with that technology, divide it by four and then use the resulting fraction as a multiplier against the recommendation factor.

Table 5-9 and Table 5-10 detail the potential improvements that are considered:

Table 5-9 Heating options

Current System	Detached	Midsemi	Flat
1 Condensing Gas	1,6,8,9	1,8,9	1,7,9
2 Combi Gas	1,6,8,9	1,8,9	1,7,9
3 Regular Gas	1,6,8,9	1,8,9	1,7,9
4 Oil	6,8,9	6,8,9	6,8,9
5 Electric	5,6,7,8,9	5,6,7,8,9	5,7,9
6 Solid	6,8,9	6,8,9	6,8,9
7 Community	7	7	7
8 GSHP	6,8,9	6,8,9	6,8,9
9 ASHP	6,8,9	8,9	7,9

As can be seen there are a number of assumptions involved in deciding which heating technologies are available for which types of dwellings: in the majority of cases it is assumed that only flats have the potential for retro-fitting a community heating system – but they have also been allowed for other dwellings with electrical heating on the assumption that these are more likely to be urban as they do not have oil or solid fuel systems; dwellings that start without a gas system are off the gas grid; not all dwellings have sufficient space for a ground source heat pump or a solid fuel store; once a community system is installed alternatives cease to be available; for gas systems non-condensing boilers are not allowed as replacements for existing systems.

Table 5-10 Fabric options and renewable options

Existing Building Element	Potential Improvement
Roof 0 (Dwelling above)	No change
Roof 1 (U=0.16 W/m^{2}K)	No change
Roof 2 (U=0.29 W/m^{2}K)	Roof 1,2
Roof 3 (U=0.68 W/m^{2}K)	Roof 1,3
Wall 1 Solid	Wall 1,3
Wall 2 Cavity	Wall 2,3
Wall 3 Retro-fit Wall Insulation	No change
Roof 0 (Dwelling above)	No change
Roof 1,2,3	No change, Solar hot water, Solar PV, Solar hot water and PV

Here, it is assumed that a roof will either be improved to a U-value of 0.16 or it will stay as it is; similarly they will either be retrofitted with wall insulation or they will not – in order to reduce the number of dwelling types needed it has been assumed that retrofitting insulation to either solid or cavity walls will achieve the same end U-value for the walls, thereby negating the need to differentiate between them when carrying out the SAP calculations. Two renewable energy measures are available in the model – solar hot water and solar photovoltaics – and it is assumed that these are possible measures as long as the dwelling has a roof, and that a suitable dwelling can have none, either or both.

The only measure that has not been included in the tables above is glazing. Whilst it has some energy efficiency impact it is difficult to model using the range of inputs available to this model as a large element of their perceived value seems to come from beyond the pure resulting energy savings; the RICS (BCIS, 2009) estimate that the payback period on double glazing is over 120 years, which is greater than their expected lifetime. Furthermore there are already high levels of double glazing installation, and even dwellings without full double glazing frequently have partial double glazing. For this model two glazing types were used: full and partial, with the level of partial double glazing set according to dwelling age, based on the EHS data, these data are reproduced in Table 5-11:

Table 5-11 Double glazing levels in initial stock

Dwelling Age Band	Percent fully double glazed	Percent of double glazing in partially double glazed dwellings
1 Pre 1945	54	35
2 1945-1964	75	56
3 1965-1990	82	52
4 1990+	96	35

As can be seen out of the initial dwelling stock in the model only 28% of it is not already fully double glazed, and the average partially double glazed dwelling is 42% double glazed. Consequently, the effect of moving from the current situation to full double glazing is limited. Therefore, instead of attempting to include extra modelling solely for this decision making, it has been assumed that new double glazing is installed when a new householder agent moves into a dwelling.

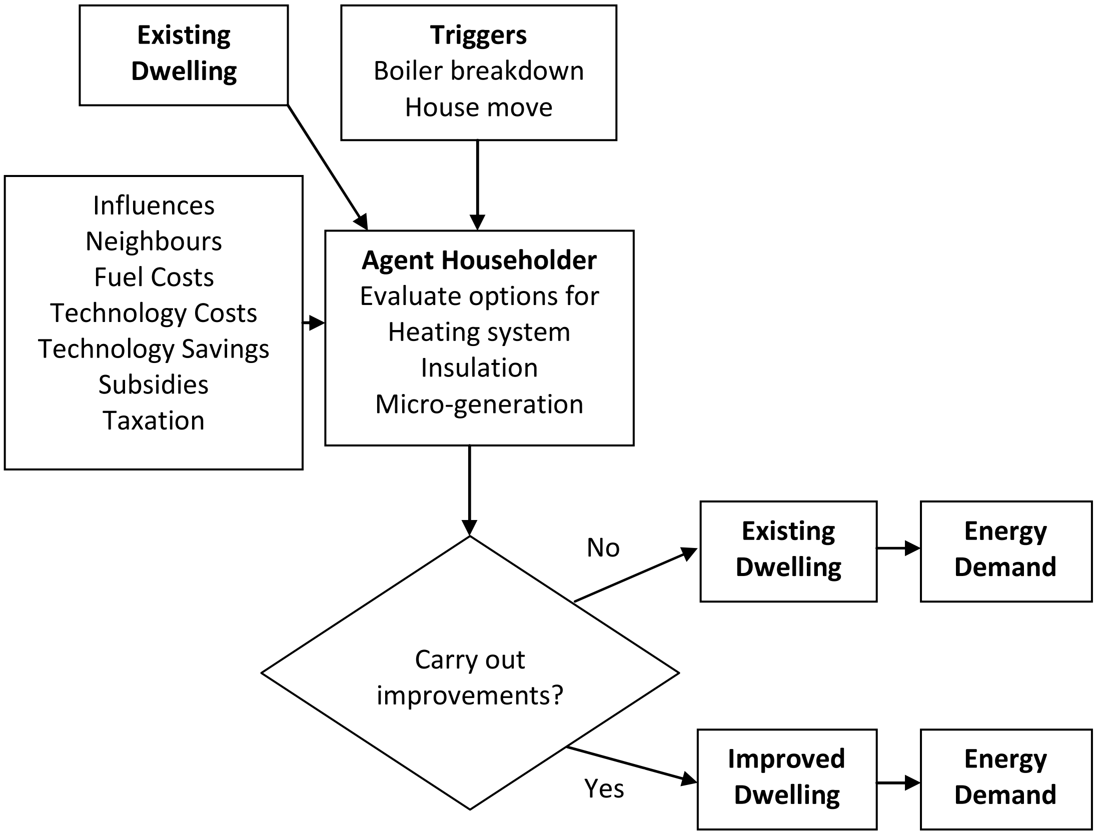
5.4.3 Decision making triggers

The householder agents in the model need to be triggered into carrying out their decision making process. The EST carried out research to identify the likely trigger points (EST, 2011) and they estimate that 22% of homeowners will consider refurbishment in the next three years. In order to simulate this there were essentially two available approaches: either select a random set of households in each year of the model and make them consider carrying out improvements to their dwellings, or make a random set move home and then consider the available improvements. Of these two options the second has been selected, since it allows for a simulation of house moving as a trigger for considering improvements. It also means that the householder agents will, over the course of a 2008-2050 simulation, be exposed to different dwelling types, as opposed to simply having the same options available each time as they would still be in the same dwelling. The house moving trigger is being used to consider all available technologies and the householder agents are aware of all the potential options available to them. Improvements that are being considered under this trigger use the discretionary co-efficients from the Element Energy research, as any improvements chosen from this trigger will be optional.

There is also a second trigger, which is solely for the heating system. Each dwelling's heating system is given a lifetime, once that lifetime is reached the system is assumed to fail and a new heating system is required. This is therefore not a discretionary choice and so the primary heating co-efficients are used as opposed to the discretionary ones, as above. There appears to be no reliable data estimating the average lifetime of a boiler, although 15 years might be a plausible average lifetime (CORGI, 2011). Therefore each heating system has been set with a randomly assigned lifetime with an average of 15 years and a standard deviation of 5 years. In addition, at the start of the model each boiler is given a randomly distributed initial age – otherwise there would be too few heating system breakdowns in the early years of a model run.

The following flowchart shows an overview of what happens to an individual householder agent:

Figure 5-3 Dwelling agent flowchart



As can be seen, if triggered in a particular year an individual householder agent will consider improvements and then decide whether or not to carry them out, leading to a change in the energy demand from their particular dwelling, thus impacting on the overall energy demand for the entire stock. The following pseudo-script provides two examples of the decision making process of one agent in the first year of a model run for PV, the first one without a PV-grant, and the second one with a PV-Grant of £2,500:

```
Price + Repay + Loanincent > None
(If inequality satisfied technology adopted)

Initial dwelling number:  12122322
Annual electric kWh:      566.75
Potential change:         12122321
Annual electric kWh:      -1042.27
Saving kWh:               1609.02

PV-Grant:£0 PV-Fit:0p Electric price: £0.0958
```

Annual saving: £0.0958 x 1609.02 = £154.14
repayment = annual saving/2/12 = £6.42

No. of neighbours with PV: 0
Effect of recommendation: £0

Householder variables: priceconst: 5.924
pricex: -0.00126 pricex2: 5.402 x 10^{-8} none: 12.793
repayconst: -1.386 repayx: 0.0826 repayx2: -0.00156
repayx3: 8.46 x 10^{-6} loanincent: -1.517 discsav: 3.124
discmain: 7.085 pvfixed:£2000 pvmarg: £4357.7
pvmain: 110 pvsize = saving kWh/850
pvsize = 1609.02/850 = 1.89

adjustedprice = pvfixed + pvmarg x pvsize + pvmain x discmain - saving x discsav
adjustedprice = 2000 + 4357.7 x 1.89 + 110 x 7.085 - 154.14 x 3.124 = 10533.87
Price = priceconst + pricex(adjustedprice) + pricex2$(\text{adjustedprice})^2$ = 5.924 - 13.27 + 5.994
Price = -1.352
Repay = repayconst + repayx(repayment) + repayx2$(\text{repayment})^2$ + repayx3$(\text{repayment})^3$
Repay = -1.386 + 0.530 - 0.064 + 0.002 = -0.918
Price + Repay + Loanincent = -1.352 -0.918 -1.517 = -3.787
None = 12.793
-3.787 < 12.793 Therefore PV not installed

The second version, with the PV grant has the same initial values and only differs when it reaches the calculation of the *adjustedprice* as follows:

adjustedprice = pvfixed + pvmarg x pvsize + pvmain x discmain - saving x discsav - pv-grant
adjustedprice = 2000 + 4357.7 x 1.89 + 110 x 7.085 - 154.14 x 3.124 - 2500 = 8033.87
Price = priceconst + pricex(adjustedprice) + pricex2$(\text{adjustedprice})^2$ = 5.924 - 10.13 + 3.49
Price = -0.716
Repay = repayconst + repayx(repayment) + repayx2$(\text{repayment})^2$ + repayx3$(\text{repayment})^3$
Repay = -1.386 + 0.530 - 0.064 + 0.002 = -0.918

```
Price + Repay + Loanincent = -0.716 -0.918 -1.517
= -3.151
None = 12.793
-3.151 < 12.793 Therefore PV not installed
```

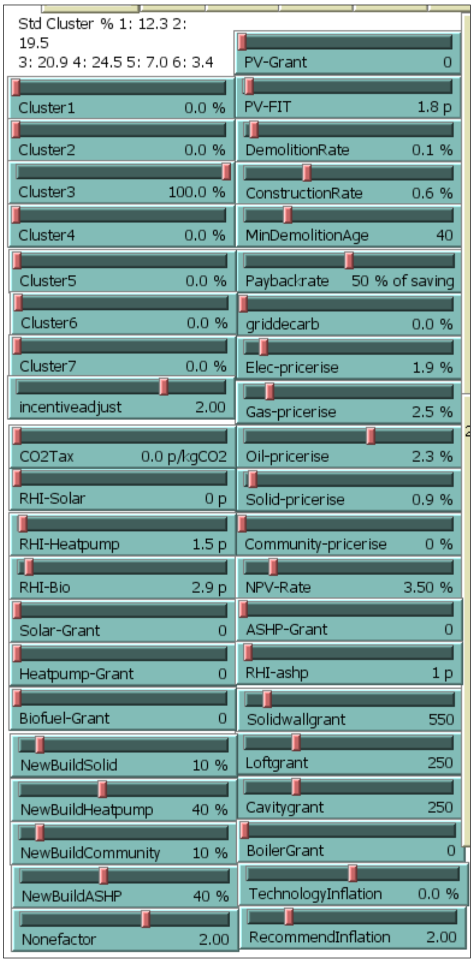
The above section shows the internal process of the householder agent in considering a technology. Initially it identifies the available improvements, just one of these – PV – is presented above. It then searches for the comparable reference house so it can identify the available saving from installing that technology. As this was taken from the first year of a model run no neighbours had PV so there was no impact from a recommendation from neighbours. The householder then determines the price of the technology, which consists of a base price – *pvfixed* – and then a marginal additional price – *pvmarg* – which is a price per kWp for the PV system. Then the householder, using its internal variables, determines the adjusted price for the technology with an impact from savings and maintenance and recommendations, etc. It then determines the impact of repayments, and finally operates the main inequality to determine whether or not to install the technology. In this case it is clear that this particular agent is a long way from deciding to install PV. Indeed, it has quite a high *NONE* value and will therefore be fairly reticent to install any technologies as this provides a high barrier for any technology to have to overcome. Nevertheless, it can be seen that the addition of the up front grant makes PV a more attractive proposition, and for another agent, with a lower status quo threshold *NONE* value it could be sufficient to change the decision.

In every year of a model run 7% of agents will be triggered to consider all available improvements via a home move, and will therefore carry out a similar exercise to the previous example. The randomly selected 7% all leave their current dwelling leaving a matching number of dwellings vacant, the moving agents are then randomly assigned to one of the vacated dwellings. The model also incorporates the ability to demolish existing dwellings and to build new ones; in the model, when a dwelling is demolished its resident agent essentially dies, and, similarly, when new dwellings are created a matching number of new agents are created to fill the new stock. In addition, others will face heating system breakdown and will therefore go through the process of considering a replacement system – but in that case they will use the primary rather than discretionary variables as they will not have the choice of deciding to do nothing. The heating system breakdown is based on an average lifetime of 15 years for a heating system, so approximately 1 out of every 15 agents will be triggered by a heating system breakdown each year in the model. Some agents will theoretically be exposed to both triggers in one year, but when that happens they will only search for a new heating system once (on the breakdown). In total then, in the first year of a model run approximately 545 households will move home and approximately 519 heating systems will breakdown. Therefore the decision making process will be run around 1,000 in every model year.

5.5 User Controls

The intended purpose for this model is to be able to create different scenarios and analyse them. In order to do so variables need to be changed to create alternative scenarios. This subsection describes the different variables that can be adjusted. A number of slider controls have been made available for this, as shown in the following image, which is a screen grab from the user interface:

Figure 5-4 Slider controls

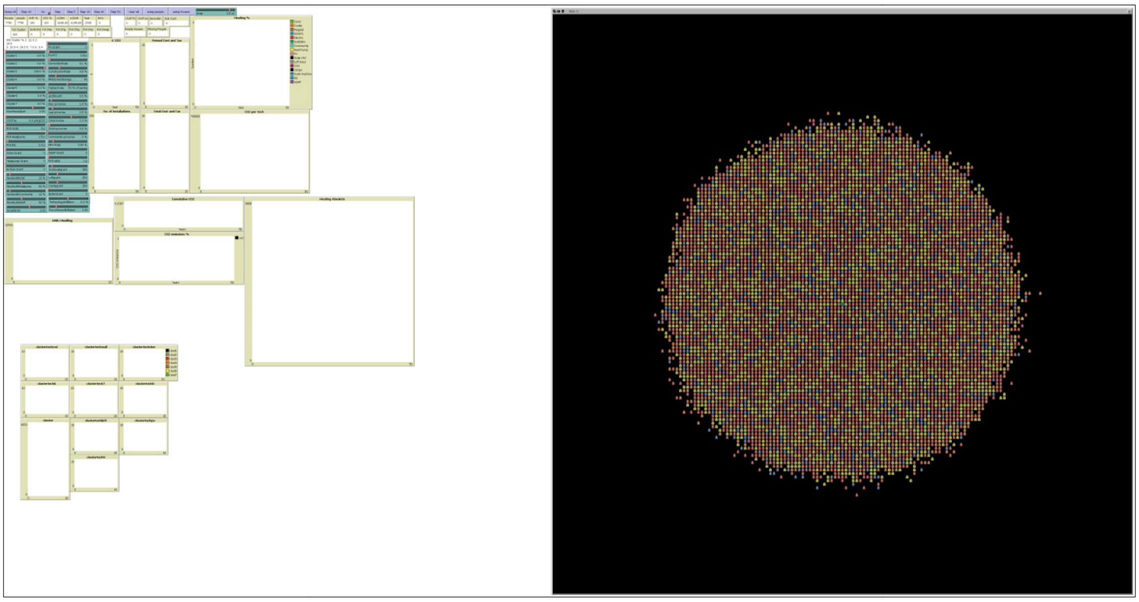


The first set of variables are for householder cluster membership. As can be seen, in this particular set up, Cluster3 is the only one with members – therefore this scenario if focussing just on that cluster. In order to consider inflationary impacts there is a number of sliders for inflation, these cover different fuel types, technology inflation, and inflation on the value of recommendations. It should be noted that the technology inflation is set at 0% - this is the default value. The model has included set estimates of the future costs of technologies based on Element Energy's Technology Cost Forecasts (Element Energy, 2008), by altering the technology inflation from its 0% figure alternative technology cost projections can be simulated. There is then a range of subsidies: those with '*grant*' in their name are up front capital grants, whereas *RHI* (renewable heat incentive) and *FIT* (feed-in tariff) variables provide an income in pence per kWh of energy produced. *NPV-rate* is used for calculating the total cost of subsidies, eg: the feed-in tariff is payable for 25 years, so the total cost is rolled up via a net present value calculation. *Paybackrate* is used to determine how much of the savings from a measure are used to repay the cost, and therefore how much should be assigned to the calculation of the impact of the repayment. Whilst the model does not have the resolution to consider different sources of funding, it is still valid to include this factor, since even if the money for a technology came from savings, as opposed to a loan, there is still a theoretical deficit in the level of an individual's savings that could be recouped from the savings made by the technology. *Griddecarb* is simply an annual percentage reduction in the carbon intensity of grid electricity. *Demolitionrate* and *constructionrate* set the percentage of dwellings to be destroyed and new dwellings to be built each year, and *mindemolitionage* sets a minimum age before a dwelling can be considered for demolition. In each year of a model run a percentage of those above the *mindemolitionage* are randomly selected for demolition and are replaced with an appropriate number of new dwellings according to the *constructionrate* value. After 2016 it is assumed that gas heating will not be an option for new dwellings due to improvements to minimum energy efficiency of new builds in the Building Regulations, and the anticipation for new homes from 2016 to be zero carbon in use. The newbuild sliders therefore control the proportions of heating systems in new builds from 2016, prior to that date they are set to match the proportions in existing dwellings. There is one further slider not shown in this screen grab, *temp*, which controls the rate at which external temperatures are projected to increase. The final two sliders are *nonefactor* and *incentiveadjust*, which are used for calibrating the model and will be discussed in more detail in a subsequent sub-section. Each one of these forty-one controls can be varied yearly in the model, therefore allowing for an almost limitless number of potential scenarios.

5.6 Model Operation

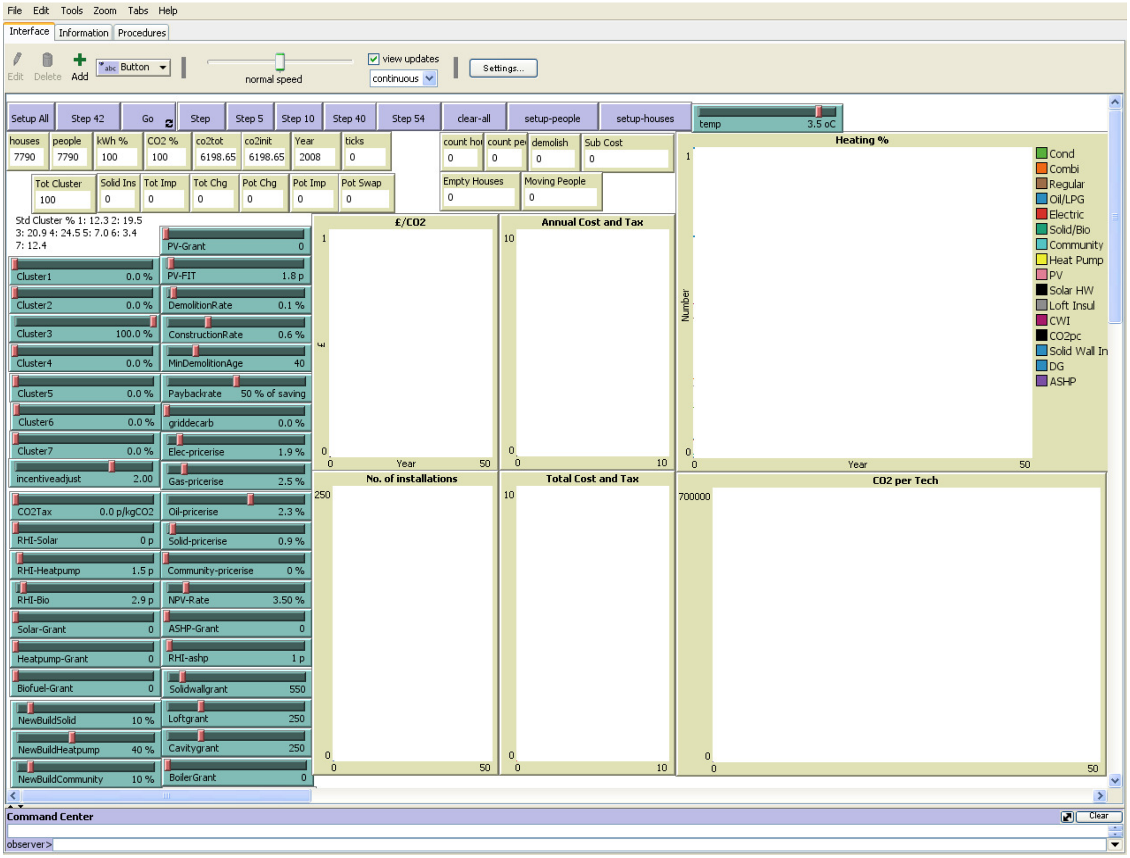
This sub-section walks through the operation of the first step (year) in the model. Once the model is loaded it needs to be setup into its initial state, when this happens the initial stock of 7,790 dwellings and householders will be created and spatially distributed on the grid; this can be seen to the right of Figure 5-5.

Figure 5-5 Initial model state



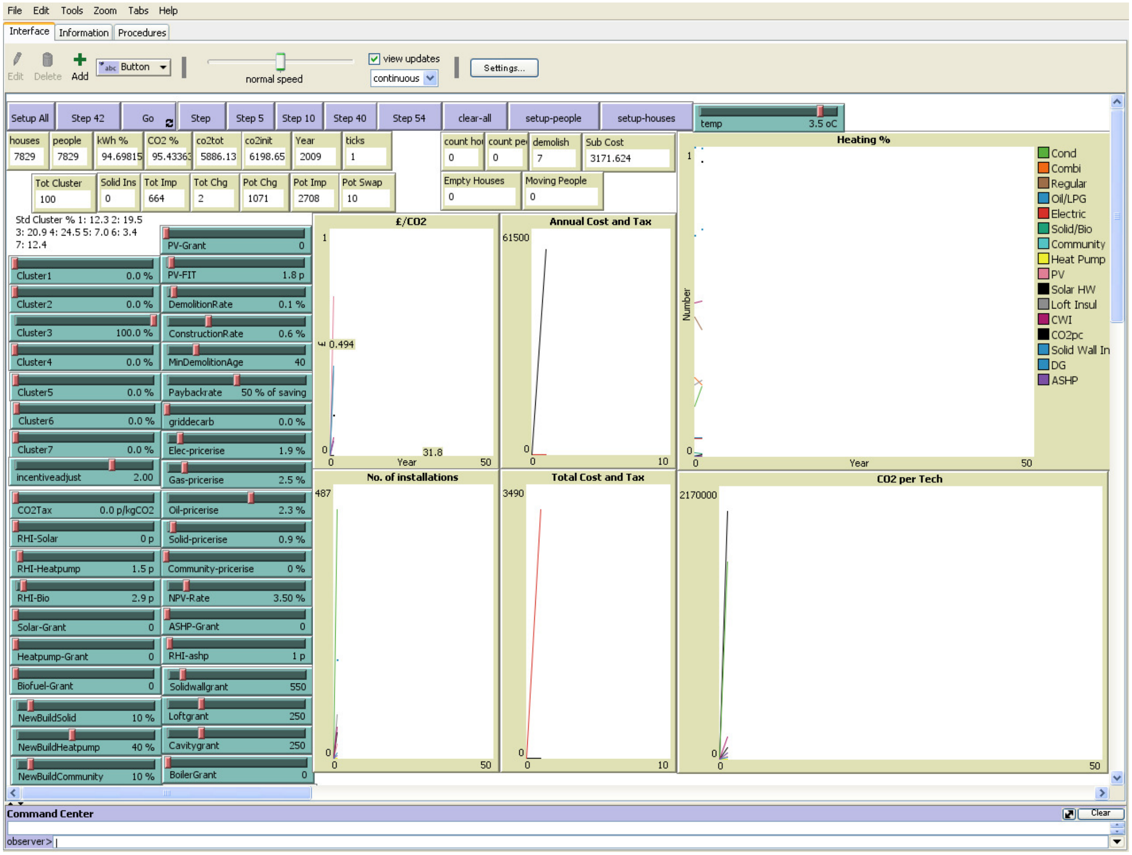
The sliders can be seen to the left, together with the grey control buttons at the top, some monitor boxes displaying values and graphs boxes that are currently blank since the model has yet to start. Normally the model is displayed on screen with only the top left quarter showing, which includes the controls and main monitors, as shown in Figure 5-6:

Figure 5-6 Default start display



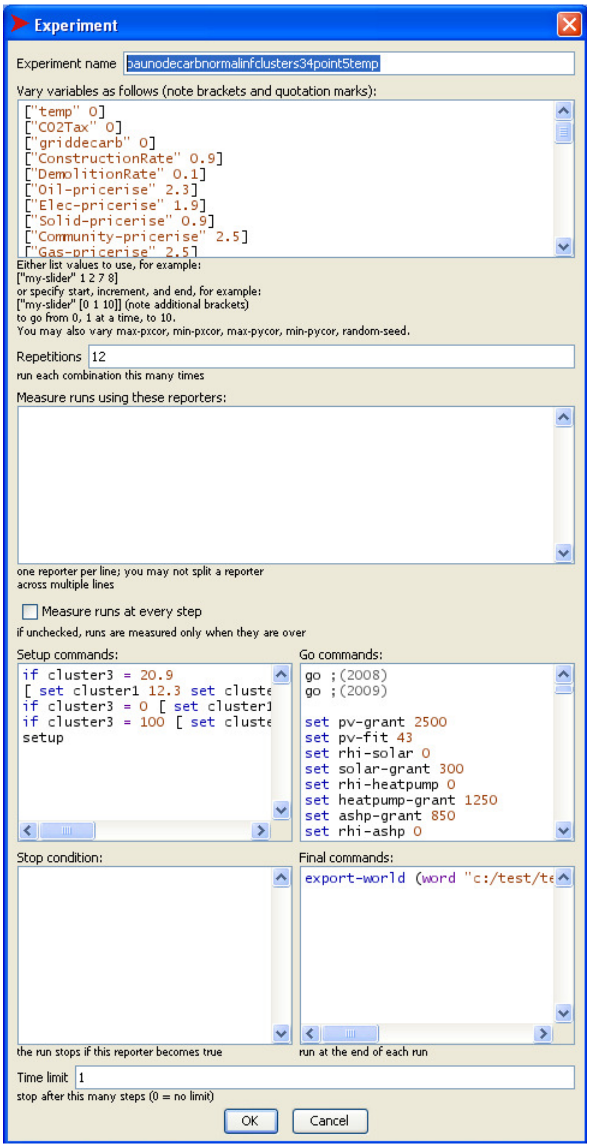
The grey buttons near the top allow for the model to run, *Go* makes the model run until it is stopped and the *Step* buttons will run the model for the number of steps specified by the number on the button. Pressing the un-numbered *Step* button will advance the model by one step (or year). This will trigger a number of actions: some dwellings will be demolished and some new ones created; some heating systems will breakdown and need replacing and some householder agents will move home and consider whole house refurbishment. Figure 5-7 shows the model's default display after one step:

Figure 5-7 Model state after one step



As can be seen all the monitors now have values, and the graphs are starting to be drawn. At the top of the screen there is a speed control and a 'view updates' tick box, by adjusting these it is possible to make the model run faster; at full speed a simulation from 2008-2050 typically takes around 45 minutes on an i5 processor. If a user wants to make adjustments to values (eg: change subsidy levels over time) this becomes a manually quite intensive process as the user would need to be intervening periodically. Fortunately there is an automated option in NetLogo that allows for such changes as well as repeated measures, called BehaviorSpace, as shown in Figure 5-8:

Figure 5-8 BehaviorSpace



Vary variables lists the starting values, *Setup commands* lists code to initialize a model run, *Go commands* has the code to run the model and change variables over time, and *Final commands* exports the model data at the end of each run. This therefore allows an operator to set up the model and then simply wait for the outputs, it also allows for simultaneous runs, subject to the processor, for instance an Intel i5 has two cores, each of which can run two threads – allowing for four simultaneous runs.

5.7 Model Calibration

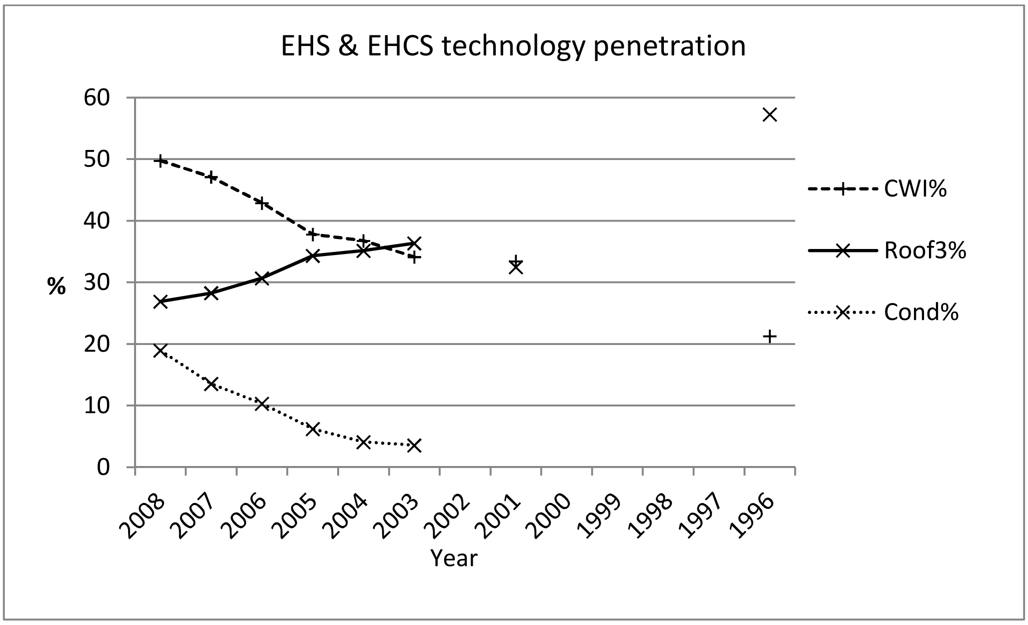
Whilst the previous subsection has described the operation of the model it can not be used for scenario analysis until it has been validated. Validation of a forecasting model is complicated by the forecasting nature of such a model – ie: it can not be tested against future data since that data does not yet exist. An alternative method is to compare its results with other forecasting tools. However, there are also problems with this approach. In this case developed model is intended to be able to simulate the actions of individuals, which is not a capability of previous models, and therefore it should not be expecting to get the same results as already existing models. Indeed if a new model simply achieved the same results as an existing model then there would be little benefit from the new approach. In addition, as discussed in section 2.2.4.2 comparing models is problematical as they typically have different start and end dates and neither the models, nor the scenarios modelled, may be fully available for third party use. The only option left then is to compare with historic data.

Windrum et al. (2007) discuss the various approaches available for validating and calibrating models, with a particular emphasis on agent based models. They acknowledge that being able to identify sufficient empirical data across all of a model's outputs is not usually possible, and consequently complete validation is not possible. Instead, this limitation needs to be recognised and acknowledged and then the model should be calibrated against the available empirical data in order to provide the model with credibility.

In using historic data the more usual approach would be to set a model's start position to match that at the beginning of the historic data and then allow it to run forward until the end of the period for which the historic data are available. Doing that in this case would require the construction of whole new data sets, not only for the householder agents, but also for the dwelling stock. As discussed in the following paragraphs the quality and resolution in the available stock data rapidly declines when looking at earlier years, which means that starting from a historical starting point is not a viable approach; instead an alternative approach is used whereby the model is set to operate backwards in time. In the main version of the model a boiler's age increases until it reaches its lifetime, at which stage alternatives at least as efficient as the current system are considered to provide a replacement. In the backwards version the age of a heating system decreases to zero, when it is replaced by one at most as efficient as the existing system. The decision making element is retained, as the householder agents have the choice to replace with the same, or a lesser technology, whereas in the forwards version the householder agents generally have the choice to replace with the same, or a better technology. Similarly, in the normal version a householder agent on moving home considers the available improvements that could be made to their new home, whereas in the backwards version the household agent on moving considers which measures to remove (if any), thus reducing the energy efficiency of their home.

For each dwelling in the model the following items can be explicitly changed by the householder agents: wall, roof, heating, solar PV, solar hot water. The English Housing Survey (EHS), and its predecessor – the English House Condition Survey (EHCS), have no data on installation levels of the two solar technologies, since existing installation levels are too low, therefore these two elements can not be used for comparing with historic installation levels. The model uses three types of gas heating system: a condensing boiler, a combination boiler and a regular boiler with a separate hot water tank. Condensing boilers are markedly more efficient than conventional boilers as they have a heat exchange system that seeks to recover some of the waste heat from the exhaust gases, which is lost energy in a conventional system. However, condensing boilers are still relatively new, and the EHCS physical survey records only contain data on condensing boilers back to 2003. Furthermore, from 2005 condensing boilers have essentially been compulsory when replacing a conventional gas system (ODPM, 2005), therefore many of the installations of condensing boilers since 2005 will have been on the breakdown of an existing system (or in a new build) where non-condensing boilers would not have been an option. Therefore tracking installed levels of condensing boilers backwards from 2005 would essentially only test the age profiles assigned to condensing boilers. This then leaves wall and roof types. The model essentially operates three wall types: as-built or retro-filled cavity walls, and solid walls (although with an option to represent insulated solid walls), which are identifiable characteristics of a dwelling, as detailed in section 5-3. Again, levels of insulated solid walls are very low and are not recorded in the historic EHCS, but retro-fitted cavity wall insulation levels are recorded in the EHCS physical survey data and so this can be used for analysing the model running backwards. The model includes four levels of roof type: the first being another dwelling above – clearly this will not change due to the actions of individuals – the other three being related to levels of loft insulation: one for less than 100mm of insulation at joist level, one for 100-200 mm, and the final one for 200mm or more of insulation. Again, there are limitations with the recording of more energy efficient measures in older data sets from the EHCS, where higher levels of insulation are not recorded. However, the older data sets do include loft insulation up to 100mm, so it is possible to use this historic data for comparison with the model when run backwards. Figure 5-9 shows the penetration rates of condensing boilers, loft insulation up to 100mm (Roof3), and cavity wall insulation, in the EHCS data back to 1996.

Figure 5-9 EHCS Technology Penetration

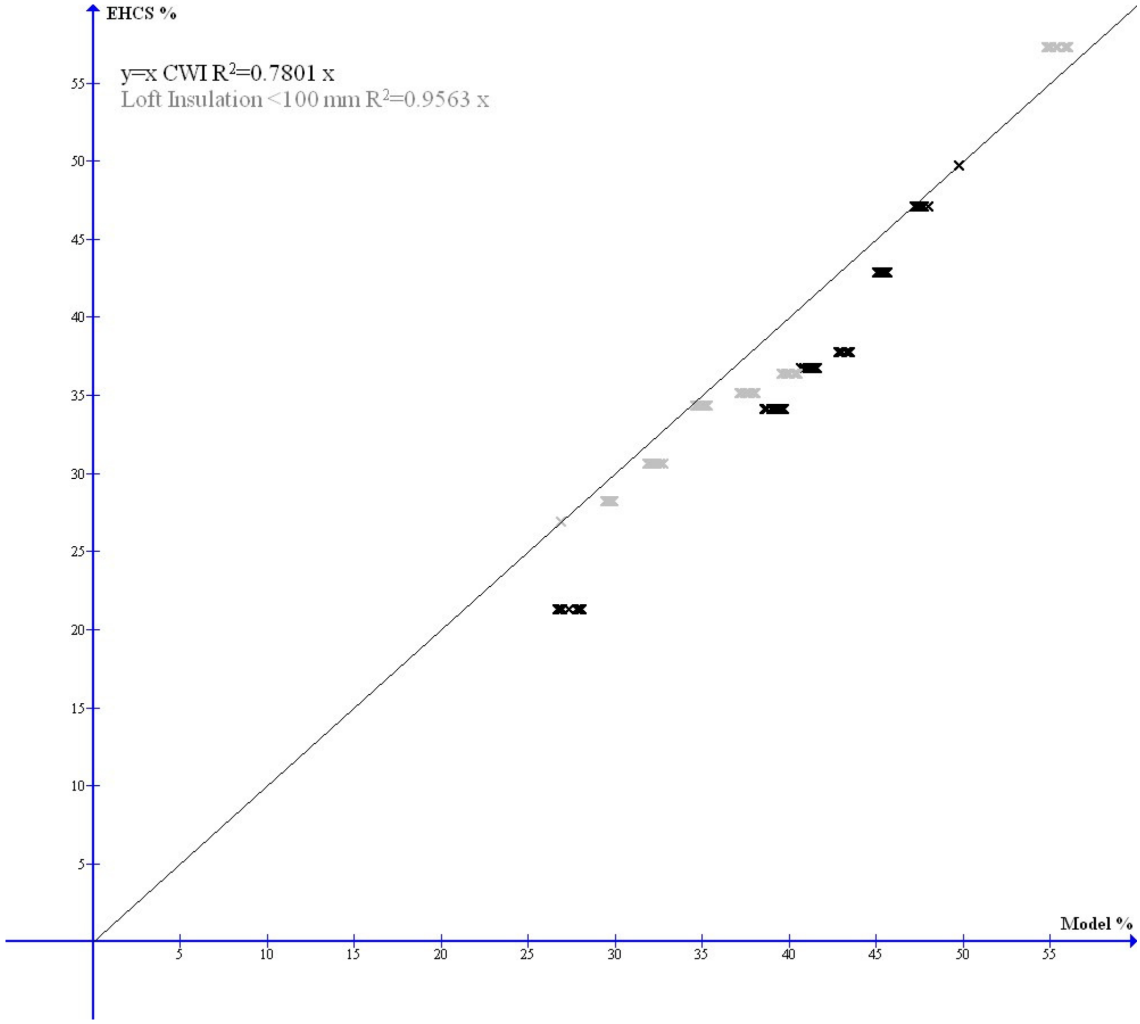


As can be seen, and as already discussed, there is no information on condensing boilers before 2003 in the physical survey. There would also appear to be an issue with the 2001 data, in that both the CWI and Roof3 figures are clearly off the trend line from 2008 back to 1996, this is likely to be due to methodological changes in the way data were collected, therefore these two data points have been excluded, and are not used for comparison with the model's outputs.

In order to run the model backwards several data sets were required to determine historic values in the model, most notably: construction rates (CLG, 2012), general inflation rate (CLG, 2011d) and fuel specific inflation rates (DECC, 2012d). Temperature changes were not a consideration over this period, the average external temperature for the three year period from 1995-1997 was 10.1°C (s.d. 0.9°C) and for the three year period 2007-2009 was 10.3°C (s.d. 0.3°C) (Parker et al., 1992).

Therefore, having set the model to represent the period from 2008 back to 1996, it was run in this backward mode with the default values in the householder agents' decision making algorithms. Figure 5-10 shows the outputs for 12 runs for cavity wall insulation and loft insulation, compared with the EHCS data.

Figure 5-10 Backwards technology diffusion in the default state



As can be seen the model in the default state gives a very good fit for the roof insulation achieving an R^2 value of 0.9563. The cavity wall insulation is a relatively good fit with an R^2 of 0.7801, but there is the potential to improve this figure. As mentioned briefly earlier, the controls for the model include *Incentiveadjust* and *Nonefactor*. These are two controls to be used to calibrate the decision making of the householder agents. The original decision making algorithm, as used for the data in Figure 5-10, is based solely on stated preference data, as opposed to real world transactions. Therefore there is likely to be some degree of variation between the model's predictions, and real world observations. Indeed, the discrepancies shown in the graph above will include this variation, together with other factors – eg: simplifications in making the model. The data suggest that the original model is generally under predicting technology take up, which, to some degree, will be a result of a mis-match between survey respondents' estimates of how they would respond in the discrete choice surveys, and how people actually behaved in the real world. The original model operates with an inequality to decide whether a technology is adopted or not, as shown below:

Adjusted Price + Monthly Repayment + LoanIncentive > None [5.1]

If the inequality is satisfied the technology is adopted, if not it is not installed. Based solely on the technology diffusion data available from the EHCS and EHS it is not possible to adjust the weightings applied to the sub-factors that contribute to the four factors in the inequality. Instead *Nonefactor* is applied as a multiplier to *None* on the right hand side of the inequality and *Incentiveadjust* is used as an extra term in the sum on the left hand side, the inequality therefore becomes:

Adjusted Price + Monthly Repayment + LoanIncentive + Incentiveadjust >
None x Nonefactor [5.2]

By altering the values for *Incentiveadjust* and *Nonefactor* it should be possible to increase the accuracy of the model in projecting the technology penetration rates back from 2008 to 1996. In this way the under prediction seen in Figure 5-10 can be reduced and the model can be calibrated against the available historic diffusion data. Table 5-12 presents the CWI and Roof3 R^2 values for a range of *Incentiveadjust* and *Nonefactor* values:

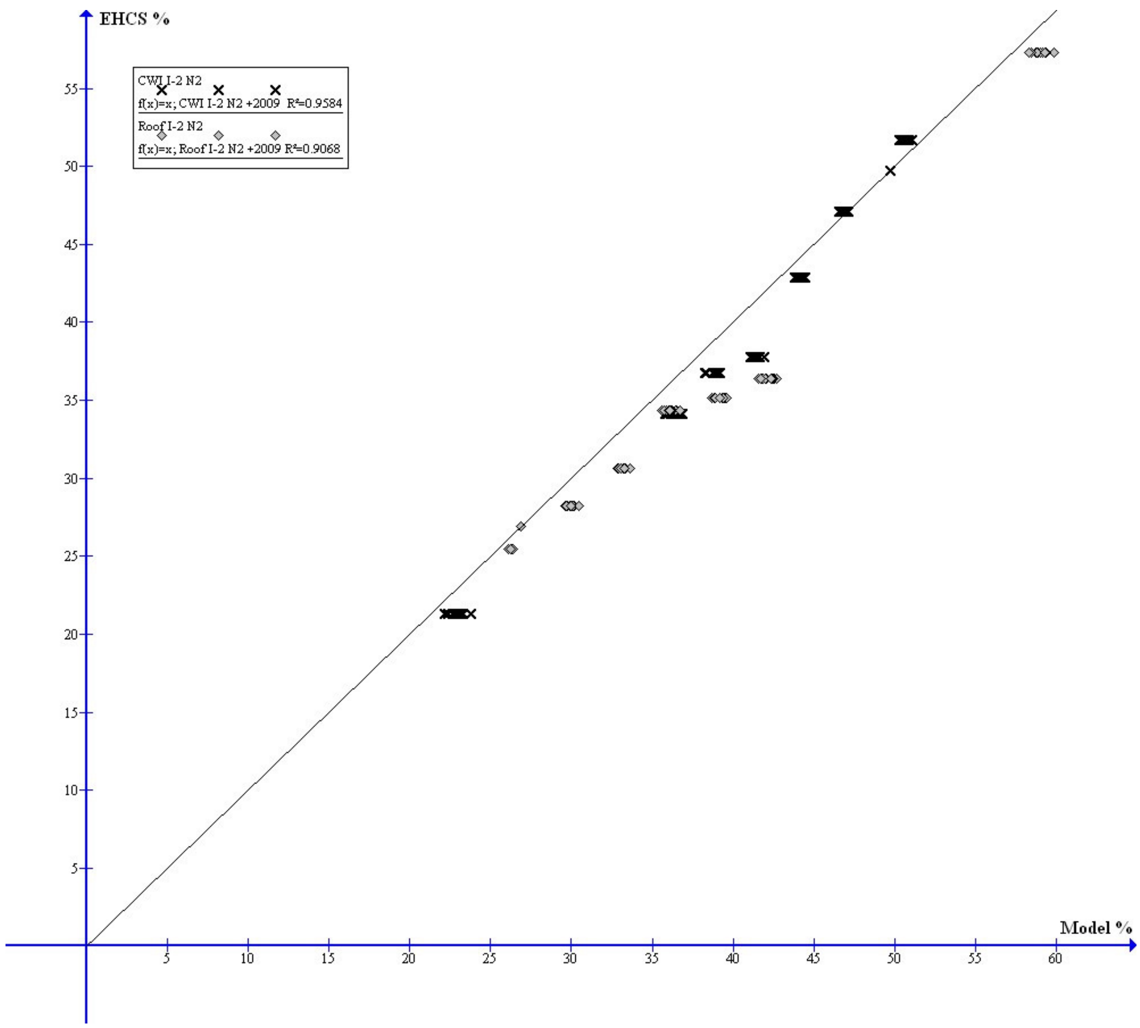
Table 5-12 R^2 values for CWI and Roof3 for a range of Incentiveadjust and Nonefactor values

Incentiveadjust	Nonefactor	CWI R^2	Roof3 R^2
0	1	0.7801	0.9563
0	2	0.9046	0.9218
1	2	0.8687	0.9404
2	2	0.8408	0.9511
-1	2	0.9300	0.9045
-1	1	0.8651	0.9312
-2	1	0.9117	0.9003
-2	**2**	**0.9487**	**0.8947**
-1.75	2	0.9383	0.8940
-2.25	2	0.8940	0.8875
-2	1.75	0.9413	0.8911
-2	2.25	0.9469	0.8850
-1.9	1.9	0.9439	0.8936
-2	2.1	0.9468	0.8862
2	0	0.9046	0.9218
0	-2	-1.2569	-0.3182
-2	0	-0.009	0.8688
-2	-1	-1.0717	-0.0799
2	-1	-1.5128	-0.5458

From Table 5-12 it can be seen that an *Incentiveadjust* value of -2 and a *Nonefactor* of 2 provide the best combination of R^2 values for cavity wall and loft insulation. This table also provides a useful sensitivity analysis. In preparing the algorithm for the householder agents decision making process the two data sets from the Energy Saving Trust and Element Energy had to be combined, and in the process some of the data had to be removed, as discussed in the previous chapter. The data that were removed impacted on the left hand side of the inequality. *Incentiveadjust* impacts on that side of the inequality, and it can be seen that the results are fairly robust to variations on that side; with *Nonefactor* fixed at the default value of 1, Incentiveadjust can vary in the range -2 to + 2 and the model still gives a good fit for both technologies. The scaling impact of *Nonefactor* can also be tested for sensitivity, and it can be seen that for values of *Nonefactor* from 0 to 2 the model still provides a good overall fit, it is only when *Nonefactor* is negative that the model performs poorly.

Therefore, it can be seen that the model is relatively robust to variations, but even so *Incentiveadjust* and *Nonefactor* values of -2 and 2 respectively do increase the fit of the model when comparing with the historic period from 2008 back to 1996. As well as the physical data available from the EHS and EHCS from 2008 to 1996, data are also available for 2009. It is therefore possible to run the model forward one year from 2008 to 2009 and to then compare the results, the same outputs for 12 runs are shown in Figure 5-11:

Figure 5-11 1996-2009 Model fit with adjusted Incentiveadjust and Nonefactor values



As can be seen this achieves a small improvement in the R^2 values, with CWI at 0.9584 and Roof3 at 0.9068.

5.8 Chapter summary

This chapter began by providing an overview of how the new model is intended to operate, and how the agents operate a decision making process to alter the energy efficiency of the dwelling stock.

It then identified NetLogo as a suitable agent based programming environment as it is particularly well suited to modelling spatially distributed agents.

There then followed a description of the conversion of the data sets for the dwelling stock and the householders into the individual dwelling and householder agents inside the model. In order for the householder agents to carry out their decision making processes two trigger points were identified – the breakdown of their existing heating system or a house move.

NetLogo provides a front end for end users of a model and the tools and controls that have been made available in this model are then described, as well as a description of how the model operates.

Finally, this chapter described the testing of the model that was carried out to ensure that it provides reasonable results. To this end the model was run backwards from 2008 to 1996 and the predicted adoption of cavity wall and roof insulation were compared with real world data from the English Housing Survey (EHS) and the English House Condition Survey (EHCS). Since the original householder decision making algorithms were designed using discrete choice survey data, this allowed for a calibration against what was effectively revealed preference data, in this way the accuracy of the model was increased. Following this calibration it could be further tested by running it forwards from 2008 to 2009. This produced a good fit for both cavity wall and loft insulation between the model's predictions and the EHS and EHCS data, with an R^2 figure of 0.9584 for cavity wall insulation and 0.9068 for loft insulation. Nevertheless, it should be remembered that this calibration was only against two technologies, as there is currently insufficient data for a full validation against all available technologies.

Since the model has now been developed and calibrated as far as possible, it can now be used for scenario analysis, which is covered in the following chapter.

Chapter 6 Simulation Results

6.1 Introduction

The first section of this chapter describes the development of the initial Business-as-Usual (BAU) scenarios, and the results found when they are run through the model; subsequent sections present alternative scenarios and their development, results and subsequent findings.

6.2 Business as Usual Scenario

As discussed in the previous chapter, the model has been developed to simulate any whole number of years in annual steps from a starting year of 2008, principally to analyse scenarios to 2050. The model has over forty variables that can be individually varied by the end user for each year in a model run. This is therefore a very highly dimensional model and as such the number of potential scenarios that can be modelled is very large. With so many potential scenarios it is clear that it is not practical to examine even a very small fraction of them. Instead a method is needed to select a manageable number of scenarios that can be run and analysed. To this end there are two main approaches for scenario selection: the first is a mathematical approach that simply lays out all the potential scenarios on an n-dimensional hypercube, and then imposes a grid over the hypercube and selects one scenario from each grid square (Flood and Korenko, 2010). This method is appropriate if all scenarios are equally likely, as it will give a fair distribution of scenarios to be tested across the entire population of potential scenarios. However, in the case of producing plausible scenarios for this research some scenarios will be more likely than others, eg: a scenario with a very high subsidy for air source heat pumps and no other subsidies and high inflation for oil heating and low inflation for all other fuels is rather less likely than other scenarios that could be imagined with a range of subsidies across technologies and more correlation of fuel inflation.

The alternative approach is to use Delphi (Linstone and Turoff, 1975)(Yang et al., 2010). Using Delphi, expert opinion is canvassed and a cluster analysis is then carried out in order to generate aggregate scenarios based on the combined expert opinions (Tapio, 2003). This would be the more appropriate method to use with this model, since different scenarios will have different (and unknown) probabilities of occurring.

However, for the scenario development for this research, the initial stage has been the development of a Business as Usual (BAU) scenario – this has been developed in a similar manner to Delphi as it has used various bodies' estimates (ONS, 2011) (CLG, 2011a) (DECC, 2012b) (EST, 2012) (Friends of the Earth, 2010) (Committee on Climate Change, 2011) (Jenkins G et al., 2009) (Element Energy, 2008) (HM Treasury, 2003) of what is the most likely future path from the current situation, based on current government policies and projections. Then, as will be discussed in the Alternative Scenarios subsection, by making changes to individual items in the BAU scenario other scenarios can be produced and the sensitivity and importance of that particular factor can be determined. Table 6-1 details the main variable values used for the initial BAU scenario, BAU-T0.2:

Table 6-1 BAU-T0.2 Scenario Assumptions

Years		2008-2009	2010-2011	2012	2013	2014-2015	2016-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Upfront Subsidies: (£)	PV-Grant	2500											
	Solar-Grant	300											
	Heatpump-Grant (GSHP)	1250											
	ASHP-Grant	850											
	Solidwall grant	1500					1370	1175	1010	870	745	640	550
	Loftgrant	250											
	Cavitygrant	250											
	Boilergrant		400										
	Biofuel-Grant	950											
Generating Subsidies (p/kWh)	PV-FIT		43	21	13	10	6	4					
	RHI-Solar				8.5		8	7	6	5	4	3	
	RHI-Heatpump (GSHP)				4.3		4	3.4	2.9	2.5	2.1	1.8	
	RHI-ASHP				3		2.6	2.2	1.9	1.6	1.4	1.2	
	RHI-Biomass Boiler				7.6		7	6	5.2	4.5	3.9	3.4	
Annual Population	Construction Rate %	0.9					0.8		0.7		0.6		
	Demolition Rate %	0.1											
Fuel Inflation %	Oil	2.3											
	Gas	2.5											
	Solid Fuel	0.9											
	Grid Electricity	1.9											

Years		2008-2009	2010-2011	2012	2013	2014-2015	2016-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Technology prices	GSHP Fixed £	7707	7707 + 5.64 * (year - 2008)^2 - 246.5 * (year -2008)							5000			
	GSHP £/kWth	290	290 + 0.22 * (year - 2008)^2 - 9.38 * (year - 2008)							190			
	ASHP Fixed £	6280	6255 + 4.33 * (year - 2008)^2 - 197 * (year - 2008)							4000			
	ASHP £/kWth	193	193 + 0.14 * (year - 2008)^2 - 6.13 * (year - 2008)							125			
	Electric heating £	2500											
	Oil heating	3000											
	Biomass heating	10777	2.201 * (year - 2008)^2 -199.6 * (year - 2008) + 10777										
	Gas condensing	2500											
	Community heating	5555											
	PV Fixed £	2000											
	PV £/kWp	4358	4358 - 874 * ln (year - 2007)									1300 - (year - 1975) * 10	
	Solar hot water Fixed £	2000											
	Solar £/kWth	911	911 + 0.36 * (year - 2008)^2 - 25.7 * (year -2008)										
	Annual Grid Decarbonisation %			11									
	Discount rate %	3.5											
	5 Yearly Average Temperature Rise °C						0.2						

Percentage changes are applied to the previous year's value, as opposed to the starting year (ie: they are compounding rather than simple). It should also be noted that the discrete choice surveys used for the decision making algorithms were carried out in 2008 and with 2008 prices, therefore all prices are given in a 2008 basis. In addition all of these values can be changed so that alternate paths, including alternative rates of change of technology costs can be modelled.

6.2.1 BAU-T0.2 Results

Each scenario has been run 12 times through the model to allow for any potential outlier runs and to provide a good average. The model provides a high level of detail in the outputs available, the main elements of which are presented in this subsection for the initial scenario BAU-T0.2, beginning with the overall CO_2 projections in Figure 6-1:

Figure 6-1 Annual CO_2 projections for BAU-T0.2

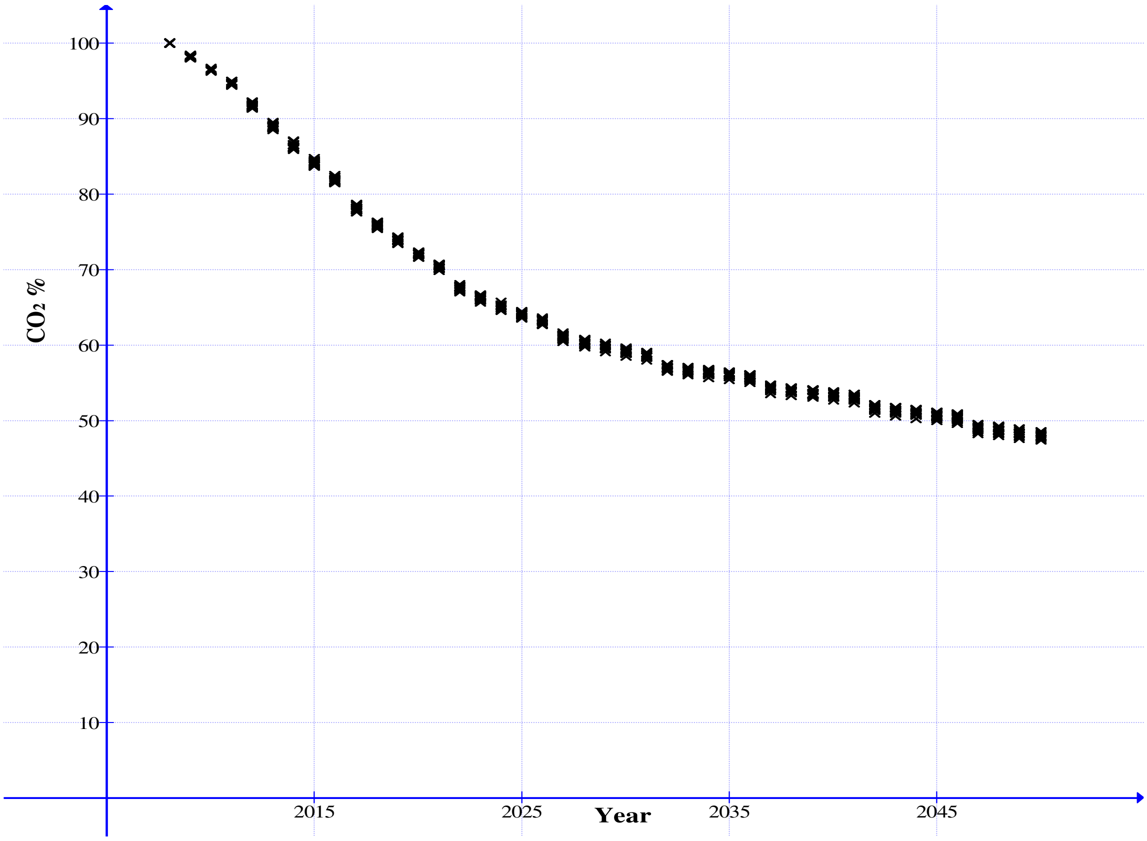


Figure 6-1 shows the annual CO_2 emissions in the model from 2008-2050, with an average 52% reduction by 2050 (standard deviation 0.4%), which is clearly well short of an 80% target. However, it should be remembered that the 80% target is from a 1990 base, so adjusting for that increases the reduction from 52% to 54.4%, this is a slight improvement, but still a long way from the target. Therefore it can be seen that in the first eighteen years from 1990-2008 very little was achieved in reducing domestic emissions.

In the figure it is not possible to distinguish between the data for the twelve repeated runs (by 2050 the range of values is only 0.75%), therefore, in subsequent figures only the means are presented for clarity.

Looking at Figure 6-1 it can be seen that the gradient is reducing over time, so that much of the reductions come in the early years. In the period 2008-2028 the graph shows approximately a 40% reduction, meaning only around a further 12 percentage points reduction is achieved in the remaining period from 2028-2050. By drilling down into the lower level outputs from the model it becomes possible to understand what is happening that is contributing to the large reductions in the early years and the smaller reductions in the latter years. Figure 6-2 and Figure 6-3 show the penetration levels of firstly the heating systems, and then the other measures, these are the total number of installations in that particular year:

Figure 6-2 BAU-T0.2 Heating system penetration rates

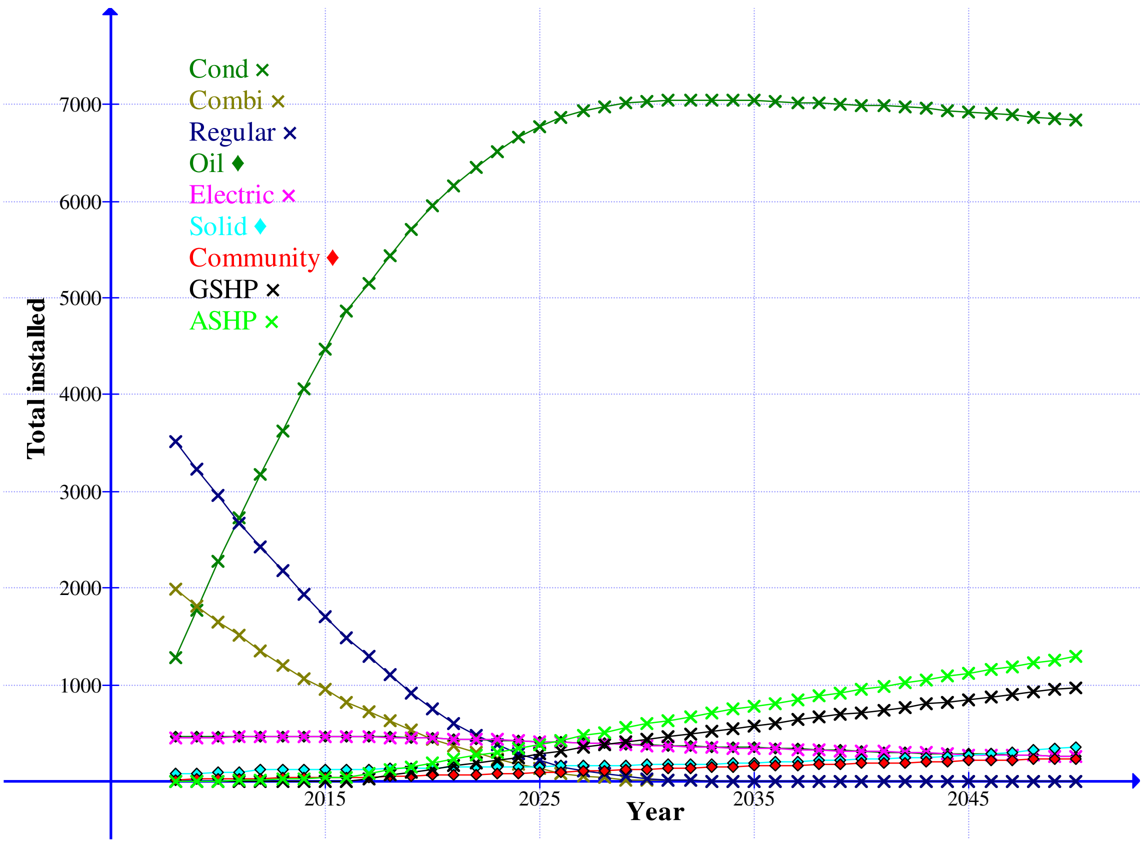
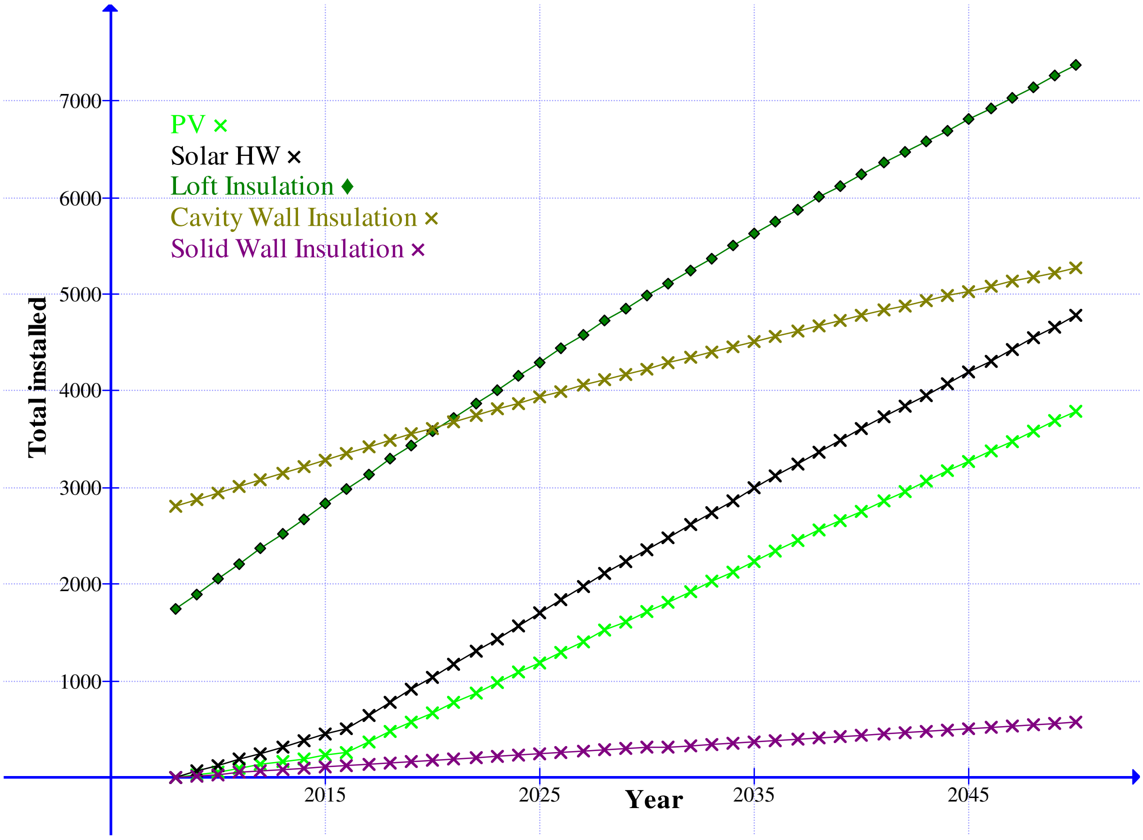


Figure 6-3 BAU-T0.2 Insulation and solar technology penetration rates



By reference to the two graphs in Figure 6-2 and Figure 6-3 it is generally possible to understand the underlying changes that are causing the reductions in the emissions shown in Figure 6-1. As already mentioned the bulk of the savings occur in the first 15 years – most of this is due to heating system changes. In particular a move from non-condensing to condensing boilers amongst the gas heating section of the population, which is over 80% of the total at the beginning of a model run.

In the latter years, the progressive increases in loft insulation and cavity wall insulation add some further savings, although these will predominantly be the dwellings where their installation has a reduced impact, since they already had some level of insulation. In addition, there is significant growth in PV and solar hot water. However, the move to condensing boilers greatly reduces the heating demand so the addition of the solar hot water has limited extra impact. Similarly, as detailed in Table 6-1, BAU-T0.2 assumes grid electricity will be decarbonised in the period up to 2030, therefore the addition of PV, whilst achieving reductions in bills for householders does not contribute a great deal to emissions reductions as it is replacing a low emission energy source – the decarbonised grid electricity. In accordance with SAP assumptions electricity from domestic scale PV systems is simply set against electricity demand and domestic storage systems are not currently considered.

Whilst this model is not directly comparable to other models due to different assumptions, methods of operation, start and end dates, it is worthwhile comparing the headline BAU result of a 54% reduction from 1990-2050 with other model's outputs, to give an indication that the results have some credibility and are of the expected order of magnitude. Johnston's (2003) results vary from 33.2% (BAU) to 64.9% (Integrated) from 1996 to 2050. Johnston's BAU scenario provides a much lower reduction, but this is to be expected due to the lower resolution with only two dwelling types, and older assumptions as the model was designed under less stringent policy assumptions. The 40% House scenario was developed using UKDCM and shows a scenario to a 60% reduction by 2050 (Boardman, 2007b). However, this is more of a backcasting model, rather than forecasting, as the intention was to see a pathway to achieve a 60% reduction. Similarly the DeCarb model (Natarajan and Levermore, 2007b) was used to identify 60% pathways, as opposed to setting initial conditions and letting the model run to provide a forecast. Nevertheless this gives an indication of the range of reductions produced by other models.

To complement this it is also useful to consider the range of outputs that this model can provide. In order to do this two non-agent based assumptions are made to provide indicative upper and lower boundaries to the model's outputs. The first is a worst case scenario, which assumes that construction and demolition happen in the same manner as the BAU scenario but assumes no further improvements occur to the existing stock; the second is a best case scenario that instead assumes all available retrofit improvements happen by 2050. The complete transformation of the stock indicates an upper bound on model scenarios of approximately a 95% CO_2 reduction from 2008 to 2050. Conversely, the lower boundary. In contrast, the worst case scenario, with the only savings coming from more efficient new dwellings projects an increase in CO_2 of 3% from 2008 to 2050, showing that, in that particular scenario, without changes to the existing stock, population increases have a greater impact than the construction of more efficient dwellings. Therefore the model is capable of modelling a very wide range of potential future pathways.

6.3 Alternative Scenarios

The previous section described the initial BAU-T0.2 scenario, which is intended to be a plausible estimate of what the current future path may be, and showed the range of outputs available from the model. Having considered the initial scenario further scenarios can be developed and, as previously discussed, there are essentially limitless further scenarios that could be developed. Rather than develop completely independent further scenarios, the decision has been made to develop a number of alternative scenarios that are variations on the original BAU-T0.2 scenario. This will allow for an analysis of the sensitivity of BAU-T0.2 to the various factors that are changed, and also begins the search for a pathway that provides a reduction closer to the 80% target figure. To this end four factors have been identified that are readily alterable, and for which there is good reason to consider an alternative estimate of their future values: temperature, fuel inflation, grid decarbonisation, and a carbon tax.

DEFRA's B1 (Jenkins G et al., 2009) scenario estimates that there is a 20% chance that average external temperatures will have increased by less than 1.4°C by the mid-2040s and a 90% chance that temperature rises will be less than 3.5°C. The initial BAU-T0.2 has 7 five year periods with a 0.2°C temperature increase, equating to the 1.4°C figure, therefore an alternative temperature scenario is suggested with 7 five year periods with a 0.5°C increase, equating to the 3.5°C value. Clearly, and as discussed in section 4.1, this is a simplification of real temperature changes which will not happen in equal stages equally across the whole year, but this simplification does allow for some level of consideration of the impact of external temperature changes.

The second element is fuel inflation, the BAU-T0.2 fuel inflation rates come from DECC's Fossil Fuel price projections (DECC, 2012c). However the rates of fuel inflation in those projections are significantly lower than real historic figures (DECC, 2012d), therefore it is proposed to have an alternative inflation scenario that doubles the initial fuel inflation rates.

The BAU-T0.2 scenario assumes 90% grid decarbonisation is achieved by 2030, as recommended in the Renewable Energy Review (Committee on Climate Change, 2011), the alternative suggested is no grid decarbonisation.

Finally the addition of a simple carbon tax on domestic energy use is considered, this has been arbitrarily set at an initial level approximating to 20-25% of electricity prices. This is distinct from current levies that are built in to electricity bills, and is applied across all fuels on a p/kgCO_2 basis.

Just four elements with two values each provides sixteen scenarios, a summary of their main features is shown in Table 6-2:

Table 6-2 Summary of Scenarios

Scenario	Inflation	Grid Decarbonisation by 2030	Temperature rise (°C/5 years)	CO_2 tax (p/kgCO_2)
BAU-T0.2	Normal	90%	0.2	0
BAU-2I-T0.2	Double	90%	0.2	0
BAU-0DE-T0.2	Normal	0	0.2	0
BAU-2I-0DE-T0.2	Double	0	0.2	0
BAU-T0.2-5C	Normal	90%	0.2	5 (+5% pa indexation applied 5 yearly)
BAU-2I-T0.2-5C	Double	90%	0.2	5 (+5% pa indexation applied 5 yearly)
BAU-0DE-T0.2-5C	Normal	0	0.2	5 (+5% pa indexation applied 5 yearly)
BAU-2I-0DE-T0.2-5C	Double	0	0.2	5 (+5% pa indexation applied 5 yearly)
BAU-T0.5	Normal	90%	0.5	0
BAU-2I-T0.5	Double	90%	0.5	0
BAU-0DE-T0.5	Normal	0	0.5	0
BAU-2I-0DE-T0.5	Double	0	0.5	0
BAU-T0.5-5C	Normal	90%	0.5	5 (+5% pa indexation applied 5 yearly)
BAU-2I-T0.5-5C	Double	90%	0.5	5 (+5% pa indexation applied 5 yearly)
BAU-0DE-T0.5-5C	Normal	0	0.5	5 (+5% pa indexation applied 5 yearly)
BAU-2I-0DE-T0.5-5C	Double	0	0.5	5 (+5% pa indexation applied 5 yearly)

BAU Business as Usual

T0.2 Low temperature

T0.5 High temperature

0DE No grid decarbonisation

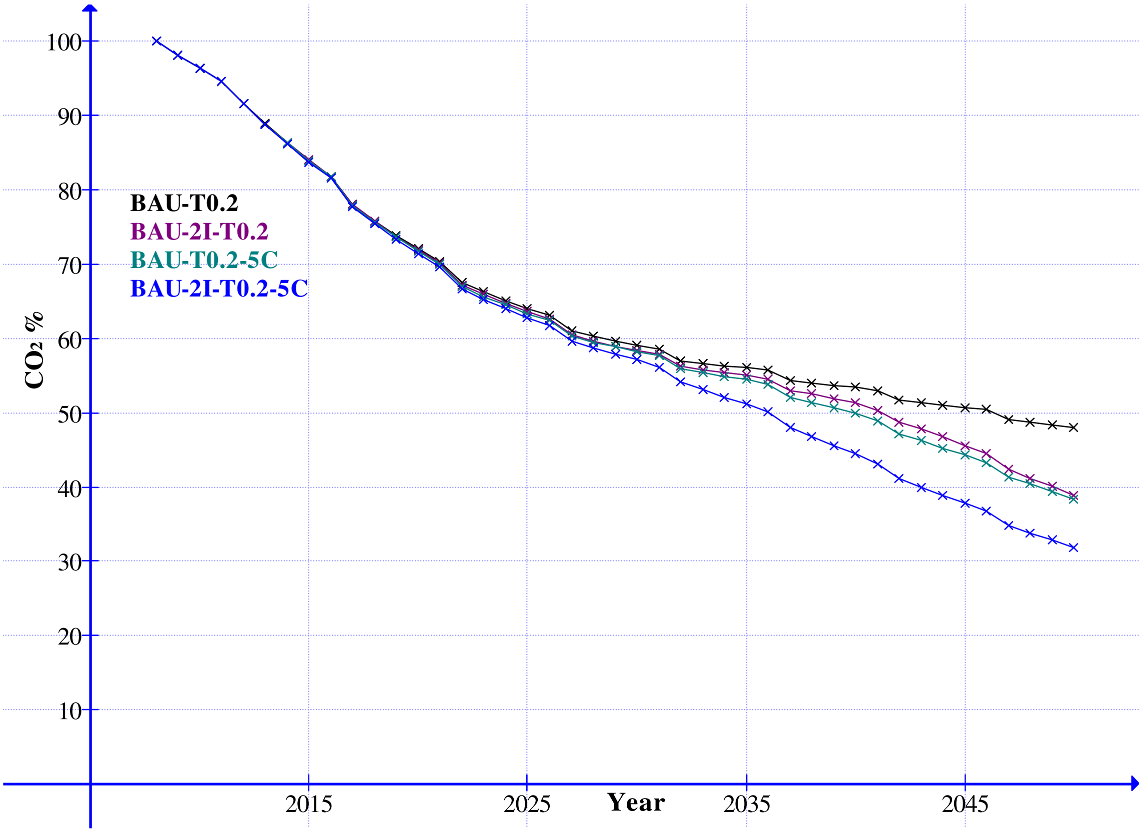
5C Carbon tax

2I High fuel price inflation

6.3.1 Headline Results

Figure 6-4, Figure 6-5, Figure 6-6 and Figure 6-7 compare the overall CO_2 reductions achieved in the various scenarios with the original BAU-T0.2 scenario.

Figure 6-4 Decarbonised scenarios annual CO_2 projections



As can be seen all four scenarios are very similar until the late 2020s, at which point the high inflation and carbon tax scenarios follow a very similar pattern, and the scenario with both high inflation and carbon tax achieves greater reductions. Since both higher inflation and carbon tax impact on fuel bills, it is not surprising that they achieve similar results, although subsequent graphs will look at technology adoption to see if particular technologies are favoured in either state.

Figure 6-5 T0.2 Non-decarbonised scenarios and BAU-T0.2 annual CO_2 projections

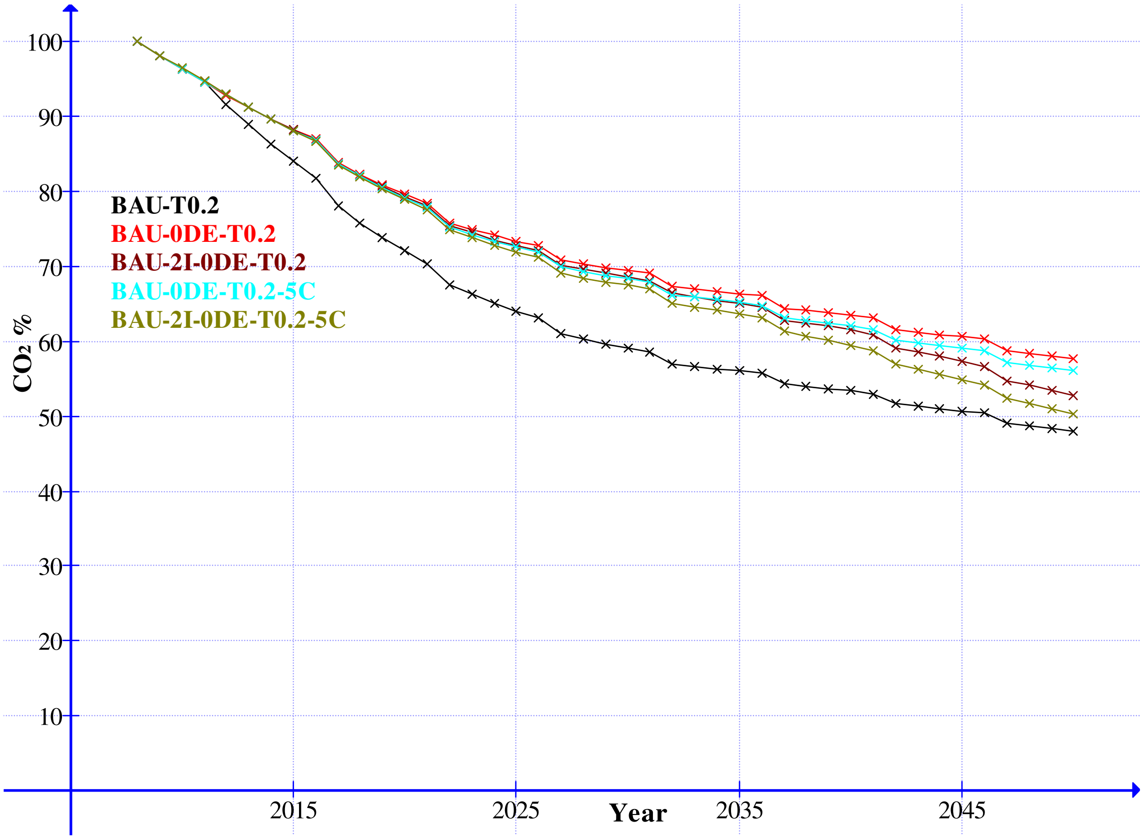
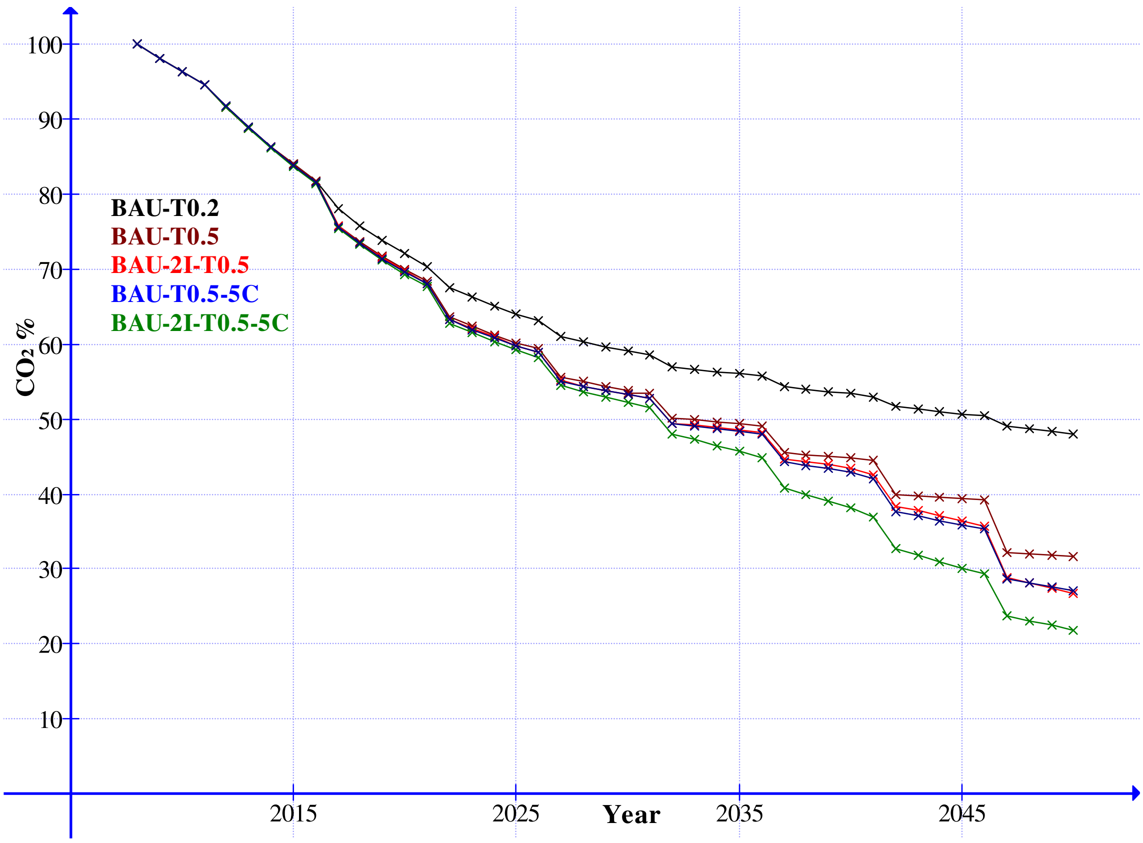


Figure 6-5 demonstrates the importance of grid-decarbonisation to achieving the 80% reduction target, since without it, even with high inflation and a carbon tax the reduction achieved is less than the base BAU-T0.2 scenario.

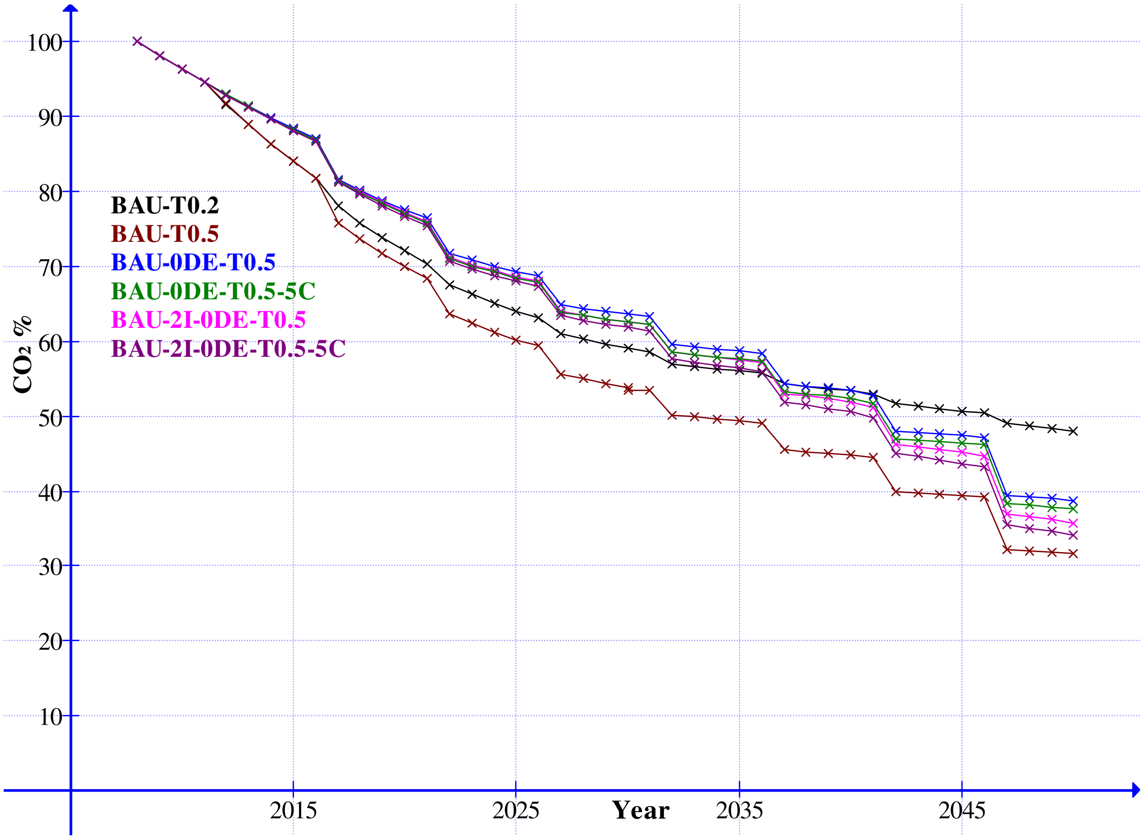
It is interesting to note the different impacts of high inflation and a carbon tax in this case as compared with the decarbonised scenarios in the previous figure. Firstly, the addition of both high inflation and a carbon tax achieves a markedly smaller increase than in the decarbonised scenarios (16 percentage points in the decarbonised scenarios and only 7% in the non-decarbonised scenarios). Also of note is the minimal impact of a carbon tax on its own – BAU-0DE-T0.2-5C. Therefore there is a notable difference in effectiveness between high inflation and a carbon tax (5 percentage points versus 1.5), whereas in the equivalent decarbonised scenarios there was essentially no difference(0.5 percentage points difference). It can be anticipated that the ineffectiveness of the carbon tax in these scenarios is due to the reduced benefit of electric heating. In the decarbonised and taxed scenarios there will be an extra incentive for heat pump heating systems, which will not be the case where grid decarbonisation does not occur. This will be confirmed in subsequent graphs that present the underlying technology penetration levels that led to the overall reduction figures.

Figure 6-6 T0.5 Decarbonised scenarios and BAU-T0.2 annual CO_2 projections



The effect of the higher temperature increases in these scenarios is clear in the discontinuities in Figure 6-6, since the temperature increases are being applied five yearly. As with the lower temperature decarbonised scenarios high inflation and a carbon tax both achieve very similar overall results, with the results from individual runs overlapping. In this case the scenario with both taxation and high inflation gets close to the 80% reduction figure, although the impact of the combination of the two factors is rather less than in the lower temperature scenarios; this is likely to be a case of diminishing returns as virtually all the easy improvement measures will have already taken place.

Figure 6-7 T0.5 Decarbonised scenarios, BAUT0.2, BAU-T0.5 annual CO_2 projections



Again, as with the lower temperature scenarios, the non-decarbonised scenario with taxation and high inflation does not achieve as great a reduction as the default BAU-T0.5 scenario. It can also be seen that it is not until the late 2030s that these scenarios start to outperform the BAU-T0.2 scenario, and this is clearly down to the larger temperature changes. In this case taxation offers a small improvement over BAU-0DE-T0.5 and high inflation provides a slightly larger small improvement, but both these changes are only a few extra percent, and the combination of the two achieves less than ten percentage points extra reduction.

Table 6-3 provides the average reduction achieved for each scenario, as well as a rebased reduction from 1990.

Table 6-3 Scenario CO_2 reductions

Scenario	Model CO_2 % reduction 2008-2050	Std deviation	Adjusted CO_2 % reduction 1990-2050
BAU-T0.2	51.96	0.38	54.44
BAU-2I-T0.2	61.15	0.40	63.16
BAU-0DE-T0.2	42.35	0.25	45.33
BAU-2I-0DE-T0.2	47.28	0.19	50.01
BAU-T0.2-5C	61.62	0.23	63.60
BAU-2I-T0.2-5C	68.15	0.26	69.80
BAU-0DE-T0.2-5C	43.88	0.26	46.78
BAU-2I-0DE-T0.2-5C	49.73	0.32	52.32
BAU-T0.5	68.38	0.23	70.01
BAU-2I-T0.5	73.30	0.24	74.68
BAU-0DE-T0.5	61.24	0.22	63.24
BAU-2I-0DE-T0.5	64.29	0.25	66.13
BAU-T0.5-5C	72.97	0.19	74.37
BAU-2I-T0.5-5C	78.16	0.29	79.29
BAU-0DE-T0.5-5C	62.40	0.34	64.34
BAU-2I-0DE-T0.5-5C	65.85	0.14	67.61

As Table 6-3 shows, even when rebased to the 1990 starting date, it is only the scenarios with the higher temperature increases that get within 10% of the 80% target, due to the reduced heating demand with higher external temperatures. However, consideration needs to be given to any negative impacts from the higher external temperatures in these scenarios – in particular, the impact on energy use should cooling systems (ie: air conditioning) begin to be used in the home. The way the model is designed the householder agents' decision making is based on the saving in their expenditure from installing a technology, which is not the case with the installation of an air conditioning system. Therefore the model does not have the data to value the comfort benefit from air cooling and therefore can not explicitly model the adoption of such technologies. However, the SAP calculations do include a figure for the energy required by a fixed cooling system, even when one is not present, so these figures can be used to give an indication of the potential impact of widescale adoption of fixed cooling systems. In scenario BAU-T0.5 the average emissions are

1.498 tCO_2/yr in 2050 per dwelling, and the average emissions from a fixed air conditioning system, based on SAP's standardized use profile, would be 17.7 $kgCO_2$/yr. Total market penetration would therefore increase energy demand by 1.2% and would therefore have a minimal impact; furthermore 100% adoption would be very unlikely, thus reducing the impact further. However, it should be noted that BAU-T0.5 is a decarbonised scenario, and an air conditioning system can expect to be electrically powered. Therefore, without the 90% grid decarbonisation, it can be seen that the emissions to satisfy the cooling demand would rise to around 177 $kgCO_2$/yr per dwelling. This suggests that 100% adoption could increase emissions by around 12%, although if it is assumed that penetration of 30-40% were to occur this increase would be proportionally lower. This therefore further shows the importance of grid decarbonisation if the domestic sector is to approach the 80% reduction target.

Another consideration is the type of householder agents used in the model. As described in the previous chapter, the initial population for the sixteen scenarios already discussed was set according to the distribution in DEFRA's behavioural research, with seven clusters with different environmental attitudes (DEFRA, 2008). Whilst the model does not have the capability to examine the impact of a pro-environmental education or advertising policy, the potential impact of such a policy can be estimated by altering the distributions of the population amongst the seven DEFRA clusters. Table 6-4 presents six of the sixteen scenarios, with the normal population, and two alternative populations, one consisting entirely of the most environmental cluster (Positive Greens), and the other with the least environmental cluster (Honestly Disengaged).

Table 6-4 1990-2050 CO_2 reductions with different populations

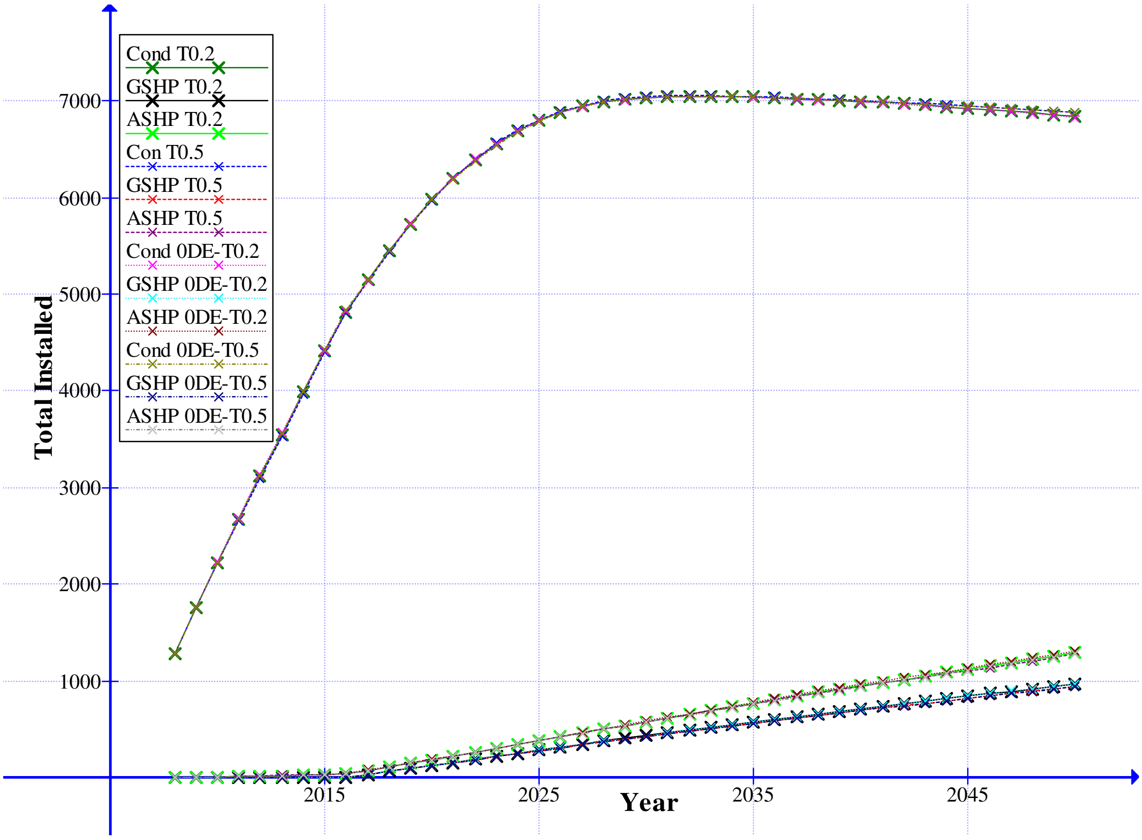
Scenario	Most environmental cluster	Normal population equivalent	Least environmental cluster
BAU-T0.2	55.94	54.44	52.36
BAU-T0.5	71.11	70.01	68.50
BAU-2I-T0.5-5C	**81.51**	79.29	76.61
BAU-0DE-T0.2	47.25	45.33	42.78
BAU-0DE-T0.5	64.78	63.24	61.42
BAU-2I-0DE-T0.5-5C	69.29	67.62	65.44

This therefore shows there is potential for some form of behavioural change policies to help drive the uptake of energy efficiency technologies. In particular, if possible, targeting such a campaign at the more recalcitrant cluster would reap more cost effective rewards. It should be noted that these two clusters are the largest in DEFRA's classification, Honestly Disengaged being 20.9% and the Positive Greens 24.5%. This suggests that further classification into smaller clusters could identify subsets at either end with more extreme results.

6.3.2 Heating System Adoption Results

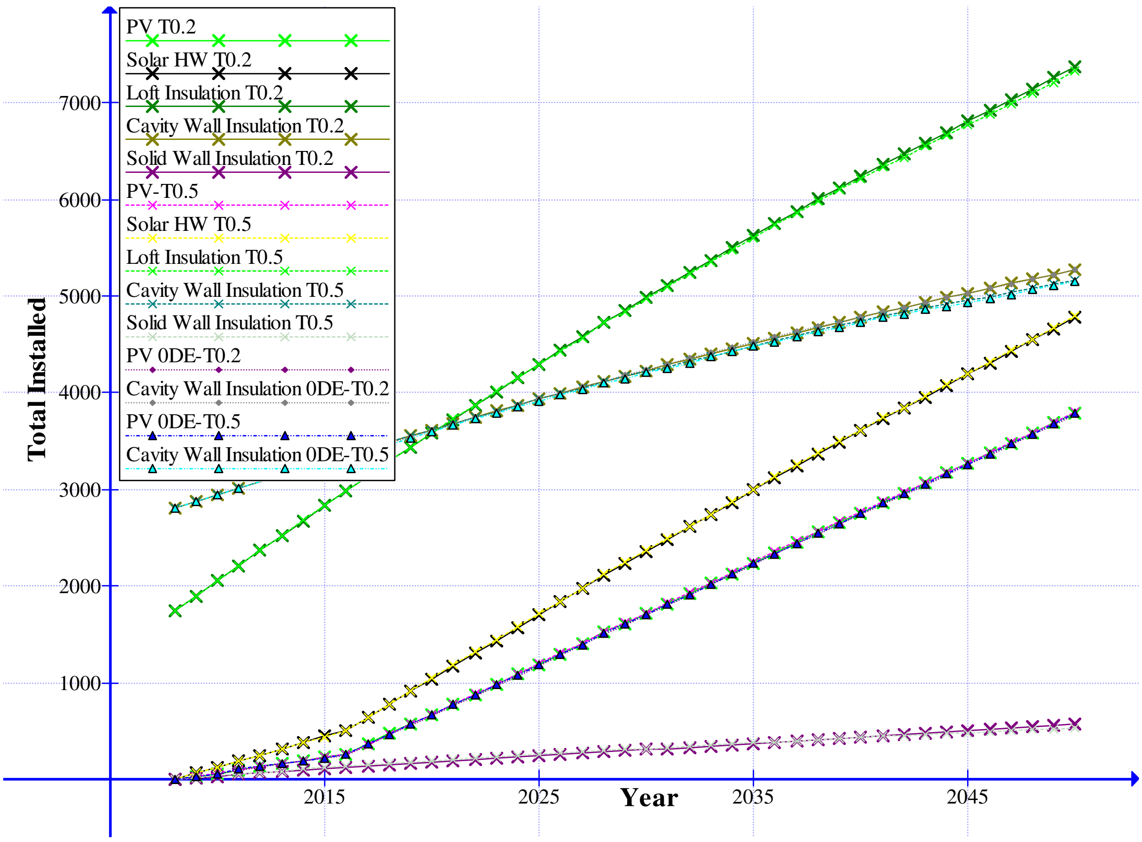
As with the BAU-T0.2 scenario, the output data for the other scenarios includes details of the penetration rates of the various technologies available in the model. The following graphs therefore examine in more detail the uptake of the available technologies. Figure 6-8 considers the three most common heating systems in the four basic scenarios, BAU-T0.2, BAU-T0.5, BAU-0DE-T0.2 and BAU-0DE-T0.5.

Figure 6-8 Heating systems for BAU-T0.2, BAU-T0.5, BAU-0DE-T0.2, BAU-0DE-T0.5



As can be seen, there is such an overlap between these four scenarios that is essentially no distinction between them as regards the choice of heating system. Therefore, although the 2008-2050 saving ranges from 42% to 68% the differences are accounted for by the change in temperature and the change in grid electricity carbon intensity, as opposed to any noticeably different decision making. This therefore establishes the base pattern for heating technology adoption, and Figure 6-9 provides similar data for the insulation and solar renewables.

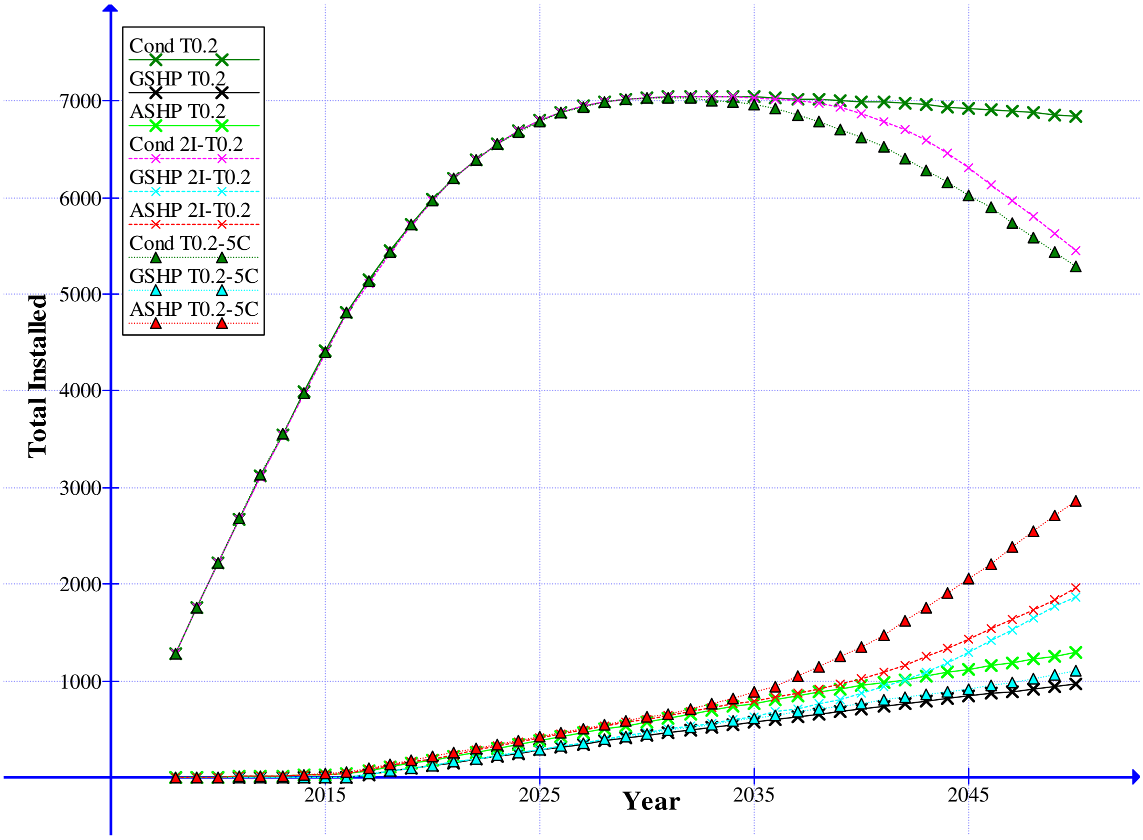
Figure 6-9 Insulation and solar renewable installations for BAU-T0.2, BAU-T0.5, BAU-0DE-T0.2, BAU-0DE-T0.5



In order not to over fill the graph only two of the five items are shown for the two decarbonised scenarios, but as can be seen the technology adoption in each of these scenarios is very similar. The only noticeable difference is that insulation levels appear to be marginally lower in the higher temperature scenarios. This is understandable since in the higher temperature scenarios heating demand is reduced and so the savings from the installation of a form of insulation are reduced, thus reducing the benefit to be gained from installation, although, as the graphs indicate this is a small effect.

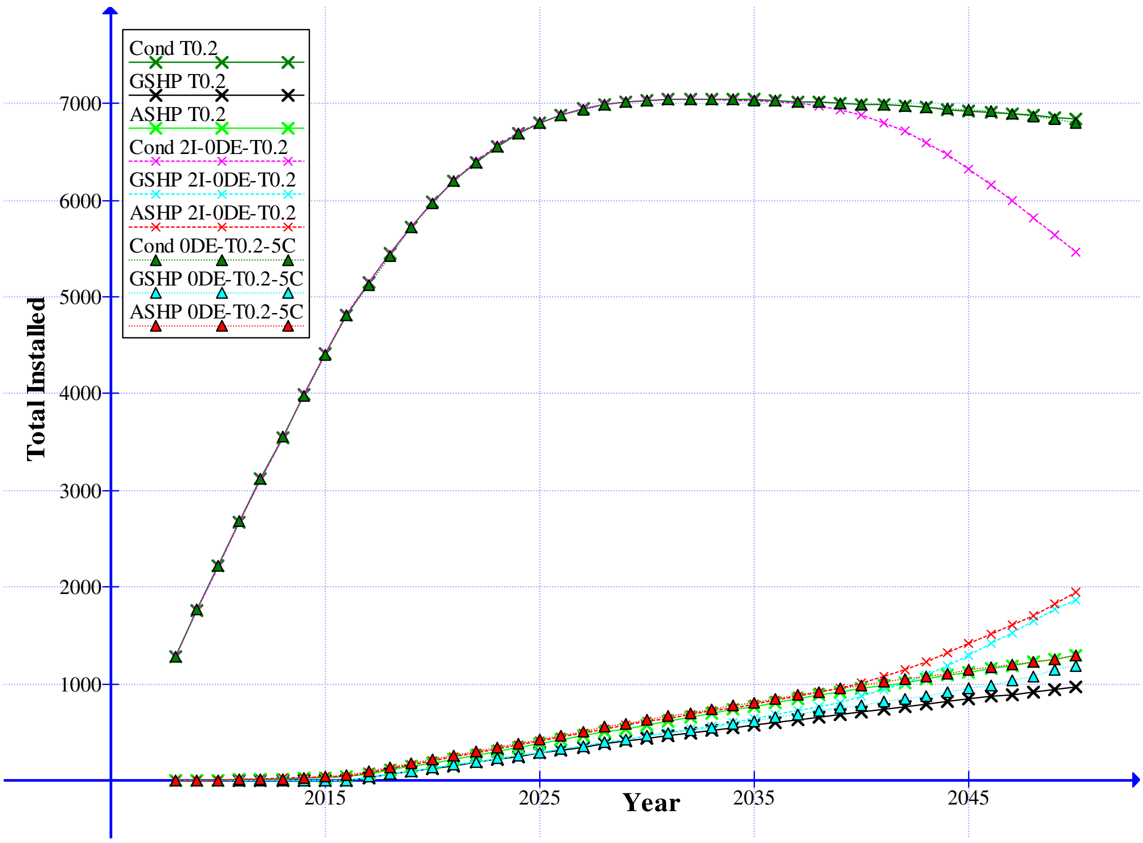
Figure 6-10, Figure 6-11, Figure 6-12 and Figure 6-13 present the heating system installations for the scenarios that have either high inflation or a carbon tax.

Figure 6-10 Heating systems for BAU-2I-T0.2, BAU-T0.2-5C



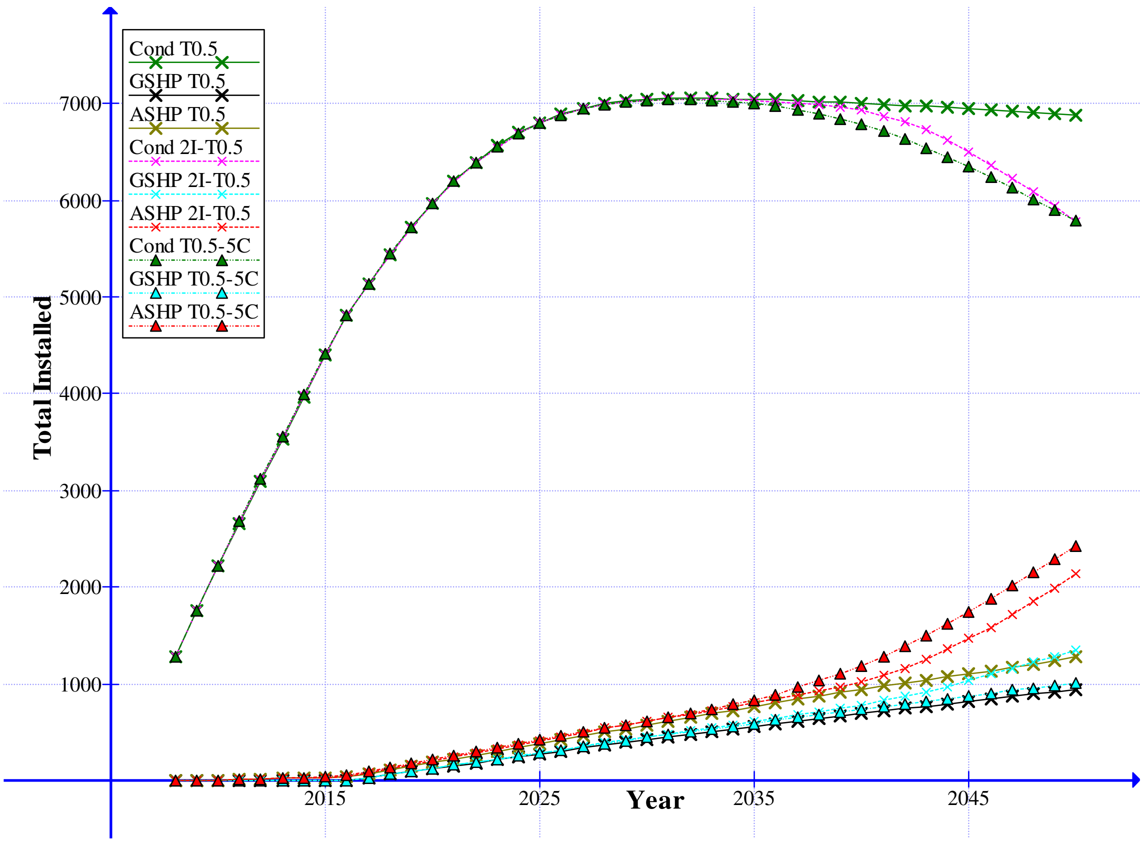
In this graph it can be seen that the higher inflation and the carbon tax both impact on the choice of heating system quite noticeably. These two scenarios start off essentially the same as BAU-T0.2, and it is not until around 2035 that the effects of the increased fuel costs begin to impact on the choice of heating system. As discussed in section 3-3 technology adoption generally take an S-curve form and in both of these two scenarios it can be assumed that if the model were allowed to continue the two heat pumps would continue their S-curve of technology adoption as they replace the condensing gas boiler as the predominant heating system. There are therefore implications from this for long term planning as it suggests a large shift from gas fired heating to grid electricity powered heating. Therefore consideration of this change needs to be carried out to consider the impacts on the grid system, and its resilience. It is also interesting to note that the two heat pump technologies have noticeably different adoption rates in the two scenarios. In the case where adoption is driven purely by energy price rises both ground and air source achieve similar penetration rates. However, when the energy price rises are carbon tax driven the air source heat pump is far more successful and the majority of changes from gas are to ASHP, with GSHP penetration being barely more than in the default BAU-T0.2 scenario.

Figure 6-11 Heating systems for BAU-2I-0DE-T0.2, BAU-0DE-T0.2-5C



In Figure 6-5 it was shown that BAU-2I-0DE-T0.2 achieved a greater CO_2 reduction than BAU-0DE-T0.2-5C, and the underlying differences in heating technology adoption can be seen above. The taxed scenario achieved a very similar overall reduction to BAU-0DE-T0.2, and this can be seen in that the condensing boilers in the taxed scenario only decline slightly from their maximum penetration level, and marginally more than the non-taxed default scenario. Looking at the performance of the heat pumps, under the carbon tax air source penetration is essentially the same as without the tax, although the tax does increase the adoption rate of ground source. It is possible, looking at the changing gradients, that were the model left to run beyond 2050 that GSHPs would have overtaken ASHPs. In these non-decarbonised scenarios the carbon tax does little to accelerate the uptake of heat pumps since they end up with similar emission levels to a condensing boiler, so that tax does not provide a strong incentive to choose one technology over another. However, the high inflation scenario is noticeably different, with a significant decline in condensing boilers, and the two heat pump technologies being broadly equally successful.

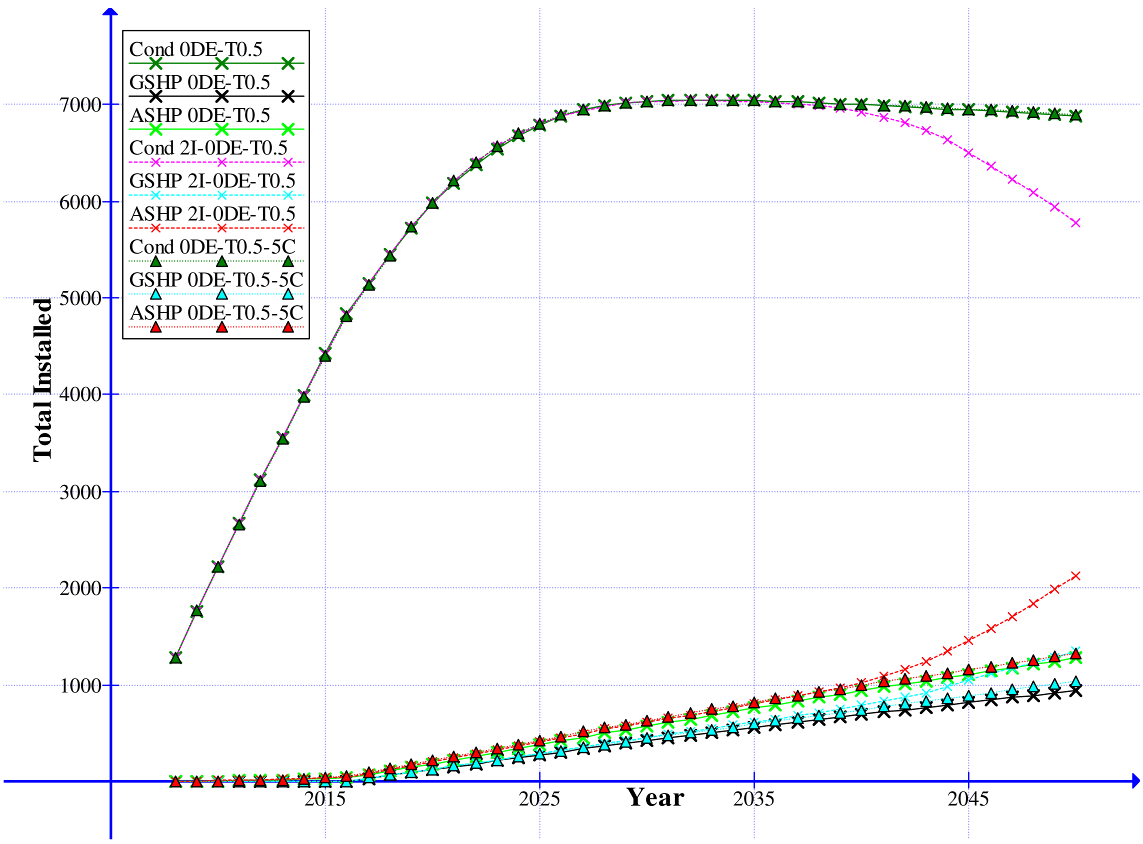
Figure 6-12 Heating systems for BAU-2I-T0.5, BAU-T0.5-5C



In Figure 6-6, where the overall CO_2 figures are presented, there is essentially no difference between the performance of these two scenarios – BAU-2I-T0.5 and BAU-T0.5-5C. However, there are clear differences to be observed at the lower level of the installation of different technologies; whilst the decline in the installed populations of condensing boilers are very similar, the rate of adoption of the two heat pump technologies differs. The adoption of GSHPs in the carbon tax scenario is essentially the same as in the BAU-T0.5 scenario, but in the high inflation scenario there is a noticeable uplift in the adoption rate of GSHPs. This is therefore very similar to the situation for BAU-2I-T0.2 and BAU-T0.2-5C. This suggests that the two technologies are competing against each other for successful diffusion into the market place and are seeking to replace the condensing boiler as the dominant technology.

It also therefore demonstrates the unintended consequences of government intervention. The model has used the highest efficiencies suggested in the current version of SAP for the heat pumps, and as such GSHPs are assumed to be more efficient than ASHPs. Therefore, in a decarbonised environment, it could be expected that a carbon tax would incentivize the adoption of ground source over air source, but these results contradict this expectation. This suggests that at the inflation and carbon tax rates chosen the marginal difference between the two technologies is such that the carbon tax saving of ground source over air source is less than the energy bill saving in the high inflation scenario. Furthermore, it also suggests that current subsidy levels provide more effective support for the less efficient technology.

Figure 6-13 Heating systems for BAU-2I-0DE-T0.5, BAU-0DE-T0.5-5C



As with the previous decarbonised scenarios, the tax achieves very little in encouraging householder agents to change heating system, there is just a marginal increase in GSHP adoption. However, the high inflation scenario does effect some change with both heat pumps having noticeable increases in penetration, although ASHPs are considerably more successful.

The next two graphs, Figure 6-14 and Figure 6-15, present the heat technology penetration for the scenarios with both high inflation and a carbon tax.

Figure 6-14 Heating systems for BAU-2I-T0.2-5C, BAU-2I-0DE-T0.2-5C

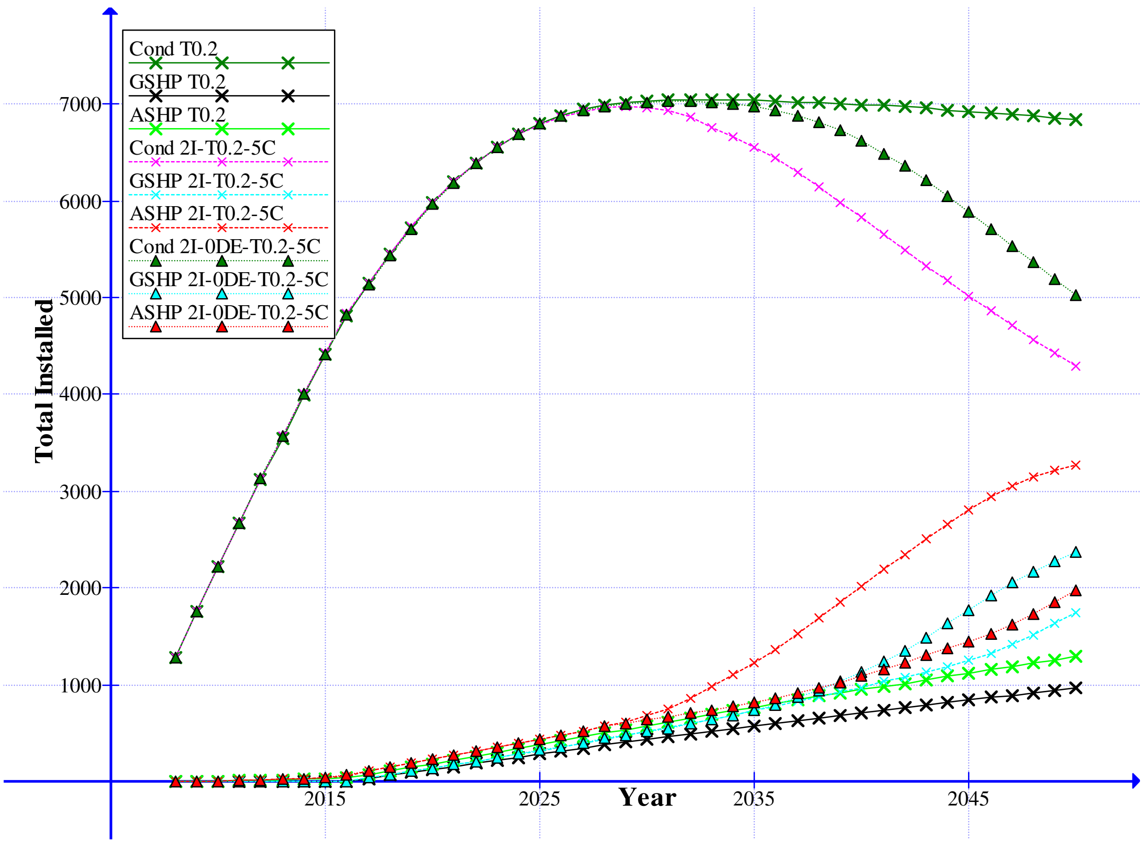
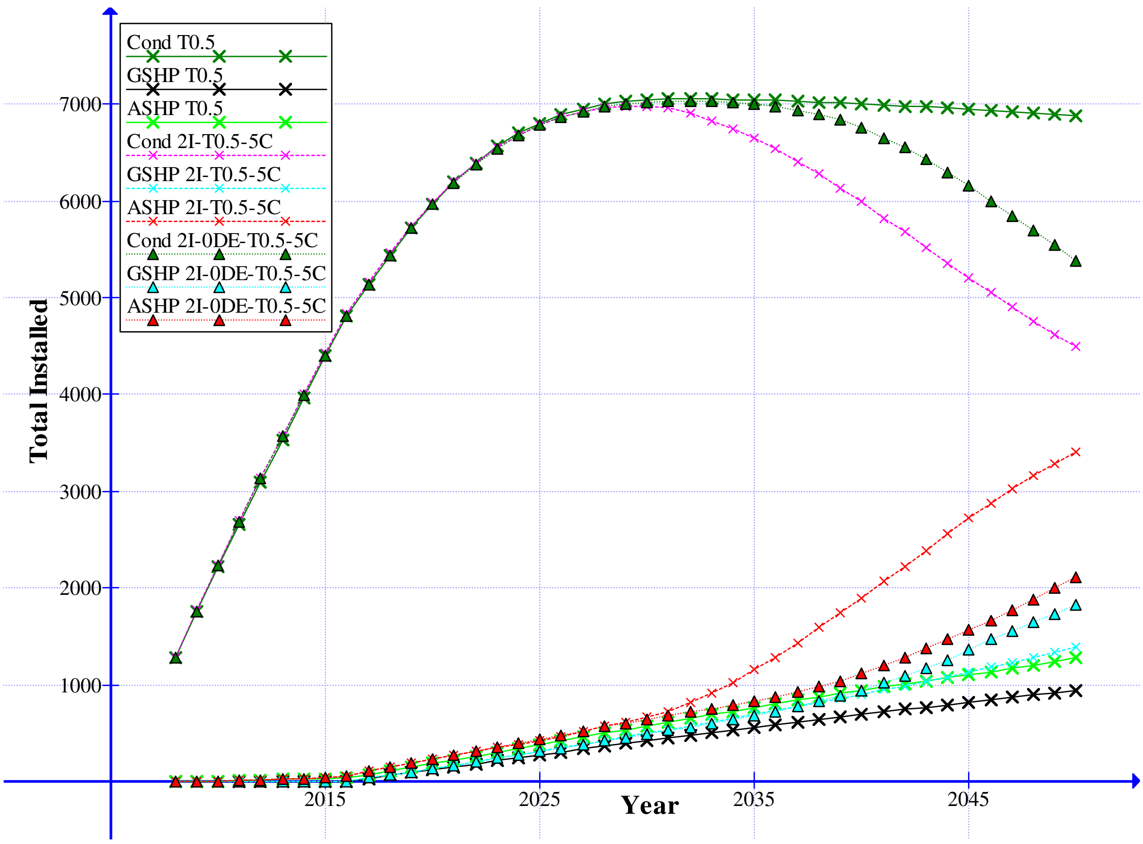


Figure 6-14 provides some very interesting underlying detail concerning the adoption of the different technologies. Firstly, with the condensing boilers, it can be seen that the combination of both high inflation and a carbon tax lead to a greater decline in condensing boiler numbers, even in the non-decarbonised scenario. Furthermore, in the decarbonised scenario, the combination means that the decline begins approximately five years earlier. The combination of the two also has some interesting implications for the competition between the two heat pump types. In the non-decarbonised scenario the ground source heat pumps are more successful than the air source ones, and this is the first scenario in which that has been observed.

Also, when looking at the decarbonised scenario, the rate of adoption of ASHPs has passed its peak and the penetration rate has almost levelled off suggesting maximum penetration has almost been reached. However, the graph indicates that GSHPs still have a long way to go as the GSHP adoption rate appears to be increasing, and it is therefore possible that were the model to continue a point would be reached when GSHP penetration overtook ASHPs. Therefore it can be seen that the combination of both high inflation and a carbon tax begins to favour ground source over air source.

Figure 6-15 Heating systems for BAU-2I-T0.5-5C, BAU-2I-0DE-T0.5-5C



The simple change of temperature for these two scenarios makes a significant difference to the diffusion of the different heating technologies compared with the scenarios in Figure 6-14. The higher external temperatures reduce the amount of heating required, and therefore reduces the running costs for a technology and consequently the savings to be had by choosing a technology with lower running costs. This effect can most clearly be seen by comparing the heat pumps from the decarbonised scenarios with the lower temperature decarbonised scenarios. In Figure

6-15 there is no indication that the rate of adoption of ASHPs has peaked and so it can be expected that were the model to be allowed to continue beyond 2050 the penetration of ASHPs into the market would continue to increase and would soon overtake the declining condensing boiler. This is in marked contrast to the lower temperature scenario where the ASHP adoption rate is clearly declining.

The high and low decarbonised scenarios are, however, broadly similar. At the higher temperature there is a marginally smaller drop off in condensing boilers than at the lower temperature, and both ground and air source heat pumps achieve some success in penetrating the market, although with ASHPs being slightly more successful.

6.3.3 Renewable Technology Adoption Results

Figure 6-16 and Figure 6-17 display the adoption of solar hot water and solar PV systems under the different scenarios.

Figure 6-16 PV and solar hot water installations for low temperature scenarios

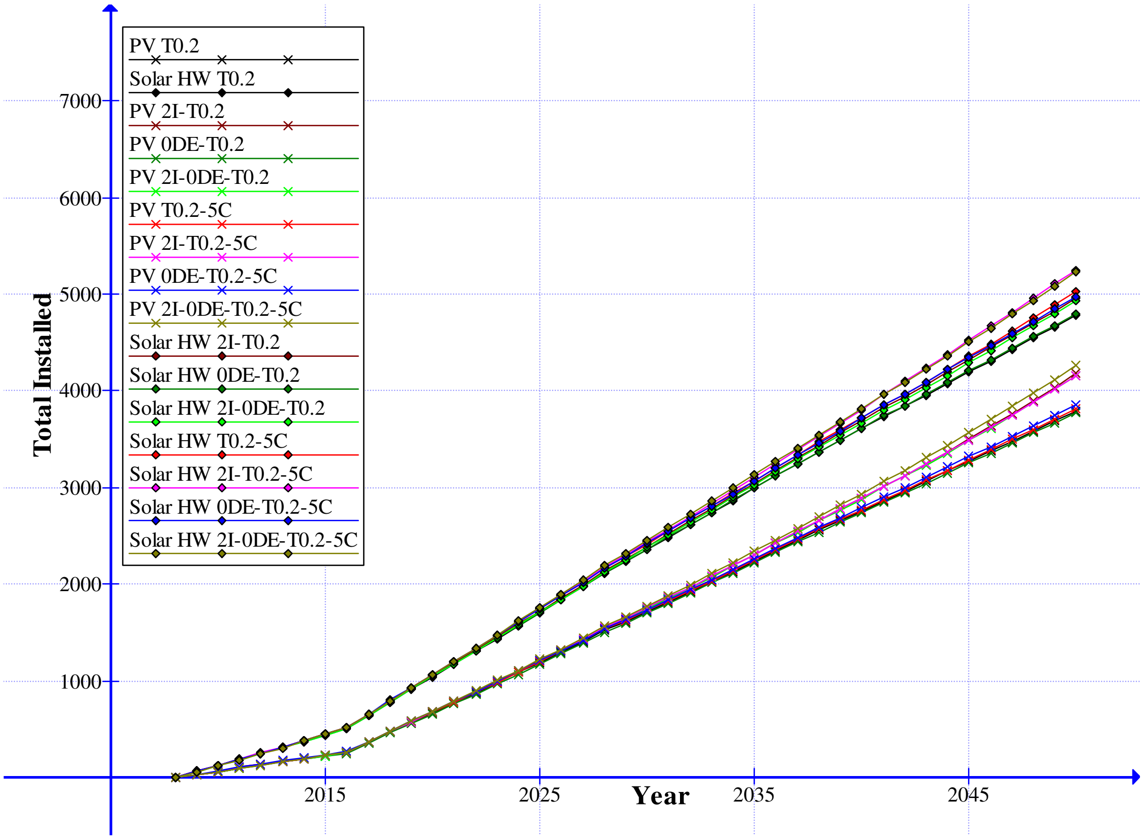
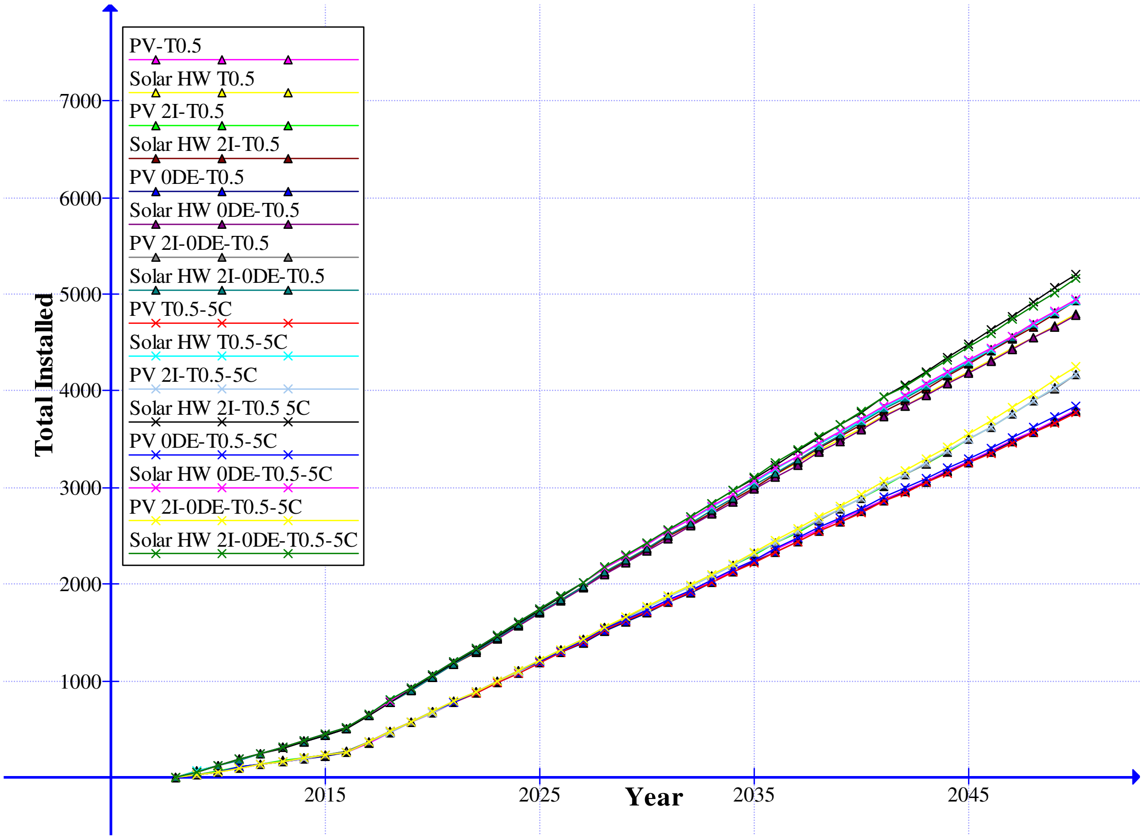


Figure 6-17 PV and solar hot water installations for high temperature scenarios



In each scenario both technologies follow a similar pattern with solar HW being the more successful of the two technologies. The changes from scenario to scenario do have some impact as can be seen in the range of final year results. Higher inflation appears to be more effective than the carbon tax at encouraging uptake, but the differences between scenarios are much less marked than with the heating systems. As these are stand alone systems, they are not competing against other technologies for adoption, and, apart from in new build dwellings, all their installations are discretionary choices.

6.3.4 Insulation Adoption Results

Similarly to the previous sub-section, Figure 6-18, Figure 6-19, Figure 6-20 and Figure 6-21 display the insulation adoption figures:

Figure 6-18 Insulation installations for un-taxed low temperature scenarios

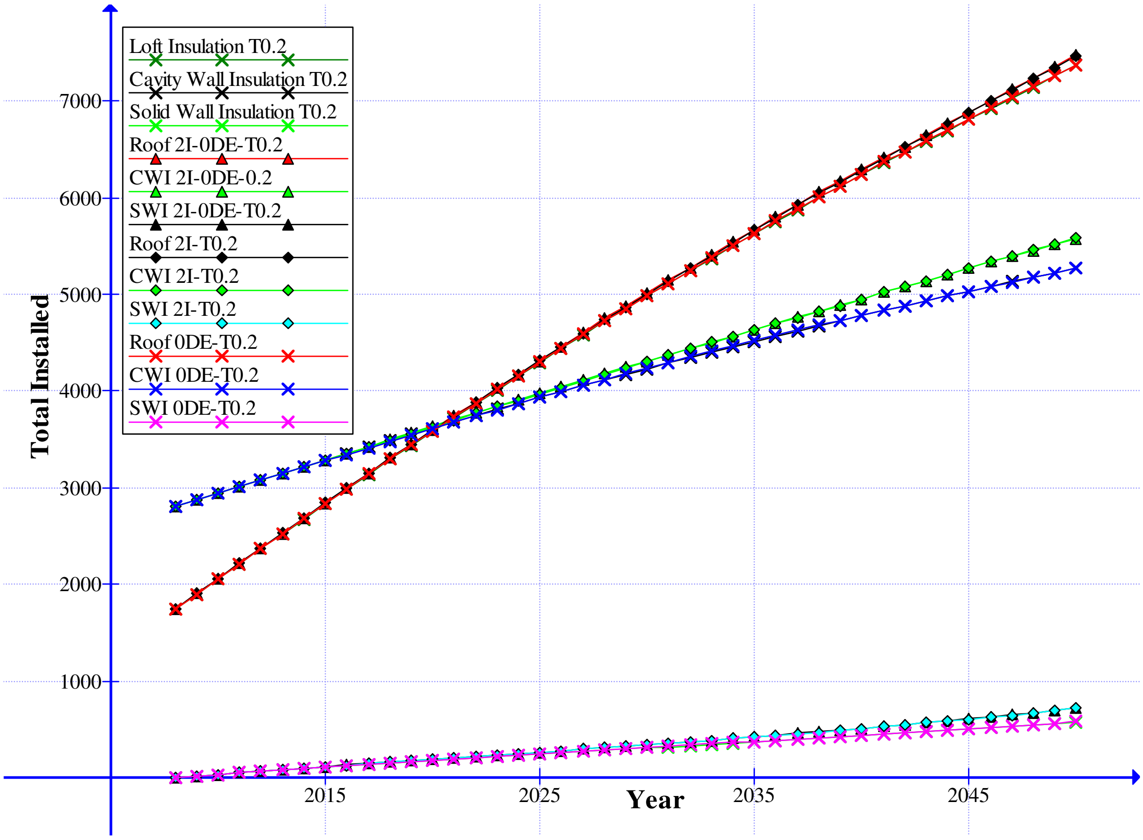


Figure 6-19 Insulation installations for taxed low temperature scenarios

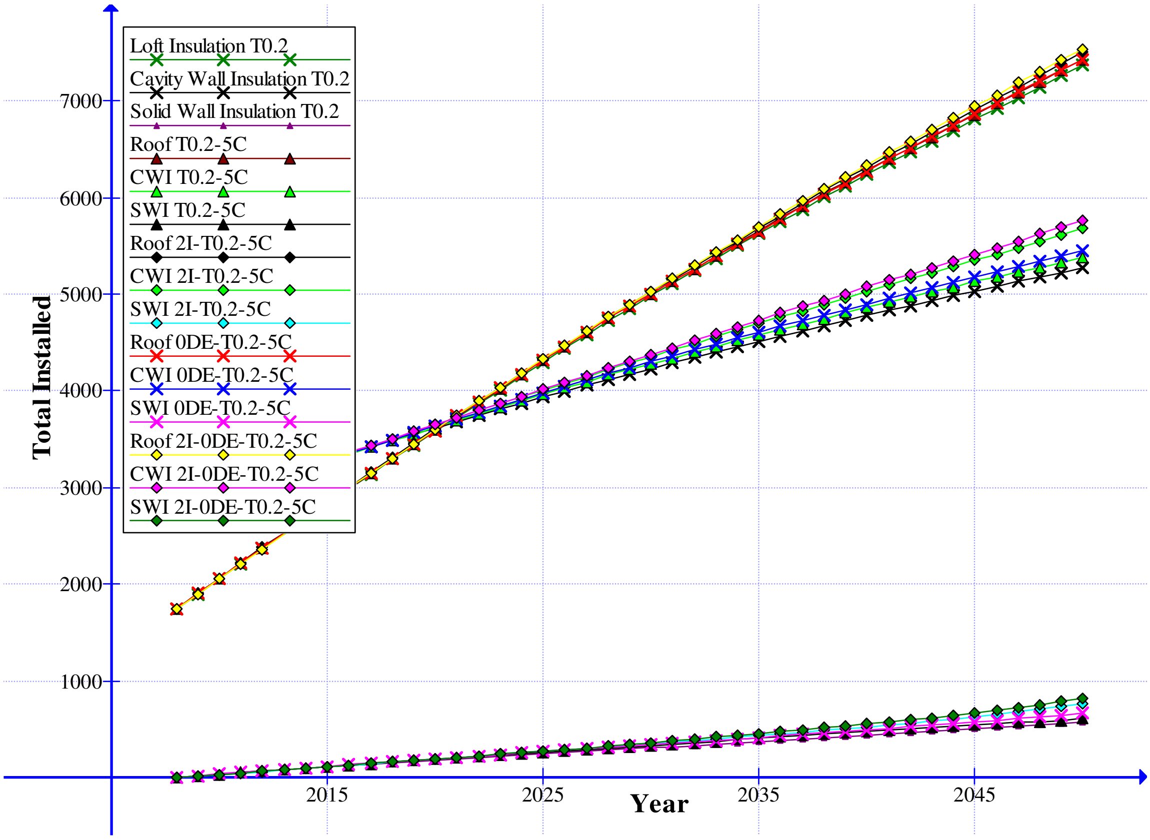


Figure 6-20 Insulation installations for un-taxed high temperature scenarios

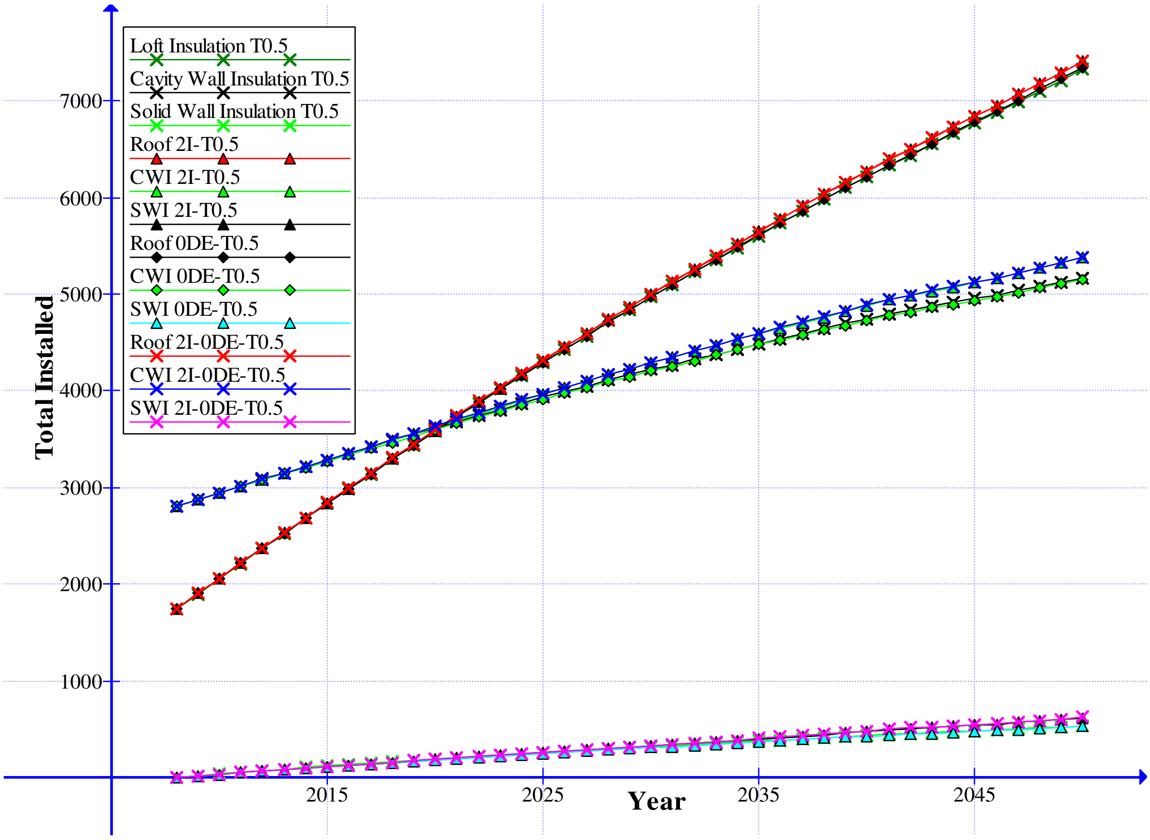
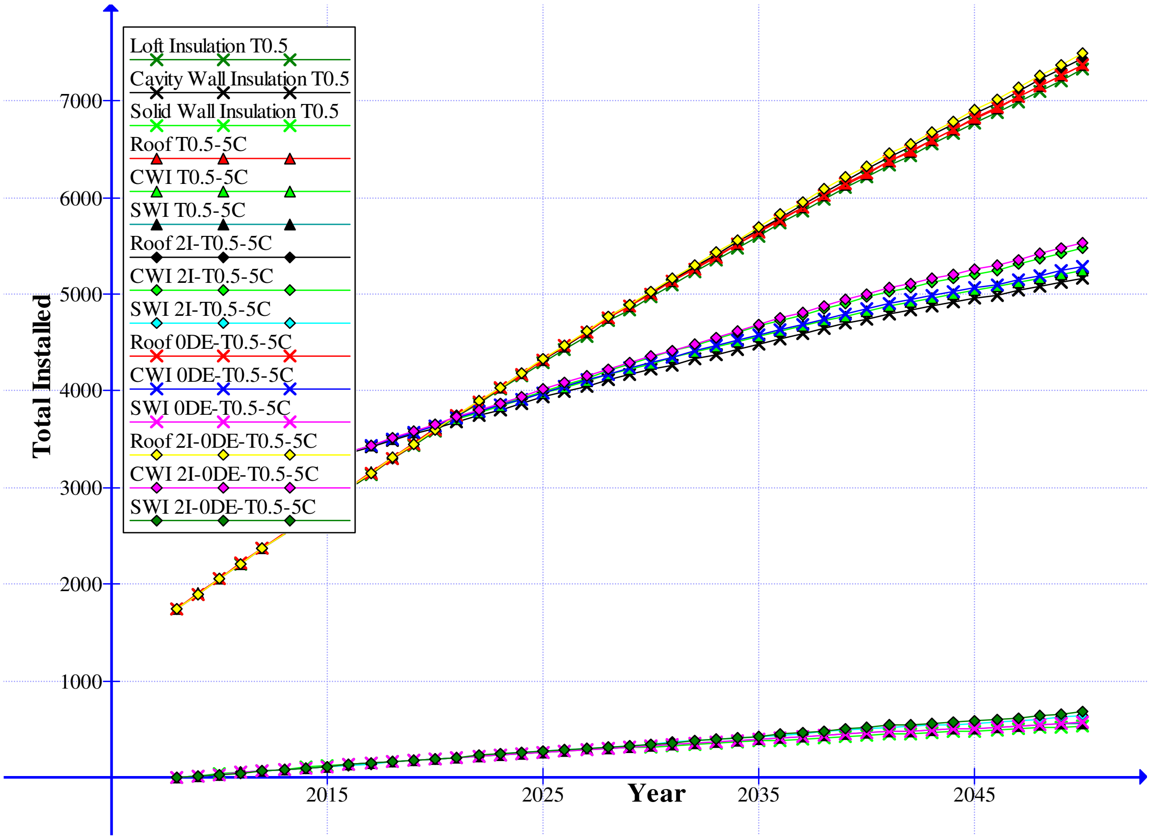


Figure 6-21 Insulation installations for taxed high temperature scenarios



In all sixteen scenarios presented above, there is little difference in the penetration of loft insulation and solid wall insulation. With loft insulation there is little room for variation since by 2050 the vast majority of dwellings have the maximum available in the model. For instance, picking one of the raw data sets at random, from the 2I-BAU-T0.2 runs, 7,512 out of the total population of 10,195 have the maximum insulation in 2050, in addition there are 388 dwellings without a loft (ie: a flat with another dwelling above), therefore around 77% of dwellings have the maximum. Furthermore the number of dwellings with the least amount of loft insulation was 718, less than half the figure for the mid-way loft insulation level. It is those dwellings with the least insulation that are more likely to be improved, since the savings moving from the mid-way level are noticeably smaller, thus reducing the benefit from the top up from the existing loft insulation levels.

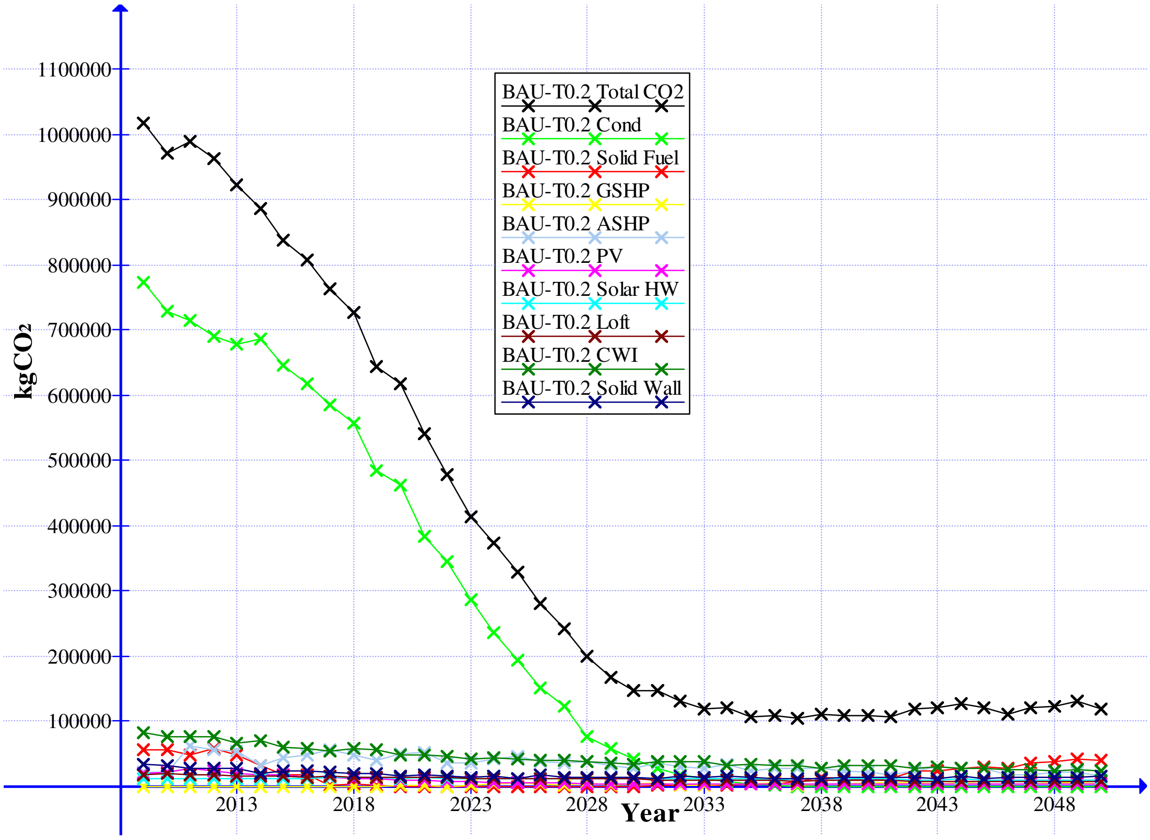
In the case of the solid wall insulation, this particular run had 751 insulated solid walls in 2050 with 1,251 uninsulated, therefore solid wall insulation penetration is still less than 50%. The relatively low uptake and the relative insensitivity to the changes of scenario suggests that even the most favourable conditions presented in these scenarios are still insufficient to encourage the majority of homeowners to take up solid wall insulation.

There is more variation visible in the cavity wall figures, this is most noticeable in the low temperature taxed scenarios presented in Figure 6-19, where there is a marked difference between the high and low inflation scenarios, and a slightly higher uptake for the non-decarbonised scenarios. This suggests that the tipping point to make householders decide to install it is fairly close, and therefore it could be easier for policy interventions to be effective. However, it is also important to consider the installation levels, and in the 2I-BAU-T0.2 scenario run used for the earlier figures in this section, only 1,100 dwellings remain with unfilled cavity walls, and of those 505 are in the newest age bracket, where the benefit from installation is greatly reduced. By way of comparison the oldest set of dwellings had 916 dwellings with filled cavities, and only 139 unfilled cavities remained, these are the dwellings which would benefit the most from cavity wall insulation.

6.3.5 Carbon Savings per Technology

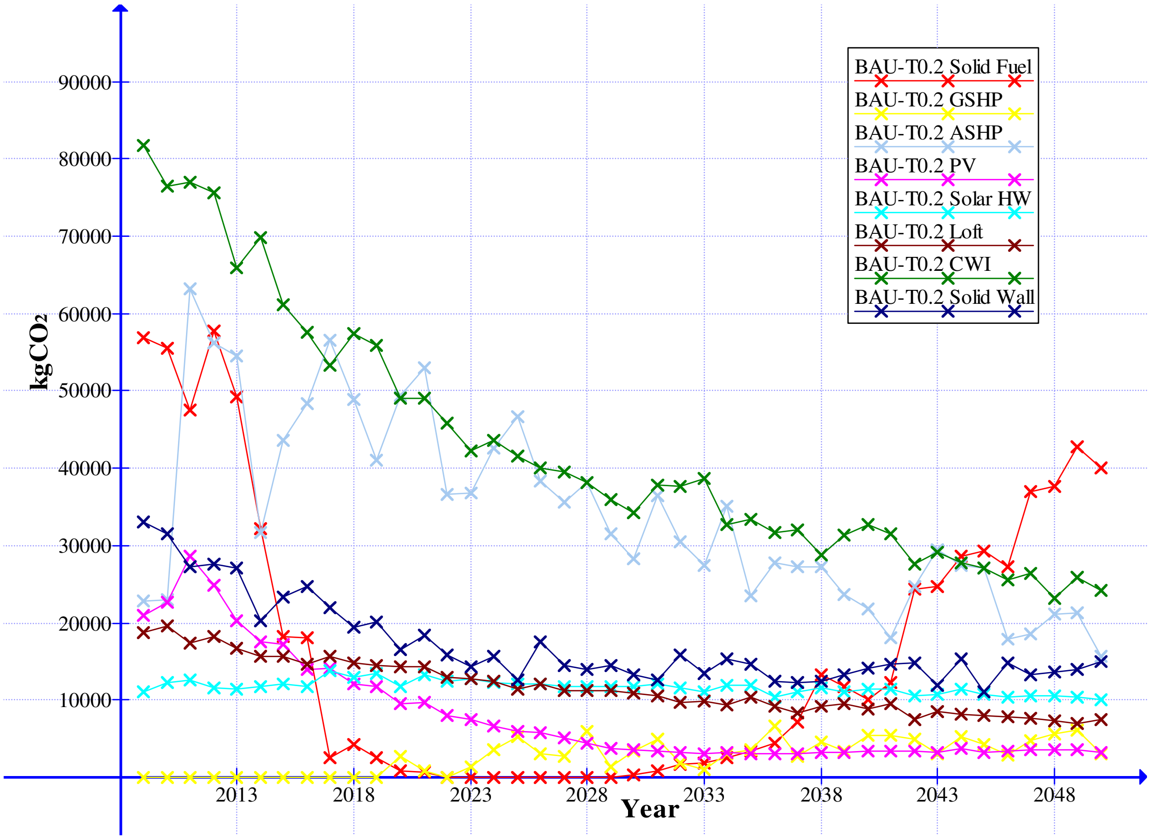
As the previous sub-section was beginning to indicate, the adoption of different technologies, in different situations, can achieve different levels of energy and CO_2 savings. In addition, there are limits to the contribution any one technology can achieve, particularly when its market penetration approaches saturation there is little headroom left for that particular technology to be able to contribute further to the reductions. Therefore, when devising policies and market interventions, it is necessary to consider the potential contribution each technology can make to the overall savings; to this end Figure 6-22 and Figure 6-23 display the CO_2 savings achieved each year in the model by each technology type for BAU-T0.2.

Figure 6-22 CO_2 saving by technology for BAU-T0.2



Clearly, this shows that the move to condensing boilers contributes the most to CO_2 savings in the BAU-T0.2 scenario. This concurs with Figure 6-2 and Figure 6-4, which showed condensing boilers becoming the dominant heating technology and the rate of CO_2 reduction declining once the condensing boiler had achieved almost total penetration. In order to examine the other technologies the same data, without the total or the condensing boiler figures, are reproduced in Figure 6-23.

Figure 6-23 CO_2 saving by technology for BAU-T0.2 excluding condensing boilers



As can be seen, due to the random variations from simulation run to simulation run, there is quite a variety in the savings achieved by a technology in any one year. Although, as seen in the overall reduction figures the cumulative effect is consistent, with the standard deviations between repeated measures being less than half a percentage point of CO_2 reduction.

Solid fuel heating (wood pellets, or similar systems) is quite interesting in that it is making a contribution in the early years, that declines to zero from 2022 to 2035, and then starts to increase, becoming the most significant technology for CO_2 reductions in the late 2040s. It is possible that in the early years it is able to compete in the market due to the presence of a larger number of less efficient systems and then due to the changing combination of capital and fuel costs and savings it begins to become competitive against the more efficient systems in the 2040s.

Solar hot water seems to be fairly constant across the whole timeframe. In contrast solar PV's contribution declines over the years despite a steady installation rate; this is because this is a decarbonised scenario, and after 2030 PV is simply providing electricity to supplant relatively low carbon grid electricity, so the CO_2 savings are reduced. Nevertheless, it remains an important contribution if it can help reduce overall demand on the grid supply.

Cavity wall insulation makes a significant contribution across the time frame, although its impact reduces noticeably. Both loft insulation and solid wall insulation contribute rather less than CWI and also decline in their effect in the latter years of the model runs, but the reduction is less severe. As discussed in the previous sub-section, the limited effect for the insulation is due to levels reaching saturation point and therefore the reduced impact from further measures.

Air source heat pumps seem to have the greatest variation from model run to model run for the annual savings achieved. When solid fuel boilers are more successful they exhibit similar levels of variation. This is likely to be due to the distorting effect from a small number of installations replacing oil boilers, or conventional electric heating; such an installation can result in a saving of several tonnes of CO_2 per year, so spikes in individual years become possible. Therefore the resolution limit of the model is being reached as random variations start to become noticeable. Nevertheless, it can be seen that ASHPs begin as one of the more significant technologies, and ground source heat pumps fail to achieve any market penetration in the early years. Then, in the second half of the model's time-frame, ASHPs' impact is declining, and it would appear that market share is being taken by both solid fuel and GSHPs. So, in the latter years, these three technologies, as well as competing against each other, are also attempting to win market share from condensing gas boilers, although in BAU-T0.2 the decline in condensing boilers is fairly minimal.

In order to have a comparison for the BAU-T0.2 results, Figure 6-24 and Figure 6-25 present the figures from BAU-2I-0DE-T0.2-5C.

Figure 6-24 CO_2 saving by technology for BAU-2I-0DE-T0.2-5C

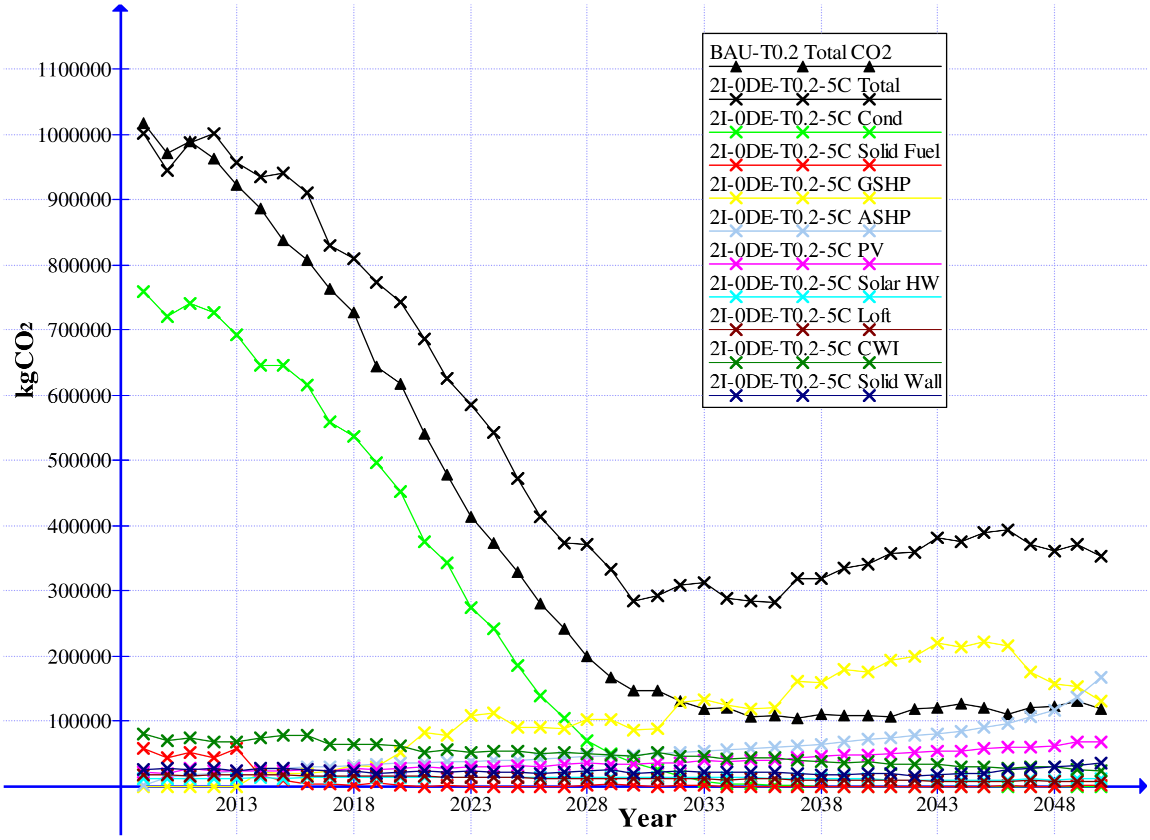
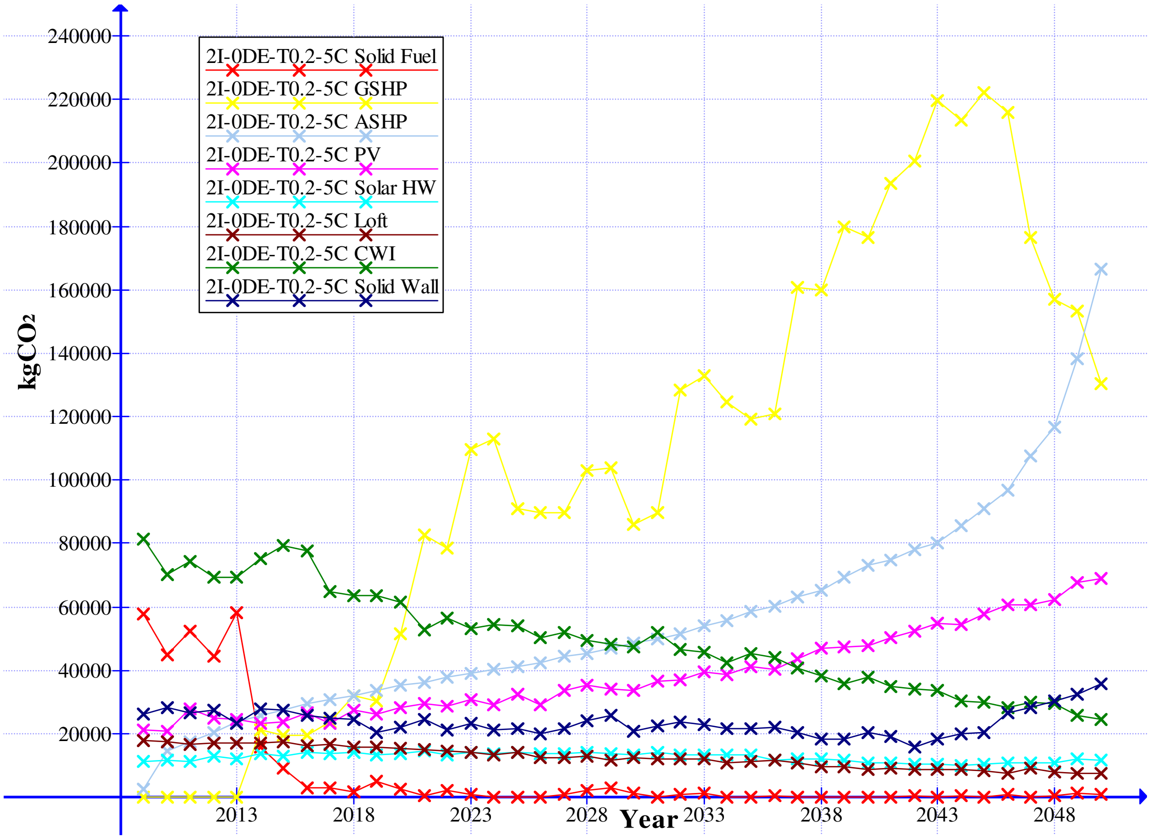


Figure 6-25 CO_2 saving by technology for BAU-2I-0DE-T0.2-5C excluding condensing boilers



It should be noted that the overall savings in Figure 6-22 for BAU-2I-0DE-T0.2-5C are larger than those for BAU-T0.2, although the total reductions in Table 6-3 show BAU-T0.2 achieving a slightly larger reduction (52% as against 50%). This is because the data used here for savings per technology is concerned only with the existing stock and is not including the effect from new builds. Evidently, in the decarbonised BAU-T0.2 the impact from new builds is sufficient to make up for the lower numbers of retro-fit installations. This again therefore demonstrates the importance of grid decarbonisation to achieving maximum reductions in the domestic sector.

Cavity wall insulation reacts in a very similar manner to the BAU-T0.2 scenario with its contribution declining over time, and the contribution from loft insulation is again fairly similar. However, there is a difference with the solid wall insulation, in that its savings are fairly static until the mid 2040s and then it looks as though the impact is starting to increase slightly at the end of the model's time-frame. This suggests that the conditions are just beginning to become more favourable for SWI installation, although, as previously discussed the extent of its impact will be limited due to the reducing numbers of uninsulated solid walls remaining.

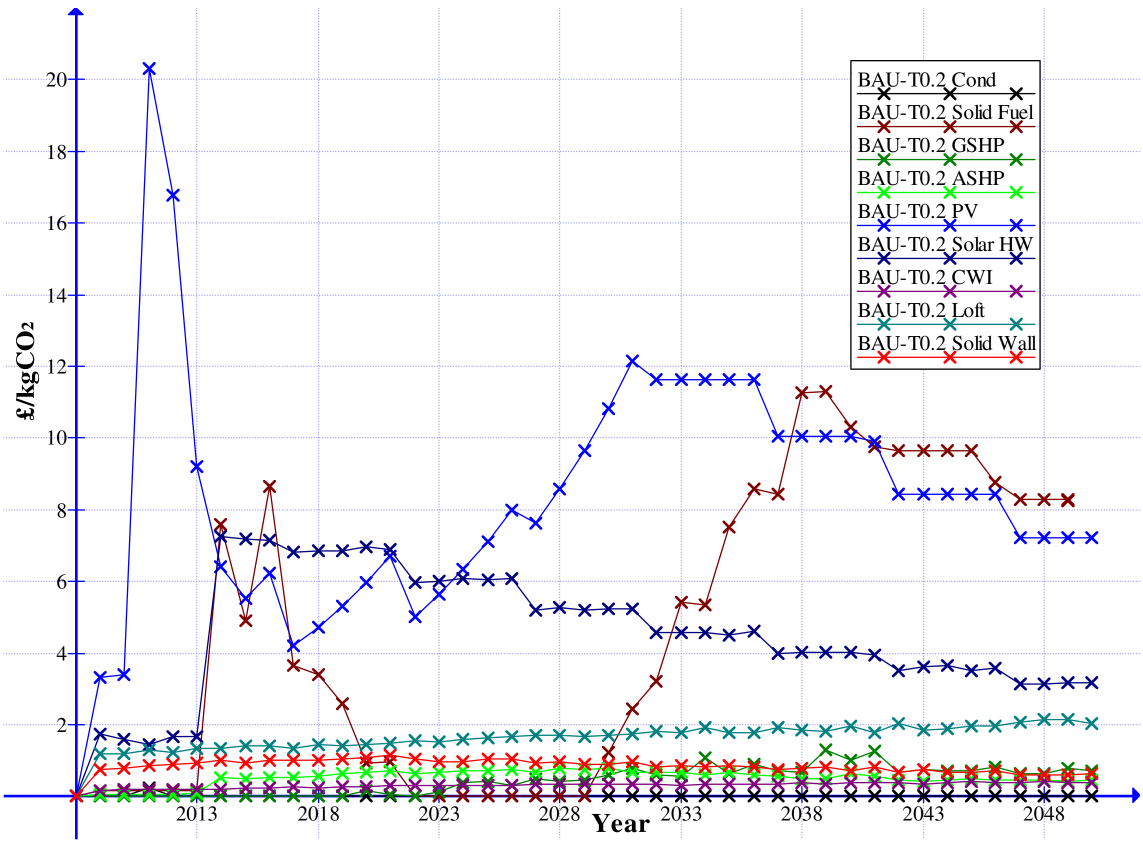
The most significant difference in this case, compared with BAU-T0.2, is clearly the heat pumps, up to 2020 with 12 simulation runs BAU-2I-0DE-T0.2-5C has 44 instances (out of 144) where ASHPs provide over 100,000 kg of CO_2 savings in a year as opposed to just 5 instances for BAU-T0.2. An even larger contrast is seen with the ground source heat pumps, Figure 6-14 shows absolute GSHP installations overtaking ASHP numbers in 2039/2040. As Figure 6-23 shows, GSHPs are providing greater annual savings than ASHPs from the early 2020s, with a peak in 2045 with average annual savings of 222,400 kg (standard deviation 31,000 kg). Again there is the issue of competing technologies, and in this case, with the success of the heat pumps, solid fuel heating fails to diffuse into the market, and most simulation runs have zero savings from solid fuel for most years from around 2020.

The other technologies to consider are the two solar technologies. For solar hot water, there is little difference between BAU-2I-0DE-T0.2-5C and BAU-T0.2. However, with PV the situation is markedly different. In BAU-T0.2 the impact from PV lessened over time, largely due to grid-decarbonisation, but in this case grid-decarbonisation does not occur, and so the PV is replacing a carbon intensive electricity supply, and therefore its impact increases. In the final year PV provides an average saving of 69,100 kg (s.d. 6,800 kg) whereas in the first year its contribution was only 21,000 kg (s.d. 3,100 kg).

6.3.6 Subsidy Cost Effectiveness

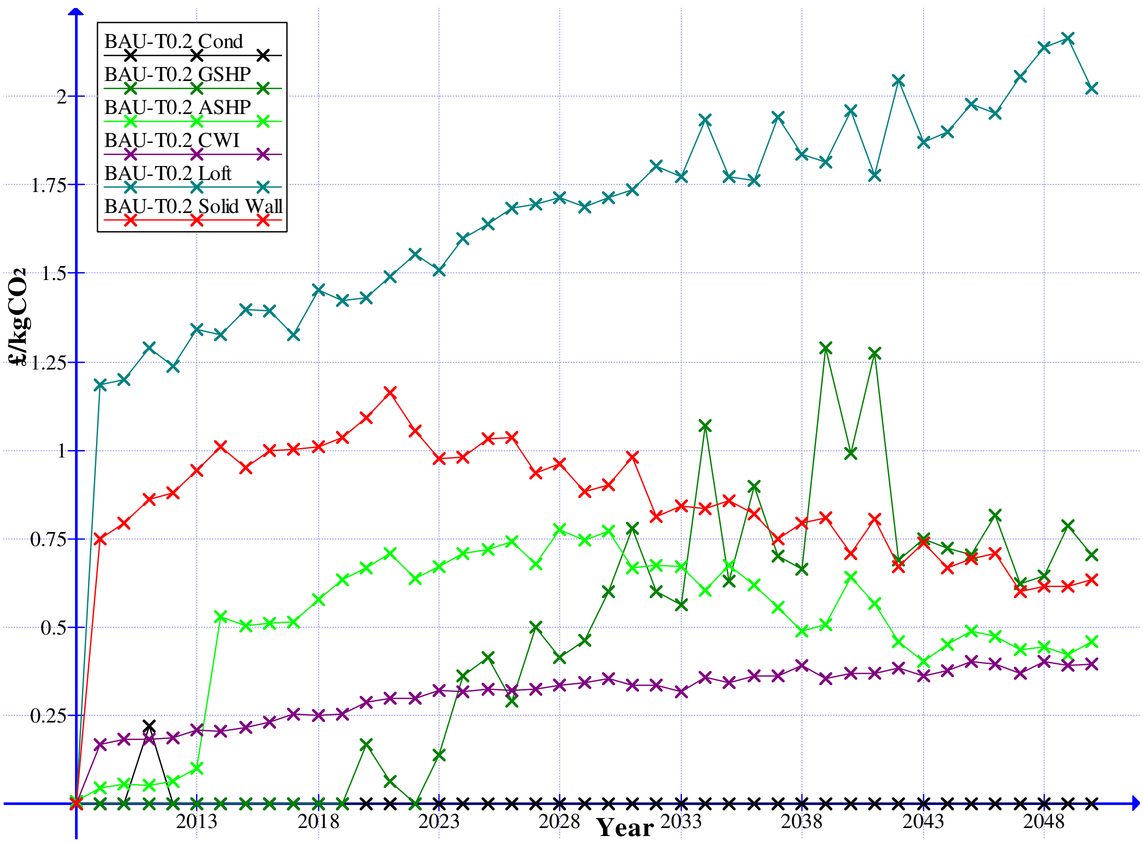
All these scenarios include subsidies to encourage the uptake of the various technologies available in the model. The next stage after considering the impact each technology makes towards the achievable CO_2 reduction is to analyse the cost implications. To do this it is necessary to calculate the subsidy cost associated with any CO_2 reduction. In doing this there are two issues to consider, firstly some subsidies are simply a one off up-front payment, whereas others are paid over a number of years (typically 25). In order to account for this upfront subsidies have simply been calculated based on their upfront cost. However, for those providing an annual income (feed in tariff and renewable heat incentive) the cost of future subsidies has been brought forward with a standard net present value calculation using the Government's recommended discount rate of 3.5% (HM Treasury, 2003). A similar argument could be made as regards the carbon saving, in that the installation of a technology results in a carbon saving, not only in the year of installation, but also in the subsequent years, whilst that technology is still in place. However, such an approach is not taken here, and the cost is simply calculated on the net present value of the subsidy applied divided by the annual carbon saving, to provide figures that are £/kgCO_2. Figure 6-26, Figure 6-27, Figure 6-28, Figure 6-29, Figure 6-30 and Figure 6-31 present these figures for a selection of the scenarios, beginning with BAU-T0.2.

Figure 6-26 Subsidy cost effectiveness in £/kgCO_2 for BAU-T0.2



BAU-T0.2 is a decarbonised scenario, and the effect of this is most noticeable with the cost effectiveness of PV subsidies. There is a peak in the cost of PV in 2011, which equates to the feed in tariff that exceeded 40p/kWh that year. After that point the cost per kilogram decreases, but it then begins to increase again in the 2020s due to the anticipated grid decarbonisation. Finally, it can then be observed stepping down as the subsidies are progressively reduced. As the graph shows the PV subsidy is one of the least cost effective ways of achieving carbon reductions in a decarbonised scenario. The subsidies for solid fuel also make that an expensive method of subsidising carbon reductions. Solar hot water is the next most expensive method, and again the impact of the reducing subsidy levels can be seen in the progressive decrease in its cost per kilogramme. In order to be able to examine the more cost effective measures in more detail, they are reproduced below:

Figure 6-27 Subsidy Cost Effectiveness in £/kgCO_2 for BAU-T0.2 Low Cost Measures



There is one non-zero entry for condensing boilers, this is for 2011 when there was a scrappage scheme to encourage the replacement of old boilers, and the graph shows that this measure cost around 25p/kgCO_2. As can be seen, over time the cost effectiveness of the loft insulation subsidy is reducing, this will be because in the initial stock there were many dwellings with the least efficient roof, and so larger savings could be made improving those dwellings. However, in the later years more of the subsidy will be spent in improving moderately insulated roof spaces. Cavity wall insulation remains one of the most cost effective measures, although it roughly halves in cost effectiveness over the 2008-2050 period – much of this reduction will be due to increases elsewhere: as roof spaces get insulated and heating systems are improved less heating energy is required and therefore less will be lost through the walls, thus reducing the impact from CWI installation.

It is interesting to note the differences between the two heat pump technologies. As discussed in the previous chapter, the model assumes that ASHPs can be used in almost any situation, but places limitations on GSHPs due to the additional space requirements. This therefore impacts on the range of heating systems against which each can successfully compete. With GSHPs it is possible to note the decrease in cost effectiveness during the grid decarbonisation in the 2020s. This suggests that in this case GSHPs may be taking market share mainly from conventional electrical heating, such that the carbon saving from the change of system would be reducing in line with reductions in the carbon intensity of the grid supply. In comparison, ASHPs are competing more generally and there is therefore a variation in cost effectiveness from one run to the next of the same scenario. Nevertheless, the ASHPs' data appear to present an initial decrease in cost effectiveness, followed by a gradual increase as grid decarbonisation and subsidy reductions occur. For comparison Figure 6-28 and Figure 6-29 show scenario BAU-0DE-T0.2, ie: the same situation but without the grid decarbonisation.

Figure 6-28 Subsidy Cost Effectiveness in £/kgCO_2 for BAU-0DE-T0.2

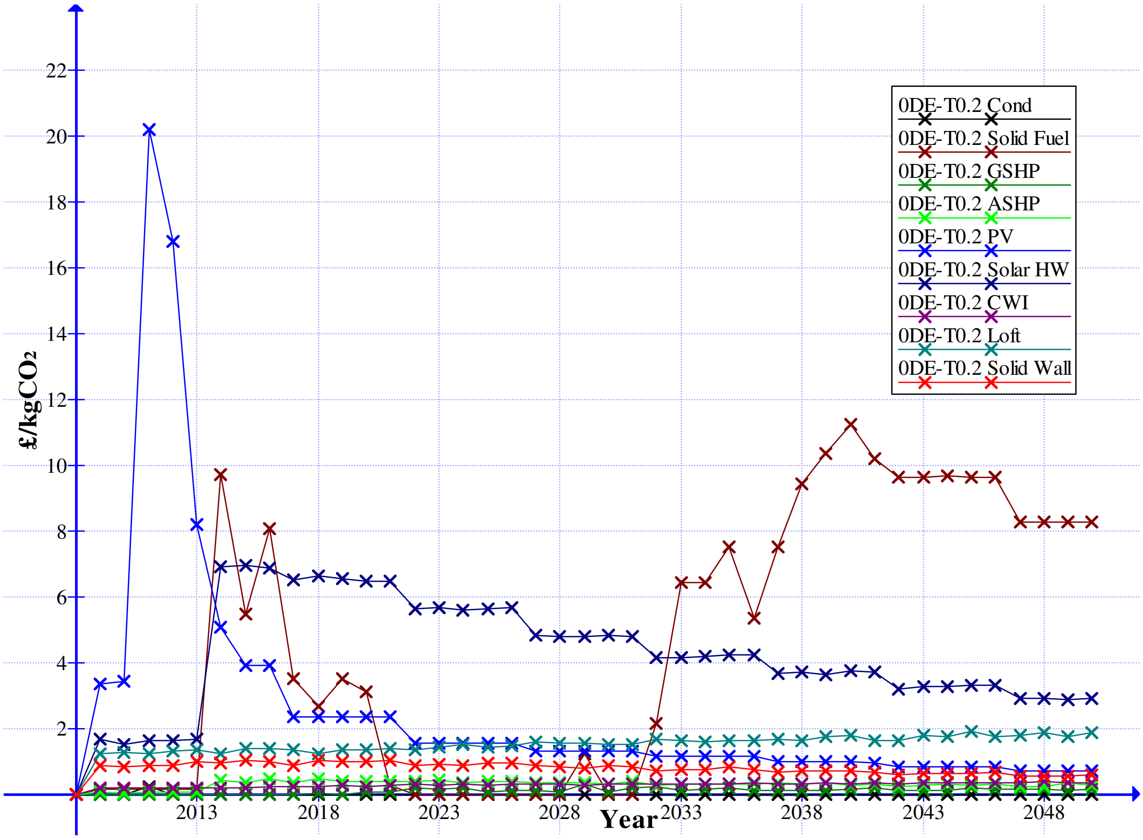
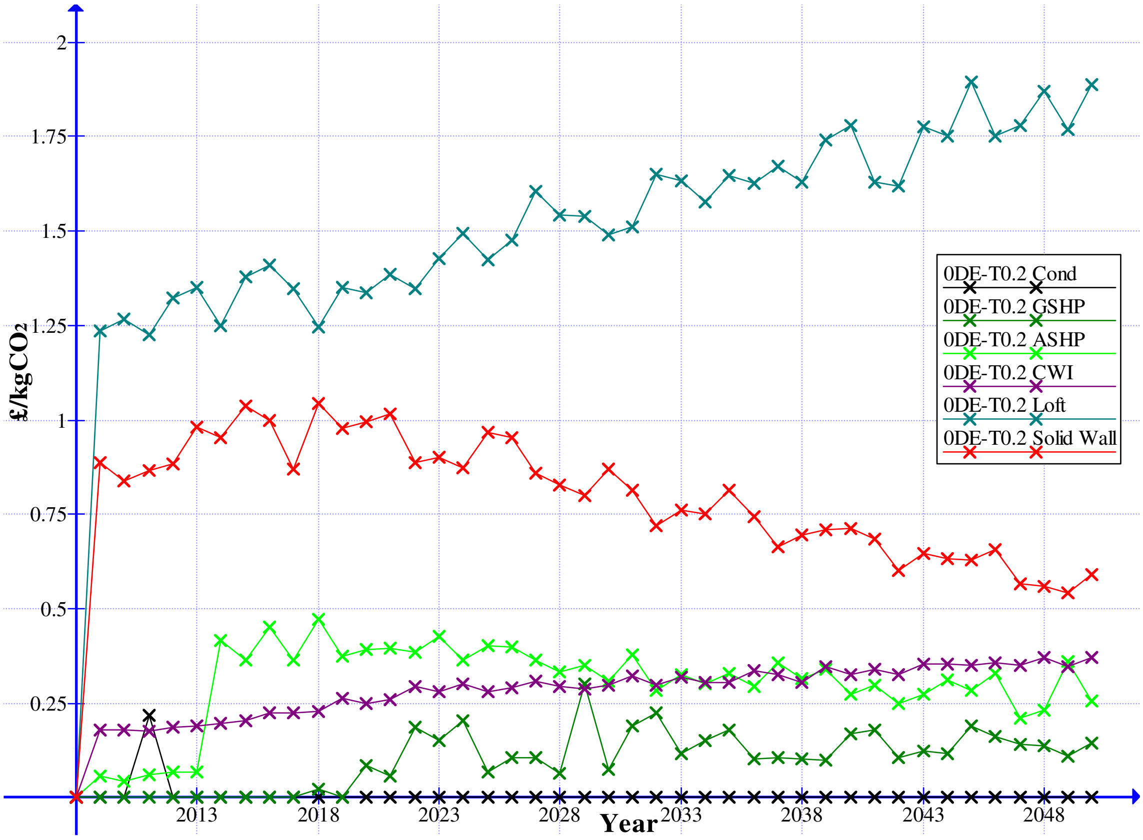


Figure 6-29 Subsidy Cost Effectiveness in £/kgCO$_2$ for BAU-0DE-T0.2 Low Cost Measures



In comparing Figure 6-26 and Figure 6-28 there is a number of similarities: most of the technologies have a cost of around £2/kgCO$_2$ or better; the same spike in PV is observed for the peak in the feed in tariff; and solid fuel and solar hot water are the least cost effective methods. Figure 6-29, then replicates Figure 6-27, showing the low cost measures in more detail for the non-decarbonised scenario. There are two main changes observable here: firstly, there is the presence of PV in the more cost effective technologies. In this case, without grid decarbonisation, PV is offering a low carbon energy source as an alternative to a carbon intensive grid and therefore proves much more cost effective in reducing overall emissions. The other difference, somewhat counter intuitively, is in the heat pumps where their cost effectiveness is increased, however the retrofit installation levels are relatively low and so it is likely that only the most favourable installations are being fitted, and if either technology were to be more successful the cost effectiveness would decrease.

As a contrast to these two, BAU-2I-T0.5-5C achieved the greatest carbon reduction (78.16% 2008-2050), it is therefore worth comparing its technology cost effectiveness, as in Figure 6-30 and Figure 6-31:

Figure 6-30 Subsidy Cost Effectiveness in £/kgCO2 for BAU-2I-T0.5-5C

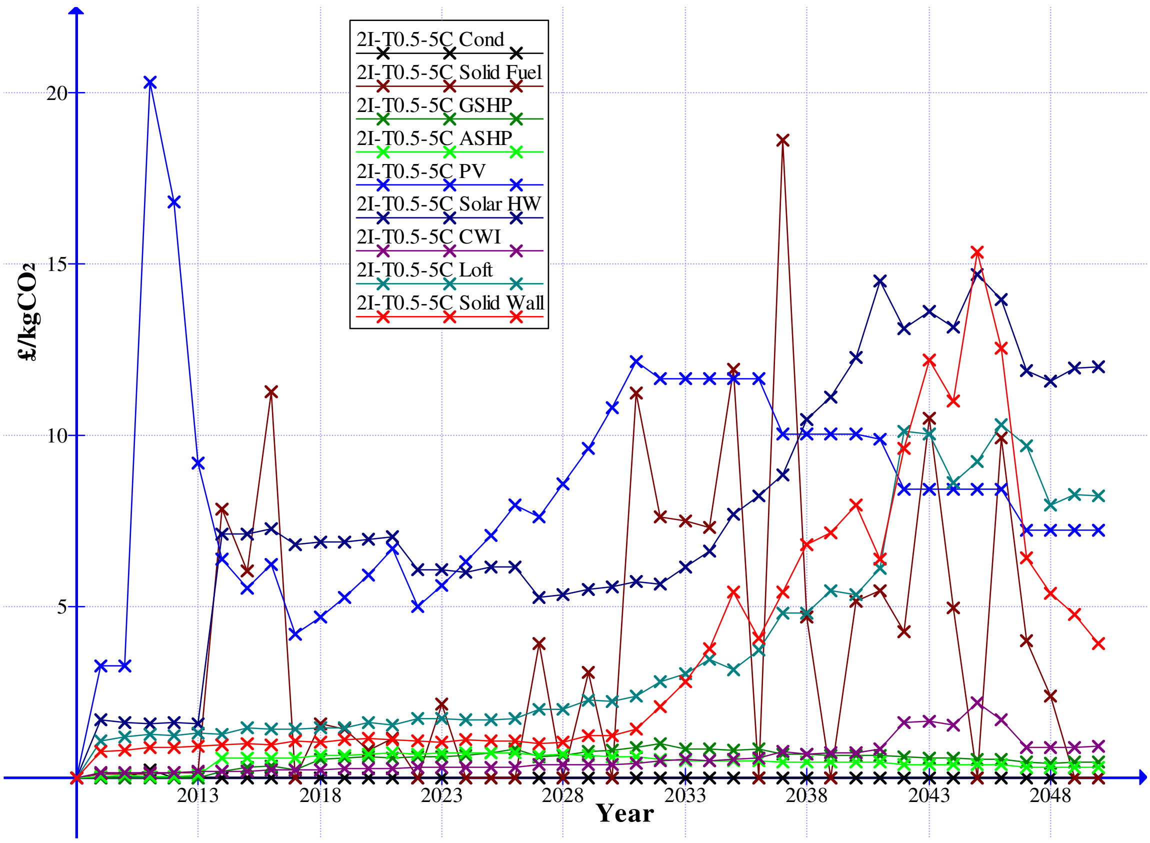
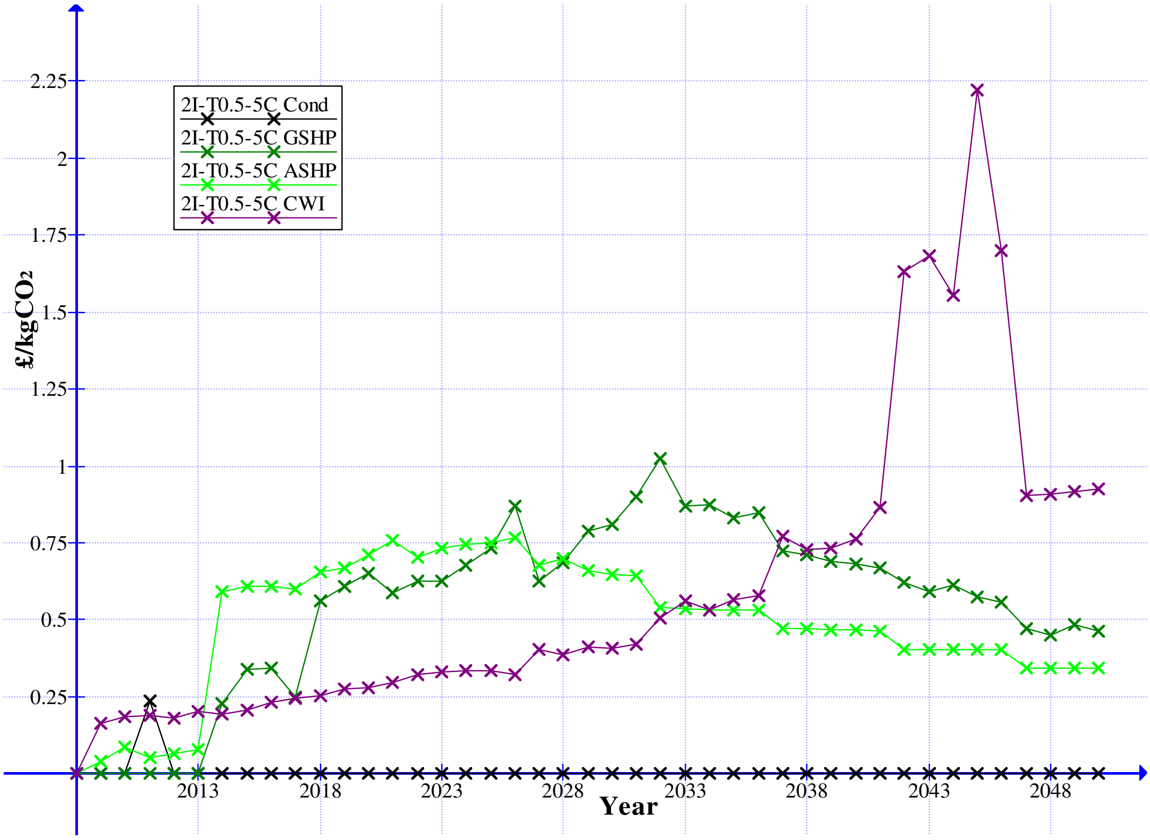


Figure 6-31 Subsidy Cost Effectiveness in £/kgCO_2 for BAU-2I-T0.5-5C Low Cost Measures

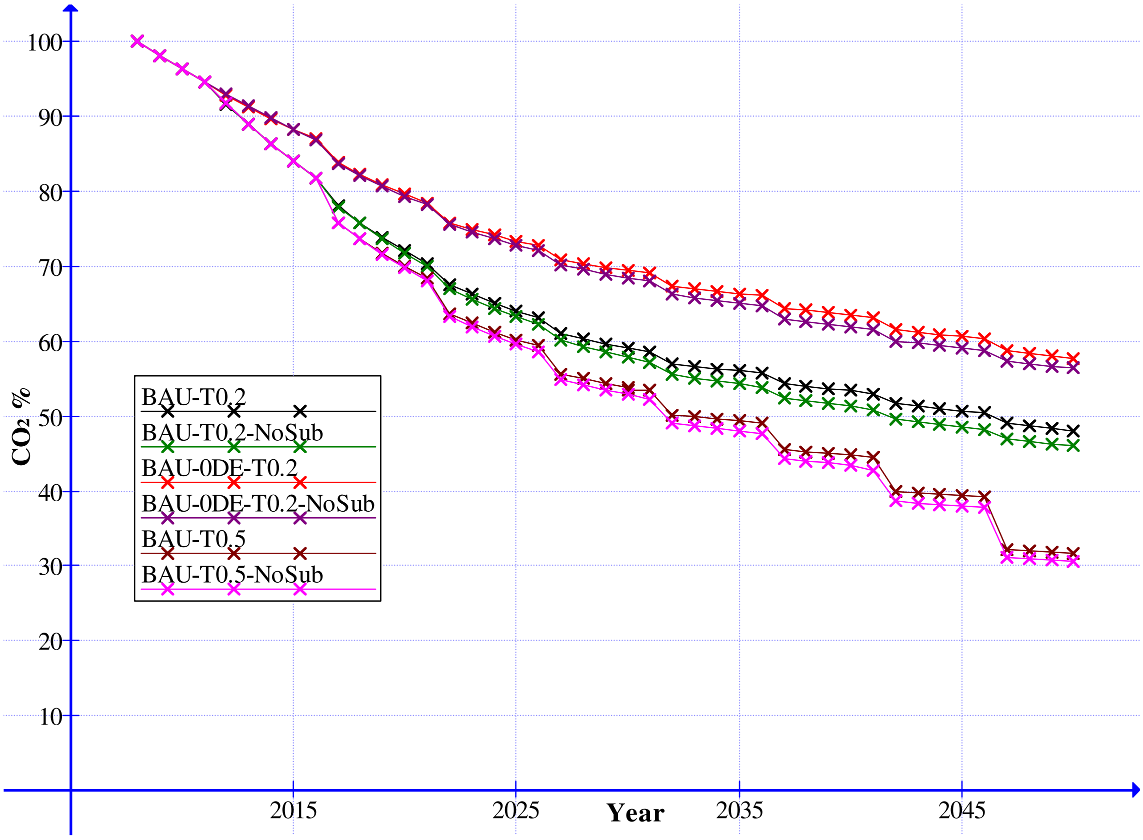


The main difference to note here is the change in the order of magnitude of these two graphs, with Figure 6-30 including items at over £90/kgCO_2, whereas in the previous scenarios peaks were around the £20 mark. Similarly, in order to display the more cost effective measures a much larger scale is needed in Figure 6-31, compared with Figure 6-27 and Figure 6-29. Again the heat pumps do relatively well compared with the other technologies for cost effectiveness. By referring to Figure 6-15 it is possible to see that diffusion of the two heat pumps only begins to become significant from the mid 2030s onwards, however, by this time the subsidies available for both technologies are estimated to have fallen to 2.1p/kWh for ground source and 1.4p/kWh for air source, as detailed in Table 6-1. This helps to explain their cost effectiveness, it would also suggest that in the high inflation and taxed scenarios heat pumps are able to compete in the market on their own merits with little requirement for incentives and market intervention to encourage their adoption.

6.3.7 Subsidy-free Scenarios

The previous sets of results described the relative cost effectiveness of the current and anticipated subsidy regime. In particular those results broadly suggest that insulation measures and then heat pumps are the most cost effective subsidized technologies to contribute to domestic carbon reductions. However, in every scenario a significant proportion of the carbon reductions initially comes from the conversion to condensing boilers, and, apart from the £300 scrappage scheme in 2011, condensing boilers receive no subsidy. This therefore demonstrates that it is possible for a technology to be chosen by a householder without the need for explicit government subsidy; although the essential banning of non-condensing boilers will have contributed to the change over. Nonetheless, some householders would adopt a technology without the need for a subsidy, so some people benefit from a subsidy for a decision that they would have made even without the extra government support. Therefore, in order to gain a better insight into true subsidy cost effectiveness, it is necessary to estimate the adoption levels with no subsidies. To aid with this Figure 6-32 to Figure 6-44 display results from three further scenarios: BAU-T0.2-NoSub, BAU-T0.5-NoSub and BAU-0DE-T0.2-NoSub – ie: three of the original scenarios but with all subsidies removed.

Figure 6-32 Annual CO_2 projections for BAU-T0.2, BAU-T0.2-NoSub, BAU-T0.5-NoSub, BAU-0DE-T0.2, BAU-0DE-T0.2-NoSub



There is a very unexpected result here that needs to be addressed, which is that in each case the version of the scenario with no subsidies achieved a marginally larger reduction. In each case the difference in averages is small between the subsidised and non-subsidised scenarios: T0.2: 1.99%; 0DE-T0.2: 1.29%; T0.5: 1.02%. In carrying out a t-test with the null hypothesis that subsidies increase the CO_2 reduction, in all three cases the null hypothesis can be rejected with p-values < 0.00001 (the p-values are so low due to the consistency in outputs between repeated scenario runs). Therefore this is a statistically significant result in terms of the model's outputs. Nevertheless, firstly, in order to check for errors, a very high subsidy scenario was generated and run, this was BAU-0DE-T0.2 but with £1000 up front subsidies for all technologies apart from condensing boilers, and 40p/kWh generating subsidies for renewable heat and electricity generation. This run achieved a 55.1% reduction in CO_2 emissions by

2050 as opposed to 42.35% for BAU-0DE-T0.2, thus demonstrating the model does provide a positive impact, as would be expected, from high levels of subsidies.

Clearly a deeper analysis of the underlying components is required to attempt to understand why the default set of subsidies has a negative impact. Therefore Figure 6-33 to Figure 6-38 compare the technology penetration figures.

Figure 6-33 BAU-T0.2 and BAU-T0.2-NoSub Technology Penetration (Common measures)

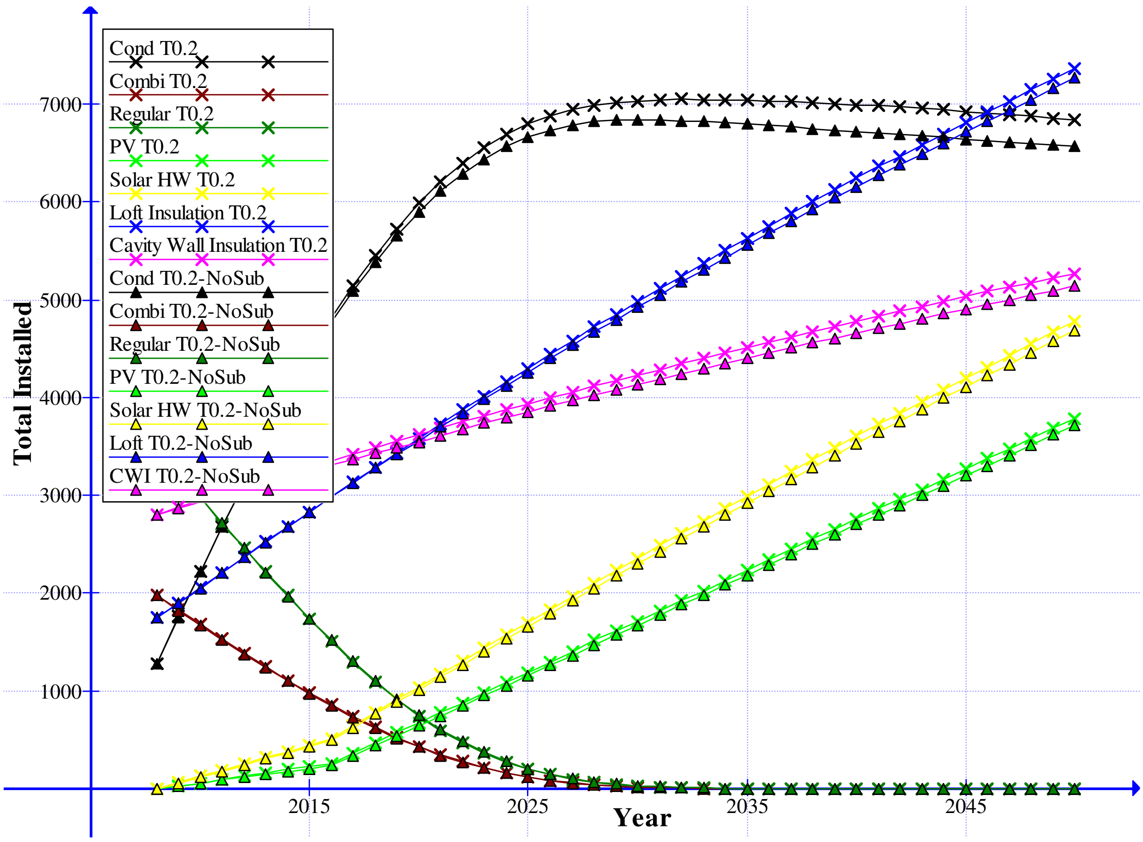


Figure 6-34 BAU-T0.2 and BAU-T0.2-NoSub Technology Penetration (Less common measures)

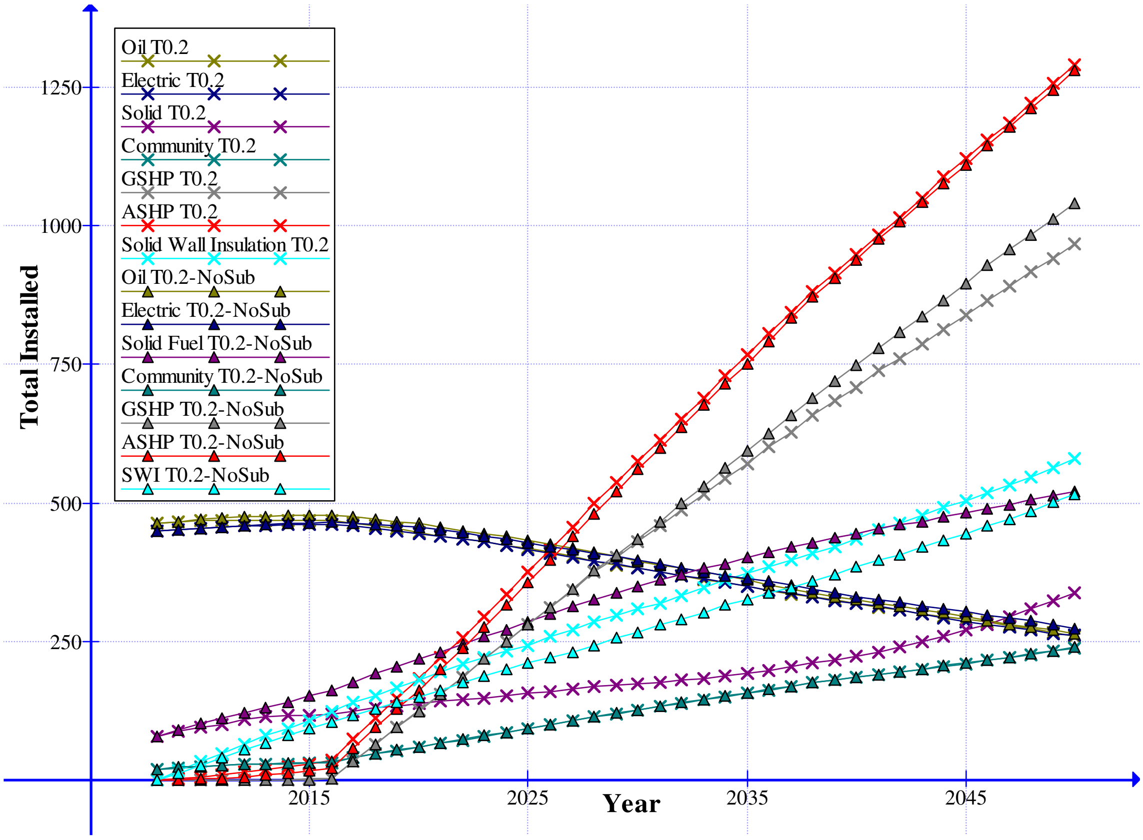


Figure 6-35 BAU-0DE-T0.2 and BAU-0DE-T0.2-NoSub Technology Penetration (Common Measures)

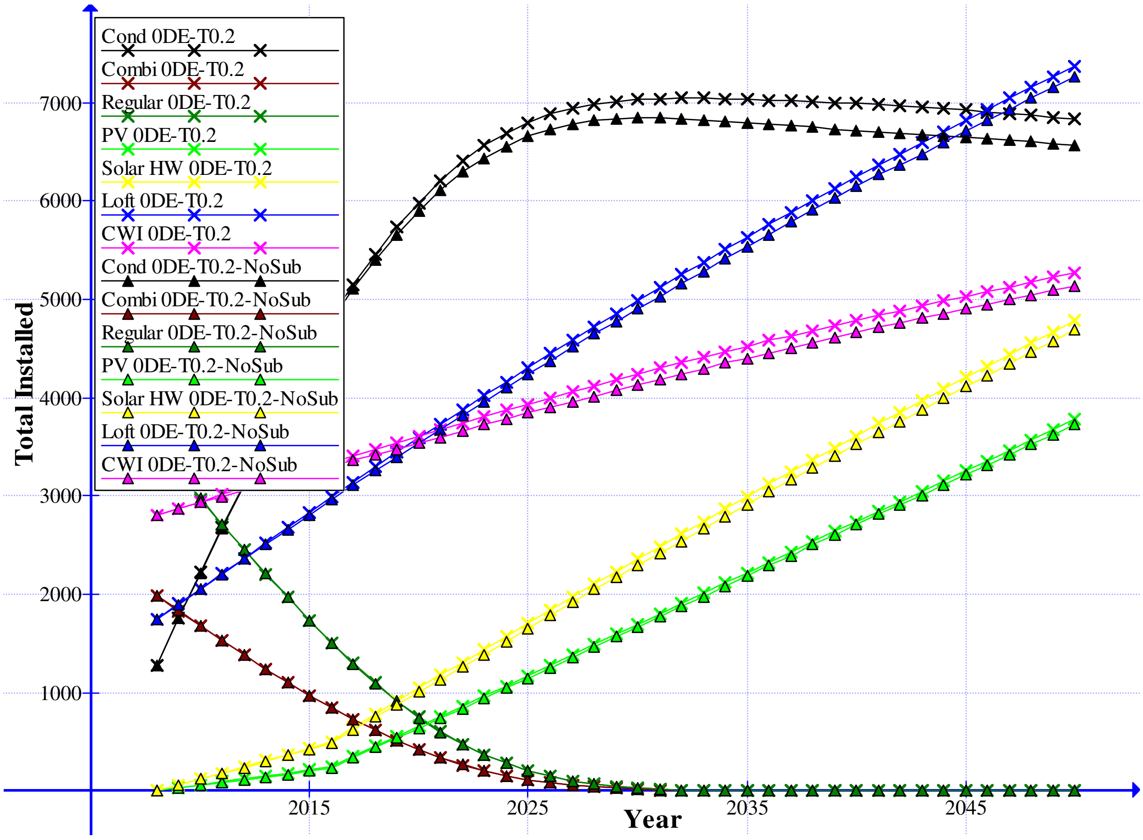


Figure 6-36 BAU-0DE-T0.2 and BAU-0DE-T0.2-NoSub Technology Penetration (Less Common Measures)

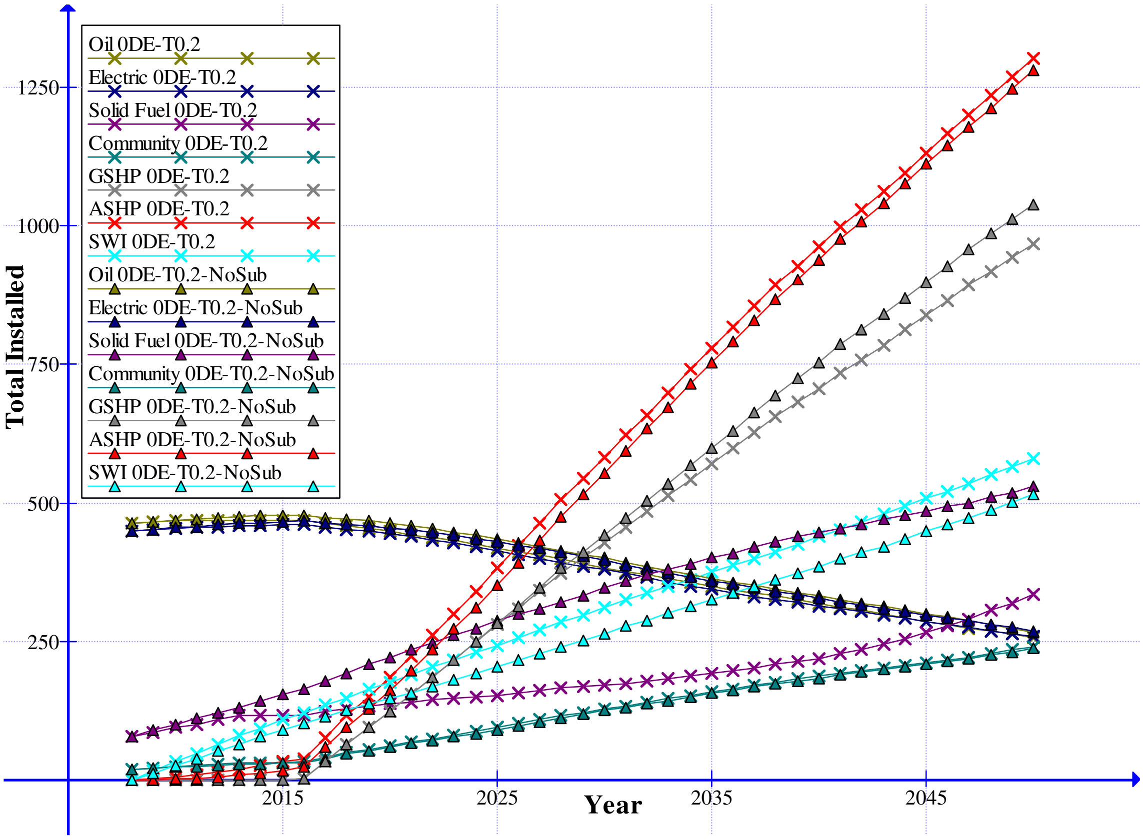


Figure 6-37 BAU-T0.5 and BAU-T0.5-NoSub Technology Penetration (Common Measures)

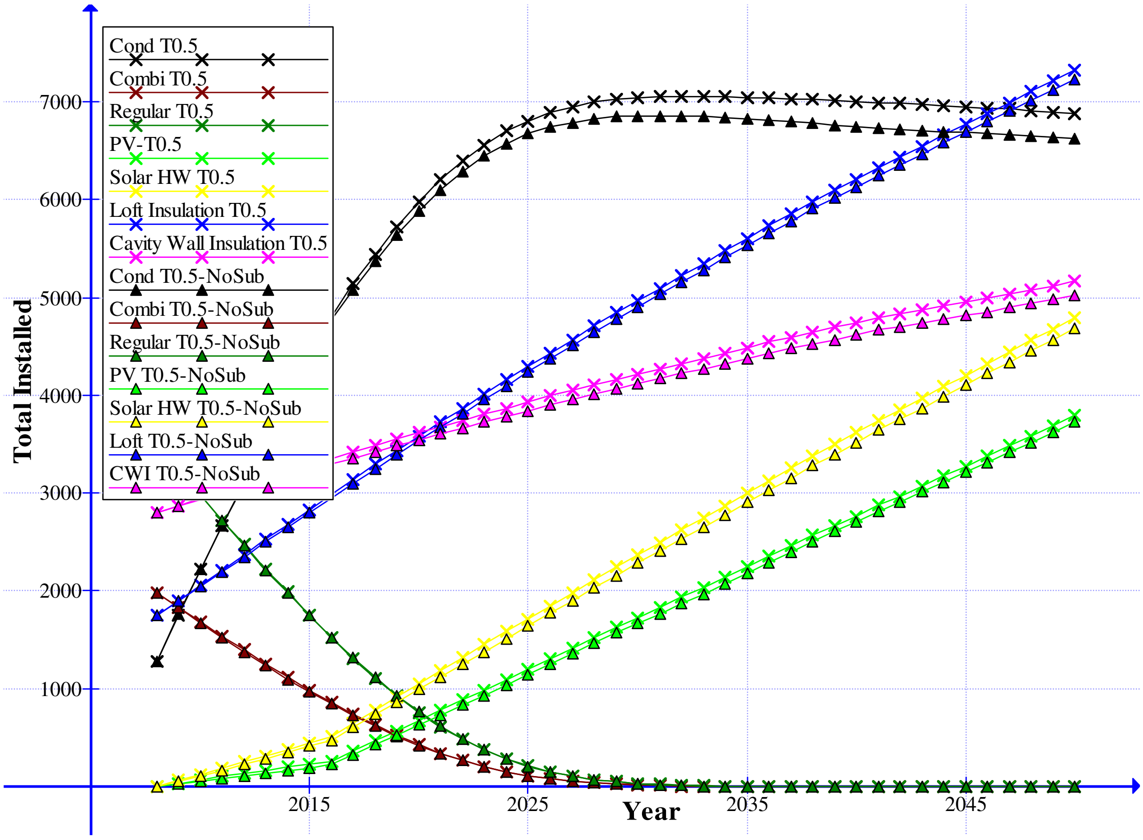
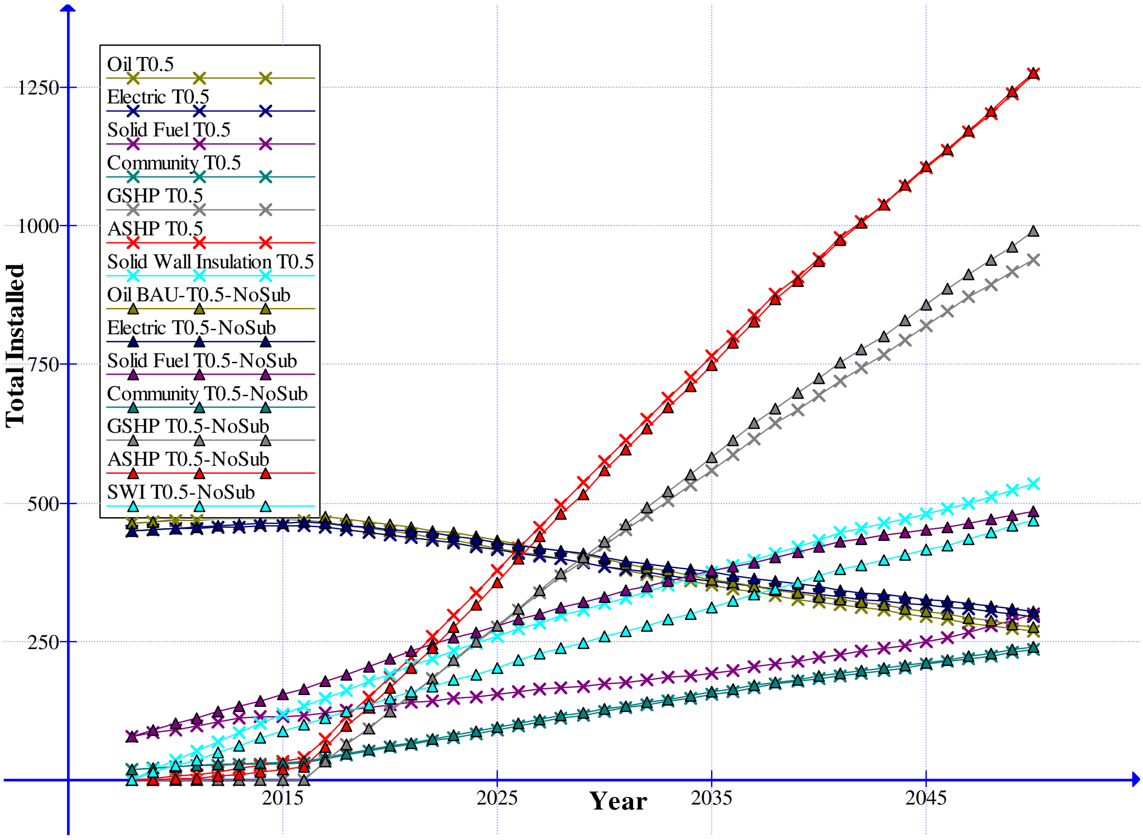


Figure 6-38 BAU-T0.5 and BAU-T0.5-NoSub Technology Penetration (Less Common Measures)



The data for each pair of scenarios (with and without subsidy) has been split in two, to allow for an easier examination of the less common technologies. In Figure 6-33, Figure 6-35 and Figure 6-37, it is possible to see the impact of the lack of subsidy leading to a slight reduction in the adoption of cavity wall and loft insulation, and solar hot water and PV systems. These reductions are, however, slight, and suggest that the current subsidies for these technologies have little impact on the decision making process. This still leaves the extra CO_2 reduction in the non-subsidised scenarios to be explained.

Figure 6-34, Figure 6-36 and Figure 6-38 provide the technology adoption for the less common technologies. In examining these figures, ASHPs, oil, electric and community heating all seem virtually unchanged. Solid wall insulation shows a clear reduction in adoption without the subsidy, which again does not explain the unexpected result. GSHPs have a slightly higher adoption rate without a subsidy, and solid fuel adoption is almost doubled without subsidy. Therefore, these two changes – principally the extra solid fuel installations – must be accounting for the unexpected increased reductions for the subsidy free scenarios.

In tandem with the increased adoption of solid fuel and GSHPs, consideration must be given to the unexpected reduction in the condensing boiler stock when subsidies are removed. This is, initially, a very counterintuitive outcome, in that the removal of subsidies from competing technologies reduces the success of the condensing boiler. However, there is a potential explanation which agrees with the findings from Faber's work (Faber et al., 2010). Without any subsidies in the system insulation and solar hot water installation figures are slightly depressed – as a result more heat is required from the heating system, and this therefore favours systems with lower running costs; hence the choice of solid fuel or GSHPs over a condensing boiler. This is similar to Faber's finding where the micro-combined heat and power systems failed to diffuse into the market place when insulation levels were high.

Therefore, the penetration levels of condensing boilers, both heat pump types, and solid fuel heating suggest that there is an issue in setting subsidy levels for competing technologies. GSHPs (typically more efficient than ASHPs) and solid fuel heating (powered by renewable wood pellets or similar fuels) have the potential to provide greater savings than other heating technologies. However, the current subsidy levels appear to favour less effective heating systems such that in the competition for market penetration the best options lose out. Furthermore, there are unexpected consequences of subsidy levels that do not immediately impact on heating systems, but are related to other building elements.

In order to check that it is the GSHPs and solid fuel heating that are providing the extra CO_2 savings, Figure 6-39 to Figure 6-44 provide the carbon savings achieved by each technology.

Figure 6-39 CO_2 Saving by Technology for BAU-T0.2 and BAU-T0.2-NoSub

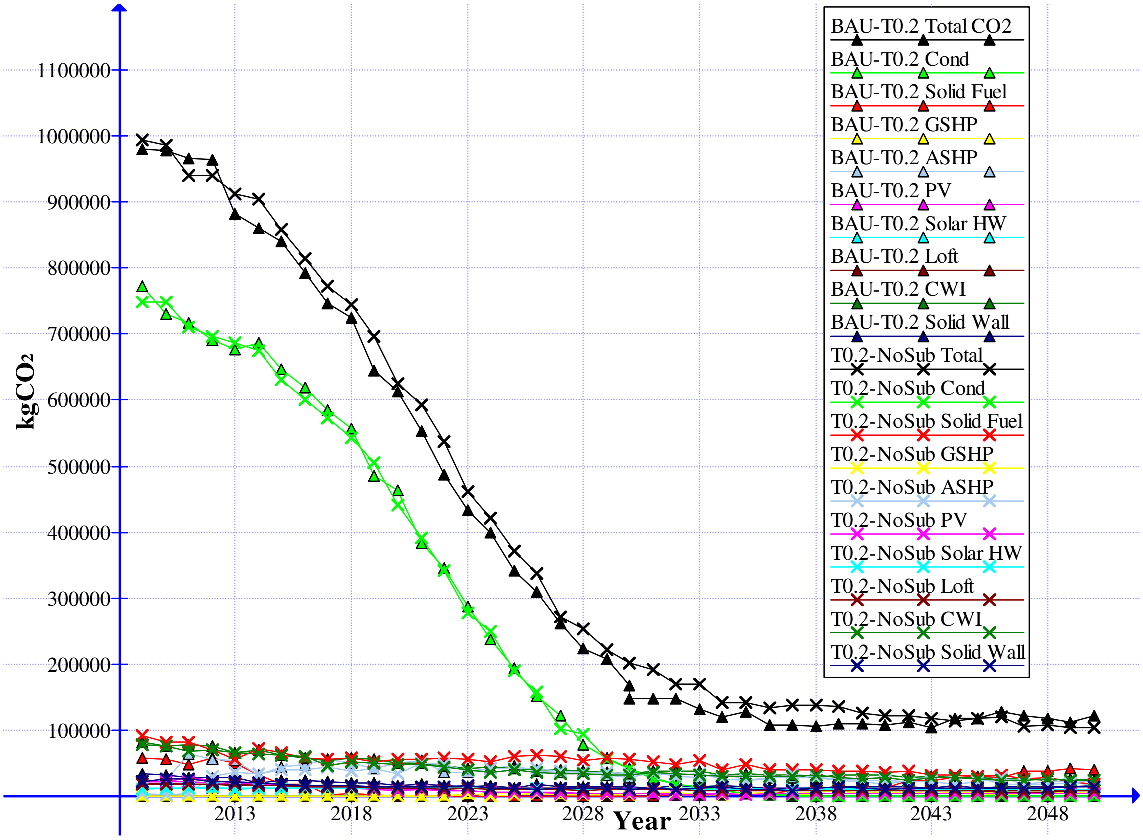


Figure 6-40 CO_2 Saving by Technology for BAU-T0.2 and BAU-T0.2-NoSub (Heat pumps and solid fuel)

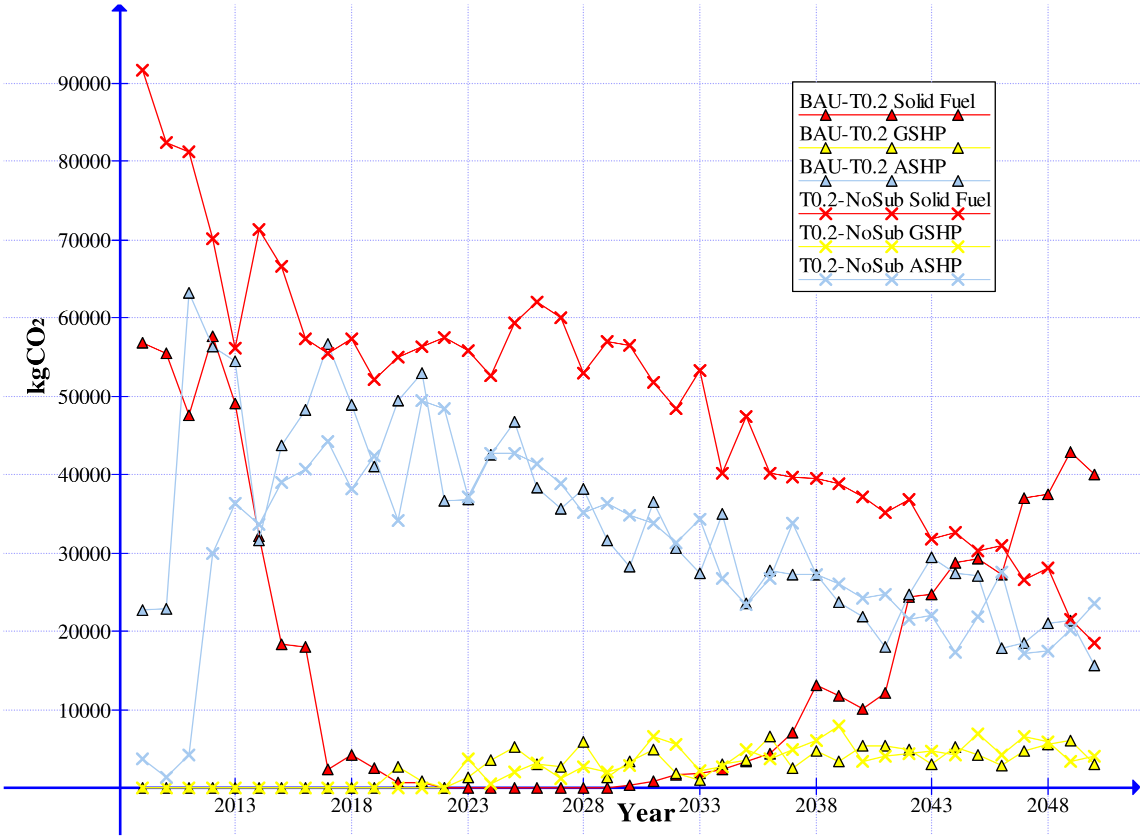


Figure 6-41 CO_2 Saving by Technology for BAU-0DE-T0.2 and BAU-0DE-T0.2-NoSub

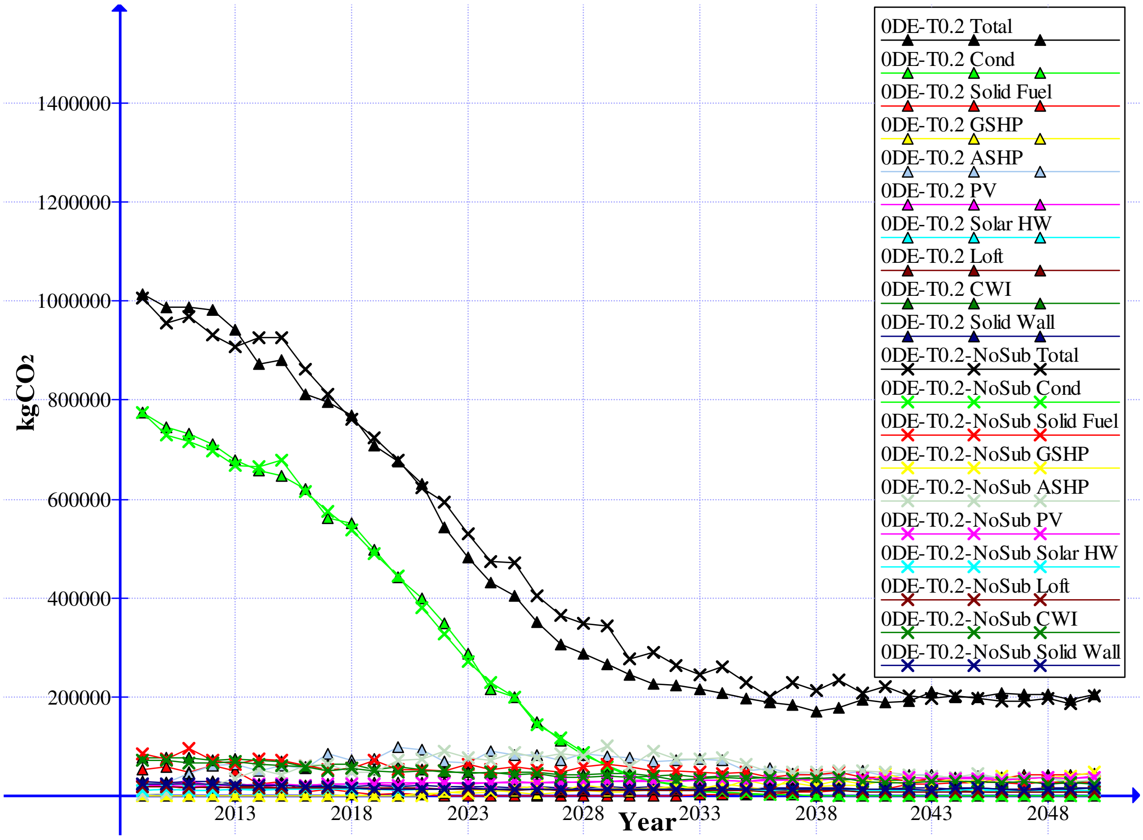


Figure 6-42 CO_2 Saving by Technology for BAU-0DE-T0.2 and BAU-0DE-T0.2-NoSub (heat pumps and solid fuel)

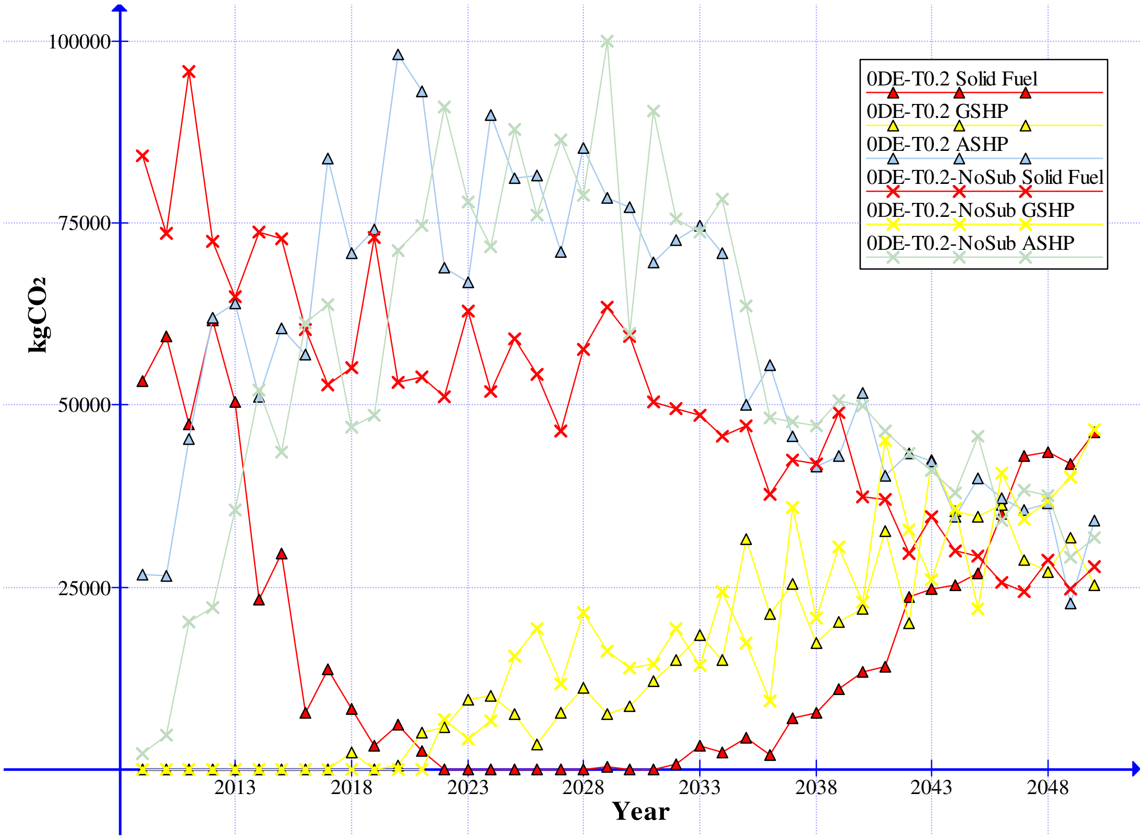


Figure 6-43 CO_2 Saving by Technology for BAU-T0.5 and BAU-T0.5-NoSub

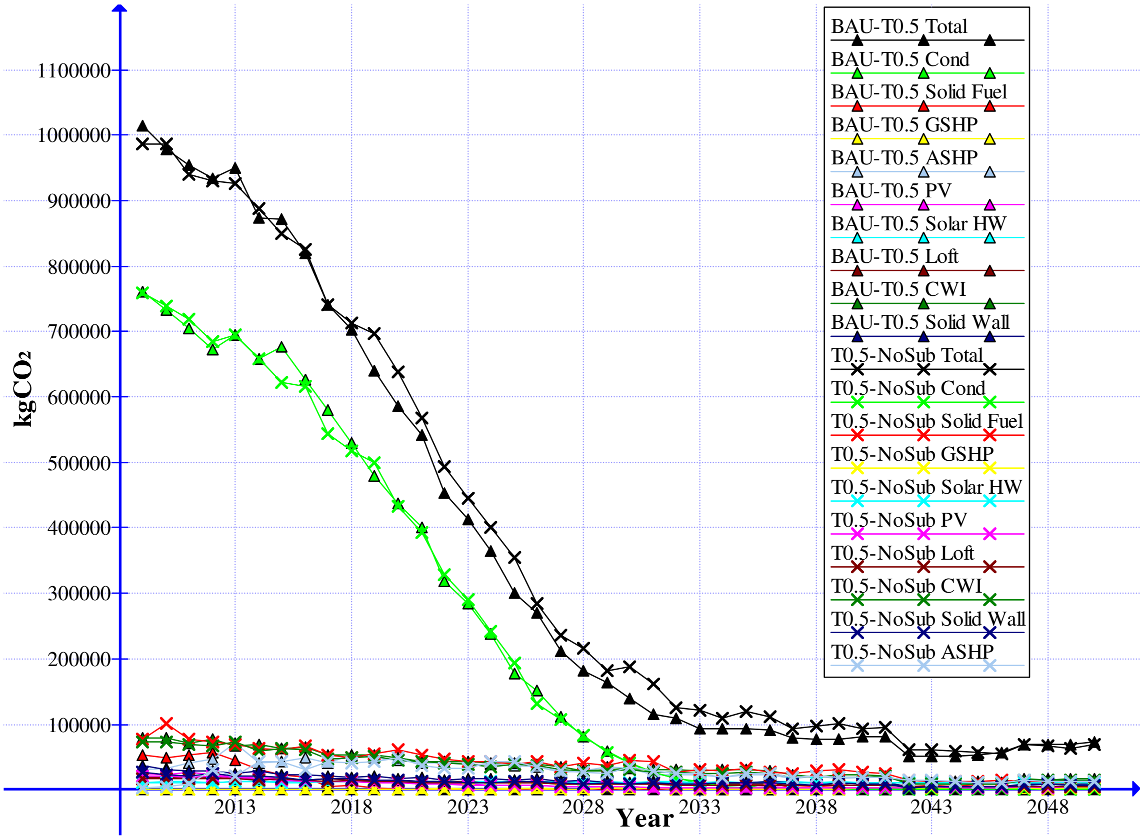
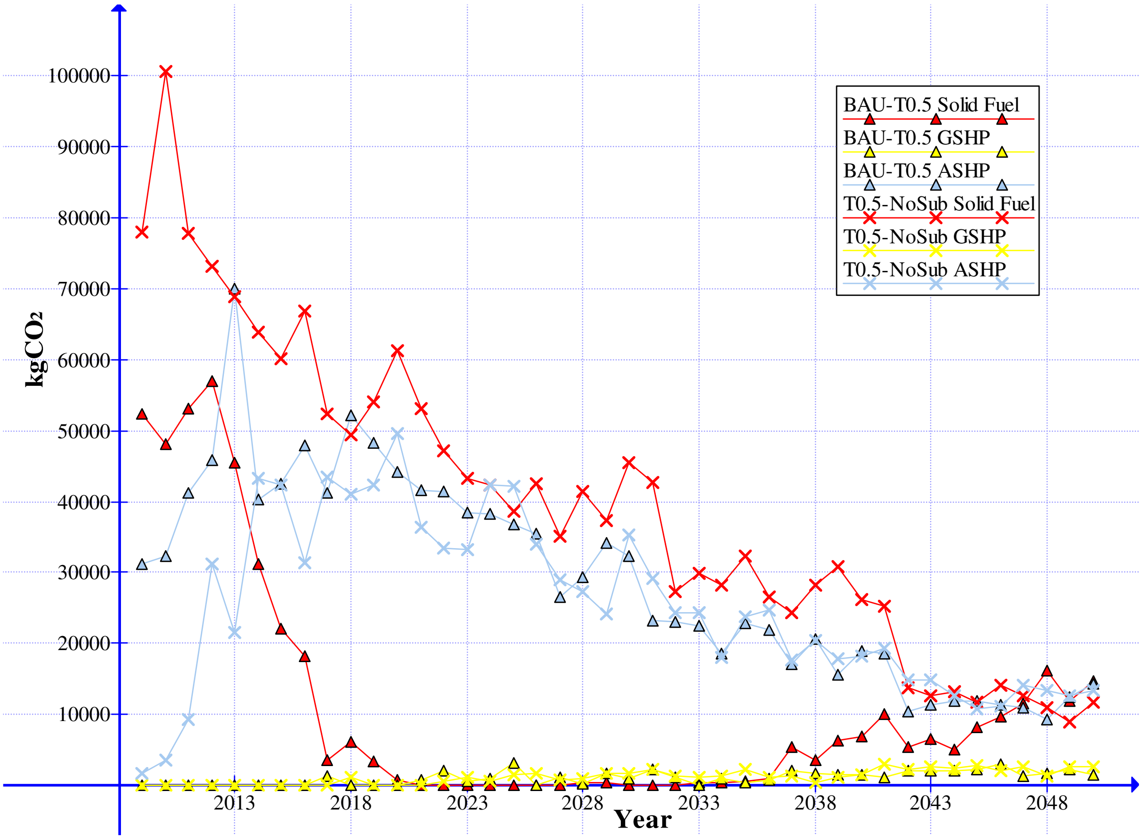


Figure 6-44 CO_2 Saving by Technology for BAU-T0.5 and BAU-T0.5-NoSub (heat pumps and solid fuel)



In Figure 6-40, Figure 6-42 and Figure 6-44, just the savings from the heating technologies are shown, as that is where the change appears to be happening with the non-subsidised scenarios. It can be generally be seen that the solid fuel heating contributes significantly larger savings in the non-subsidised scenarios. This therefore strongly suggests that current subsidy rates, as tested in the BAU scenarios, can be ineffective in increasing emission reductions, due to encouraging the uptake of non-optimal technologies.

6.3.8 Energy Demand by Fuel Type

One final set of data that is included in the model is concerned with energy demand by fuel type. Some of the model runs see a significant uptake of heat pumps and a corresponding move away from gas fired heating. Whilst the raw data on energy demand is not directly related to the CO_2 reduction targets, it is still important data for long term energy planners, when it comes to energy security and planning how the energy demand will be satisfied.

Table 6-5 presents the initial energy demand by fuel type for the total model population, and then the final energy demand by fuel type for two scenarios, BAU-T0.2 and BAU-2I-T0.2-5C; the second of these has one of the highest adoption levels of heat pumps and so will exhibit the greatest change in mains electricity demand.

Table 6-5 Energy demand by fuel type

Scenario/Year	Electricity Heat (MWh/yr)	Electricity Non-heat (MWh/yr)	Gas (MWh/yr)	Solid fuel (MWh/yr)	Oil/LPG (MWh/yr)	Community (MWh/yr)
2008	9,100	4,400	196,300	3,500	16,600	300
BAU-T0.2 2050	15,200	-100	104,900	10,500	6,500	2,000
2I-T0.2-5C 2050	16,600	-900	45,200	5,400	2,700	1,500

As can be seen, there are significant implications for grid electricity supply. The estimated installations of PV essentially match the ancillary electricity demand (pumps etc.) although there is likely to be a time mis-match. PV will provide most of its energy during the day in the summer, whereas much of the heating related energy demand will be in the winter evenings and nights.

As well as the implications for grid electricity supply these results have implications for fuel suppliers more generally, as significant drop offs are observed in the demand for both mains gas and oil and LPG for non-gas-grid dwellings.

6.4 Chapter summary

In this chapter an initial business as usual (BAU) scenario has been developed, which is intended to be an estimate of a simple continuation of current policies. This predicts an emissions reduction from 1990-2050 of 54.44% which is considerably short of the 80% target.

Further scenarios were then developed that consisted of variations on the initial BAU scenario. Only those scenarios that assumed higher external temperature increases achieved reductions in excess of 70%. It was also found that after the initial reductions shown in BAU larger scale savings relied to a large extent on grid decarbonisation and a related move away from gas to electric (heat pump) heating.

Scenarios were also run without any subsidies, in order to attempt to determine their cost effectiveness. However, when doing this it was found that overall the subsidy free scenarios achieved a marginal, but statistically significant, larger reduction. By careful analysis of the adoption rates of the individual technologies it was determined that this was due to a complex interaction between building elements. Specifically, without subsidies insulation installations were reduced allowing for potentially greater savings from the installation of innovative heating systems. Therefore care is needed by policy makers when setting subsidies and incentives to avoid such unexpected consequences.

The following chapter concludes this research and presents the conclusions and recommendations.

Chapter 7 Conclusions & Recommendations

7.1 Introduction

As stated in chapter 1, the principal aim of this research was to:

> Develop a new long term domestic energy stock model capable of simulating individual households' decision making processes

In order to be able to do this the following subsidiary objectives had to be met:

- Carry out a comprehensive literature review
- Identify shortcomings in existing domestic energy models
- Identify suitable methods to address the identified shortcomings
- Produce a domestic energy model using new modelling methods and techniques
- Test the new long term domestic energy stock model
- Carry out policy and scenario analyses with the new model

The following sections provide the resulting conclusions as well as recommendations for future work.

7.2 Conclusions

This research has focussed on long term domestic stock models, and their use for modelling future scenarios to find suitable pathways to achieve the 2050 80% CO_2 emissions reduction target.

The model developed incorporates a simulation of the technology buying behaviour of individual households, which is a feature that has been missing from previous stock models. The outputs do suggest that it is technically possible, as out of the sixteen main scenarios analysed one (BAU-2I-T0.5-5C) achieved over 79%, two more over 74%

and a fourth over 70%. With the addition of some behavioural change it was possible to increase the reduction for the most favourable scenario up to 81.51%. Previous models have also indicated that it is technically possible (eg: the Home Truths report (Boardman, 2007a)).

It can also be seen from the technology penetration levels observed in the scenario runs that still higher reductions are technically possible. However, they also indicate there is a significant variation between the technically possible and what is realistically feasible (a complete stock transformation using the technologies available in the model would lead to a 95% reduction). External temperature changes have a significant impact and none of the lower temperature scenarios achieved reductions over 70%, although the external temperature changes were applied in a simplified manner. Whilst larger external temperature rises will help in achieving larger emissions reductions in this country, if they were reproduced globally they would be likely to have more significant and negative impacts in many other countries (Parry et al., 2007). In addition, there could be a greater take up of air conditioning, which would reduce savings, and the model does not explicitly capture uptake of such systems. It can therefore be anticipated that there will be a need for policy makers to monitor temperature changes, as higher temperature increases may mean more global issues to deal with, whilst lower temperature increases will need larger interventions, if the domestic sector is to achieve the desired emissions reductions.

If there is a combination of both low temperature increases and no grid decarbonisation the scenarios presented in this research fail to achieve reductions over 53%, which is a long way short of the 80% target, and would therefore put extra pressure on other sectors to make extra reductions to make up for a shortfall in the domestic sector. In contrast, since it is known that reductions greater than 80% are technically possible in the domestic sector, then there could be pressure applied from other sectors, where there might be less technological capability readily available to achieve such large scale reductions.

In all the scenarios, the initial reductions come from a move to condensing boilers, however subsequent reductions in the more promising scenarios are mainly led by moves away from gas heating, predominantly to electrically powered heat pumps. Therefore, it can be seen that the adoption of heat pumps will greatly increase demand on the grid electricity supply, and it is possible for policy makers to use the model to run scenarios to estimate the increased demand for grid electricity.

As well as the increased demand for electricity, the scenario runs also show a significant increase in domestic generation from the installation of PV systems. This extra electricity supply will obviously be of use in the grid system. However, there may be issues over the resilience of the local grid system if large amounts of electricity are being fed back in at the sub-station level. There will therefore be a need to verify the ability of local grids to successfully deal with large variations in both supply and demand. A further consideration with the combination of PV and heat pumps is that they do not match well time-wise. PV systems produce electricity during the day (ie: they are dependent on sunlight), whereas heat pump demand is highest in winter evenings and nights when PV systems will not be supplying any electricity. Over the course of a single day, it can be anticipated that there will be much larger changes in electricity demand with a complex combination of PV supply and heat pump demand occurring at different times of the day. There would therefore appear to be a place for electricity storage, if sufficiently efficient and robust methods can be developed and deployed.

The scenarios tested in the previous chapter included a consideration of a carbon tax across all fuel types on a p/kgCO_2 basis. This would appear to be a potentially useful extra policy measure to encourage greater uptake of energy efficient technologies. Depending on scenario, the addition of the tax, at the level chosen here, could increase the reduction achieved by almost ten percentage points. Whilst hypothecation of taxes is generally not favoured in the UK (Seely, 2011) it has been considered non-governmentally for green taxes (Green Fiscal Commission, 2009). It can be expected that an extra tax would not be popular, and there could also be concerns about the potential for increasing fuel poverty. However it may be that a hypothecation pledge and the use of the revenues raised to enhance subsidy levels may make a tax more acceptable, and if the subsidy levels were increased could make them more effective; however, this would clearly be a matter for politicians.

Another important outcome from this research relates to the impact of subsidy levels when there are competing technologies. In the case of the insulation technologies there is no particular competition between them as they serve different purposes. However, in the case of the heating and hot water systems a dwelling essentially needs one system to satisfy this need, and therefore different technologies will be competing for market share. In this model three low carbon heating systems were available, ground and air source heat pumps and solid fuel (biomass) boilers. The model further expects all three of these technologies to be eligible for subsidies and with the estimated subsidy levels used, the installations of solid fuel boilers were suppressed in favour of the heat pumps, and principally air source heat pumps. From a carbon reduction perspective, the popularity of these three should be reversed as biomass has the greatest potential for carbon reduction, then GSHPs and then ASHPs; although the model suggested that heat pumps are more effective on a £/kgCO_2 basis. Furthermore, if grid decarbonisation is not achieved then the carbon savings attributable to heat pumps are greatly reduced as they rely on grid electricity. Scenarios BAU-2I-T0.2-5C and BAU-2I-0DE-T0.2-5C have the highest uptakes of heat pumps, and in the decarbonised version heat pumps provide 54% more CO_2 savings than in the non-decarbonised version. This difference is even more marked when considering the period after 2030 (ie: once the grid decarbonisation has been completed) where the heat pumps in the decarbonised scenario provide over twice as much of a saving as in the non-decarbonised version.

7.3 Recommendations for further work

As would be expected with a complex forecasting model there is a number of limitations, which typically lead to recommendations for future work. In this case these can generally be divided into dwelling stock limitations and householder agent limitations.

The model is currently limited to owner-occupied dwellings in England, as sampled in the English Housing Survey for 2008. Therefore the natural next step would be to extend the model to the entire housing sector. The English Housing Survey (CLG, 2010) does include both socially and privately rented stock, so the physical data required should be relatively straightforward to collect. Rather more work will be required for the agent element in this case. It would seem sensible to maintain a distinction between private and social renting during data collection at this stage. With the social stock, the social landlords are typically governmental, or quasi-governmental, bodies with several thousand dwellings under their control. Given this size of organisation and the level of governmental control, it would seem reasonable to expect similar decision making by the different landlords in the sector. Although it would clearly be down to the individual researchers designing this research, it would seem that some form of focus group consisting of the appropriate professional from a number of social landlords could be a promising avenue for data gathering to understand the energy efficiency improvement decision making process in the social landlord sector.

As discussed in Chapter 4, there is rather more variation amongst private landlords. The private landlord ranges from individuals who let out a single property to large companies employing teams of professionals to manage their portfolios. Further consideration would therefore need to be given to the appropriate method for data collection in this sector of the market. It might be the case that different methods are required at different ends of the market. For instance, focus groups or interviews may be more appropriate for the large landlords with employed professionals and stock management programmes in place; but for the individual landlord it may be that developing a discrete choice survey may be the more appropriate method to use.

If these methods can be developed and applied to the English housing stock, it can then be extended to cover the rest of the United Kingdom. Similar techniques can also be used to provide input data to use the model in other jurisdictions. Alternatively the model could be reduced in scale and used regionally, this may be of particular benefit to the utility companies in being able to understand likely changes in energy demand at a lower than national level, which may help to identify potential weak spots in the infrastructure that might be missed with a higher level analysis.

The model is set up with nine available heating systems, and there were assumptions made as to their availability for different dwellings, as described in chapter 5. In particular it was assumed that dwellings that start the model without a gas heating system are assumed to be off the mains gas supply, and therefore can not have a gas system. There were then further assumptions, eg: space limitations impacting on the availability of solid fuel systems and ground source heat pumps. These were blanket assumptions as some restrictions had to be made as there will be practical limitations in many real world cases, but for which there is not the data available to be able to accurately determine the exact number of dwellings which should be subject to such restrictions. There is therefore the potential to increase the model by providing extra resolution where these simplifications and assumptions have been made.

The next limitation concerns the renewable technologies. As discussed, in the model construction section, certain technologies were excluded, as they are only applicable in a limited number of sites. Nevertheless both solar PV and solar hot water have been included, and it has been assumed that they can both be used in any dwelling that has a roof. Some real dwellings will not have sufficient roof space for both, although it is possible to install these technologies at ground level, although a ground level installation is likely to suffer from greater overshadowing, which will reduce performance. Furthermore, in the real world roofs have different orientations that will impact on their performance, therefore roofs were uniformly assumed to be oriented 45° from optimum (ie: facing south-east or south-west) to attempt to produce an average performance. This limitation is similar to general SAP limitations of using standardised occupancy and performance values, and increased model resolution would allow for a consideration of differently performing solar systems.

Since the introduction of SAP2009 (BRE, 2011a), it has included geographically based temperature data for the different regions. However, to limit the number of dwelling types, this model has simply taken the temperature figures for the Midlands, as a suitable average region, and applied them to the whole of England. Again, increased model resolution would allow for a more complete representation of the dwelling stock, and would also make lower level regional analysis possible.

As the model is currently constructed it is only considering changes that impact on heating and hot water and electricity generation in the home. Whilst heating and hot water currently make up around 80% of domestic demand, if large scale reductions are achieved due to insulation and more efficient technology, then the proportion of energy demand attributable to appliances will increase. Therefore there is the potential to begin to incorporate appliance usage into the model to make it fully comprehensive of energy use in the home. Currently the model produces data with an annual resolution, with the anticipated shift to grid electricity powered heating systems, and the anticipated uptake in domestic electricity generation, there is likely to be more variation in short term electricity demand. Therefore there could be benefits to be had from incorporating load profiling data into the model's householder agents in order to simulate their electricity use. Whilst it would be possible to operate the model in such a way as to provide load estimates perhaps at half hourly resolution, it would significantly increase the computer workload thus drastically increasing the time to carry out a scenario run and also greatly increasing the levels of output data. As a result, an alternative approach might be to allow the model to create the extra resolution for maybe one day per season in particular years of interest. The model would therefore be able to give outputs at both an annual level and also over short time periods, if combined with a regional approach this could provide very useful information for planners in managing the electricity grid system, by having an estimate of the likely ranges of supply and demand many years in advance.

Principally, the agents' decision making is essentially based on discrete choice surveys conducted in 2008, with some rebalancing based on real world decisions in the period from 1996-2008 taken from the English Housing Survey data (CLG, 2011c). It can be anticipated that over the course of the period up to 2050 attitudes will change, and therefore the weights ascribed in the decision making algorithm will be altered. The model does allow for a variation in the population of agents, but does not include an assessment of the likely rate of change in the householder agents. In particular the model does not include the impact of past experience. If a householder had a heat pump in a previous dwelling, this could make them more favourable (or less if they had problems with it) towards using an innovative system in the future. Since there is a limited number of renewable technologies currently installed it will take time for sufficient data to become available to be able to include the impact of experience on the decision making process.

A similar limitation applies to the impact of friends and neighbours, as discussed in Chapter 4. The available data provides estimated impacts on willingness to pay for the effect of a recommendation from a friend, a plumber, and both. The model is not accurately representing this, and assumes that an individual householder agent's network of friends consists of its immediate neighbours and that the more of them with a particular technology the larger the impact will be on the decision making process.

There is therefore an argument for longitudinal studies to update the behavioural elements of the model, and to use newly available data to regularly recalibrate the model, and to use more technologies in the calibration process as further data become available. The English Housing Survey, and similar data sets in the other parts of the United Kingdom, already provide this for the dwelling stock, so it is the decision making that can be improved over time. To some extent changes to the housing stock over time will provide revealed preference data with which to keep recalibrating the decision making data, but over the years, if energy efficiency technologies become more established as a social norm, then there is an argument for periodically updating the discrete choice survey data, as a higher resolution of information can be achieved in this manner. In conjunction with this, further behavioural research could improve the simulation of the decision making process, in particular in quantifying the impact of previous experience of a technology and a more complete analysis of the network impact from technology recommendations.

As discussed in Chapter 6 – the Results chapter – by 2050 there may be countable numbers of fixed air conditioning systems being installed in the dwelling stock. The decision making process is essentially an economically based algorithm carrying out calculations on the savings that can be achieved. However, the installation of a cooling system leads to an increase in costs, although it should be leading to an increase in thermal comfort, and as such the model can not simulate the decision making involved in the purchase and installation of such equipment. Although, as discussed, the SAP data includes an estimate of the annual energy demand to power such systems should they be installed, so that their impact can be predicted for different assumed uptake rates. The model could therefore be improved by a more complete inclusion of cooling systems, together with a way to simulate the decision making involved in their purchase.

In a similar way to the issue of air conditioning installations, the model assumes energy demand will average out according to SAP's standardised usage profiles, and that therefore savings will accumulate as per SAP's assessment of energy demand. However, it can be anticipated that there will be some element of increasing energy efficiency contributing to improved thermal comfort – ie: people using new heating systems more so that they have a mix of thermal comfort gain, as well as their economic gain from the reduced running costs. This factor is generally referred to as the rebound effect, and it is difficult to quantify its extent with estimates ranging from 0-100% (Sorrell et al., 2009). With such levels of uncertainty as to the extent of its impact, it is clearly beyond the scope of this research to attempt to identify a suitable value; instead it just needs to be remembered as a caveat that some proportion of potential savings may be lost to comfort gains. Again, this is an argument for including a range of usage profiles in the model to provide some simulation of changing day to day behaviour in different thermal environments.

In the model it is also assumed that all agents are aware of all the technologies available to them, and are basing their decision making on the estimated savings each technology can provide. Up until now, it is reasonably safe to assume that this has not been the case and that the majority of households have not had sufficient knowledge to be able to consider all the potential technologies they could use to satisfy their energy needs. However, it is possible that the UK is approaching a situation where something closer to such a theoretical perfect knowledge environment exists via Green Deal Assessments (BRE, 2013b). Under the Green Deal, an accredited assessor will carry out an RdSAP based assessment of a dwelling and produce a recommendations report, using an occupancy assessment so that the estimate usage is more closely related to that particular household, as opposed to the standard occupancy profile in SAP. This report lists the available recommendations, together with an indicative cost range, and estimated annual savings on energy bills – ie: broadly similar data to that used to drive the decision making algorithm in the model. However, it is not yet known how common these will be as the Green Deal Assessment Reports only began to be available from January 2013 (EST, 2013).

A similar limitation applies to the source of funding. Some householders will be able to fund improvements from savings; others may not be so fortunate and will therefore need to rely on Green Deal finance, or similar. The EST data (Skelton et al., 2009) included some element of varying impacts from different sources but did not include sufficient resolution to be able to be included in the model. Therefore the model could be further improved by a greater understanding of the technological awareness of households and their differing attitudes to various financing and funding schemes.

7.4 Concluding Remarks

This research identified short comings in existing domestic energy stock models when it comes to the decision making of individual households in carrying out energy efficiency improvements to their homes. A way forward to deal with this limitation was identified, and a new model has been developed using agents to simulate individuals.

Initial results indicated that the 80% emissions reduction target by 2050 is unlikely to be met under current policies, therefore more work will be required by policy makers to achieve the 80% target. The results also indicated that, due to the complex interaction between different building elements, current subsidy levels are counterproductive, and therefore policy makers need to carry out further analysis to determine alternative sets of policy interventions.

There is now the opportunity for the model to begin to be used by relevant parties, and there is also the potential for researchers to develop the model further.

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Appendix A
Agent Home Owner Model of Energy (AHOME) User Manual

A.1 Introduction

The Agent Home Owner Model of Energy (AHOME) is a novel agent based domestic energy stock model that allows users to input various scenarios to test potential pathways to 2050, or any other desired data.

AHOME models the owner-occupied dwelling stock for England from a starting year of 2008.

A.2 Installation

AHOME was written in version 4.1.3 of NetLogo (Wilensky, 1999).

NetLogo is available for free download from
http://ccl.northwestern.edu/netlogo/download.shtml

Please ensure that you download version 4.1.3, there may be errors if a different version is used. Please also note that NetLogo is available cross platform and can be run in Windows, Mac OS X and Linux.

Once you have downloaded NetLogo for your operating system please run the downloaded installation file(s), to install NetLogo on your computer.

AHOME calls on a number of data files during operation, and these should all be in the same directory. It is therefore recommended that you create a directory for AHOME which needs to contain the following files:

ahome1.nlogo [This is the main AHOME programme file]
refhouses0.txt . . . refhouses40.txt [These are the data files for the potential dwelling

stock]

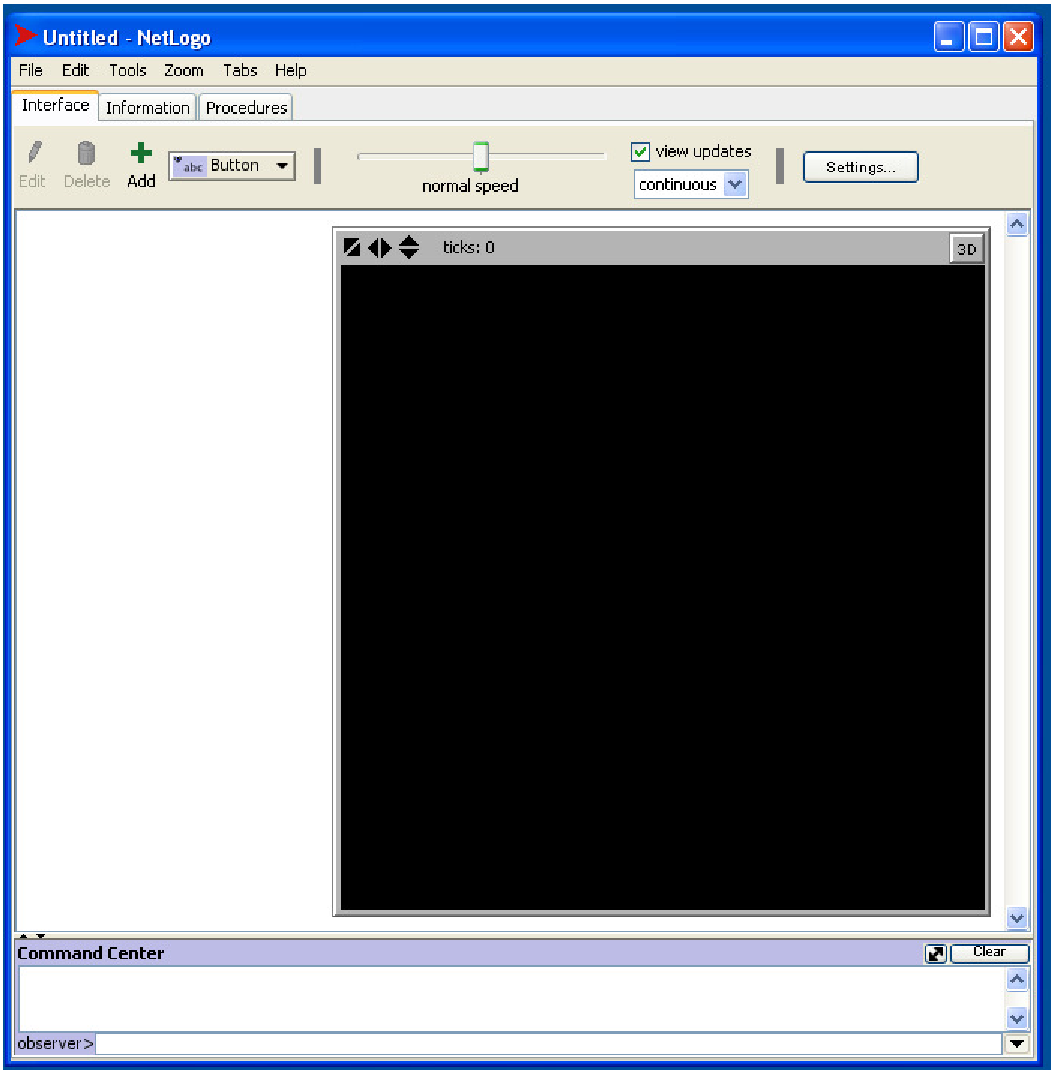
ownerstartwithcool.txt [This is the data file for the initial dwelling stock]

Once this has been done the model will be ready for use.

A.3 Starting AHOME

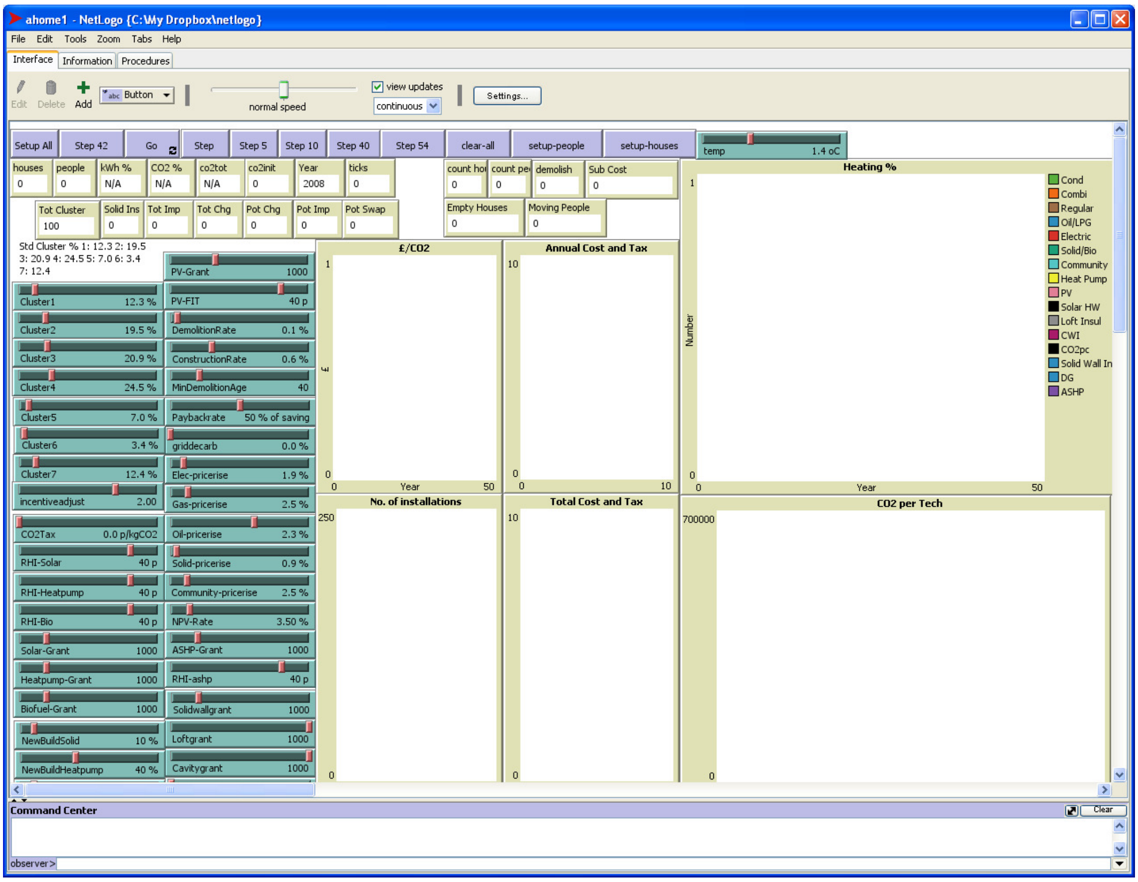
When you first start NetLogo you will be presented with an empty modelling space, as shown in Figure A-0-1:

Figure A-0-1 NetLogo start screen



By going to the file menu, in the top left of the screen, AHOME can be opened in the normal way by opening the file ahome1.nlogo the screen will then change to:

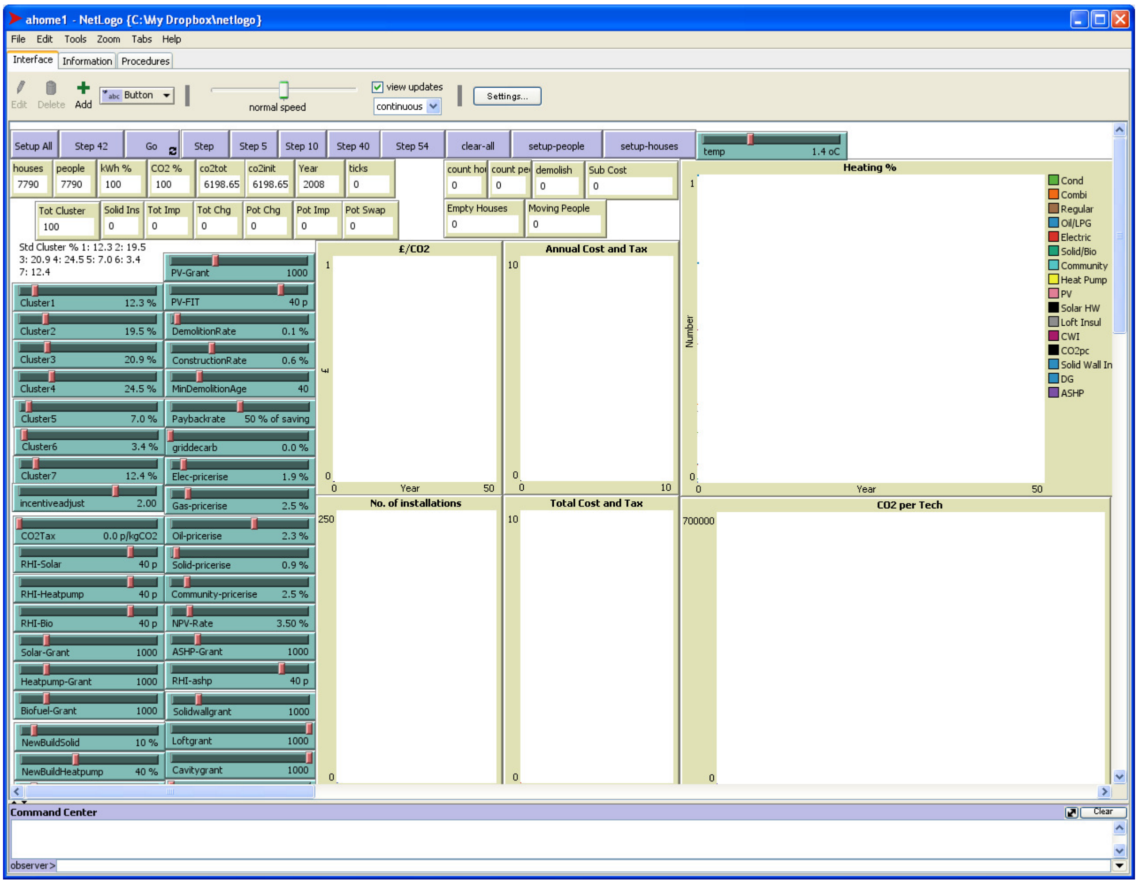
Figure A-0-2 AHOME initial display



A text only version of this user manual is now available on the Information tab at the top of the page, the Procedures tab displays the source code, and the Interface tab is the default display, as shown in Figure A-0-2.

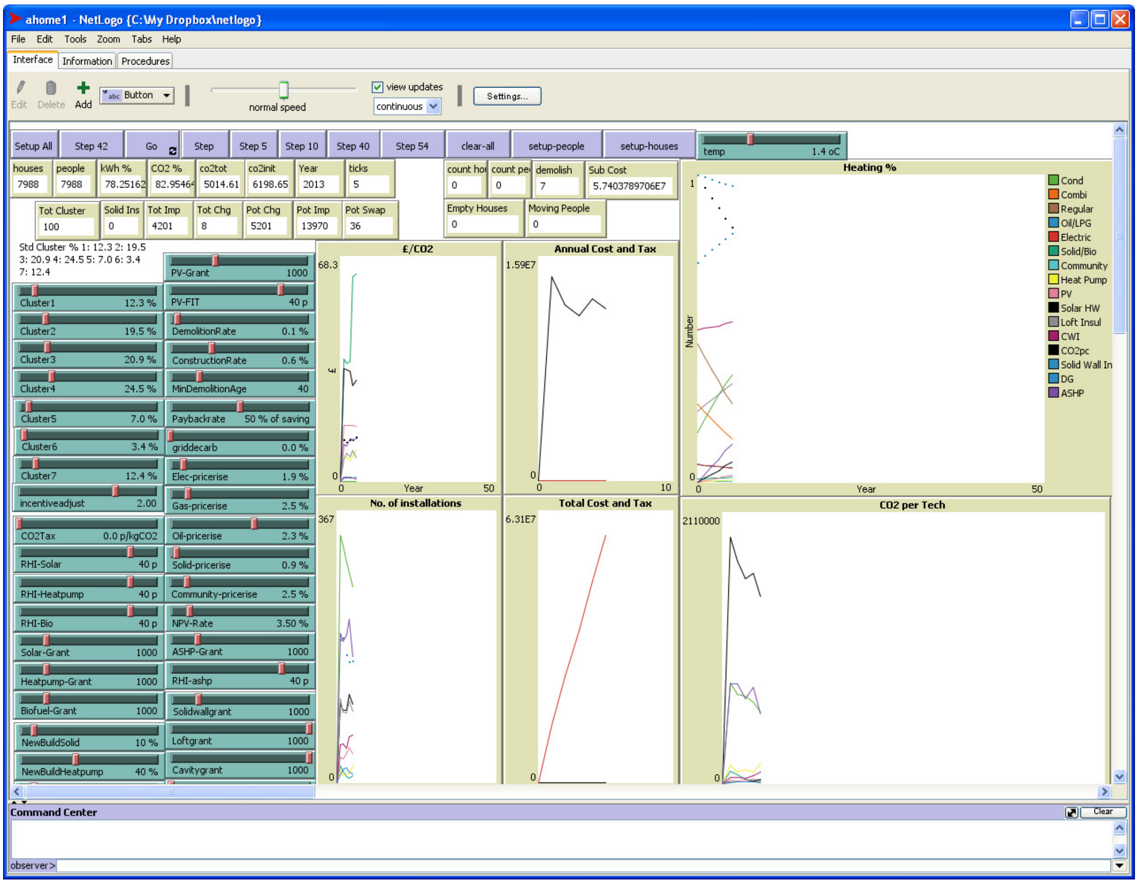
The white boxes to the right will display graphs of data as the model is being run. Down the left hand side there are slider controls that allow the user to vary the population, energy prices, subsidies, etc. There are then buttons along the top that control the running of the model, 'Go' will make the model keep going forever (or until stopped), 'Step' advances the model through one year, 'Step 5' through 5 years, etc. Underneath these buttons are monitors displaying certain data, it can be seen that when first loaded there are no people and no houses; the 'Setup All' button needs to be pressed to generate the initial dwelling stock and householders, these values will then change, as in Figure A-0-3:

Figure A-0-3 AHOME after 'Setup All'



The following figure shows the display after the 'Step 5' button has been used – ie the model has been progressed five years.

Figure A-0-4 AHOME after 'Step 5'



Due to the complexity of the programme it is recommended that the maximum speed setting of NetLogo is chosen, to do this simply uncheck the 'view updates' tick box. Depending on your computer a full model run to 2050 will take some time, by way of indication on an Intel i5 processor a run takes approximately 45 minutes.

It is therefore possible to set all the sliders at the start and run the model for the full 42 years. Or alternatively, you can set sliders and then use the 'Step' 'Step 5' and 'Step 10' buttons to allow greater intervention, eg: changing a subsidy level every year, or every 5 years, etc. It is possible to adjust the sliders during a run but the program takes a while to respond, so whilst using 'Step 42' adjustments can be made this technique should only be used to check that there is some sort of effect. Accurate measurements should then be made be re-running the model and making changes only on a Step or Step 5 type basis.

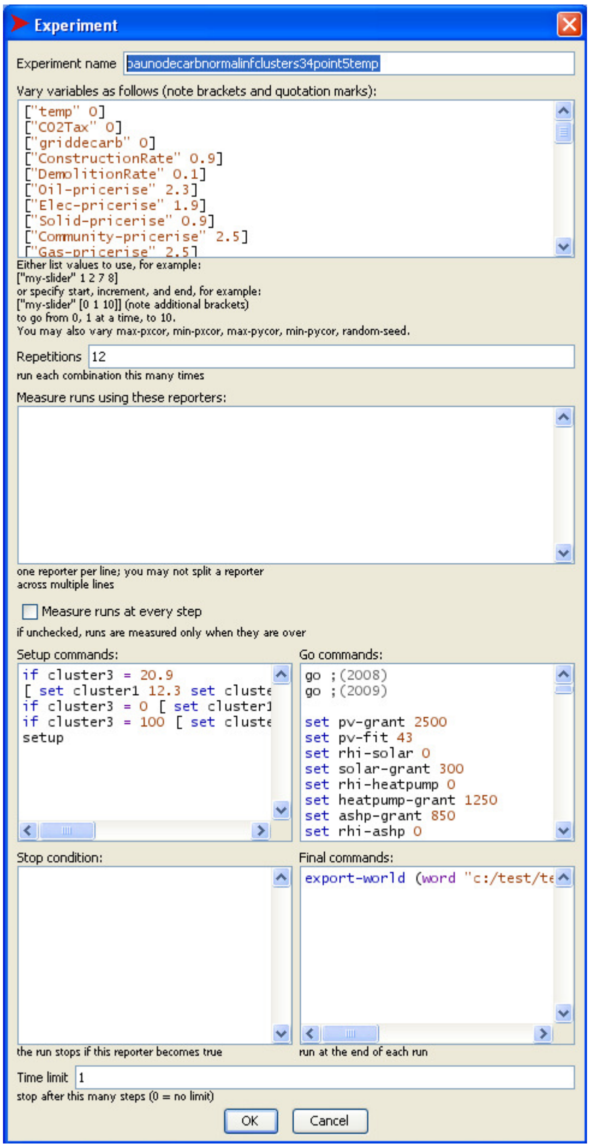
As well as the final output on the screen it is possible to use File and Export to produce csv files of most of the model data, allowing for subsequent more detailed analysis.

A.4 Automation with BehaviorSpace

Running a model with manual interventions, using the method described in the previous section will be very labour intensive, particularly when repeated runs are required. However, this workload can be reduced by automating the process. To do this NetLogo provides a feature called BehaviorSpace, which is found under the Tools menu.

BehaviorSpace also allows for optimised usage of a processor. For instance an Intel i5 processor has two cores, and can run two threads per core. Therefore BehaviorSpace can run four simulations on an i5 simultaneously, thus greatly reducing the time involved when carrying out repeated runs. The BehaviorSpace interface is shown in Figure A-0-5

Figure A-0-5 BehaviorSpace



As it suggests the top entry gives a name to the experiment. The second sets the initial values of all the variables. If two different values are given for an entry then the model will run the desired number of times with each option; the repetitions box sets this number. In the particular run in this screen grab three different values for cluster3 had been set in the 'Vary variables' input box; 'Setup commands' has then been used to control further changes based on those three options (ie: different populations in each of the seven householder clusters). 'Go commands' is here used to advance the model one year at a time and then change variables (subsidies, construction rates etc.), as desired for the particular scenario being studied. 'Stop condition' could be used to halt a run early (eg: if a particular technology achieved a desired penetration level). The 'Final commands' box is here used to export the data from each run to .csv files for subsequent analysis. Finally, 'Time limit' sets how many times the model will cycle through the 'Go commands' for each simulation run.

A.5 NetLogo Resources

NetLogo User Manual: http://ccl.northwestern.edu/netlogo/faq.html

NetLogo Users' Group: http://groups.yahoo.com/group/netlogo-users/

Appendix B Source Code

```
; SET UP THE WORLD
breed [houses house] ; declares houses as a type of agent
breed [people person] ; declares people as a type of agent
breed [refhouses refhouse] ; declares the reference houses as a type of agent

houses-own
[ idnumber ageband detach glazing wall roof heat hw pv heatkwh hkwh wkwh
electrickwh ckwh solidins upgradetime boiler-life runningcost nsolid solidwall
newowner npv ncwi ncond nsolidinsul emissions empty age difference differenceheat
differencewater saving savingelec save1 save6 save7 save8 save9 save1a save6a
save7a save8a save9a priceconst pricex pricex2 none adjustedprice repayconst repayx
subnpv8old subnpv9old repayx2 repayx3 repay nroof nhw  elec1 elec6 elec7 elec8
elec9 heat1 heat6 heat7 heat8 heat9 h1 h6 h7 h8 h9 w1 w6 w7 w8 w9 diff1 diff6 diff7
diff8 sav1 sav6 sav7 sav8 sav9 savpv savcwi savloft savwall savshw subgrant1
subgrant6 subgrant8 subgrant9 subgrantpv subgrantcwi subgrantloft subgrantwall
subgrantshw n1 n4 n5 n6 n7 n8 n9 adjust1 adjust4 adjust5 adjust6 adjust7 adjust8
adjust9 heatgshp heatashp demolishpotential demolished new id1 id2 id3 id4 id5 id6
id7 repay1 repay2 repay3 repay4 repay5 repay6 repay7 repay8 repay9 improved
changed oldidnumber heatold repayment repayment1 repayment4 repayment5
repayment6 repayment7 repayment8 repayment9 heattax electax heattaxpotloft
electaxpotloft heattaxpotcwi electaxpotcwi heattaxpotwall electaxpotwall heattaxpot1
electaxpot1 heattaxpot6 electaxpot6 heattaxpot7 electaxpot7 heattaxpot8
electaxpot8 heattaxpot9 electaxpot9 heataxpotpv electaxpotpv heattaxpotshw
electaxpotshw subnpv1 subnpv6 subnpv8 subnpv9 subnpvpv subnpvcwi subnpvloft
subnpvwall subnpvshw return6 return8 return9 returnpv pvoutput returnshw
shwoutput loftoutput hrf runningcost5 runningcostpot8 runningcostpot9
runningcostpot6 runningcostpot1 runningcostpot7 oldidlist lookupref lookupcwi
lookuproof lookuphw lookuppv lookupsolid lookupdg loanincent fuelstore garden
cupboard primfriend primsav primmain discfriend discsav discmain lhs1 lhs4 lhs5 lhs6
lhs7 lhs8 lhs9 settemp]
; lists attributes of houses

refhouses-own
[ idnumber ageband detach glazing wall roof heat hw pv heatkwh hkwh wkwh
electrickwh ckwh solidins upgradetime boiler-life newowner npv ncwi ncond
nsolidinsul emissions empty age lookupref]
; lists attributes of reference houses

people-own
[ econ environ indif searchtime moving age npv ncwi ncond nsolidinsul cluster accept
priceconst pricex pricex2 pricex3 none repayconst repayx repayx2 repayx3 instpv
instshw instloft instcwi instwall inst6 inst7 inst8 inst9 newperson loanincent fuelstore
garden cupboard primfriend primsav primmain discfriend discsav discmain]
```

; lists attributes of people newperson = 1 if hatched this tick

globals
[gas-price gas-standing gas-co2 oil-price oil-standing oil-co2 elec-peak-price elec-off-price elec-off-standing elec-co2 solidwalldet solidwallsemi solidwallflat solid-price solid-co2 community-price community-standing community-co2 elec elec-sold gas insul boiler solidinsul photo x a b c y z solidx techinf neigh co2 co2init cumco2 rand empty-houses-list moving-people-list totalkwh idref totalheatkwh totalelectrickwh totalcoolkwh totalkwhinit elecfixed elecmain oilfixed oilmain biomass biomassmain condensfixed condensmain pvfixed pvmarg pvmain years solarfixed solarmarg solarmain gshpfixed gshpmarg gshpmain gshptest ashpfixed ashpmarg ashpmain co21 co22 co23 co24 co25 co26 co27 co28 co29 co2tot commfixed commmain construct potchange potimprov potswap demolish demolish-list demolish-potential-list demolishedcount demolishsurplus det1 det2 det3 heating1 heating4 heating5 heating6 heating7 heating8 heating9 improvements changes roof0 roof1 hw1 hw2 pv1 pv2 idref1 idref6 idref7 idref8 idref9 idcool solidprice subsidycost totalcostperco2 rhisolarcost rhiheatpumpcost rhibiocost solargrantcost heatpumpgrantcost biofuelgrantcost pvfitcost pvgrantcost cwicost loftcost solidwallcost co2totold saving1 saving6 saving8 saving9 savingpv savingcwi savingloft savingwall savingshw dgtot dgold cost1 cost6 cost8 cost9 costpv costcwi costloft costwall costshw totalcost totalsav revenue revenuetot costpersav1 costpersav6 costpersav8 costpersav9 costpersavpv costpersavcwi costpersavloft costpersavwall costpersavshw heattaxtot electaxtot clust1pv clust1shw clust1loft clust1cwi clust1wall clust16 clust18 clust2pv clust2shw clust2loft clust2cwi clust2wall clust26 clust28 clust3pv clust3shw clust3loft clust3cwi clust3wall clust36 clust38 clust4pv clust4shw clust4loft clust4cwi clust4wall clust46 clust48 clust5pv clust5shw clust5loft clust5cwi clust5wall clust56 clust58 clust6pv clust6shw clust6loft clust6cwi clust6wall clust66 clust68 clust7pv clust7shw clust7loft clust7cwi clust7wall clust76 clust78 clust17 clust27 clust37 clust47 clust57 clust67 clust77 clust1 clust2 clust3 clust4 clust5 clust6 clust7 clust19 clust29 clust39 clust49 clust59 clust69 clust79 recinf tempset refsource]
; list of variables used

; age codes 1 pre 45, 2 45-64, 3 65-90, 4 90+
; detach codes 1 detach 2 midsemi 3 flat
; glazing 1 dg 2 part
; wall 1 solid 2 cavity 3 filled cavity
; roof 0 no roof, 1 U 0.16, 2 U 0.29, 3 U 0.68
; heat 1 cond 2 combi 3 regular 4 oil/lpg 5 electric 6
; solid 7 community 8 ground source heat pump
; (gshp) 9 air source heat pump (ashp),
; hw and pv 1 yes 2 no idnumber concatenation of above
; solidwall: 0 not solid, 1 solid

```
to setup

  clear-all ; clears data from any previous runs
  setup-refhouses  setup-houses setup-people  setup-prices  do-plots
   ; sets up world and year 0 plots taken

end




to setup-houses

   set-default-shape houses "house"
   file-open "ownerstartwithcool.txt"
   create-houses 7790
       [   set empty 1 set idnumber file-read set ageband file-read set detach file-read set
glazing file-read set wall file-read set roof file-read set heat file-read set hw file-read
set pv file-read set hkwh file-read set wkwh file-read set electrickwh file-read set ckwh
file-read set boiler-life random-normal 15 5 set upgradetime random boiler-life set
settemp temp]    file-close
; creates 7790 houses based on 781 unique types
   ask houses
     [ set oldidlist [] set heatkwh hkwh + wkwh
       ifelse ageband = 1
       [ set age 64 + random 137 set color red ]
       [ ifelse ageband = 2
         [ set age 44 + random 19 set color orange ]
         [  ifelse ageband = 3
           [set age 18 + random 25 set color yellow ]
           [set age random 25 set color blue  ]
         ]
        ]
      ]
   ; assigns ages based on the four age bands up to a maximum age of 200

   ask houses [ while [ any? other houses-here ] [  rt random-float 360 jump random-
float 4 move-to patch-here ] ]
; moves houses so only one per square and then centres them on their patch
   ask houses [ if wall = 1 and ageband < 4 [ set solidwall 1 ] ]
; highlights solidwall dwelling - ageband 4 and wall = 1 timber frame
   ask houses
    [ if heat = 5
      [ if detach = 1
        [ if ageband = 1 [ set hrf 0.04 ]
          if ageband = 2 or ageband = 3 [ set hrf 0.26 ]
```

```
          if ageband = 4 [ set hrf 0.12]
        ]
        if detach = 2
          [ ifelse ageband = 4
            [ set hrf 0.12]
            [ set hrf 0.6]
          ]
        if detach = 3
          [ if ageband < 2.5 [ set hrf 0.58 ] if ageband = 3 [ set hrf 0.57 ] if ageband = 4 [
set hrf 0.13] ]
       ]
     ]
    ; sets high rate factor for storage heating systems

end




to setup-refhouses

  set tempset temp * 10
  set refsource word "refhouses" tempset
  set refsource word refsource ".txt"
  set-default-shape refhouses "target"
  file-open refsource
  create-refhouses 7992
[ set idnumber file-read set ageband file-read set detach file-read set glazing file-read
set wall file-read set roof file-read set heat file-read set hw file-read set pv file-read set
hkwh file-read set wkwh file-read set electrickwh file-read set ckwh file-read]
  file-close
  ask refhouses [ set heatkwh hkwh + wkwh ]

end




to redo-refhouses

  if tempset < temp * 10
  [
    ask refhouses [die]
    setup-refhouses
    ask houses
```

```
    [ set idcool idnumber
      create-link-with one-of refhouses with [idnumber = idcool ] set heatkwh [heatkwh]
of one-of link-neighbors
      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of link-
neighbors set electrickwh [electrickwh] of one-of link-neighbors
      set ckwh [ckwh] of one-of link-neighbors set settemp temp ask my-links [die]
    ]

  ]

end




to setup-people

  set-default-shape people "person" set empty-houses-list [] set moving-people-list []
; Clusters DEFRA segments: 1: Cautious 2: Concerned 3: Honest 4: Positive
; 5: Sideline 6: Stalled 7: Waste

  create-people round (cluster1 * 77.9)
[ set color gray set cluster 1 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 4.79 3.820
  set priceconst random-normal 4.784 1.096 set pricex -0.00139 set pricex2 (6.254 * 10
^ -8)
  set repayx 0.108 set repayx2 (-0.00207) set repayx3 0.0000127 set repayconst (-
random-normal 1.619 0.784)
  set loanincent (- random-normal 1.497 0.904) ]

  create-people round (cluster2 * 77.9)
[ set color gray set cluster 2 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 4.89 3.718
  set priceconst random-normal 4.400 1.106 set pricex -0.00126 set pricex2 (5.402 * 10
^ -8)
  set repayx 0.0826 set repayx2 (-0.00156) set repayx3 0.00000846 set repayconst (-
random-normal 1.134 0.816)
  set loanincent (- random-normal 1.497 0.826) ]

  create-people round (cluster3 * 77.9)
[set color gray set cluster 3 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 5.57 3.866
  set priceconst random-normal 3.978 1.057 set pricex -0.00112 set pricex2 (4.702 * 10
^ -8)
  set repayx 0.0862 set repayx2 (-0.00165) set repayx3 0.00000946 set repayconst (-
random-normal 1.206 0.792)
```

```
  set loanincent (- random-normal 1.396 0.890) ]

  create-people round (cluster4 * 77.9)
[set color gray set cluster 4 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 4.29 3.674
  set priceconst random-normal 5.001 1.091 set pricex -0.00144 set pricex2 (6.281 * 10
^ -8)
  set repayx 0.0948 set repayx2 (-0.00173) set repayx3 0.00000989 set repayconst (-
random-normal 1.435 0.824)
  set loanincent (- random-normal 1.518 0.833) ]

  create-people round (cluster5 * 77.9)
[set color gray set cluster 5 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 4.99 3.874
  set priceconst random-normal 5.282 1.103 set pricex -0.00153 set pricex2 (6.747 * 10
^ -8)
  set repayx 0.0605 set repayx2 (-0.000812) set repayx3 0.00000254 set repayconst (-
random-normal 1.081 0.881)
  set loanincent (- random-normal 1.492 0.913) ]

  create-people round (cluster6 * 77.9)
[set color gray set cluster 6 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 5.13 4.429
  set priceconst random-normal 4.089 1.067 set pricex -0.00117 set pricex2 (5.009 * 10
^ -8)
  set repayx 0.0784 set repayx2 (-0.00142) set repayx3 0.000008913 set repayconst (-
random-normal 1.275 0.778)
  set loanincent (- random-normal 1.369 0.884) ]

  create-people round (cluster7 * 77.9)
[set color gray set cluster 7 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 5.12 3.957
  set priceconst random-normal 4.293 1.061 set pricex -0.00123 set pricex2 (5.347 * 10
^ -8)
  set repayx 0.0834 set repayx2 (-0.00151) set repayx3 0.00000835 set repayconst (-
random-normal 1.238 0.750)
  set loanincent (- random-normal 1.384 0.839) ]

ifelse count people = count houses
  []
  [ ifelse count people > count houses
    [ let rounderror ( count people - count houses ) ask n-of rounderror people [die] ]
    [ let rounderror ( count houses - count people )
      create-people rounderror
      [ let proportion ( random 101 )
; creates right number of people for new dwellings and puts them in proportion to
different clusters
```

```
ifelse proportion <= cluster1 * 100
 [ set color gray set cluster 1 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 4.79 3.820 set priceconst random-normal 4.784 1.096
  set pricex -0.00139 set pricex2 (6.254 * 10 ^ -8) set repayx 0.108 set repayx2 (-
0.00207) set repayx3 0.0000127 set repayconst (- random-normal 1.619 0.784)
  set loanincent (- random-normal 1.497 0.904) ]

 [ ifelse proportion <= (cluster1 + cluster2) * 100
   [ set color gray set cluster 2 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 4.89 3.718 set priceconst random-normal 4.400 1.106
    set pricex -0.00126 set pricex2 (5.402 * 10 ^ -8) set repayx 0.0826 set
repayx2 (-0.00156) set repayx3 0.00000846 set repayconst (- random-normal 1.134
0.816)
    set loanincent (- random-normal 1.497 0.826) ]

   [ ifelse proportion <= ( clust1 + cluster2 + cluster3) * 100
     [ set color gray set cluster 3 set moving 1 setxy 0 0 set age 20 + random 60
set none random-normal 5.57 3.866 set priceconst random-normal 3.978 1.057
      set pricex -0.00112 set pricex2 (4.702 * 10 ^ -8) set repayx 0.0862 set
repayx2 (-0.00165) set repayx3 0.00000946
      set repayconst (- random-normal 1.206 0.792) set loanincent (- random-
normal 1.396 0.890) ]

     [ ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 ) * 100
       [ set color gray set cluster 4 set moving 1 setxy 0 0 set age 20 + random
60 set none random-normal 4.29 3.674 set priceconst random-normal 5.001 1.091
        set pricex -0.00144 set pricex2 (6.281 * 10 ^ -8) set repayx 0.0948 set
repayx2 (-0.00173) set repayx3 0.00000989
        set repayconst (- random-normal 1.435 0.824) set loanincent (- random-
normal 1.518 0.833) ]

       [ ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 + cluster5 )
* 100
         [ set color gray set cluster 5 set moving 1 setxy 0 0 set age 20 + random
60 set none random-normal 4.99 3.874
          set priceconst random-normal 5.282 1.103 set pricex -0.00153 set
pricex2 (6.747 * 10 ^ -8) set repayx 0.0605 set repayx2 (-0.000812)
          set repayx3 0.00000254 set repayconst (- random-normal 1.081
0.881) set loanincent (- random-normal 1.492 0.913) ]

         [ ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 + cluster5
+ cluster6 ) * 100
           [ set color gray set cluster 6 set moving 1 setxy 0 0 set age 20 +
random 60 set none random-normal 5.13 4.429
            set priceconst random-normal 4.089 1.067 set pricex -0.00117 set
pricex2 (5.009 * 10 ^ -8) set repayx 0.0784 set repayx2 (-0.00142)
```

```
                         set repayx3 0.000008913 set repayconst (- random-normal 1.275
0.778) set loanincent (- random-normal 1.369 0.884) ]
                        [ set color gray set cluster 7 set moving 1 setxy 0 0 set age 20 +
random 60 set none random-normal 5.12 3.957
                         set priceconst random-normal 4.293 1.061 set pricex -0.00123 set
pricex2 (5.347 * 10 ^ -8) set repayx 0.0834 set repayx2 (-0.00151)
                         set repayx3 0.00000835 set repayconst (- random-normal 1.238
0.750) set loanincent (- random-normal 1.384 0.839)
                        ]
                      ]
                   ]
                ]
             ]
          ]
       ]
     ]
  ]

ask houses [ set empty-houses-list fput self empty-houses-list ]
ask people [ move-to first empty-houses-list ask first empty-houses-list  [ set empty-
houses-list butfirst empty-houses-list ] ]
ask houses [ set empty 0 ] ask people [ set moving 0 ] ; ensures 1 person per house
ask people
[ set fuelstore random-normal 1381 215 set garden random-normal 1629 268 set
cupboard random-normal 596 107 set primfriend random-normal 372 131 set primsav
random-normal 2.91 0.3  set primmain random-normal 5.87 0.6  set discfriend
random-normal 553 143 set discsav random-normal 2.95 0.53 set discmain random-
normal 9.21 1.7 ]

end




to setup-prices

; initial price and CO2 data from SAP for H1 2008
; elec: heat 5, oil: heat 4, biomass: heat 6, condens: heat 1, gshp: heat 8, comm: heat 7
  set elecfixed 2500 set elecmain 44 set oilfixed 3000 set oilmain 88 set biomass 10777
set biomassmain 220 set condensfixed 2500 set condensmain 88
  set pvfixed 2000 set pvmarg 4357.7 set pvmain 110 set solarfixed 2000 set solarmarg
911.11 set solarmain 44 set gshpfixed 7707.2 set gshpmarg 289.67 set gshpmain 44
  set commfixed 5555 set commmain 88 set solidwalldet 13905 set solidwallsemi 6149
set solidwallflat 2503
  set gas-price 0.024  set gas-standing 72  set gas-co2 0.194 set oil-price 0.0355  set oil-
standing 0.11  set oil-co2 0.261
```

```
  set elec-peak-price 0.103  set elec-off-price 0.0492  set elec-off-standing 26.82  set
elec 0.0958  set elec-co2 0.422  set elec-sold 0.0766
  set solid-price 0.0493 set solid-co2 0.028  set community-price 0.0293  set
community-standing 72  set community-co2 0.179
  set ashpfixed 6280 set ashpmarg 193 set ashpmain 44 set techinf 1 set recinf 1
  set totalelectrickwh sum [electrickwh] of houses  set totalheatkwh sum [heatkwh] of
houses  set totalkwh totalelectrickwh + totalheatkwh set totalkwhinit totalkwh
  set totalcoolkwh sum [ckwh] of houses

  set co21 gas-co2 * sum [heatkwh] of houses with [ heat = 1 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 1]
  set co22 gas-co2 * sum [heatkwh] of houses with [ heat = 2 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 2]
  set co23 gas-co2 * sum [heatkwh] of houses with [ heat = 3 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 3]
  set co24 oil-co2 * sum [heatkwh] of houses with [ heat = 4 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 4]
  set co25 elec-co2 * sum [heatkwh] of houses with [ heat = 5 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 5]
  set co26 solid-co2 * sum [heatkwh] of houses with [ heat = 6 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 6]
  set co27 community-co2 * sum [heatkwh] of houses with [ heat = 7 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 7]
  set co28 elec-co2 * sum [heatkwh] of houses with [ heat = 8 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 8]
  set co29 elec-co2 * sum [heatkwh] of houses with [ heat = 9 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 9]
  set co2tot co21 + co22 + co23 + co24 + co25 + co26 + co27 + co28 + co29 set co2init
co2tot set co2totold co2tot set cumco2 co2tot
  set dgtot count houses with [glazing = 1] set dgold dgtot
  set saving1 0 set saving6 0 set saving8 0 set savingpv 0 set savingcwi 0 set savingloft 0
set savingwall 0 set savingshw 0
  set cost1 0 set cost6 0 set cost8 0 set costpv 0 set costcwi 0 set costcwi 0 set costloft
0 set costwall 0 set costshw 0
  set costpersav1 0 set costpersav6 0 set costpersav8 0 set costpersavpv 0 set
costpersavcwi 0 set costpersavloft 0 set costpersavwall 0 set costpersavshw 0

ask houses [ set electax co2tax * electrickwh * elec-co2 / 100 if electax < 0 [ set electax
0 ]
  ifelse heat < 3.5
    [ set heattax co2tax * heatkwh * gas-co2 / 100]
    [ ifelse heat = 4
      [ set heattax co2tax * heatkwh * oil-co2 / 100]
      [ ifelse heat = 5
        [ set heattax co2tax * heatkwh * elec-co2 / 100]
        [ ifelse heat = 6
          [ set heattax co2tax * heatkwh * solid-co2 / 100]
```

```
        [ ifelse heat = 7
          [ set heattax co2tax * heatkwh * community-co2 / 100]
          [ set heattax co2tax * heatkwh * elec-co2 / 100] ] ] ] ] ]
set heattaxtot sum [heattax] of houses set electaxtot sum [electax] of houses
set revenue heattaxtot + electaxtot set revenuetot revenue

end




to go
; actually run the programme
; Go runs once for each year of the model

redo-refhouses
ask links [die] ; belt and braces check to clear any reference links from previous year
reset-counters ; resets various monitors to 0 to check for changes in coming year
kill ;  sub-routine to replace old people and houses
ask links [die] ; belt and braces check to clear any reference links from reset or kill routines
move-people ; routine to make some people move home
move-home ; routine to consider improvements after moving home
ask links [die] ; belt and braces check to clear any reference links from move-people and move-home
 ask houses [ if boiler-life < upgradetime [ breakdown ]  ]
; if the boiler life is less than the upgrade time starts the breakdown routine to buy a new boiler
ask links [die] ; belt and braces check to clear any reference links from breakdown
set co2 sum [emissions] of houses set totalelectrickwh sum [electrickwh] of houses
set totalheatkwh sum [heatkwh] of houses set totalkwh sum [heatkwh + electrickwh] of houses
set totalcoolkwh sum [ckwh] of houses
update-prices do-plots ; update prises and then draw graphs
tick ; adds one to the counter - equivalent to one year

end




to reset-counters
; resets all annual monitors to zero
```

```
set saving1 0 set saving6 0 set saving8 0 set saving9 0 set savingpv 0 set savingcwi 0 set
savingloft 0 set savingwall 0 set savingshw 0  set cost1 0 set cost6 0 set cost8 0 set
cost9 0 set costpv 0 set costcwi 0 set costcwi 0 set costloft 0 set costwall 0 set costshw
0 set costpersav1 0 set costpersav6 0 set costpersav8 0 set costpersav9 0 set
costpersavpv 0 set costpersavcwi 0 set costpersavloft 0 set costpersavwall 0 set
costpersavshw 0 set totalcost 0 set totalsav 0

ask houses [ set age age + 1 set upgradetime upgradetime + 1 set oldidnumber 0 set
sav1 0 set sav6 0 set sav8 0 set sav9 0 set savpv 0 set savcwi 0 set savloft 0 set savwall
0 set savshw 0 set subnpv1 0 set subnpv6 0 set subnpv8 0 set subnpv9 0 set subnpvpv
0 set subnpvcwi 0 set subnpvloft 0 set subnpvwall 0 set subnpvshw 0 set subgrant1 0
set subgrant6 0 set subgrant8 0 set subgrant9 0 set subgrantpv 0 set subgrantcwi 0 set
subgrantloft 0 set subgrantwall 0 set subgrantshw 0 ]

ask houses [ set electax co2tax * electrickwh * elec-co2 / 100 if electax < 0 [ set electax
0 ]
  ifelse heat < 3.5
    [ set heattax co2tax * heatkwh * gas-co2 / 100]
    [ ifelse heat = 4
      [ set heattax co2tax * heatkwh * oil-co2 / 100]
      [ ifelse heat = 5
        [ set heattax co2tax * heatkwh * elec-co2 / 100]
        [ ifelse heat = 6
          [ set heattax co2tax * heatkwh * solid-co2 / 100]
          [ ifelse heat = 7
            [ set heattax co2tax * heatkwh * community-co2 / 100]
            [ set heattax co2tax * heatkwh * elec-co2 / 100] ] ] ] ]  ]

set clust1pv 0 set clust1shw 0 set clust1loft 0 set  clust1cwi 0 set  clust1wall  0 set
clust16  0 set clust18  0 set clust2pv  0 set clust2shw  0 set clust2loft  0 set clust2cwi  0
set clust2wall  0 set clust26  0 set clust28  0 set clust3pv  0 set clust3shw  0 set
clust3loft  0 set clust3cwi  0 set clust3wall  0 set clust36  0 set clust38 0 set clust4pv  0
set clust4shw  0 set clust4loft 0 set  clust4cwi 0 set  clust4wall  0 set clust46  0 set
clust48  0 set clust5pv 0 set  clust5shw  0 set clust5loft 0 set  clust5cwi  0 set clust5wall
0 set clust56  0 set clust58  0 set clust6pv  0 set clust6shw  0 set clust6loft  0 set
clust6cwi  0 set clust6wall 0 set  clust66  0 set clust68 0 set clust7pv  0 set clust7shw  0
set clust7loft 0 set  clust7cwi 0 set  clust7wall 0 set  clust76  0 set clust78  0 set clust17
0 set clust27 0 set clust37 0 set clust47 0 set clust57 0 set clust67 0 set clust77 0 set
clust19 0 set clust29 0 set clust39 0 set clust49 0 set clust59 0 set clust69 0 set clust79
0

ask people [ set instpv 0 set instshw 0 set instloft 0 set instcwi 0 set instwall 0 set inst6
0 set inst8 0 set inst7 0 set newperson 0 set inst9 0 ]

end
```

```
to move-people
; selects a random 7% of population and makes them move home

ask houses [ while [ any? other houses-here ]
        [  rt random-float 360 jump random-float 3 move-to patch-here ]     ]
set empty-houses-list [] set moving-people-list []
ask people [ if random 100 < 7
          [ ask houses-here [ set newowner 1 set empty 1 ] set moving 1 ] ]
ask people [ if any? other people-here  [  set moving 1 ]  ]
ask people [ if not any? houses-here [set moving 1 ]  ]
ask houses [ if not any? people-here [set empty 1 ] ]
ask houses with [ empty = 1 ] [ set empty-houses-list fput self empty-houses-list ]
ask people with [ moving = 1 ]  [ if not empty? empty-houses-list
   [ move-to first empty-houses-list move-to patch-here ask first empty-houses-list [
set empty-houses-list butfirst empty-houses-list ]  ]  ]

end




to kill

ask people
  [ if age > 90 [  set age 20 + random 20 ] ]
; Kills off people at age 90 replaces with new people roughly between 20 and 40.
; Not currently of any effect, but ready for future use for considering age of people on
choices
; and cluster membership
set construct int ( count houses * constructionrate / 100 ) set demolish int ( count
houses * demolitionrate / 100 )
ask houses with [ age >= mindemolitionage ] [set demolished 1 ] set demolishedcount
count houses with [demolished = 1]
set demolishsurplus demolishedcount - demolish
; determines number of houses to be demolished and built
ifelse demolishsurplus = 0  [ ] ;stop ]
 [ ifelse demolishsurplus < 0
    [ ask n-of ( - demolishsurplus ) houses with [ demolished = 0 ] [ set demolished 1 ] ]
    [ ask n-of demolishsurplus houses with [ demolished = 1 ] [ set demolished 0 ] ] ]
ask houses with [ demolished = 1 ] [ ask people-here [die] die  ]
; destroys selected houses and occupants

ifelse ticks < 8
```

```
[ ; setting proportions of attributes for new dwellings up to 2016
  ; - proportions based on existing stock proportions
  set det1 int ( (count houses with [detach = 1] / count houses) * construct )
  set det3 int ( (count houses with [detach = 3] / count houses) * construct ) set det2
construct - det1 - det3
  set heating4 int ( (count houses with [ heat = 4 ] / count houses ) * construct )
  set heating5 int ( (count houses with [ heat = 5 ] / count houses ) * construct )
  set heating6 int ( (count houses with [ heat = 6 ] / count houses ) * construct )
  set heating7 int ( (count houses with [ heat = 7 ] / count houses ) * construct )
  set heating8 int ( (count houses with [ heat = 8 ] / count houses ) * construct )
  set heating9 int ( (count houses with [ heat = 9 ] / count houses ) * construct )
  set heating1 construct - heating9 - heating8 - heating7 - heating6 - heating5 -
heating4
  set roof0 int ( (count houses with [ roof = 0 ] / count houses ) * construct ) set roof1
construct - roof0
  set hw1 int ( ( count houses with [ hw = 1 ] / count houses ) * construct ) set hw2
construct - hw1
  set pv1 int ( ( count houses with [ pv = 1 ] / count houses ) * construct ) set pv2
construct - pv1
  create-houses construct
    [ set oldidlist [] set solidwall 0 set ageband 4 set glazing 1 set wall 2 set new 1 set
boiler-life random-normal 15 5 set empty 1
      setxy 0 0 while [any? other houses-here] [  rt random-float 360 fd random-float
3  move-to patch-here ]   ]
  ask n-of det1 houses with [ new = 1] [ set detach 1 set new 2]
  ask n-of det2 houses with [ new = 1] [ set detach 2 set new 2]
  ask n-of det3 houses with [ new = 1] [ set detach 3 set new 2]
  ask n-of heating1 houses with [ new = 2 ] [ set heat 1 set new 3 ]
  ask n-of heating4 houses with [ new = 2 ] [ set heat 4 set new 3 ]
  ask n-of heating5 houses with [ new = 2 ] [ set heat 5 set new 3 ]
  ask n-of heating6 houses with [ new = 2 ] [ set heat 6 set new 3 ]
  ask n-of heating7 houses with [ new = 2 ] [ set heat 7 set new 3 ]
  ask n-of heating8 houses with [ new = 2 ] [ set heat 8 set new 3 ]
  ask n-of heating9 houses with [ new = 2 ] [ set heat 9 set new 3 ]
  ask n-of roof0 houses with [ new = 3 and detach = 3 ] [ set roof 0 set new 4 ]
  ask n-of roof1 houses with [ new = 3 ] [ set roof 1 set new 4 ]
  ask n-of hw1 houses with [ new = 4 and roof = 1 ] [ set hw 1 set new 5 ]
  ask n-of hw2 houses with [ new = 4 ] [ set hw 2 set new 5 ]
  ask n-of pv1 houses with [ new = 5 and roof = 1 ] [ set pv 1 set new 6 ]
  ask n-of pv2 houses with [ new = 5 ] [ set pv 2 set new 6 ]
  ask houses with [ new = 6 ]
    [ set id1 word ageband detach set id2 word glazing wall set id3 word roof heat
set id4 word hw pv set id5 word id1 id2 set id6 word id3 id4 set id7 word id5 id6 set
idnumber read-from-string id7 set idref idnumber
      if heat = 5
        [ if detach = 1 [ if ageband = 1 [ set hrf 0.04 ] if ageband = 2 or ageband = 3 [ set
hrf 0.26 ] if ageband = 4 [ set hrf 0.12] ]
```

```
            if detach = 2 [ ifelse ageband = 4 [ set hrf 0.12] [ set hrf 0.6] ]
            if detach = 3 [ if ageband < 2.5 [ set hrf 0.58 ] if ageband = 3 [ set hrf 0.57 ] if
ageband = 4 [ set hrf 0.13] ]
           ]
         create-link-with one-of refhouses with [ idnumber = idref ] set electrickwh [
electrickwh ] of one-of link-neighbors set heatkwh [ heatkwh ] of one-of link-neighbors
set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors
set ckwh [ckwh] of one-of link-neighbors
         ask my-links [ set color magenta ] ]
    ask links  with [ color = magenta ] [ die ]
   ]

  [; 2016+ new houses - detachment proportion based on existing stock
   ; - heating according to sliders for newbuild heat type
    set det1 int ( (count houses with [detach = 1] / count houses) * construct )
    set det3 int ( (count houses with [detach = 3] / count houses) * construct )
    set det2 construct - det1 - det3
    set heating6 int ( newbuildsolid / (newbuildsolid + newbuildheatpump +
newbuildcommunity + newbuildashp) * construct )
    set heating7 int ( newbuildcommunity / (newbuildsolid + newbuildheatpump +
newbuildcommunity + newbuildashp) * construct )
    set heating9 int ( newbuildashp / (newbuildsolid + newbuildheatpump +
newbuildcommunity + newbuildashp) * construct )
    set heating8 construct - heating6 - heating7 - heating9
    set roof0 int ( (count houses with [ roof = 0 ] / count houses ) * construct )
    set roof1 construct - roof0
    create-houses construct
      [ set oldidlist [] set solidwall 0 set ageband 4 set glazing 1 set wall 1 set new 1 set
boiler-life random-normal 15 5 set empty 1
        setxy 0 0 while [any? other houses-here] [  rt random-float 360 fd random-float
3  move-to patch-here ]   ]
    ask n-of det1 houses with [ new = 1] [ set detach 1 set new 2]
    ask n-of det2 houses with [ new = 1] [ set detach 2 set new 2]
    ask n-of det3 houses with [ new = 1] [ set detach 3 set new 2]
    ifelse heating7 <= det3
      [ ask n-of heating7 houses with [ new = 2 and detach = 3 ] [ set heat 7 set new 3 ]
]
      [ ask n-of det3 houses with [ new = 2 and detach = 3] [ set heat 7 set new 3 ]
    ask n-of ( heating7 - det3) houses with [ new = 2 ] [ set heat 7 set new 3 ]    ]
    ask n-of heating6 houses with [ new = 2 ] [ set heat 6 set new 3 ]
    ask n-of heating8 houses with [ new = 2 ] [ set heat 8 set new 3 ]
    ask n-of heating9 houses with [ new = 2 ] [ set heat 9 set new 3 ]
    ask n-of roof0 houses with [ new = 3 and detach = 3 ] [ set roof 0 set hw 2 set pv 2
set new 6 ]
    ask n-of roof1 houses with [ new = 3 ] [ set roof 1 set hw 1 set pv 1 set new 6 ]
    ask houses with [ new = 6 ]
```

```
        [ set id1 word ageband detach set id2 word glazing wall set id3 word roof heat set
id4 word hw pv
          set id5 word id1 id2 set id6 word id3 id4 set id7 word id5 id6 set idnumber read-
from-string id7 set idref idnumber
          if heat = 5
          [ if detach = 1 [ if ageband = 1 [ set hrf 0.04 ] if ageband = 2 or ageband = 3 [ set
hrf 0.26 ] if ageband = 4 [ set hrf 0.12] ]
            if detach = 2 [ ifelse ageband = 4 [ set hrf 0.12] [ set hrf 0.6] ]
            if detach = 3 [ if ageband < 2.5 [ set hrf 0.58 ] if ageband = 3 [ set hrf 0.57 ] if
ageband = 4 [ set hrf 0.13] ] ]
          create-link-with one-of refhouses with [ idnumber = idref ] set electrickwh [
electrickwh ] of one-of link-neighbors
          set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of link-
neighbors set ckwh [ckwh] of one-of link-neighbors
          set heatkwh [ heatkwh ] of one-of link-neighbors ask my-links [ set color
magenta ] ]
     ask links  with [ color = magenta ] [ die ]
    ]

 create-people construct
  [ set fuelstore random-normal 1381 215 set garden random-normal 1629 268 set
cupboard random-normal 596 107 set primfriend random-normal 372 131 set primsav
random-normal 2.91 0.3  set primmain random-normal 5.87 0.6 set discfriend random-
normal 553 143 set discsav random-normal 2.95 0.53 set discmain random-normal
9.21 1.7 set newperson 1 let proportion ( random 100001 )
; creates right number of people for new dwellings and puts them in proportion to
different clusters
    ifelse proportion <= cluster1 * 1000 ;12285 – default value
      [ set color gray set cluster 1 set moving 1 setxy 0 0 set age 20 + random 60 set none
random-normal 4.79 3.820 set priceconst random-normal 4.784 1.096 set pricex -
0.00139 set pricex2 (6.254 * 10 ^ -8) set repayx 0.108 set repayx2 (-0.00207) set
repayx3 0.0000127 set repayconst (- random-normal 1.619 0.784) set loanincent (-
random-normal 1.497 0.904) ]
      [ ifelse proportion <= (cluster1 + cluster2 )* 1000 ;31772
        [ set color gray set cluster 2 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 4.89 3.718 set priceconst random-normal 4.400 1.106 set pricex
-0.00126 set pricex2 (5.402 * 10 ^ -8) set repayx 0.0826 set repayx2 (-0.00156) set
repayx3 0.00000846 set repayconst (- random-normal 1.134 0.816) set loanincent (-
random-normal 1.497 0.826) ]
        [ ifelse proportion <= (cluster1 + cluster2 + cluster3) * 1000 ; 52722
          [ set color gray set cluster 3 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 5.57 3.866 set priceconst random-normal 3.978 1.057 set pricex
-0.00112 set pricex2 (4.702 * 10 ^ -8) set repayx 0.0862 set repayx2 (-0.00165) set
repayx3 0.00000946 set repayconst (- random-normal 1.206 0.792) set loanincent (-
random-normal 1.396 0.890) ]
          [ ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4) * 1000 ;77176
```

```
          [ set color gray set cluster 4 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 4.29 3.674 set priceconst random-normal 5.001 1.091 set pricex
-0.00144 set pricex2 (6.281 * 10 ^ -8) set repayx 0.0948 set repayx2 (-0.00173) set
repayx3 0.00000989 set repayconst (- random-normal 1.435 0.824) set loanincent (-
random-normal 1.518 0.833) ]
          [ ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 + cluster5) * 1000
;84211
           [ set color gray set cluster 5 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 4.99 3.874 set priceconst random-normal 5.282 1.103 set pricex
-0.00153 set pricex2 (6.747 * 10 ^ -8) set repayx 0.0605 set repayx2 (-0.000812) set
repayx3 0.00000254 set repayconst (- random-normal 1.081 0.881) set loanincent (-
random-normal 1.492 0.913) ]
           [ ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 + cluster5 +
cluster6) * 1000; 87625
             [ set color gray set cluster 6 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 5.13 4.429 set priceconst random-normal 4.089 1.067 set pricex
-0.00117 set pricex2 (5.009 * 10 ^ -8) set repayx 0.0784 set repayx2 (-0.00142) set
repayx3 0.000008913 set repayconst (- random-normal 1.275 0.778) set loanincent (-
random-normal 1.369 0.884) ]
             [ set color gray set cluster 7 set moving 1 setxy 0 0 set age 20 + random 60 set
none random-normal 5.12 3.957 set priceconst random-normal 4.293 1.061 set pricex
-0.00123 set pricex2 (5.347 * 10 ^ -8) set repayx 0.0834 set repayx2 (-0.00151) set
repayx3 0.00000835 set repayconst (- random-normal 1.238 0.750) set loanincent (-
random-normal 1.384 0.839)]
            ]
          ]
        ]
      ]
    ]
   while [any? other people-here and not any? houses-here] [  rt random-float 360 fd
random-float 10 move-to patch-here ]  ; checks only 1 person per house
  ]
ifelse count people = count houses
 []
; Checks the right number of people exist for the houses and makes any adjustment
needed
; due to rounding errors
 [ ifelse count people > count houses
  [ let rounderror ( count people - count houses )
    ask n-of rounderror people with [newperson = 1] [die] ]
  [ let rounderror ( count houses - count people )
    create-people rounderror
     [ set fuelstore random-normal 1381 215 set garden random-normal 1629 268 set
cupboard random-normal 596 107 set primfriend random-normal 372 131 set primsav
random-normal 2.91 0.3  set primmain random-normal 5.87 0.6 set discfriend random-
normal 553 143 set discsav random-normal 2.95 0.53 set discmain random-normal
9.21 1.7
```

let proportion (random 101) *; creates right number of people for new dwellings and puts them in proportion to different clusters*
ifelse proportion <= cluster1 * 100
[set color gray set cluster 1 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 4.79 3.820 set priceconst random-normal 4.784 1.096 set pricex -0.00139 set pricex2 (6.254 * 10 ^ -8) set repayx 0.108 set repayx2 (-0.00207) set repayx3 0.0000127 set repayconst (- random-normal 1.619 0.784) set loanincent (- random-normal 1.497 0.904)]
[ifelse proportion <= (cluster1 + cluster2) * 100
[set color gray set cluster 2 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 4.89 3.718 set priceconst random-normal 4.400 1.106 set pricex -0.00126 set pricex2 (5.402 * 10 ^ -8) set repayx 0.0826 set repayx2 (-0.00156) set repayx3 0.00000846 set repayconst (- random-normal 1.134 0.816) set loanincent (- random-normal 1.497 0.826)]
[ifelse proportion <= (cluster1 + cluster2 + cluster3) * 100
[set color gray set cluster 3 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 5.57 3.866 set priceconst random-normal 3.978 1.057 set pricex -0.00112 set pricex2 (4.702 * 10 ^ -8) set repayx 0.0862 set repayx2 (-0.00165) set repayx3 0.00000946 set repayconst (- random-normal 1.206 0.792) set loanincent (- random-normal 1.396 0.890)]
[ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4) * 100
[set color gray set cluster 4 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 4.29 3.674 set priceconst random-normal 5.001 1.091 set pricex -0.00144 set pricex2 (6.281 * 10 ^ -8) set repayx 0.0948 set repayx2 (-0.00173) set repayx3 0.00000989 set repayconst (- random-normal 1.435 0.824) set loanincent (- random-normal 1.518 0.833)]
[ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 + cluster5) * 100
[set color gray set cluster 5 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 4.99 3.874 set priceconst random-normal 5.282 1.103 set pricex -0.00153 set pricex2 (6.747 * 10 ^ -8) set repayx 0.0605 set repayx2 (-0.000812) set repayx3 0.00000254 set repayconst (- random-normal 1.081 0.881) set loanincent (- random-normal 1.492 0.913)]
[ifelse proportion < (cluster1 + cluster2 + cluster3 + cluster4 + cluster5 + cluster6) * 100
[set color gray set cluster 6 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 5.13 4.429 set priceconst random-normal 4.089 1.067 set pricex -0.00117 set pricex2 (5.009 * 10 ^ -8) set repayx 0.0784 set repayx2 (-0.00142) set repayx3 0.000008913 set repayconst (- random-normal 1.275 0.778)
set loanincent (- random-normal 1.369 0.884)]
[set color gray set cluster 7 set moving 1 setxy 0 0 set age 20 + random 60 set none random-normal 5.12 3.957
set priceconst random-normal 4.293 1.061
set pricex -0.00123 set pricex2 (5.347 * 10 ^ -8) set repayx 0.0834 set repayx2 (-0.00151) set repayx3 0.00000835 set repayconst (- random-normal 1.238 0.750)
set loanincent (- random-normal 1.384 0.839)]
]

```
              ]
            ]
          ]
        ]
      ]
   ]
  ]

end



to update-prices ; inflate fuel bills and decrease technology costs

set techinf techinf * (1 + technologyinflation / 100)
set recinf recinf * (1 + recommendinflation / 100)
ifelse ticks < 33
  [ set pvmarg ( 4357.7 - 873.5 * ln ( ticks + 1 ) ) * techinf  ]
  [ ifelse ticks >= 33 and ticks < 42 [ set pvmarg ( 1300 - (ticks - 33) * 10 ) * techinf ] [ set
pvmarg 1200 * techinf ] ]
ifelse ticks < 42
  [ set solarmarg ( 911.11 + 0.3643 * ticks * ticks - 25.66 * ticks ) * techinf set biomass (
2.2014 * ticks * ticks - 199.58 * ticks + 10777 ) * techinf]
  [ set solarmarg 450 * techinf  set biomass 6160 * techinf ]
ifelse ticks < 23
  [ set gshpfixed ( 7707.2 + 5.6406 * ticks * ticks - 246.52 * ticks ) * techinf set
gshpmarg ( 289.67 + 0.2205 * ticks * ticks - 9.3735 * ticks ) * techinf  set ashpfixed (
6255.2 + 4.3262 * ticks * ticks - 196.68 * ticks ) * techinf set ashpmarg ( 192.6 + 0.1394
* ticks * ticks - 6.1256 * ticks ) * techinf ]
  [ set gshpfixed 5000 * techinf set gshpmarg 190 * techinf  set ashpfixed 4000 *
techinf set ashpmarg 125 * techinf ]

set gas-price gas-price * ( 1 + gas-pricerise / 100 ) set gas-standing gas-standing * ( 1 +
gas-pricerise / 100 )
set oil-price oil-price * ( 1 + oil-pricerise / 100 ) set oil-standing oil-standing * ( 1 + gas-
pricerise / 100 )
set elec-peak-price elec-peak-price * ( 1 + elec-pricerise / 100 ) set elec-off-price elec-
off-price * ( 1 + elec-pricerise / 100 )
set elec-off-standing elec-off-standing * ( 1 + elec-pricerise / 100 ) set elec elec * ( 1 +
elec-pricerise / 100 )
set elec-co2 elec-co2 * ( 1 - griddecarb / 100 ) set solid-price solid-price * ( 1 + solid-
pricerise / 100 )
set community-price community-price * ( 1 + community-pricerise / 100 )
set community-standing community-standing * ( 1 + community-pricerise / 100 ) set
elec-sold elec-sold * ( 1 + elec-pricerise / 100 )
```

```
set co21 gas-co2 * sum [heatkwh] of houses with [ heat = 1 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 1]
set co22 gas-co2 * sum [heatkwh] of houses with [ heat = 2 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 2]
set co23 gas-co2 * sum [heatkwh] of houses with [ heat = 3 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 3]
set co24 oil-co2 * sum [heatkwh] of houses with [ heat = 4 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 4]
set co25 elec-co2 * sum [heatkwh] of houses with [ heat = 5 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 5]
set co26 solid-co2 * sum [heatkwh] of houses with [ heat = 6 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 6]
set co27 community-co2 * sum [heatkwh] of houses with [ heat = 7 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 7]
set co28 elec-co2 * sum [heatkwh] of houses with [ heat = 8 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 8]
set co29 elec-co2 * sum [heatkwh] of houses with [ heat = 9 ] + elec-co2 * sum
[electrickwh] of houses with [heat = 9]
set co2totold co2tot set co2tot co21 + co22 + co23 + co24 + co25 + co26 + co27 + co28
+ co29 set cumco2 cumco2 + co2tot
set changes sum [changed] of houses set improvements sum [improved] of houses
set saving9 sum [ sav9 ] of houses with [ heat = 9 and sav9 > 0]
set cost9 ( sum [ subnpv9 ] of houses with [ heat = 9 and sav9 > 0]) + sum [subgrant9]
of houses with [ heat = 9 and sav9 > 0]
set savingpv sum [ savpv ] of houses with [ pv = 1 ] ; ask houses [ set sav8 0 ]
set costpv ( sum [ subnpvpv ] of houses with [ pv = 1 ] ) + sum [subgrantpv] of houses
with [ pv = 1 ]
set savingcwi sum [ savcwi ] of houses with [ wall = 3 ]
set costcwi  sum [subgrantcwi] of houses with [ wall = 3 ]
set savingloft sum [ savloft ] of houses with [ roof = 1 ]
set costloft sum [subgrantloft] of houses with [ roof = 1 ]
set savingwall sum [ savwall ] of houses with [ wall = 3 and solidwall = 1  ]
set costwall ( sum [ subnpvwall ] of houses with [ wall = 3 and solidwall = 1 ]) + sum
[subgrantwall] of houses with [ wall = 3 and solidwall = 1 ]
set savingshw sum [ savshw ] of houses with [ hw = 1 ]
set costshw ( sum [ subnpvshw ] of houses with [ hw = 1 ]) + sum [subgrantshw] of
houses with [ hw = 1 ]
ifelse cost6 = 0  [ set costpersav6 0 ]  [ set costpersav6 cost6 / saving6 set totalcost
totalcost + cost6 set totalsav totalsav + saving6]
ifelse cost8 = 0  [ set costpersav8 0 ]  [ set costpersav8 cost8 / saving8 set totalcost
totalcost + cost8 set totalsav totalsav + saving8]
ifelse cost9 = 0  [ set costpersav9 0 ]  [ set costpersav9 cost9 / saving9 set totalcost
totalcost + cost9 set totalsav totalsav + saving9]
ifelse costpv = 0  [ set costpersavpv 0 ]  [ set costpersavpv costpv / savingpv set
totalcost totalcost + costpv set totalsav totalsav + savingpv]
ifelse cost1 = 0  [ set costpersav1 0 ]  [ set costpersav1 cost1 / saving1 set totalcost
totalcost + cost1 set totalsav totalsav + saving1 ]
```

```
ifelse costcwi = 0  [ set costpersavcwi 0 ]  [ set costpersavcwi costcwi / savingcwi set
totalcost totalcost + costcwi set totalsav totalsav + savingcwi]
ifelse costloft = 0  [ set costpersavloft 0 ]  [ set costpersavloft costloft / savingloft set
totalcost totalcost + costloft set totalsav totalsav + savingloft]
ifelse costwall = 0  [ set costpersavwall 0 ]  [ set costpersavwall costwall / savingwall
set totalcost totalcost + costwall set totalsav totalsav + savingwall]
ifelse costshw = 0  [ set costpersavshw 0 ]  [ set costpersavshw costshw / savingshw set
totalcost totalcost + costshw set totalsav totalsav + savingshw]
ifelse totalcost = 0 [ set totalcostperco2 0 ] [ set  totalcostperco2 totalcost / totalsav ]
set dgold dgtot set dgtot count houses with [glazing = 1]
set heattaxtot sum [heattax] of houses set electaxtot sum [electax] of houses
set revenue heattaxtot + electaxtot set revenuetot revenuetot + revenue

set clust1pv count people with [ cluster = 1 and instpv = 1 ] set clust2pv count people
with [ cluster = 2 and instpv = 1 ]
set clust3pv count people with [ cluster = 3 and instpv = 1 ] set clust4pv count people
with [ cluster = 4 and instpv = 1 ]
set clust5pv count people with [ cluster = 5 and instpv = 1 ] set clust6pv count people
with [ cluster = 6 and instpv = 1 ]
set clust7pv count people with [ cluster = 7 and instpv = 1 ] set clust1shw count people
with [ cluster = 1 and instshw = 1 ]
set clust2shw count people with [ cluster = 2 and instshw = 1 ] set clust3shw count
people with [ cluster = 3 and instshw = 1 ]
set clust4shw count people with [ cluster = 4 and instshw = 1 ] set clust5shw count
people with [ cluster = 5 and instshw = 1 ]
set clust6shw count people with [ cluster = 6 and instshw = 1 ] set clust7shw count
people with [ cluster = 7 and instshw = 1 ]
set clust1loft count people with [ cluster = 1 and instloft = 1 ] set clust2loft count
people with [ cluster = 2 and instloft = 1 ]
set clust3loft count people with [ cluster = 3 and instloft = 1 ] set clust4loft count
people with [ cluster = 4 and instloft = 1 ]
set clust5loft count people with [ cluster = 5 and instloft = 1 ] set clust6loft count
people with [ cluster = 6 and instloft = 1 ]
set clust7loft count people with [ cluster = 7 and instloft = 1 ] set clust1wall count
people with [ cluster = 1 and instwall = 1 ]
set clust2wall count people with [ cluster = 2 and instwall = 1 ] set clust3wall count
people with [ cluster = 3 and instwall = 1 ]
set clust4wall count people with [ cluster = 4 and instwall = 1 ] set clust5wall count
people with [ cluster = 5 and instwall = 1 ]
set clust6wall count people with [ cluster = 6 and instwall = 1 ] set clust7wall count
people with [ cluster = 7 and instwall = 1 ]
set clust1cwi count people with [ cluster = 1 and instcwi = 1 ] set clust2cwi count
people with [ cluster = 2 and instcwi = 1 ]
set clust3cwi count people with [ cluster = 3 and instcwi = 1 ] set clust4cwi count
people with [ cluster = 4 and instcwi = 1 ]
set clust5cwi count people with [ cluster = 5 and instcwi = 1 ] set clust6cwi count
people with [ cluster = 6 and instcwi = 1 ]
```

set clust7cwi count people with [cluster = 7 and instcwi = 1] set clust16 count people with [cluster = 1 and inst6 = 1]
set clust26 count people with [cluster = 2 and inst6 = 1] set clust36 count people with [cluster = 3 and inst6 = 1]
set clust46 count people with [cluster = 4 and inst6 = 1] set clust56 count people with [cluster = 5 and inst6 = 1]
set clust66 count people with [cluster = 6 and inst6 = 1] set clust76 count people with [cluster = 7 and inst6 = 1]
set clust17 count people with [cluster = 1 and inst7 = 1] set clust27 count people with [cluster = 2 and inst7 = 1]
set clust37 count people with [cluster = 3 and inst7 = 1] set clust47 count people with [cluster = 4 and inst7 = 1]
set clust57 count people with [cluster = 5 and inst7 = 1] set clust67 count people with [cluster = 6 and inst7 = 1]
set clust77 count people with [cluster = 7 and inst7 = 1] set clust18 count people with [cluster = 1 and inst8 = 1]
set clust28 count people with [cluster = 2 and inst8 = 1] set clust38 count people with [cluster = 3 and inst8 = 1]
set clust48 count people with [cluster = 4 and inst8 = 1] set clust58 count people with [cluster = 5 and inst8 = 1]
set clust68 count people with [cluster = 6 and inst8 = 1] set clust78 count people with [cluster = 7 and inst8 = 1]
set clust19 count people with [cluster = 1 and inst9 = 1] set clust29 count people with [cluster = 2 and inst9 = 1]
set clust39 count people with [cluster = 3 and inst9 = 1] set clust49 count people with [cluster = 4 and inst9 = 1]
set clust59 count people with [cluster = 5 and inst9 = 9] set clust69 count people with [cluster = 6 and inst9 = 1]
set clust79 count people with [cluster = 7 and inst9 = 1] set clust1 count people with [cluster = 1] set clust2 count people with [cluster = 2]
set clust3 count people with [cluster = 3] set clust4 count people with [cluster = 4]
set clust5 count people with [cluster = 5]
set clust6 count people with [cluster = 6] set clust7 count people with [cluster = 7]

end

to breakdown

set potchange potchange + 1 set potimprov potimprov + 1
; increase count of potential improvements
set priceconst [priceconst] of one-of people-here set pricex [pricex] of one-of people-here set pricex2 [pricex2] of one-of people-here

```
set repayconst [repayconst ] of one-of people-here set repayx [ repayx ] of one-of
people-here set repayx2 [ repayx2 ] of one-of people-here
set repayx3 [ repayx3] of one-of people-here set none (nonefactor * [none] of one-of
people-here ) set loanincent [loanincent] of one-of people-here
set fuelstore [ fuelstore ] of one-of people-here set garden [ garden ] of one-of people-
here set cupboard [ cupboard ] of one-of people-here
set primfriend recinf * [ primfriend ] of one-of people-here set primsav recinf * [
primsav ] of one-of people-here set primmain recinf * [ primmain ] of one-of people-
here


ifelse heat = 1
  [    set idref6 idnumber + 500 set idref7 idnumber + 600 set idref8 idnumber + 700
set idref9 idnumber + 800
      ; idref numbers used to refer to the reference houses
      ; to determine the extent of energy savings available
      set runningcost ( heatkwh * gas-price + gas-standing + electrickwh * elec )
      create-link-with one-of refhouses with [idnumber = idref8 ] set heatgshp
[heatkwh] of one-of link-neighbors ask my-links [die]
      create-link-with one-of refhouses with [idnumber = idref9 ] set heatashp
[heatkwh] of one-of link-neighbors ask my-links [die]

      if detach = 1
        [   heat6price heat9price heat8price ; runs subroutines to calculate savings
available from different heating options
           set n1 count (houses-on neighbors) with [ heat = 1 ] set save1 0 set
repayment1 (save1 / 12) * (paybackrate / 100 )
           set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 *
repayment1 + repayx3 * repayment1 * repayment1 * repayment1
           set adjust1 condensfixed + condensmain * primmain - save1 * primsav  -
primfriend * n1 / 4
           if adjust1 < 0 [ set adjust1 0 ]
           set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 +
loanincent + incentiveadjust + repay1
           ; calculation of running costs with existing technology and adjusted price
           ifelse lhs8 >= lhs6 and lhs8 > lhs1 and lhs8 > lhs9 ; adjust8 <= adjust6 and
adjust8 < adjust1 and adjust8 < adjust9
           ; if adjusted price of 8 (ground source heat pump) is cheapest of alternatives
available
           ; decision algorithm used to determine whether to install
             [ ifelse lhs8 > none
               [ choice8 set improved ( improved + 1 )  ] ; if threshold reached new
technology installed
               [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15 5
set upgradetime 0 ] ]
               ; if threshold not reached existing technology remains,
               ; renewed if boiler has broken down
```

```
            ]
           [ ifelse lhs6 > lhs8 and lhs6 > lhs1 and lhs6 >= lhs9 ; adjust6 < adjust8 and
adjust6 < adjust1 and adjust6 <= adjust9 ; if adjusted price of 6 (solid fuel) was
cheapest, decision made to consider that instead
             [ ifelse lhs6 > none
               [ choice6 set improved ( improved + 1 ) ]
               [set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ] ]
             ]
             [ ifelse lhs9 > lhs8 and lhs9 > lhs6 and lhs9 > lhs1 ;  adjust9 < adjust8 and
adjust9 < adjust6 and adjust9 < adjust1
               [ ifelse lhs9 > none ; priceconst + pricex * adjust9 + pricex2 * adjust9 *
adjust9 + loanincent + incentiveadjust + repay9 > none
                 [ choice9 set improved ( improved + 1 ) ]
                 [set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal
15 5 set upgradetime 0 ] ]
               ]
               [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ]  ]
             ]
           ]
         ]

    if detach = 3
      [   heat7price heat9price
        set n1 count (houses-on neighbors) with [ heat = 1 ] set save1 0 set
repayment1 (save1 / 12) * (paybackrate / 100 )
        set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 *
repayment1 + repayx3 * repayment1 * repayment1 * repayment1
        set adjust1 condensfixed + condensmain * primmain - save1 * primsav  -
primfriend * n1 / 4
        if adjust1 < 0 [ set adjust1 0 ]
        set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 +
loanincent + incentiveadjust + repay1
        ifelse lhs7 > lhs1 and lhs7 > lhs9 ; adjust7 < adjust1 and adjust7 < adjust9
          [ ifelse lhs7 > none ; priceconst + pricex * adjust7 + pricex2 * adjust7 *
adjust7 + loanincent + incentiveadjust + repay7 > none
              [ choice7 set improved ( improved + 1 ) ]
              [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ] ]
          ]
          [ ifelse lhs9 >= lhs7 and lhs9 > lhs1 ; adjust9 <= adjust7 and adjust9 <
adjust1
              [ ifelse priceconst + pricex * adjust9 + pricex2 * adjust9 * adjust9 +
loanincent + incentiveadjust + repay9 > none
                [ choice9 set improved ( improved + 1 )  ]
```

```
                    [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal
15 5 set upgradetime 0 ] ]
                  ]
                 [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ]  ]
              ]
        ]

     if detach = 2
       [   heat8price heat9price
          set n1 count (houses-on neighbors) with [ heat = 1 ] set save1 0 set
repayment1 (save1 / 12) * (paybackrate / 100 )
          set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 *
repayment1 + repayx3 * repayment1 * repayment1 * repayment1
          set adjust1 condensfixed + condensmain * primmain - save1 * primsav  -
primfriend * n1 / 4             if adjust1 < 0 [ set adjust1 0 ]
          set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 +
loanincent + incentiveadjust + repay1
          ifelse lhs8 > lhs1 and lhs8 >= lhs9
             [ ifelse lhs8 > none
                 [ choice8 set improved ( improved + 1 )  ]
                 [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ] ]
              ]
             [ ifelse lhs9 > lhs8 and lhs9 > lhs1
                 [ ifelse lhs9 > none
                     [ choice9 set improved ( improved + 1 ) ]
                     [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal
15 5 set upgradetime 0 ] ]
                  ]
                 [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ]  ]
              ]
        ]
   ]

  [ ifelse heat = 2
     [  set runningcost ( heatkwh * gas-price + gas-standing + electrickwh * elec )
       if detach = 1
          [    set idref1 idnumber - 100 set idref6 idnumber + 400 set idref8 idnumber +
600 set idref9 idnumber + 700 create-link-with one-of refhouses with [idnumber =
idref8 ]
             set heatgshp [heatkwh] of one-of link-neighbors ask my-links [die]
heat6price heat8price heat1price heat9price
             ifelse lhs8 >= lhs6 and lhs8 > lhs1 and lhs8 > lhs9
               [    ifelse lhs8 > none
                   [ choice8 set improved ( improved + 1 ) ]
```

```
                    [ if boiler-life < upgradetime
                      [ create-link-with one-of refhouses with [idnumber = idref1 ]
; If new tech not adopted and boiler breakdown have to change to condensing
                        set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                        set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                        set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                        set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                        set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                      ]
                    ]
                ]
                [ ifelse lhs6 > lhs8 and lhs6 > lhs1 and lhs6 > lhs9
                    [ ifelse lhs6 > none
                        [ choice6 set improved ( improved + 1 ) ]
                        [ if boiler-life < upgradetime
                          [ create-link-with one-of refhouses with [idnumber = idref1 ]
                            set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                            set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                            set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                            set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                            set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                          ]
                        ]
                    ]
                    [ ifelse lhs9 >= lhs8 and lhs9 > lhs6 and lhs9 > lhs1
                        [ ifelse lhs9 > none
                            [ choice9 set improved ( improved + 1 ) ]
                            [ if boiler-life < upgradetime
                              [ create-link-with one-of refhouses with [idnumber = idref1 ]
                                set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                                set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of
one-of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
```

```
                              set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh]
of one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15
5 set upgradetime 0
                              set oldidnumber idnumber set oldidlist fput idnumber oldidlist
set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                              set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                              ]
                            ]
                        ]
                        [ if boiler-life < upgradetime
                          [ create-link-with one-of refhouses with [idnumber = idref1 ]
                            set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                            set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                            set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                            set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                            set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                          ]
                        ]
                      ]
                    ]
                 ]
        if detach = 3
           [ set idref7 idnumber + 500 set idref1 idnumber - 100 set idref9 idnumber +
700 heat7price heat1price heat9price
            ifelse lhs7 > lhs1 and lhs7 > lhs9
              [ ifelse lhs7 > none
                 [ choice7 set improved ( improved + 1 ) ]
                 [ if boiler-life < upgradetime
                   [ create-link-with one-of refhouses with [idnumber = idref1 ]
                     set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                     set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                     set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                     set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist set idnumber idref1
                     set improved ( improved + 1 ) set subgrant1 boilergrant set cost1
cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
```

```
                    ]
                  ]
               ]
              [ ifelse lhs9 >= lhs7 and lhs9 > lhs1
                 [ ifelse lhs9 > none
                    [ choice9 set improved ( improved + 1 ) ]
                    [ if boiler-life < upgradetime
                      [ create-link-with one-of refhouses with [idnumber = idref1 ]
                       set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                       set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                       set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                       set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                       set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                      ]
                    ]
                  ]
                 [ if boiler-life < upgradetime
                   [ create-link-with one-of refhouses with [idnumber = idref1 ]
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                   ]
                 ]
              ]
           ]
       if detach = 2
          [ set idref8 idnumber + 600 set idref1 idnumber - 100 set idref9 idnumber +
700
           create-link-with one-of refhouses with [idnumber = idref8 ] set heatgshp
[heatkwh] of one-of link-neighbors ask my-links [die]
           heat8price heat1price heat9price
           ifelse lhs8 > lhs1 and lhs8 > lhs9
             [ ifelse lhs8 > none
```

```
                    [ choice8 set improved ( improved + 1 ) ]
                    [ if boiler-life < upgradetime
                      [ create-link-with one-of refhouses with [idnumber = idref1 ]
                       set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                       set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                       set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                       set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                       set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                      ]
                     ]
                 ]
                [ ifelse lhs9 >= lhs8 and lhs9 > lhs1
                    [ ifelse lhs9 > none
                        [ choice9 set improved ( improved + 1 ) ]
                        [ if boiler-life < upgradetime
                          [ create-link-with one-of refhouses with [idnumber = idref1 ]
                           set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                           set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                           set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                           set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                           set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                          ]
                        ]
                     ]
                    [ if boiler-life < upgradetime
                     [ create-link-with one-of refhouses with [idnumber = idref1 ]
                      set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                      set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                      set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
```

```
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                    ]
                  ]
               ]
           ]
      ]

     [ ifelse heat = 3
        [ set runningcost ( heatkwh * gas-price + gas-standing + electrickwh * elec )
         if detach = 1
           [ set idref1 idnumber - 200 set idref6 idnumber + 300 set idref8 idnumber +
500 set idref9 idnumber + 600
            heat6price heat8price heat1price heat9price
            ifelse lhs8 >= lhs6 and lhs8 > lhs1 and lhs8 > lhs9
             [ ifelse lhs8 > none
                [ choice8 set improved ( improved + 1 ) ]
                [ if boiler-life < upgradetime
                   [ create-link-with one-of refhouses with [idnumber = idref1 ]
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                    ]
                  ]
               ]
             [ ifelse lhs6 > lhs8 and lhs6 > lhs1 and lhs6 > lhs9
                [ ifelse lhs6 > none
                   [ choice6 set improved ( improved + 1 )  ]
                   [ if boiler-life < upgradetime
                      [ create-link-with one-of refhouses with [idnumber = idref1 ]
                       set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                       set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                       set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                       set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
```

```
                        set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                        ]
                      ]
                    ]
                   [ ifelse lhs9 >= lhs8 and lhs9 > lhs1 and lhs9 >= lhs6
                     [ ifelse lhs9 > none
                       [ choice9 set improved ( improved + 1 ) ]
                       [ if boiler-life < upgradetime
                         [ create-link-with one-of refhouses with [idnumber = idref1 ]
                          set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                          set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of
one-of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                          set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh]
of one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15
5 set upgradetime 0
                          set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                          set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1  set saving1 saving1 + sav1
                          ]
                        ]
                      ]
                     [ if boiler-life < upgradetime
                       [ create-link-with one-of refhouses with [idnumber = idref1 ]
                        set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                        set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                        set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                        set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                        set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                        ]
                      ]
                    ]
                  ]
                ]
              if detach = 3
               [ set idref7 idnumber + 400 set idref1 idnumber - 200 set idref9 idnumber +
600
                heat7price heat1price heat9price
                ifelse lhs7 > lhs1 and lhs7 > lhs9
```

```
          [ ifelse lhs7 > none
            [ choice7 set improved ( improved + 1 ) ]
            [ if boiler-life < upgradetime
              [ create-link-with one-of refhouses with [idnumber = idref1 ]
               set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
               set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
               set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
               set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
               set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
              ]
            ]
          ]
          [ ifelse lhs9 >= lhs7 and lhs9 > lhs1
            [ ifelse lhs9 > none
              [ choice9 set improved ( improved + 1 ) ]
              [ if boiler-life < upgradetime
                [ create-link-with one-of refhouses with [idnumber = idref1 ]
                 set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                 set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                 set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                 set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                 set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                ]
              ]
            ]
            [ if boiler-life < upgradetime
              [ create-link-with one-of refhouses with [idnumber = idref1 ]
               set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
               set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
               set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
```

```
                  set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                  set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                 ]
               ]
             ]
           ]
         if detach = 2
          [ set idref8 idnumber + 500 set idref1 idnumber - 200 set idref9 idnumber +
600
           heat8price heat1price heat9price
           ifelse lhs8 > lhs1 and lhs8 > lhs9
            [ ifelse lhs8 > none
              [ choice8 set improved ( improved + 1 ) ]
              [ if boiler-life < upgradetime
                [ create-link-with one-of refhouses with [idnumber = idref1 ]
                  set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                  set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                  set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                  set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                  set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                 ]
               ]
             ]
            [ ifelse lhs9 >= lhs8 and lhs9 > lhs1
              [ ifelse lhs9 > none
                [ choice9 set improved ( improved + 1 ) ]
                [ if boiler-life < upgradetime
                  [ create-link-with one-of refhouses with [idnumber = idref1 ]
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
```

```
              ]
            ]
          ]
          [ if boiler-life < upgradetime
            [ create-link-with one-of refhouses with [idnumber = idref1 ]
             set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
             set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
             set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
             set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
             set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
            ]
          ]
        ]
      ]
    ]

    [ ifelse heat = 4
      [ set runningcost ( heatkwh * oil-price + oil-standing + electrickwh * elec ) set
idref6 idnumber + 200 set idref8 idnumber + 400 set idref9 idnumber + 500
       heat6price heat8price heat9price
       set n4 count (houses-on neighbors) with [ heat = 4 ] set saving 0 set
repayment4 (saving / 12) * (paybackrate / 100 )
       set repay4 repayconst + repayx * repayment4 + repayx2 * repayment4 *
repayment4 + repayx3 * repayment4 * repayment4 * repayment4
       set adjust4 oilfixed + oilmain * primmain - primfriend * n4 / 4
       if adjust4 < 0 [ set adjust4 0 ]
       set lhs4 priceconst + pricex * adjust4 + pricex2 * adjust4 * adjust4 +
loanincent + incentiveadjust + repay4
       ifelse lhs4 > lhs6 and lhs8 > lhs4 and lhs8 > lhs9
        [ ifelse lhs8 > none
          [ choice8 set improved ( improved + 1 ) ]
          [ if boiler-life < upgradetime
            [ set boiler-life random-normal 15 5 set upgradetime 0 ]
          ]
        ]
        [ ifelse lhs6 >= lhs8 and lhs6 >= lhs4 and lhs6 >= lhs9
          [ ifelse lhs6 > none
           [ choice6 set improved ( improved + 1 ) ]
           [ if boiler-life < upgradetime
             [ set boiler-life random-normal 15 5 set upgradetime 0 ]
           ]
```

```
                  ]
                 [ ifelse lhs9 > lhs8 and lhs9 > lhs6 and lhs9 > lhs4
                   [ ifelse lhs9 > none
                     [ choice9 set improved ( improved + 1 ) ]
                     [ if boiler-life < upgradetime
                        [ set heat 4 set boiler-life random-normal 15 5 set upgradetime 0 ]
                      ]
                    ]
                   [ if boiler-life < upgradetime
                     [ set heat 4 set boiler-life random-normal 15 5 set upgradetime 0 ]
                    ]
                  ]
                ]
              ]

           [ ifelse heat = 5
             [ set runningcost ( 0.8 * elec-off-price * hkwh + 0.2 * elec-peak-price * hkwh
+ elec-off-standing + (1 - hrf) * elec-off-price * wkwh
                        + hrf * elec-peak-price * wkwh  + 0.81 * elec-peak-price *
electrickwh + 0.19 * elec-off-price * electrickwh )
                set idref6 idnumber + 100 set idref7 idnumber + 200 set idref8 idnumber +
300  set idref9 idnumber + 400
                ifelse detach = 3
                 [ set n5 count (houses-on neighbors) with [ heat = 5 ] set saving 0 set
repayment5 ( saving / 12 ) * (paybackrate / 100 )
                  set repay5 repayconst + repayx * repayment5 + repayx2 * repayment5 *
repayment5 + repayx3 * repayment5 * repayment5 * repayment5
                  set adjust5 elecfixed + elecmain * primmain - primfriend * n5 / 4
                  if adjust5 < 0 [ set adjust5 0 ]
                  set lhs5 priceconst + pricex * adjust5 + pricex2 * adjust5 * adjust5 +
loanincent + incentiveadjust + repay5
                  heat7price heat9price
                  ifelse lhs7 > lhs5 and lhs7 > lhs9
                   [ ifelse lhs7 > none
                     [ choice7 set improved ( improved + 1 ) ]
                     [ if boiler-life < upgradetime
                        [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0 ]
                      ]
                    ]
                   [ ifelse lhs9 >= lhs7 and lhs9 > lhs5
                     [ ifelse lhs9 > none
                        [ choice9 set improved ( improved + 1 ) ]
                        [ if boiler-life < upgradetime
                           [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0
]
                         ]
                      ]
```

```
                  [ if boiler-life < upgradetime
                     [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0 ]
                   ]
                ]
              ]

             [ set n5 count (houses-on neighbors) with [ heat = 5 ] set saving 0 set
repayment5 ( saving / 12 ) * (paybackrate / 100 )
              set repay5 repayconst + repayx * repayment5 + repayx2 * repayment5 *
repayment5 + repayx3 * repayment5 * repayment5 * repayment5
              set adjust5 elecfixed + elecmain * primmain - primfriend * n5 / 4
              if adjust5 < 0 [ set adjust5 0 ]
              set lhs5 priceconst + pricex * adjust5 + pricex2 * adjust5 * adjust5 +
loanincent + incentiveadjust + repay5
              heat7price heat6price heat8price heat9price
              ifelse lhs8 > lhs5 and lhs8 > lhs7 and lhs8 > lhs6 and lhs8 > lhs9
               [ ifelse lhs8 > none
                  [ choice8 set improved ( improved + 1 ) ]
                  [ if boiler-life < upgradetime
                     [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0 ]
                   ]
                ]
               [ ifelse lhs7 >= lhs8 and lhs7 > lhs6 and lhs7 > lhs5 and lhs7 > lhs9
                  [ ifelse lhs7 > none
                     [ choice7 set improved ( improved + 1 ) ]
                     [ if boiler-life < upgradetime
                        [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0
]
                      ]
                   ]
                  [ ifelse lhs6 >= lhs7 and lhs6 >= lhs8 and lhs6 > lhs5 and lhs6 > lhs9
                     [ ifelse lhs6 > none
                        [ choice6  set improved ( improved + 1 ) ]
                        [ if boiler-life < upgradetime
                           [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                         ]
                      ]
                     [ ifelse lhs9 >= lhs6 and lhs9 >= lhs7 and lhs9 >= lhs8 and lhs9 > lhs5
                        [ ifelse lhs9 > none
                           [ choice9 set improved ( improved + 1 ) ]
                           [ if boiler-life < upgradetime
                              [ set heat 5 set boiler-life random-normal 15 5 set
upgradetime 0 ]
                            ]
                         ]
                        [ if boiler-life < upgradetime
```

```
                              [ set heat 5 set boiler-life random-normal 15 5 set
upgradetime 0 ]
                            ]
                          ]
                        ]
                      ]
                    ]
                  ]

                [ ifelse heat = 6 and boiler-life < upgradetime
                  [ set runningcost ( heatkwh * solid-price + electrickwh * elec ) set
potimprov potimprov - 1 set potswap potswap + 1 set idref7 idnumber + 100
                    set idref8 idnumber + 200 set idref9 idnumber + 300 set n6 count
(houses-on neighbors) with [ heat = 6 ] set saving 0
                    set repayment6 ( saving / 12 ) * ( paybackrate / 100 )
                    set repay6 repayconst + repayx * repayment6 + repayx2 * repayment6 *
repayment6 + repayx3 * repayment6 * repayment6 * repayment6
                    set adjust6 biomass + fuelstore + cupboard + biomassmain * primmain -
primfriend * n6 / 4
                    if adjust6 < 0 [ set adjust6 0 ]
                    set lhs6 priceconst + pricex * adjust6 + pricex2 * adjust6 * adjust6 +
loanincent + incentiveadjust + repay6
                    heat8price heat9price
                    ifelse lhs8 > lhs6 and lhs8 > lhs9
                      [ ifelse lhs8 > none
                          [ choice8 set changed ( changed + 1 )]
                          [ if boiler-life < upgradetime
                            [ set boiler-life random-normal 15 5 set upgradetime 0 ask people-
here [set inst6 0] ]
                          ]
                      ]
                      [ ifelse lhs9 > lhs6 and lhs9 >= lhs8
                          [ ifelse lhs9 > none
                              [ choice9 set changed ( changed + 1 )]
                              [ if boiler-life < upgradetime
                                  [ set boiler-life random-normal 15 5 set upgradetime 0 ask
people-here [set inst6 0] ]
                              ]
                          ]
                          [ if boiler-life < upgradetime
                              [ set boiler-life random-normal 15 5 set upgradetime 0 ask people-
here [set inst6 0] ]
                          ]
                      ]
                  ]

                  [ ifelse heat = 8 and boiler-life < upgradetime
```

```
                    [ set runningcost ( hkwh * 0.8 * elec-peak-price + hkwh * 0.2 * elec-off-
price + wkwh * 0.7 * elec-peak-price + wkwh * 0.3 * elec-off-price
                                  + electrickwh * (elec-peak-price * 0.81 + elec-off-price *
0.19) + elec-off-standing )
                     set potimprov potimprov - 1 set potswap potswap + 1 set idref6
idnumber - 200  set idref9 idnumber + 100
                     set n8 count (houses-on neighbors) with [ heat = 8 ] set saving 0 set
repayment8 ( saving / 12 ) * (paybackrate / 100 )
                     set repay8 repayconst + repayx * repayment8 + repayx2 * repayment8
* repayment8 + repayx3 * repayment8 * repayment8 * repayment8
                     set adjust8 gshpfixed + gshpmarg * heatgshp / 1200 + garden +
cupboard + gshpmain * primmain - primfriend * n8 / 4
                       if adjust8 < 0 [ set adjust8 0 ]
                       set lhs8 priceconst + pricex * adjust8 + pricex2 * adjust8 * adjust8 +
loanincent + incentiveadjust + repay8
                       ifelse detach = 3
                         [ heat6price heat9price
                          ifelse lhs6 > lhs8 and lhs6 >= lhs9
                           [ ifelse lhs6 > none
                             [ choice6 set changed ( changed + 1 )]
                             [ if boiler-life < upgradetime
                               [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                              ]
                            ]
                           [ ifelse lhs9 > lhs8 and lhs9 > lhs6
                              [ ifelse lhs9 > none
                                [ choice9 set changed ( changed + 1 )]
                                [ if boiler-life < upgradetime
                                  [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                 ]
                               ]
                              [ if boiler-life < upgradetime
                                [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                               ]
                            ]
                          ]
                         [ ifelse detach = 1
                          [ heat6price heat9price
                            ifelse lhs6 > lhs8 and lhs6 >= lhs9
                              [ ifelse lhs6 > none
                                 [ choice6 set changed ( changed + 1 )]
                                 [ if boiler-life < upgradetime
                                    [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                  ]
                               ]
                              [ ifelse lhs9 > lhs6 and lhs9 > lhs8
                                [ ifelse lhs9 > none
```

```
                                        [ choice9 set changed ( changed + 1 )]
                                        [ if boiler-life < upgradetime
                                          [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                         ]
                                      ]
                                     [ if boiler-life < upgradetime
                                        [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                      ]
                                    ]
                                 ]
                                [ heat9price
                                 if lhs9 > lhs8
                                   [ ifelse lhs9 > none
                                      [ choice9 set changed ( changed + 1 ) ]
                                      [ if boiler-life < upgradetime
                                         [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                       ]
                                    ]
                                 ]
                               ]
                           ]
                          [ ifelse heat = 9 and boiler-life < upgradetime
                             [ set runningcost ( hkwh * 0.8 * elec-peak-price + hkwh * 0.2 * elec-
off-price + wkwh * 0.7 * elec-peak-price + wkwh * 0.3 * elec-off-price
                                         + electrickwh * (elec-peak-price * 0.81 + elec-off-price *
0.19) + elec-off-standing )
                               set potimprov potimprov - 1 set potswap potswap + 1 set idref6
idnumber - 300  set idref7 idnumber - 200 set idref8 idnumber - 100
                               set n9 count (houses-on neighbors) with [ heat = 9 ] set saving 0 set
repayment9 ( saving / 12 ) * (paybackrate / 100 )
                               set repay9 repayconst + repayx * repayment9 + repayx2 *
repayment9 * repayment9 + repayx3 * repayment9 * repayment9 * repayment9
                               set adjust9 ashpfixed + ashpmarg * heatashp / 1200 + cupboard +
ashpmain * primmain - primfriend * n9 / 4
                               if adjust9 < 0 [ set adjust9 0 ]
                               set lhs9 priceconst + pricex * adjust9 + pricex2 * adjust9 * adjust9 +
loanincent + incentiveadjust + repay9
                               ifelse detach = 3
                                [ heat7price
                                 ifelse lhs7 > lhs9
                                   [ ifelse lhs7 > none
                                      [ choice7 set changed (changed + 1) ]
                                      [ if boiler-life < upgradetime
                                         [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                      ]
                                    ]
                                   [ if boiler-life < upgradetime
```

```
                  [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                ]
              ]
              [ ifelse detach = 1
               [ heat8price heat6price
                 ifelse lhs8 > lhs9 and lhs8 >= lhs6
                   [ ifelse lhs8 > none
                       [ choice8 set changed ( changed + 1 )]
                       [ if boiler-life < upgradetime
                         [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                        ]
                    ]
                   [ ifelse lhs6 > lhs9 and lhs6 > lhs8
                       [ ifelse lhs6 > none
                           [ choice6 set changed ( changed + 1 )]
                           [ if boiler-life < upgradetime
                               [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                            ]
                        ]
                       [ if boiler-life < upgradetime
                           [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                        ]
                    ]
                ]
               [ heat8price
                 if lhs8 > lhs9
                  [ ifelse lhs8 > none
                       [ choice8 set changed ( changed + 1 )]
                       [ if boiler-life < upgradetime
                         [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                        ]
                   ]
               ]
              ]
            ]
           [ if boiler-life < upgradetime
              [ set boiler-life random-normal 15 5 set upgradetime 0 ]
            ]
          ]
        ]
      ]
    ]
   ]
  ]
 ]

ask my-links [die ]
```

```
end




to discretionary

set potchange potchange + 1 set potimprov potimprov + 1
; increase count of potential improvements
set fuelstore [ fuelstore ] of one-of people-here set garden [ garden ] of one-of people-
here set cupboard [ cupboard ] of one-of people-here

ifelse heat = 1
  [   set idref6 idnumber + 500 set idref7 idnumber + 600 set idref8 idnumber + 700
set idref9 idnumber + 800
      ; idref numbers used to refer to the reference houses
      ; to determine the extent of energy savings available
      set runningcost ( heatkwh * gas-price + gas-standing + electrickwh * elec )
      create-link-with one-of refhouses with [idnumber = idref8 ] set heatgshp
[heatkwh] of one-of link-neighbors ask my-links [die]
      create-link-with one-of refhouses with [idnumber = idref9 ] set heatashp
[heatkwh] of one-of link-neighbors ask my-links [die]

      if detach = 1
        [   discheat6price discheat9price discheat8price
; runs subroutines to calculate savings available from different heating options
           set n1 count (houses-on neighbors) with [ heat = 1 ] set save1 0 set
repayment1 (save1 / 12) * (paybackrate / 100 )
           set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 *
repayment1 + repayx3 * repayment1 * repayment1 * repayment1
           set adjust1 condensfixed + condensmain * discmain  - discfriend * n1 / 4
           if adjust1 < 0 [ set adjust1 0 ]
           set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 +
loanincent + incentiveadjust + repay1
            ; calculation of running costs with existing technology and adjusted price
           ifelse lhs8 >= lhs6 and lhs8 > lhs1 and lhs8 > lhs9 ;  adjust8 <= adjust6 and
adjust8 < adjust1 and adjust8 < adjust9
           ; if adjusted price of 8 (ground source heat pump) is cheapest of alternatives
available decision algorithm used to determine whether to install
             [ ifelse lhs8 > none
               [ choice8 set improved ( improved + 1 )  ] ; if threshold reached new
technology installed
               [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15 5
set upgradetime 0 ] ]
               ; if threshold not reached existing technology remains
               ; renewed if boiler has broken down
```

```
             ]
            [ ifelse lhs6 > lhs8 and lhs6 > lhs1 and lhs6 >= lhs9
; if adjusted price of 6 (solid fuel) was cheapest, decision made to consider that instead
              [ ifelse lhs6 > none
                 [ choice6 set improved ( improved + 1 ) ]
                 [set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ] ]
              ]
              [ ifelse lhs9 > lhs8 and lhs9 > lhs6 and lhs9 > lhs1
                 [ ifelse lhs9 > none
                    [ choice9 set improved ( improved + 1 ) ]
                    [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal
15 5 set upgradetime 0 ] ]
                 ]
                 [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ]  ]
              ]
            ]
         ]

      if detach = 3
        [   discheat7price discheat9price
           set n1 count (houses-on neighbors) with [ heat = 1 ] set save1 0 set
repayment1 (save1 / 12) * (paybackrate / 100 )
           set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 *
repayment1 + repayx3 * repayment1 * repayment1 * repayment1
           set adjust1 condensfixed + condensmain * discmain - discfriend * n1 / 4
           if adjust1 < 0 [ set adjust1 0 ]
           set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 +
loanincent + incentiveadjust + repay1
           ifelse lhs7 > lhs1 and lhs7 > lhs9
              [ ifelse lhs7 > none
                 [ choice7 set improved ( improved + 1 ) ]
                 [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ] ]
              ]
              [ ifelse lhs9 >= lhs7 and lhs9 > lhs1
                 [ ifelse lhs9 > none
                    [ choice9 set improved ( improved + 1 )  ]
                    [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal
15 5 set upgradetime 0 ] ]
                  ]
                 [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ]  ]
              ]
         ]
```

```
    if detach = 2
      [   discheat8price discheat9price
          set n1 count (houses-on neighbors) with [ heat = 1 ] set save1 0 set
repayment1 (save1 / 12) * (paybackrate / 100 )
          set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 *
repayment1 + repayx3 * repayment1 * repayment1 * repayment1
          set adjust1 condensfixed + condensmain * discmain - discfriend * n1 / 4
          if adjust1 < 0 [ set adjust1 0 ]
          set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 +
loanincent + incentiveadjust + repay1
          ifelse lhs8 > lhs1 and lhs8 >= lhs9
            [ ifelse lhs8 > none
              [ choice8 set improved ( improved + 1 )  ]
              [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ] ]
            ]
            [ ifelse lhs9 > lhs8 and lhs9 > lhs1
              [ ifelse lhs9 > none
                [ choice9 set improved ( improved + 1 ) ]
                [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal
15 5 set upgradetime 0 ] ]
              ]
              [ set heat 1 if boiler-life < upgradetime [ set boiler-life random-normal 15
5 set upgradetime 0 ]  ]
            ]
        ]
    ]

  [ ifelse heat = 2
     [  set runningcost ( heatkwh * gas-price + gas-standing + electrickwh * elec )
       if detach = 1
         [    set idref1 idnumber - 100 set idref6 idnumber + 400 set idref8 idnumber +
600 set idref9 idnumber + 700 create-link-with one-of refhouses with [idnumber =
idref8 ]
             set heatgshp [heatkwh] of one-of link-neighbors ask my-links [die]
discheat6price discheat8price discheat1price discheat9price
             ifelse lhs8 >= lhs6 and lhs8 > lhs1 and lhs8 > lhs9
               [    ifelse lhs8 > none
                  [ choice8 set improved ( improved + 1 ) ]
                  [ if boiler-life < upgradetime
                    [ create-link-with one-of refhouses with [idnumber = idref1 ]
                      set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
```

```
                         set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                         set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                         set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                        ]
                      ]
                ]
                [ ifelse lhs6 > lhs8 and lhs6 > lhs1 and lhs6 > lhs9
                    [ ifelse lhs6 > none
                        [ choice6 set improved ( improved + 1 ) ]
                        [ if boiler-life < upgradetime
                          [ create-link-with one-of refhouses with [idnumber = idref1 ]
                           set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                           set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                           set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                           set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                           set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                          ]
                        ]
                    ]
                    [ ifelse lhs9 >= lhs8 and lhs9 >= lhs6 and lhs9 > lhs1
                        [ ifelse lhs9 > none
                            [ choice9 set improved ( improved + 1 ) ]
                            [ if boiler-life < upgradetime
                              [ create-link-with one-of refhouses with [idnumber = idref1 ]
                               set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                               set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of
one-of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                               set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh]
of one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15
5 set upgradetime 0
                               set oldidnumber idnumber set oldidlist fput idnumber oldidlist
set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                               set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                              ]
                            ]
```

```
                    ]
                    [ if boiler-life < upgradetime
                      [ create-link-with one-of refhouses with [idnumber = idref1 ]
                        set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                        set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                        set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                        set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                        set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                      ]
                    ]
                  ]
                ]
              ]
        if detach = 3
          [ set idref7 idnumber + 500 set idref1 idnumber - 100 set idref9 idnumber +
700 discheat7price discheat1price discheat9price
           ifelse lhs7 > lhs1 and lhs7 > lhs9
             [ ifelse lhs7 > none
                 [ choice7 set improved ( improved + 1 ) ]
                 [ if boiler-life < upgradetime
                   [ create-link-with one-of refhouses with [idnumber = idref1 ]
                     set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                     set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                     set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                     set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist set idnumber idref1
                     set improved ( improved + 1 ) set subgrant1 boilergrant set cost1
cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                   ]
                 ]
             ]
             [ ifelse lhs9 >= lhs7 and lhs9 > lhs1
                 [ ifelse lhs9 > none
                     [ choice9 set improved ( improved + 1 ) ]
                     [ if boiler-life < upgradetime
                       [ create-link-with one-of refhouses with [idnumber = idref1 ]
```

```
                          set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                          set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                          set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                          set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                          set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                         ]
                       ]
                   ]
                  [ if boiler-life < upgradetime
                    [ create-link-with one-of refhouses with [idnumber = idref1 ]
                      set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                      set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                      set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                      set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                     ]
                   ]
               ]
           ]
       if detach = 2
          [ set idref8 idnumber + 600 set idref1 idnumber - 100 set idref9 idnumber +
700
            create-link-with one-of refhouses with [idnumber = idref8 ] set heatgshp
[heatkwh] of one-of link-neighbors ask my-links [die]
            discheat8price discheat1price discheat9price
            ifelse lhs8 > lhs1 and lhs8 > lhs9
              [ ifelse lhs8 > none
                  [ choice8 set improved ( improved + 1 ) ]
                  [ if boiler-life < upgradetime
                    [ create-link-with one-of refhouses with [idnumber = idref1 ]
                      set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
```

```
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                   ]
                 ]
              ]
             [ ifelse lhs9 >= lhs8 and lhs9 > lhs1 ; adjust9 <= adjust8 and adjust9 <
adjust1
                [ ifelse lhs9 > none ; priceconst + pricex * adjust9 + pricex2 * adjust9 *
adjust9 + loanincent + incentiveadjust + repay9 > none
                   [ choice9 set improved ( improved + 1 ) ]
                   [ if boiler-life < upgradetime
                     [ create-link-with one-of refhouses with [idnumber = idref1 ]
                       set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                       set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                       set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                       set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                       set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                      ]
                    ]
                 ]
                [ if boiler-life < upgradetime
                  [ create-link-with one-of refhouses with [idnumber = idref1 ]
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                  ]
                 ]
              ]
```

```
          ]
        ]

      [ ifelse heat = 3
        [ set runningcost ( heatkwh * gas-price + gas-standing + electrickwh * elec )
          if detach = 1
           [ set idref1 idnumber - 200 set idref6 idnumber + 300 set idref8 idnumber +
500 set idref9 idnumber + 600
             discheat6price discheat8price discheat1price discheat9price
             ifelse lhs8 >= lhs6 and lhs8 > lhs1 and lhs8 > lhs9
              [ ifelse lhs8 > none
                 [ choice8 set improved ( improved + 1 ) ]
                 [ if boiler-life < upgradetime
                    [ create-link-with one-of refhouses with [idnumber = idref1 ]
                      set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                      set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                      set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                      set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                    ]
                 ]
              ]
              [ ifelse lhs6 > lhs8 and lhs6 > lhs1 and lhs6 > lhs9
                 [ ifelse lhs6 > none
                    [ choice6 set improved ( improved + 1 )  ]
                    [ if boiler-life < upgradetime
                       [ create-link-with one-of refhouses with [idnumber = idref1 ]
                         set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                         set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                         set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                         set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                         set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                       ]
                    ]
                 ]
```

```
[ ifelse lhs9 >= lhs8 and lhs9 > lhs1 and lhs9 >= lhs6
   [ ifelse lhs9 > none
      [ choice9 set improved ( improved + 1 ) ]
      [ if boiler-life < upgradetime
         [ create-link-with one-of refhouses with [idnumber = idref1 ]
           set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
           set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
           set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5 set upgradetime 0
           set oldidnumber idnumber set oldidlist fput idnumber oldidlist set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
           set idnumber idref1 set improved ( improved + 1 ) set subgrant1 boilergrant set cost1 cost1 + subnpv1 + subgrant1  set saving1 saving1 + sav1
         ]
      ]
   ]
   [ if boiler-life < upgradetime
      [ create-link-with one-of refhouses with [idnumber = idref1 ]
        set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
        set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
        set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5 set upgradetime 0
        set oldidnumber idnumber set oldidlist fput idnumber oldidlist set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
        set idnumber idref1 set improved ( improved + 1 ) set subgrant1 boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
      ]
   ]
]
]
]
if detach = 3
 [ set idref7 idnumber + 400 set idref1 idnumber - 200 set idref9 idnumber + 600
  discheat7price discheat1price discheat9price
  ifelse lhs7 > lhs1 and lhs7 > lhs9
    [ ifelse lhs7 > none
       [ choice7 set improved ( improved + 1 ) ]
       [ if boiler-life < upgradetime
          [ create-link-with one-of refhouses with [idnumber = idref1 ]
```

```
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                   ]
                 ]
               ]
              [ ifelse lhs9 >= lhs7 and lhs9 > lhs1
                [ ifelse lhs9 > none
                  [ choice9 set improved ( improved + 1 ) ]
                  [ if boiler-life < upgradetime
                    [ create-link-with one-of refhouses with [idnumber = idref1 ]
                      set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                      set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                      set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                      set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                      set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                    ]
                  ]
                ]
                [ if boiler-life < upgradetime
                  [ create-link-with one-of refhouses with [idnumber = idref1 ]
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                  ]
```

```
            ]
          ]
        ]
      if detach = 2
       [ set idref8 idnumber + 500 set idref1 idnumber - 200 set idref9 idnumber +
600
         discheat8price discheat1price discheat9price
         ifelse lhs8 > lhs1 and lhs8 > lhs9 ; adjust8 < adjust1 and adjust8 < adjust9
           [ ifelse lhs8 > none
             [ choice8 set improved ( improved + 1 ) ]
             [ if boiler-life < upgradetime
               [ create-link-with one-of refhouses with [idnumber = idref1 ]
                set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
               ]
             ]
           ]
           [ ifelse lhs9 >= lhs8 and lhs9 > lhs1
             [ ifelse lhs9 > none
               [ choice9 set improved ( improved + 1 ) ]
               [ if boiler-life < upgradetime
                 [ create-link-with one-of refhouses with [idnumber = idref1 ]
                  set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors ) *
elec-co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                  set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                  set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                  set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                  set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                 ]
               ]
             ]
             [ if boiler-life < upgradetime
               [ create-link-with one-of refhouses with [idnumber = idref1 ]
```

```
                    set sav1 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-
co2 + (heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * gas-co2)
                    set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set electrickwh [electrickwh] of one-of link-neighbors
                    set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die] set heat 1 set boiler-life random-normal 15 5
set upgradetime 0
                    set oldidnumber idnumber set oldidlist fput idnumber oldidlist set
oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
                    set idnumber idref1 set improved ( improved + 1 ) set subgrant1
boilergrant set cost1 cost1 + subnpv1 + subgrant1 set saving1 saving1 + sav1
                    ]
                  ]
                ]
              ]
            ]

          [ ifelse heat = 4
            [ set runningcost ( heatkwh * oil-price + oil-standing + electrickwh * elec ) set
idref6 idnumber + 200 set idref8 idnumber + 400 set idref9 idnumber + 500
              discheat6price discheat8price discheat9price
              set n4 count (houses-on neighbors) with [ heat = 4 ] set saving 0 set
repayment4 (saving / 12) * (paybackrate / 100 )
              set repay4 repayconst + repayx * repayment4 + repayx2 * repayment4 *
repayment4 + repayx3 * repayment4 * repayment4 * repayment4
              set adjust4 oilfixed + oilmain * primmain - primfriend * n4 / 4
              if adjust4 < 0 [ set adjust4 0 ]
              set lhs4 priceconst + pricex * adjust4 + pricex2 * adjust4 * adjust4 +
loanincent + incentiveadjust + repay4
              ifelse lhs8 > lhs6 and lhs8 > lhs4 and lhs8 > lhs9
               [ ifelse lhs8 > none
                 [ choice8 set improved ( improved + 1 ) ] ; set subsidycost subsidycost +
subnpv8 + subgrant8 ]
                 [ if boiler-life < upgradetime
                   [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                 ]
               ]
               [ ifelse lhs6 >= lhs8 and lhs6 >= lhs4 and lhs6 >= lhs9
                 [ ifelse lhs6 > none
                  [ choice6 set improved ( improved + 1 ) ]
                  [ if boiler-life < upgradetime
                    [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                   ]
                 ]
                 [ ifelse lhs9 > lhs8 and lhs9 > lhs6 and lhs9 > lhs4
                    [ ifelse lhs9 > none
                      [ choice9 set improved ( improved + 1 ) ]
```

```
                  [ if boiler-life < upgradetime
                     [ set heat 4 set boiler-life random-normal 15 5 set upgradetime 0 ]
                   ]
                 ]
                [ if boiler-life < upgradetime
                   [ set heat 4 set boiler-life random-normal 15 5 set upgradetime 0 ]
                 ]
               ]
             ]
           ]

           [ ifelse heat = 5
              [ set runningcost ( 0.8 * elec-off-price * hkwh + 0.2 * elec-peak-price * hkwh
+ elec-off-standing + (1 - hrf) * elec-off-price * wkwh
                         + hrf * elec-peak-price * wkwh  + 0.81 * elec-peak-price *
electrickwh + 0.19 * elec-off-price * electrickwh )
               set idref6 idnumber + 100 set idref7 idnumber + 200 set idref8 idnumber +
300  set idref9 idnumber + 400
               ifelse detach = 3
                [ set n5 count (houses-on neighbors) with [ heat = 5 ] set saving 0 set
repayment5 ( saving / 12 ) * (paybackrate / 100 )
                 set repay5 repayconst + repayx * repayment5 + repayx2 * repayment5 *
repayment5 + repayx3 * repayment5 * repayment5 * repayment5
                 set adjust5 elecfixed + elecmain * primmain - primfriend * n5 / 4
                 if adjust5 < 0 [ set adjust5 0 ]
                 set lhs5 priceconst + pricex * adjust5 + pricex2 * adjust5 * adjust5 +
loanincent + incentiveadjust + repay5
                 discheat7price discheat9price
                 ifelse lhs7 > lhs5 and lhs7 > lhs9 ; adjust7 < adjust5 and adjust7 < adjust9
                  [ ifelse  lhs7 > none ; priceconst + pricex * adjust7 + pricex2 * adjust7 *
adjust7 + loanincent + incentiveadjust + repay7  > none
                   [ choice7 set improved ( improved + 1 ) ]
                   [ if boiler-life < upgradetime
                      [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0 ]
                    ]
                  ]
                 [ ifelse lhs9 >= lhs7 and lhs9 > lhs5
                   [ ifelse lhs9 > none
                      [ choice9 set improved ( improved + 1 ) ]
                      [ if boiler-life < upgradetime
                         [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0
]
                       ]
                    ]
                   [ if boiler-life < upgradetime
                      [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0 ]
                    ]
```

```
]
]

[ set n5 count (houses-on neighbors) with [ heat = 5 ] set saving 0 set
repayment5 ( saving / 12 ) * (paybackrate / 100 )
set repay5 repayconst + repayx * repayment5 + repayx2 * repayment5 *
repayment5 + repayx3 * repayment5 * repayment5 * repayment5
set adjust5 elecfixed + elecmain * discmain - saving * discsav -
discfriend * n5 / 4
if adjust5 < 0 [ set adjust5 0 ]
set lhs5 priceconst + pricex * adjust5 + pricex2 * adjust5 * adjust5 +
loanincent + incentiveadjust + repay5
discheat7price discheat6price discheat8price discheat9price
ifelse lhs8 > lhs5 and lhs8 > lhs7 and lhs8 > lhs6 and lhs8 > lhs9
  [ ifelse priceconst + pricex * adjust8 + pricex2 * adjust8 * adjust8 +
loanincent + incentiveadjust + repay8  > none
    [ choice8 set improved ( improved + 1 ) ]
    [ if boiler-life < upgradetime
      [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0 ]
    ]
  ]
  [ ifelse lhs7 >= lhs8 and lhs7 > lhs6 and lhs7 > lhs5 and lhs7 > lhs9 ;
adjust7 <= adjust8 and adjust7 < adjust6 and adjust7 < adjust5 and adjust7 < adjust9
    [ ifelse lhs7 > none
      [ choice7 set improved ( improved + 1 ) ]
      [ if boiler-life < upgradetime
        [ set heat 5 set boiler-life random-normal 15 5 set upgradetime 0
]
      ]
    ]
    [ ifelse lhs6 >= lhs7 and lhs6 >= lhs8 and lhs6 > lhs5 and lhs6 > lhs9
      [ ifelse lhs6 > none
        [ choice6  set improved ( improved + 1 ) ]
        [ if boiler-life < upgradetime
          [ set boiler-life random-normal 15 5 set upgradetime 0 ]
        ]
      ]
      [ ifelse lhs9 >= lhs6 and lhs9 >= lhs7 and lhs9 >= lhs8 and lhs9 > lhs5
        [ ifelse lhs9 > none
          [ choice9 set improved ( improved + 1 ) ]
          [ if boiler-life < upgradetime
            [ set heat 5 set boiler-life random-normal 15 5 set
upgradetime 0 ]
          ]
        ]
        [ if boiler-life < upgradetime
```

```
                                  [ set heat 5 set boiler-life random-normal 15 5 set
upgradetime 0 ]
                                ]
                              ]
                            ]
                          ]
                        ]
                      ]

                    [ ifelse heat = 6 and boiler-life < upgradetime
                      [ set runningcost ( heatkwh * solid-price + electrickwh * elec ) set
potimprov potimprov - 1 set potswap potswap + 1 set idref7 idnumber + 100
                        set idref8 idnumber + 200 set idref9 idnumber + 300 set n6 count
(houses-on neighbors) with [ heat = 6 ] set saving 0
                        set repayment6 ( saving / 12 ) * ( paybackrate / 100 )
                        set repay6 repayconst + repayx * repayment6 + repayx2 * repayment6 *
repayment6 + repayx3 * repayment6 * repayment6 * repayment6
                        set adjust6 biomass + fuelstore + cupboard + biomassmain * discmain -
discfriend * n6 / 4
                        if adjust6 < 0 [ set adjust6 0 ]
                        discheat8price discheat9price
                        ifelse lhs8 > lhs6 and lhs8 > lhs9
                          [ ifelse lhs8 > none
                            [ choice8 set changed ( changed + 1 )]
                            [ if boiler-life < upgradetime
                              [ set boiler-life random-normal 15 5 set upgradetime 0 ask people-
here [set inst6 0] ]
                            ]
                          ]
                          [ ifelse lhs9 > lhs6 and lhs9 >= lhs8
                            [ ifelse priceconst + pricex * adjust9 + pricex2 * adjust9 * adjust9 +
loanincent + incentiveadjust + repay9  > none
                              [ choice9 set changed ( changed + 1 )]
                              [ if boiler-life < upgradetime
                                [ set boiler-life random-normal 15 5 set upgradetime 0 ask
people-here [set inst6 0] ]
                              ]
                            ]
                            [ if boiler-life < upgradetime
                              [ set boiler-life random-normal 15 5 set upgradetime 0 ask people-
here [set inst6 0] ]
                            ]
                          ]
                        ]

                      [ ifelse heat = 8 and boiler-life < upgradetime
```

```
                    [ set runningcost ( hkwh * 0.8 * elec-peak-price + hkwh * 0.2 * elec-off-
price + wkwh * 0.7 * elec-peak-price + wkwh * 0.3 * elec-off-price
                                  + electrickwh * (elec-peak-price * 0.81 + elec-off-price *
0.19) + elec-off-standing )
                     set potimprov potimprov - 1 set potswap potswap + 1 set idref6
idnumber - 200  set idref9 idnumber + 100
                     set n8 count (houses-on neighbors) with [ heat = 8 ] set saving 0 set
repayment8 ( saving / 12 ) * (paybackrate / 100 )
                     set repay8 repayconst + repayx * repayment8 + repayx2 * repayment8
* repayment8 + repayx3 * repayment8 * repayment8 * repayment8
                     set adjust8 gshpfixed + gshpmarg * heatgshp / 1200 + garden +
cupboard + gshpmain * discmain - discfriend * n8 / 4
                       if adjust8 < 0 [ set adjust8 0 ]
                       set lhs8 priceconst + pricex * adjust8 + pricex2 * adjust8 * adjust8 +
loanincent + incentiveadjust + repay8
                       ifelse detach = 3
                         [ discheat6price discheat9price
                          ifelse lhs6 > lhs8 and lhs6 >= lhs9
                           [ ifelse lhs6 > none
                             [ choice6 set changed ( changed + 1 )]
                             [ if boiler-life < upgradetime
                               [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                              ]
                            ]
                           [ ifelse lhs9 > lhs8 and lhs9 > lhs6
                             [ ifelse lhs9 > none
                               [ choice9 set changed ( changed + 1 )]
                               [ if boiler-life < upgradetime
                                 [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                ]
                              ]
                             [ if boiler-life < upgradetime
                               [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                              ]
                            ]
                          ]
                         [ ifelse detach = 1
                          [ discheat6price discheat9price
                           ifelse lhs6 > lhs8 and lhs6 >= lhs9
                             [ ifelse lhs6 > none
                                [ choice6 set changed ( changed + 1 )]
                                [ if boiler-life < upgradetime
                                   [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                 ]
                              ]
                             [ ifelse lhs9 > lhs6 and lhs9 > lhs8
                               [ ifelse lhs9 > none
```

```
                              [ choice9 set changed ( changed + 1 )]
                              [ if boiler-life < upgradetime
                                [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                               ]
                            ]
                            [ if boiler-life < upgradetime
                              [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                            ]
                          ]
                        ]
                        [ discheat9price
                          if lhs9 > lhs8
                            [ ifelse lhs9 > none
                              [ choice9 set changed ( changed + 1 ) ]
                              [ if boiler-life < upgradetime
                                [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                              ]
                            ]
                        ]
                      ]
                  ]
                  [ ifelse heat = 9 and boiler-life < upgradetime
                    [ set runningcost ( hkwh * 0.8 * elec-peak-price + hkwh * 0.2 * elec-
off-price + wkwh * 0.7 * elec-peak-price + wkwh * 0.3 * elec-off-price
                                    + electrickwh * (elec-peak-price * 0.81 + elec-off-price *
0.19) + elec-off-standing )
                      set potimprov potimprov - 1 set potswap potswap + 1 set idref6
idnumber - 300  set idref7 idnumber - 200 set idref8 idnumber - 100
                      set n9 count (houses-on neighbors) with [ heat = 9 ] set saving 0 set
repayment9 ( saving / 12 ) * (paybackrate / 100 )
                      set repay9 repayconst + repayx * repayment9 + repayx2 *
repayment9 * repayment9 + repayx3 * repayment9 * repayment9 * repayment9
                      set adjust9 ashpfixed + ashpmarg * heatashp / 1200 + cupboard +
ashpmain * discmain - discfriend * n9 / 4
                      if adjust9 < 0 [ set adjust9 0 ]
                      ifelse detach = 3
                        [ discheat7price
                          ifelse lhs7 > lhs9
                            [ ifelse lhs7 > none
                              [ choice7 set changed (changed + 1) ]
                              [ if boiler-life < upgradetime
                                [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                              ]
                            ]
                            [ if boiler-life < upgradetime
                              [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                            ]
```

```
                              ]
                              [ ifelse detach = 1
                               [ discheat8price discheat6price
                                 ifelse lhs8 > lhs9 and lhs8 >= lhs6
                                   [ ifelse lhs8 > none
                                       [ choice8 set changed ( changed + 1 )]
                                       [ if boiler-life < upgradetime
                                         [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                        ]
                                    ]
                                   [ ifelse lhs6 > lhs9 and lhs6 > lhs8
                                       [ ifelse lhs6 > none
                                           [ choice6 set changed ( changed + 1 )]
                                           [ if boiler-life < upgradetime
                                               [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                            ]
                                        ]
                                       [ if boiler-life < upgradetime
                                           [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                        ]
                                    ]
                                ]
                               [ discheat8price
                                 if lhs8 > lhs9
                                  [ ifelse lhs8 > none
                                       [ choice8 set changed ( changed + 1 )]
                                       [ if boiler-life < upgradetime
                                         [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                                        ]
                                   ]
                               ]
                              ]
                           ]
                          [ if boiler-life < upgradetime
                              [ set boiler-life random-normal 15 5 set upgradetime 0 ]
                           ]
                        ]
                     ]
                  ]
               ]
            ]
         ]
      ]

ask my-links [die ]
end
```

```
to choice6

ask people-here [set inst6 1]
create-link-with one-of refhouses with [idnumber = idref6 ]
ifelse heat = 8 or heat = 9
  []
  [ ifelse  heat < 4
     [ set sav6 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-co2 +
(heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * solid-co2) ]
     [ ifelse heat = 4
        [ set sav6 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-co2 +
(heatkwh * elec-co2 - [heatkwh] of one-of link-neighbors * solid-co2) ]
        [ ifelse heat = 5
           [ set sav6 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * oil-co2 - [heatkwh] of one-of link-neighbors * solid-co2) ]
           [ if heat = 7
              [ set sav6 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * community-co2 - [heatkwh] of one-of link-neighbors * solid-co2) ]
           ]
        ]
     ]
   set subgrant6 biofuel-grant set subsidycost subsidycost + subnpv6 + subgrant6  set
saving6 saving6 + sav6 set cost6 cost6 + subnpv6 + subgrant6
  ]
set electrickwh [electrickwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-
neighbors  set wkwh [wkwh] of one-of link-neighbors
set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-
neighbors ask my-links [die] set heat 6 set boiler-life random-normal 15 5 set
upgradetime 0
set oldidnumber idnumber set idnumber idref6 set oldidlist fput oldidnumber oldidlist
set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist

end

to choice7

ask people-here [set inst7 1]
```

```
create-link-with one-of refhouses with [idnumber = idref7 ]
set electrickwh [electrickwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-
neighbors set wkwh [wkwh] of one-of link-neighbors
set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-
neighbors ask my-links [die] set heat 7 set boiler-life random-normal 15 5 set
upgradetime 0
set oldidnumber idnumber set idnumber idref7  set oldidlist fput oldidnumber oldidlist
set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist

end




to choice8

ask people-here [set inst8 1]
create-link-with one-of refhouses with [idnumber = idref8 ]
ifelse heat = 6 or heat = 9
  []
  [ ifelse  heat < 4
     [ set sav8 ( electrickwh - [electrickwh] of one-of link-neighbors) * elec-co2 +
(heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
     [ ifelse heat = 4
        [ set sav8 ( electrickwh - [electrickwh] of one-of link-neighbors) * elec-co2 +
(heatkwh * elec-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
        [ ifelse heat = 5
           [ set sav8 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * oil-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
           [ if heat = 7
              [ set sav8 ( electrickwh - [electrickwh] of one-of link-neighbors  ) * elec-co2 +
(heatkwh * community-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
            ]
         ]
      ]
   set subgrant8 heatpump-grant set subsidycost subsidycost + subnpv8 + subgrant8
set saving8 saving8 + sav8 set cost8 cost8 + subnpv8 + subgrant8
  ]
set electrickwh [electrickwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-
neighbors set wkwh [wkwh] of one-of link-neighbors
set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-
neighbors ask my-links [die] set heat 8 set boiler-life random-normal 15 5 set
upgradetime 0
set oldidnumber idnumber set idnumber idref8 set oldidlist fput oldidnumber oldidlist
set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist
```

```
end




to choice9

ask people-here [set inst9 1]
create-link-with one-of refhouses with [idnumber = idref9 ]
ifelse heat = 6 or heat = 8
 []
 [ ifelse  heat < 4
     [ set sav9 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * gas-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
     [ ifelse heat = 4
       [ set sav9 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * elec-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
       [ ifelse heat = 5
          [ set sav9 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * oil-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
          [ if heat = 7
             [ set sav9 ( electrickwh - [electrickwh] of one-of link-neighbors ) * elec-co2 +
(heatkwh * community-co2 - [heatkwh] of one-of link-neighbors * elec-co2) ]
           ]
        ]
      ]
   set subgrant9 ashp-grant set subsidycost subsidycost + subnpv9 + subgrant9 set
saving9 saving9 + sav9 set cost9 cost9 + subnpv9 + subgrant9
  ]
set electrickwh [electrickwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-
neighbors set wkwh [wkwh] of one-of link-neighbors
set heatkwh [heatkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-
neighbors ask my-links [die] set heat 9 set boiler-life random-normal 15 5 set
upgradetime 0
set oldidnumber idnumber set idnumber idref9 set oldidlist fput oldidnumber oldidlist
set oldidlist fput 3 oldidlist set oldidlist fput ticks oldidlist

end




to heat1price
```

```
create-link-with one-of refhouses with [idnumber = idref1 ] set elec1 [ electrickwh ] of
one-of link-neighbors set heat1 [ heatkwh] of one-of link-neighbors
set h1 [ hkwh] of one-of link-neighbors set w1 [wkwh] of one-of link-neighbors
ask my-links [die] set n1 count (houses-on neighbors) with [ heat = 1 ]
set electaxpot1 elec1 * elec-co2 * co2tax / 100 if electaxpot1 < 0 [ set electaxpot1 0 ]
set heattaxpot1 heat1 * gas-co2 * co2tax / 100
set runningcostpot1 heat1 * gas-price + gas-standing + elec1 * elec
set save1 runningcost - runningcostpot1 + heattax + electax - heattaxpot1 -
electaxpot1
ifelse save1 < 0 [set save1a 0] [ set save1a save1] set repayment1 ( save1a / 12 ) *
(paybackrate / 100 )
set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 * repayment1
+ repayx3 * repayment1 * repayment1 * repayment1
set adjust1 condensfixed + condensmain * primmain - save1 * primsav  - primfriend *
n1 / 4 - boilergrant
if adjust1 < 0 [ set adjust1 0 ]
set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 + loanincent +
incentiveadjust + repay1

end




to heat6price

create-link-with one-of refhouses with [idnumber = idref6 ] set elec6 [ electrickwh ] of
one-of link-neighbors set heat6  [ heatkwh] of one-of link-neighbors
set h6 [ hkwh] of one-of link-neighbors set w6 [ wkwh] of one-of link-neighbors ask
my-links [die]
set n6 count (houses-on neighbors) with [ heat = 6 ]
set electaxpot6 elec6 * elec-co2 * co2tax / 100 if electaxpot6 < 0 [ set electaxpot6 0 ]
set heattaxpot6 heat6 * solid-co2 * co2tax / 100
set runningcostpot6 heat6 * solid-price + elec6 * elec
set save6 runningcost - runningcostpot6 + heattax + electax - heattaxpot6 -
electaxpot6
ifelse save6 < 0 [set save6a 0] [ set save6a save6] set repayment1 ( save6a / 12 ) *
(paybackrate / 100 )
set repay6 repayconst + repayx * repayment6 + repayx2 * repayment6 * repayment6
+ repayx3 * repayment6 * repayment6 * repayment6
set adjust6 biomass + fuelstore + cupboard + biomassmain * primmain - save6 *
primsav  - primfriend * n6 / 4 - biofuel-grant - ( rhi-bio / 100 ) * heat6 * primsav
if adjust6 < 0 [ set adjust6 0 ]
set return6 rhi-bio * heat6 / 100
set years 1
```

```
repeat 25 [ set subnpv6 subnpv6 + return6 / ( 1 + npv-rate / 100 ) ^ years set years
years + 1 ] set years 1
set lhs6 priceconst + pricex * adjust6 + pricex2 * adjust6 * adjust6 + loanincent +
incentiveadjust + repay6
end




to heat7price

create-link-with one-of refhouses with [idnumber = idref7 ] set elec7 [ electrickwh ] of
one-of link-neighbors set heat7 [ heatkwh] of one-of link-neighbors
set h7 [ hkwh] of one-of link-neighbors set w7 [ wkwh] of one-of link-neighbors ask
my-links [die]
set n7 count (houses-on neighbors) with [ heat = 7 ] ; set difference heatkwh - heat7
set electaxpot7 elec7 * elec-co2 * co2tax / 100 if electaxpot7 < 0 [ set electaxpot7 0 ]
set heattaxpot7 heat7 * community-co2 * co2tax / 100
set runningcostpot7 heat7 * community-price + community-standing + elec7 * elec
set save7 runningcost - runningcostpot7 + heattax + electax - heattaxpot7 -
electaxpot7
ifelse save7 < 0 [set save7a 0] [ set save7a save7] set repayment1 ( save7a / 12 ) *
(paybackrate / 100 )
set repay7 repayconst + repayx * repayment7 + repayx2 * repayment7 * repayment7
+ repayx3 * repayment7 * repayment7 * repayment7
set adjust7 commfixed + commmain * primmain - save7 * primsav - primfriend * n7 / 4
if adjust7 < 0 [ set adjust7 0 ]
set lhs6 priceconst + pricex * adjust7 + pricex2 * adjust7 * adjust7 + loanincent +
incentiveadjust + repay7

end




to heat8price

create-link-with one-of refhouses with [idnumber = idref8 ] set elec8 [ electrickwh ] of
one-of link-neighbors set heat8 [ heatkwh] of one-of link-neighbors set heatgshp heat8
set h8 [ hkwh] of one-of link-neighbors set w8 [ wkwh] of one-of link-neighbors
ask my-links [die] set n8 count (houses-on neighbors) with [ heat = 8 ]
set electaxpot8 elec8 * elec-co2 * co2tax / 100 if electaxpot8 < 0 [ set electaxpot8 0 ]
set heattaxpot8 heat8 * elec-co2 * co2tax / 100
set runningcostpot8 h8 * (0.8 * elec-peak-price + 0.2 * elec-off-price) + w8 * ( 0.7 *
elec-peak-price + 0.3 * elec-off-price ) + elec-off-standing
```

```
   + elec8 * (elec-peak-price * 0.81 + elec-off-price * 0.19 )
set save8 runningcost - runningcostpot8 + heattax + electax - heattaxpot8 -
electaxpot8
ifelse save8 < 0 [set save8a 0] [ set save8a save8] set repayment8 ( save8a / 12 ) *
(paybackrate / 100 )
set repay8 repayconst + repayx * repayment8 + repayx2 * repayment8 * repayment8
+ repayx3 * repayment8 * repayment8 * repayment8
set adjust8 gshpfixed + gshpmarg * heatgshp / 1200 + garden + cupboard + gshpmain
* primmain - save8 * primsav  - primfriend * n8 / 4  - heatpump-grant - ( rhi-heatpump
/ 100 ) * heat8 * primsav
if adjust8 < 0 [ set adjust8 0 ]
set return8 rhi-heatpump * heat8 / 100
set years 1
repeat 25 [ set subnpv8 subnpv8 + return8 / ( 1 + npv-rate / 100 ) ^ years set years
years + 1  ] set years 1
set subnpv8old subnpv8
set lhs8 priceconst + pricex * adjust8 + pricex2 * adjust8 * adjust8 + loanincent +
incentiveadjust + repay8
end




to heat9price

create-link-with one-of refhouses with [idnumber = idref9 ] set elec9 [ electrickwh ] of
one-of link-neighbors set heat9 [ heatkwh] of one-of link-neighbors set heatashp heat9
set h9 [ hkwh] of one-of link-neighbors set w9 [ wkwh] of one-of link-neighbors
ask my-links [die] set n9 count (houses-on neighbors) with [ heat = 9 ]
set electaxpot9 elec9 * elec-co2 * co2tax / 100 if electaxpot9 < 0 [ set electaxpot9 0 ]
set heattaxpot9 heat9 * elec-co2 * co2tax / 100
set runningcostpot9 h9 * (0.8 * elec-peak-price + 0.2 * elec-off-price) + w9 * ( 0.7 *
elec-peak-price + 0.3 * elec-off-price ) + elec-off-standing
   + elec9 * (elec-peak-price * 0.81 + elec-off-price * 0.19 )
set save9 runningcost - runningcostpot9 + heattax + electax - heattaxpot9 -
electaxpot9
ifelse save9 < 0 [set save9a 0] [ set save9a save9] set repayment9 ( save9a / 12 ) *
(paybackrate / 100 )
set repay9 repayconst + repayx * repayment9 + repayx2 * repayment9 * repayment9
+ repayx3 * repayment9 * repayment9 * repayment9
set adjust9 ashpfixed + ashpmarg * heatashp / 1200 + cupboard + ashpmain *
primmain - save9 * primsav  - primfriend * n9 / 4  - ashp-grant - ( rhi-ashp / 100 ) *
heat9 * primsav
if adjust9 < 0 [ set adjust9 0 ]
set return9 rhi-ashp * heat9 / 100
set years 1
```

```
repeat 25 [ set subnpv9 subnpv9 + return9 / ( 1 + npv-rate / 100 ) ^ years set years
years + 1  ] set years 1
set subnpv9old subnpv9
set lhs9 priceconst + pricex * adjust9 + pricex2 * adjust9 * adjust9 + loanincent +
incentiveadjust + repay9
end




to discheat1price

create-link-with one-of refhouses with [idnumber = idref1 ] set elec1 [ electrickwh ] of
one-of link-neighbors set heat1 [ heatkwh] of one-of link-neighbors
set h1 [ hkwh] of one-of link-neighbors set w1 [wkwh] of one-of link-neighbors
ask my-links [die] set n1 count (houses-on neighbors) with [ heat = 1 ]
set electaxpot1 elec1 * elec-co2 * co2tax / 100 if electaxpot1 < 0 [ set electaxpot1 0 ]
set heattaxpot1 heat1 * gas-co2 * co2tax / 100
set runningcostpot1 heat1 * gas-price + gas-standing + elec1 * elec
set save1 runningcost - runningcostpot1 + heattax + electax - heattaxpot1 -
electaxpot1
ifelse save1 < 0 [set save1a 0] [ set save1a save1] set repayment1 ( save1a / 12 ) *
(paybackrate / 100 )
set repay1 repayconst + repayx * repayment1 + repayx2 * repayment1 * repayment1
+ repayx3 * repayment1 * repayment1 * repayment1
set adjust1 condensfixed + condensmain * discmain - save1 * discsav  - discfriend * n1
/ 4 - boilergrant
if adjust1 < 0 [ set adjust1 0 ]
set lhs1 priceconst + pricex * adjust1 + pricex2 * adjust1 * adjust1 + loanincent +
incentiveadjust + repay1

end




to discheat6price

create-link-with one-of refhouses with [idnumber = idref6 ] set elec6 [ electrickwh ] of
one-of link-neighbors set heat6  [ heatkwh] of one-of link-neighbors
set h6 [ hkwh] of one-of link-neighbors set w6 [ wkwh] of one-of link-neighbors ask
my-links [die]
set n6 count (houses-on neighbors) with [ heat = 6 ]
set electaxpot6 elec6 * elec-co2 * co2tax / 100 if electaxpot6 < 0 [ set electaxpot6 0 ]
set heattaxpot6 heat6 * solid-co2 * co2tax / 100
```

```
set runningcostpot6 heat6 * solid-price + elec6 * elec
set save6 runningcost - runningcostpot6 + heattax + electax - heattaxpot6 -
electaxpot6
ifelse save6 < 0 [set save6a 0] [ set save6a save6] set repayment1 ( save6a / 12 ) *
(paybackrate / 100 )
set repay6 repayconst + repayx * repayment6 + repayx2 * repayment6 * repayment6
+ repayx3 * repayment6 * repayment6 * repayment6
set adjust6 biomass + fuelstore + cupboard + biomassmain * discmain - save6 * discsav
- discfriend * n6 / 4 - biofuel-grant - ( rhi-bio / 100 ) * heat6 * discsav
if adjust6 < 0 [ set adjust6 0 ]
set return6 rhi-bio * heat6 / 100
set years 1
repeat 25 [ set subnpv6 subnpv6 + return6 / ( 1 + npv-rate / 100 ) ^ years set years
years + 1 ] set years 1
set lhs6 priceconst + pricex * adjust6 + pricex2 * adjust6 * adjust6 + loanincent +
incentiveadjust + repay6

end




to discheat7price

create-link-with one-of refhouses with [idnumber = idref7 ] set elec7 [ electrickwh ] of
one-of link-neighbors set heat7 [ heatkwh] of one-of link-neighbors
set h7 [ hkwh] of one-of link-neighbors set w7 [ wkwh] of one-of link-neighbors ask
my-links [die]
set n7 count (houses-on neighbors) with [ heat = 7 ] ; set difference heatkwh - heat7
set electaxpot7 elec7 * elec-co2 * co2tax / 100 if electaxpot7 < 0 [ set electaxpot7 0 ]
set heattaxpot7 heat7 * community-co2 * co2tax / 100
set runningcostpot7 heat7 * community-price + community-standing + elec7 * elec
set save7 runningcost - runningcostpot7 + heattax + electax - heattaxpot7 -
electaxpot7
ifelse save7 < 0 [set save7a 0] [ set save7a save7] set repayment1 ( save7a / 12 ) *
(paybackrate / 100 )
set repay7 repayconst + repayx * repayment7 + repayx2 * repayment7 * repayment7
+ repayx3 * repayment7 * repayment7 * repayment7
set adjust7 commfixed + commmain * discmain - save7 * discsav - discfriend * n7 / 4
if adjust7 < 0 [ set adjust7 0 ]
set lhs7 priceconst + pricex * adjust7 + pricex2 * adjust7 * adjust7 + loanincent +
incentiveadjust + repay7

end
```

```
to discheat8price

create-link-with one-of refhouses with [idnumber = idref8 ] set elec8 [ electrickwh ] of
one-of link-neighbors set heat8 [ heatkwh] of one-of link-neighbors set heatgshp heat8
set h8 [ hkwh] of one-of link-neighbors set w8 [ wkwh] of one-of link-neighbors
ask my-links [die] set n8 count (houses-on neighbors) with [ heat = 8 ]
set electaxpot8 elec8 * elec-co2 * co2tax / 100 if electaxpot8 < 0 [ set electaxpot8 0 ]
set heattaxpot8 heat8 * elec-co2 * co2tax / 100
set runningcostpot8 h8 * (0.8 * elec-peak-price + 0.2 * elec-off-price) + w8 * ( 0.7 *
elec-peak-price + 0.3 * elec-off-price ) + elec-off-standing
   + elec8 * (elec-peak-price * 0.81 + elec-off-price * 0.19 )
set save8 runningcost - runningcostpot8 + heattax + electax - heattaxpot8 -
electaxpot8
ifelse save8 < 0 [set save8a 0] [ set save8a save8] set repayment8 ( save8a / 12 ) *
(paybackrate / 100 )
set repay8 repayconst + repayx * repayment8 + repayx2 * repayment8 * repayment8
+ repayx3 * repayment8 * repayment8 * repayment8
set adjust8 gshpfixed + gshpmarg * heatgshp / 1200 + garden + cupboard + gshpmain
* discmain - save8 * discsav  - discfriend * n8 / 4  - heatpump-grant - ( rhi-heatpump /
100 ) * heat8 * discsav
if adjust8 < 0 [ set adjust8 0 ]
set return8 rhi-heatpump * heat8 / 100
set years 1
repeat 25 [ set subnpv8 subnpv8 + return8 / ( 1 + npv-rate / 100 ) ^ years set years
years + 1  ] set years 1
set subnpv8old subnpv8
set lhs8 priceconst + pricex * adjust8 + pricex2 * adjust8 * adjust8 + loanincent +
incentiveadjust + repay8

end
```

```
to discheat9price

create-link-with one-of refhouses with [idnumber = idref9 ] set elec9 [ electrickwh ] of
one-of link-neighbors set heat9 [ heatkwh] of one-of link-neighbors set heatashp heat9
set h9 [ hkwh] of one-of link-neighbors set w9 [ wkwh] of one-of link-neighbors
ask my-links [die] set n9 count (houses-on neighbors) with [ heat = 9 ]
set electaxpot9 elec9 * elec-co2 * co2tax / 100 if electaxpot9 < 0 [ set electaxpot9 0 ]
set heattaxpot9 heat9 * elec-co2 * co2tax / 100
```

```
set runningcostpot9 h9 * (0.8 * elec-peak-price + 0.2 * elec-off-price) + w9 * ( 0.7 *
elec-peak-price + 0.3 * elec-off-price ) + elec-off-standing
   + elec9 * (elec-peak-price * 0.81 + elec-off-price * 0.19 )
set save9 runningcost - runningcostpot9 + heattax + electax - heattaxpot9 -
electaxpot9
ifelse save9 < 0 [set save9a 0] [ set save9a save9] set repayment9 ( save9a / 12 ) *
(paybackrate / 100 )
set repay9 repayconst + repayx * repayment9 + repayx2 * repayment9 * repayment9
+ repayx3 * repayment9 * repayment9 * repayment9
set adjust9 ashpfixed + ashpmarg * heatashp / 1200 + cupboard + ashpmain *
discmain - save9 * discsav  - discfriend * n9 / 4  - ashp-grant - ( rhi-ashp / 100 ) * heat9
* discsav
if adjust9 < 0 [ set adjust9 0 ]
set return9 rhi-ashp * heat9 / 100
set years 1
repeat 25 [ set subnpv9 subnpv9 + return9 / ( 1 + npv-rate / 100 ) ^ years set years
years + 1  ] set years 1
set subnpv9old subnpv9
set lhs9 priceconst + pricex * adjust9 + pricex2 * adjust9 * adjust9 + loanincent +
incentiveadjust + repay9

end




to move-home

; routine for searching for new tech on moving home

ask people
  [ if moving = 1
     [ ask houses-here
        [ if age > 4
           [  set priceconst [ priceconst ] of one-of people-here set pricex [ pricex ] of one-
of people-here set pricex2 [pricex2] of one-of people-here
             set repayconst [repayconst ] of one-of people-here set repayx [ repayx ] of
one-of people-here set repayx2 [ repayx2 ] of one-of people-here
             set repayx3 [ repayx3] of one-of people-here set none (nonefactor * [none] of
one-of people-here ) set loanincent [loanincent] of one-of people-here
             set discfriend recinf * [discfriend] of one-of people-here set discsav recinf *
[discsav] of one-of people-here set discmain recinf * [discmain] of one-of people-here
             discretionary
             if wall = 2
               [ set lookupcwi (idnumber + 10000) create-link-with one-of refhouses with [
idnumber = [lookupcwi] of myself  ] set potimprov potimprov + 1
```

```
                ask my-links [ set color red ] set ncwi count (houses-on neighbors) with
[wall = 3 ] set difference ( heatkwh - [ heatkwh] of one-of link-neighbors )
                set differenceheat ( hkwh - [ hkwh] of one-of link-neighbors ) set
differencewater ( wkwh - [ wkwh] of one-of link-neighbors )
                ifelse heat < 3.5
                  [ set heattaxpotcwi ([heatkwh] of one-of link-neighbors) * gas-co2 *
co2tax / 100 set saving difference * gas-price + heattax - heattaxpotcwi  ]
                  [ ifelse heat = 4
                     [ set heattaxpotcwi ([heatkwh] of one-of link-neighbors) * oil-co2 *
co2tax / 100 set saving difference * oil-price + heattax - heattaxpotcwi ]
                     [ ifelse heat = 5 or heat = 8 or heat = 9
                        [ set heattaxpotcwi ([heatkwh] of one-of link-neighbors) * elec-co2 *
co2tax / 100 elecsavecalc set saving savingelec + heattax - heattaxpotcwi ]
                        [ ifelse heat = 6
                           [ set heattaxpotcwi ([heatkwh] of one-of link-neighbors) * solid-co2
* co2tax / 100 set saving difference * solid-price + heattax - heattaxpotcwi ]
                           [ set heattaxpotcwi ([heatkwh] of one-of link-neighbors) *
community-co2 * co2tax / 100 set saving difference * community-price + heattax -
heattaxpotcwi  ]
                        ]
                     ]
                  ]
                set repayment (saving / 12) * (paybackrate / 100 )
                set repay repayconst + repayx * repayment + repayx2 * repayment *
repayment + repayx3 * repayment * repayment * repayment let adjustedpricetest (
500 - cavitygrant)
                if adjustedpricetest < 0 [ set adjustedpricetest 0 ] set adjustedprice
adjustedpricetest - saving * discsav - discfriend * ncwi / 4
                if priceconst + pricex * adjustedprice + pricex2 * adjustedprice *
adjustedprice + loanincent + incentiveadjust + repay > none
                  [ set subgrantcwi cavitygrant
                    ifelse heat < 3.5
                      [ set savcwi difference * gas-co2 ]
                      [ ifelse heat = 4
                         [ set savcwi difference * oil-co2 ]
                         [ ifelse heat = 5 or heat = 8 or heat = 9
                            [ set savcwi difference * elec-co2 ]
                            [ ifelse heat = 6
                               [ set savcwi difference * solid-co2 ]
                               [ set savcwi difference * community-co2 ]
                            ]
                         ]
                      ]
                    set wall 3  ask people-here [set instcwi 1] set heattax heattaxpotcwi set
electrickwh [electrickwh] of one-of link-neighbors
```

```
set heatkwh [heatkwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-neighbors
set oldidlist fput idnumber oldidlist set oldidlist fput 5 oldidlist set oldidlist fput ticks oldidlist set idnumber lookupcwi set improved ( improved + 1 )
]
ask my-links [die]
if glazing = 2
[ set lookupdg (idnumber - 100000) create-link-with one-of refhouses with [idnumber = [lookupdg] of myself ] set glazing 1
set oldidlist fput idnumber oldidlist set oldidlist fput 6 oldidlist set oldidlist fput ticks oldidlist set idnumber lookupdg
set electrickwh [electrickwh] of one-of link-neighbors set heatkwh [ heatkwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-neighbors set ckwh [ckwh] of one-of link-neighbors
set wkwh [wkwh] of one-of link-neighbors ask my-links [die]
]
]
if roof > 0
[ if hw = 2
[ set lookuphw ( idnumber - 10 ) create-link-with one-of refhouses with [ idnumber = [lookuphw] of myself ] ask my-links [ set color magenta ] set potimprov potimprov + 1
set nhw count (houses-on neighbors) with [roof = 1 ] set difference (heatkwh - [heatkwh] of one-of link-neighbors )
set differenceheat ( hkwh - [ hkwh] of one-of link-neighbors ) set differencewater ( wkwh - [ wkwh] of one-of link-neighbors )
ifelse heat < 3.5
[ set heattaxpotshw ([heatkwh] of one-of link-neighbors) * gas-co2 * co2tax / 100 set saving difference * gas-price + heattax - heattaxpotshw  ]
[ ifelse heat = 4
[ set heattaxpotshw ([heatkwh] of one-of link-neighbors) * oil-co2 * co2tax / 100 set saving difference * oil-price + heattax - heattaxpotshw ]
[ ifelse heat = 5 or heat = 8 or heat = 9
[ set heattaxpotshw ([heatkwh] of one-of link-neighbors) * elec-co2 * co2tax / 100 elecsavecalc set saving savingelec + heattax - heattaxpotshw ]
[ ifelse heat = 6
[ set heattaxpotshw ([heatkwh] of one-of link-neighbors) * solid-co2 * co2tax / 100 set saving difference * solid-price + heattax - heattaxpotshw ]
[ set heattaxpotshw ([heatkwh] of one-of link-neighbors) * community-co2 * co2tax / 100 set saving difference * community-price + heattax - heattaxpotshw  ]
]
]
]
```

```
                    set repayment (saving / 12) * (paybackrate / 100 ) set repay repayconst
+ repayx * repayment + repayx2 * repayment * repayment + repayx3 * repayment *
repayment * repayment
                    let adjustedpricetest solarfixed + solarmarg * difference / 850 - solar-
grant
                    if adjustedpricetest < 0 [ set adjustedpricetest 0 ]
                    set adjustedprice adjustedpricetest + solarmain * discmain - saving *
discsav  - discfriend * nhw / 4 - ( rhi-solar / 100 ) * difference * discsav
                    if priceconst + pricex * adjustedprice + pricex2 * adjustedprice *
adjustedprice + loanincent + incentiveadjust + repay > none
                     [ set subgrantshw solar-grant set shwoutput difference set returnshw
rhi-solar * difference / 100
                       ifelse heat < 3.5
                        [ set savshw difference * gas-co2 ]
                        [ ifelse heat = 4
                           [ set savshw difference * oil-co2 ]
                           [ ifelse heat = 5 or heat = 8 or heat = 9
                              [ set savshw difference * elec-co2 ]
                              [ ifelse heat = 6
                                 [ set savshw difference * solid-co2 ]
                                 [ set savshw difference * community-co2 ]
                              ]
                           ]
                        ]
                       set years 1 repeat 25 [ set subnpvshw subnpvshw + returnshw / ( 1 +
npv-rate / 100 ) ^ years set years years + 1 ] set years 1
                       set hw 1  ask people-here [set instshw 1] set heattax heattaxpotshw
set electrickwh [electrickwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-
neighbors
                       set wkwh [wkwh] of one-of link-neighbors set heatkwh [heatkwh] of
one-of link-neighbors set ckwh [ckwh] of one-of link-neighbors
                       set oldidlist fput idnumber oldidlist set oldidlist fput 2 oldidlist set
oldidlist fput ticks oldidlist  set idnumber (idnumber - 10) set improved (improved + 1)
                     ]
                     ask my-links [die]
                     if glazing = 2
                      [ set lookupdg (idnumber - 100000) create-link-with one-of refhouses
with [idnumber = [lookupdg] of myself ] set glazing 1
                        set oldidlist fput idnumber oldidlist set oldidlist fput 6 oldidlist set
oldidlist fput ticks oldidlist set idnumber lookupdg
                        set electrickwh [electrickwh] of one-of link-neighbors set heatkwh [
heatkwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-neighbors set ckwh
[ckwh] of one-of link-neighbors
                        set wkwh [wkwh] of one-of link-neighbors ask my-links [die]
                       ]
                  ]
                ifelse roof = 3
```

```
                  [ set lookuproof ( idnumber - 2000 ) create-link-with one-of refhouses
with [ idnumber = [lookuproof] of myself ] ask my-links [ set color black ] set potimprov
potimprov + 1
                   set nroof count (houses-on neighbors) with [roof = 1 ]set difference (
heatkwh - [ heatkwh ] of one-of link-neighbors )
                   set differenceheat ( hkwh - [ hkwh] of one-of link-neighbors ) set
differencewater ( wkwh - [ wkwh] of one-of link-neighbors )
                   ifelse heat < 3.5
                    [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * gas-co2 *
co2tax / 100 set saving difference * gas-price + heattax - heattaxpotloft ]
                    [ ifelse heat = 4
                      [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * oil-co2 *
co2tax / 100 set saving difference * oil-price + heattax - heattaxpotloft ]
                      [ ifelse heat = 5 or heat = 8 or heat = 9
                        [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * elec-co2
* co2tax / 100 elecsavecalc set saving savingelec + heattax - heattaxpotloft ]
                        [ ifelse heat = 6
                          [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * solid-
co2 * co2tax / 100 set saving difference * solid-price  + heattax - heattaxpotloft ]
                          [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) *
community-co2 * co2tax / 100 set saving difference * community-price  + heattax -
heattaxpotloft ]
                         ]
                       ]
                     ]
                   set repayment (saving / 12) * (paybackrate / 100 )
                   set repay repayconst + repayx * repayment + repayx2 * repayment *
repayment + repayx3 * repayment * repayment * repayment let adjustedpricetest (
500 - loftgrant)
                   if adjustedpricetest < 0 [ set adjustedpricetest 0 ]
                   set adjustedprice adjustedpricetest - saving * discsav - discfriend * nroof
/ 4
                   if priceconst + pricex * adjustedprice + pricex2 * adjustedprice *
adjustedprice + loanincent + incentiveadjust + repay > none
                    [ set subgrantloft loftgrant set loftoutput difference
                     ifelse heat < 3.5
                      [ set savloft difference * gas-co2 ]
                      [ ifelse heat = 4 [ set savloft difference * oil-co2 ]
                        [ ifelse heat = 5 or heat = 8 or heat = 9
                          [ set savloft difference * elec-co2 ]
                          [ ifelse heat = 6 [ set savloft difference * solid-co2 ]
                            [ set savloft difference * community-co2 ]
                          ]
                        ]
                      ]
```

```
                        set roof 1  ask people-here [set instloft 1] set heattax heattaxpotloft
set electrickwh [electrickwh] of one-of link-neighbors set heatkwh [heatkwh] of one-of
link-neighbors
                        set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-of
link-neighbors set ckwh [ckwh] of one-of link-neighbors set oldidlist fput idnumber
oldidlist set oldidlist fput 4 oldidlist
                        set oldidlist fput ticks oldidlist set idnumber lookuproof set improved
( improved + 1)
                       ]
                     ask my-links [die]
                     if glazing = 2
                       [ set lookupdg (idnumber - 100000) create-link-with one-of refhouses
with [idnumber = [lookupdg] of myself] set glazing 1 set oldidlist fput idnumber
oldidlist
                        set oldidlist fput 6 oldidlist set oldidlist fput ticks oldidlist set
idnumber lookupdg
                        set electrickwh [electrickwh] of one-of link-neighbors set heatkwh [
heatkwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-neighbors
                        set wkwh [wkwh] of one-of link-neighbors set ckwh [ckwh] of one-of
link-neighbors ask my-links [die]
                       ]
                    ]
                    [ if roof = 2
                       [ set lookuproof ( idnumber - 1000 ) create-link-with one-of refhouses
with [ idnumber = [lookuproof] of myself ] ask my-links [ set color black ] set potimprov
potimprov + 1
                        set nroof count (houses-on neighbors) with [roof = 1 ] set difference (
heatkwh - [ heatkwh ] of one-of link-neighbors )
                        set differenceheat ( hkwh - [ hkwh] of one-of link-neighbors ) set
differencewater ( wkwh - [ wkwh] of one-of link-neighbors )
                        ifelse heat < 3.5
                          [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * gas-co2 *
co2tax / 100 set saving difference * gas-price + heattax - heattaxpotloft ]
                          [ ifelse heat = 4
                             [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * oil-co2
* co2tax / 100 set saving difference * oil-price + heattax - heattaxpotloft ]
                             [ ifelse heat = 5 or heat = 8 or heat = 9
                                [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) * elec-
co2 * co2tax / 100 elecsavecalc set saving savingelec + heattax - heattaxpotloft ]
                                [ ifelse heat = 6
                                   [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) *
solid-co2 * co2tax / 100 set saving difference * solid-price  + heattax - heattaxpotloft ]
                                   [ set heattaxpotloft ([heatkwh] of one-of link-neighbors) *
community-co2 * co2tax / 100 set saving difference * community-price  + heattax -
heattaxpotloft ]
                                 ]
                              ]
```

```
              ]
            set repayment (saving / 12) * (paybackrate / 100 ) set repay
repayconst + repayx * repayment + repayx2 * repayment * repayment + repayx3 *
repayment * repayment * repayment
            let adjustedpricetest ( 500 - loftgrant) if adjustedpricetest < 0 [ set
adjustedpricetest 0 ]
            set adjustedprice adjustedpricetest - saving * discsav - discfriend *
nroof / 4
            if priceconst + pricex * adjustedprice + pricex2 * adjustedprice *
adjustedprice + loanincent + incentiveadjust + repay > none
             [ set subgrantloft loftgrant set loftoutput difference ; set savloft
saving
              ifelse heat < 3.5
               [ set savloft difference * gas-co2 ]
               [ ifelse heat = 4
                 [ set savloft difference * oil-co2 ]
                 [ ifelse heat = 5 or heat = 8 or heat = 9
                   [ set savloft difference * elec-co2 ]
                   [ ifelse heat = 6
                     [ set savloft difference * solid-co2 ]
                     [ set savloft difference * community-co2 ]
                   ]
                 ]
               ]
              set roof 1  ask people-here [set instloft 1] set electrickwh
[electrickwh] of one-of link-neighbors set heatkwh [heatkwh] of one-of link-neighbors
              set hkwh [hkwh] of one-of link-neighbors set wkwh [wkwh] of one-
of link-neighbors set ckwh [ckwh] of one-of link-neighbors set oldidlist fput idnumber
oldidlist set oldidlist fput 4 oldidlist
              set oldidlist fput ticks oldidlist set idnumber lookuproof set
improved (improved + 1)
             ]
            ask my-links [die]
            if glazing = 2
             [ set lookupdg (idnumber - 100000) create-link-with one-of
refhouses with [idnumber = [lookupdg] of myself ] set glazing 1 set oldidlist fput
idnumber oldidlist
              set oldidlist fput 6 oldidlist set oldidlist fput ticks oldidlist set
idnumber lookupdg set electrickwh [electrickwh] of one-of link-neighbors
              set heatkwh [ heatkwh] of one-of link-neighbors set hkwh [hkwh] of
one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die]
             ]
           ]
          ]
        ]
```

```
if wall = 1 and ageband < 4
  [ set lookupsolid ( idnumber + 20000 ) set potimprov potimprov + 1 create-link-with one-of refhouses with [ idnumber = [lookupsolid] of myself ]
    ask my-links [ set color cyan ] set nsolid count ( houses-on neighbors ) with [ wall = 3 and solidwall = 1 ]
    set difference ( heatkwh - [heatkwh] of one-of link-neighbors ) set differenceheat ( hkwh - [ hkwh] of one-of link-neighbors )
    set differencewater ( wkwh - [ wkwh] of one-of link-neighbors )
    ifelse heat < 4
      [ set heattaxpotwall ([heatkwh] of one-of link-neighbors) * gas-co2 * co2tax / 100 set saving difference * gas-price + heattax - heattaxpotwall ]
      [ ifelse heat = 4
        [ set heattaxpotwall ([heatkwh] of one-of link-neighbors) * oil-co2 * co2tax / 100 set saving difference * oil-price + heattax - heattaxpotwall ]
        [ ifelse heat = 5 or heat = 8 or heat = 9
          [ set heattaxpotwall ([heatkwh] of one-of link-neighbors) * elec-co2 * co2tax / 100 elecsavecalc set saving savingelec + heattax - heattaxpotwall ]
          [ ifelse heat = 6
            [ set heattaxpotwall ([heatkwh] of one-of link-neighbors) * solid-co2 * co2tax / 100 set saving difference * solid-price  + heattax - heattaxpotwall ]
            [ set heattaxpotwall ([heatkwh] of one-of link-neighbors) * community-co2 * co2tax / 100 set saving difference * community-price  + heattax - heattaxpotwall ]
          ]
        ]
      ]
    ifelse detach = 1
      [ set solidprice solidwalldet ]
      [ ifelse detach = 2
        [ set solidprice solidwallsemi ]
        [ set solidprice solidwallflat ]
      ]
      set repayment (saving / 12) * (paybackrate / 100 ) set repay repayconst + repayx * repayment + repayx2 * repayment * repayment + repayx3 * repayment * repayment * repayment
      set adjustedprice solidprice - saving * discsav - discfriend * nsolid / 4 - solidwallgrant
      if priceconst + pricex * adjustedprice + pricex2 * adjustedprice * adjustedprice + loanincent + incentiveadjust + repay > none
        [ ifelse heat < 3.5
          [ set savwall difference * gas-co2 ]
          [ ifelse heat = 4
            [ set savwall difference * oil-co2 ]
            [ ifelse heat = 5 or heat = 8 or heat = 9
              [ set savwall difference * elec-co2 ]
              [ ifelse heat = 6
                [ set savwall difference * solid-co2 ]
```

```
                              [ set savwall difference * community-co2 ]
                            ]
                          ]
                        ]
                       set electrickwh [electrickwh] of one-of link-neighbors set heatkwh
[heatkwh] of one-of link-neighbors set hkwh [hkwh] of one-of link-neighbors
                       set wkwh [wkwh] of one-of link-neighbors set ckwh [ckwh] of one-of
link-neighbors set oldidlist fput idnumber oldidlist set oldidlist fput 5 oldidlist set
oldidlist fput ticks oldidlist
                       set idnumber idnumber + 20000 set improved (improved + 1) set wall
3 set heattax heattaxpotwall set subgrantwall solidwallgrant ask people-here [set
instwall 1]
                       set solidwall 1
                      ]
                    ask my-links [die]
                    if glazing = 2
                     [ set lookupdg (idnumber - 100000) create-link-with one-of refhouses
with [idnumber = [lookupdg] of myself ] set glazing 1 set oldidlist fput idnumber
oldidlist
                       set oldidlist fput 6 oldidlist set oldidlist fput ticks oldidlist set idnumber
lookupdg set electrickwh [electrickwh] of one-of link-neighbors
                       set heatkwh [ heatkwh] of one-of link-neighbors set hkwh [hkwh] of
one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors ask my-links [die]
                      ]
                ]

         ifelse roof = 0 or pv = 1
                [ ] ;stop
                [ set lookuppv ( idnumber - 1 ) set potimprov potimprov + 1 create-
link-with one-of refhouses with [idnumber = [lookuppv] of myself ] ask my-links [set
color yellow]
                 set npv count (houses-on neighbors) with [ pv = 1 ] set difference (
electrickwh - [ electrickwh] of one-of link-neighbors )
                 set electaxpotpv ([electrickwh] of one-of link-neighbors) * elec-co2 *
co2tax / 100 if electaxpotpv < 0 [ set electaxpotpv 0 ]
                 set saving difference * ( elec-sold + elec ) / 2 + electax - electaxpotpv
set repayment (saving / 12) * (paybackrate / 100 )
                 set repay repayconst + repayx * repayment + repayx2 * repayment *
repayment + repayx3 * repayment * repayment * repayment
                 set adjustedprice pvfixed + pvmarg * difference / 850 + pvmain *
discmain - saving * discsav  - discfriend * npv / 4 - pv-grant - ( pv-fit / 100 ) * difference
* discsav
                 if adjustedprice < 0 [ set adjustedprice 0 ]
                 if priceconst + pricex * adjustedprice + pricex2 * adjustedprice *
adjustedprice + loanincent + incentiveadjust + repay > none
```

```
                        [ set subgrantpv pv-grant set pvoutput ( electrickwh - [electrickwh] of
one-of link-neighbors ) set savpv pvoutput * elec-co2 set returnpv pv-fit * pvoutput /
100
                         set years 1 repeat 25 [ set subnpvpv subnpvpv + returnpv / ( 1 +
npv-rate / 100 ) ^ years set years years + 1 ] set years 1
                         set pv 1 ask people-here [set instpv 1] set electax electaxpotpv set
electrickwh [electrickwh] of one-of link-neighbors
                         set heatkwh [heatkwh] of one-of link-neighbors set hkwh [hkwh] of
one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors set ckwh [ckwh] of
one-of link-neighbors
                         set oldidlist fput idnumber oldidlist set oldidlist fput 1 oldidlist set
oldidlist fput ticks oldidlist set idnumber (idnumber - 1) set improved (improved + 1)
                        ]
                       ask my-links [die]
                       if glazing = 2
                        [ set lookupdg (idnumber - 100000) create-link-with one-of
refhouses with [idnumber = [lookupdg] of myself ] set glazing 1 set oldidlist fput
idnumber oldidlist
                         set oldidlist fput 6 oldidlist set oldidlist fput ticks oldidlist set
idnumber lookupdg set electrickwh [electrickwh] of one-of link-neighbors set ckwh
[ckwh] of one-of link-neighbors
                         set heatkwh [ heatkwh] of one-of link-neighbors set hkwh [hkwh] of
one-of link-neighbors set wkwh [wkwh] of one-of link-neighbors ask my-links [die]
                        ]
                      ]
           ]
        ]
     ]
  ]

ask people with [ moving = 1 ] [ if not empty? empty-houses-list [ move-to first empty-
houses-list move-to patch-here
ask first empty-houses-list [ set empty-houses-list butfirst empty-houses-list ]] ]
set empty-houses-list [] set moving-people-list []
ask houses [ while [ any? other houses-here ][  rt random-float 360 jump random-float
3 move-to patch-here ] ]
ask people  [ifelse any? houses-here [ set moving 0 ] [set moving 1 ] if any? other
people-here [set moving 1] ]
ask houses [ ifelse not any? people-here [set empty 1 set empty-houses-list fput self
empty-houses-list ] [ set empty 0 ] ]
ask people with [ moving = 1 ][ if not empty? empty-houses-list [ move-to first empty-
houses-list
move-to patch-here ask first empty-houses-list  [ set empty-houses-list butfirst empty-
houses-list ] ] ]
ask people with [ moving = 1 ] [ set moving 0 ]ask houses with [ empty = 1 ] [ set empty
0 ]
```

```
end



to elecsavecalc

ifelse heat = 5
  [ set savingelec differenceheat * (elec-peak-price * 0.8 + elec-off-price * 0.2) +
differencewater * (elec-peak-price * hrf + elec-off-price * (1 - hrf) ) ]
  [ set savingelec differenceheat * (elec-peak-price * 0.8 + elec-off-price * 0.2) +
differencewater * (elec-peak-price * 0.7 + elec-off-price * 0.3 ) ]
;calculates heat running host for heat 5 (storage heater) and heat 8 or 9 (heat pump)

end



to do-plots

set-current-plot "Heating %"
  set-current-plot-pen "Cond" plot ( count houses  with [ heat = 1 ] ) / count houses
  set-current-plot-pen "Combi"  plot ( count houses  with [ heat = 2 ] ) / ( count houses
)
  set-current-plot-pen "Regular" plot ( count houses  with [ heat = 3 ] ) / count houses
  set-current-plot-pen "Oil/LPG" plot ( count houses  with [ heat = 4 ] ) / count houses
  set-current-plot-pen "Electric"  plot ( count houses  with [ heat = 5 ] ) / ( count houses
)
  set-current-plot-pen "Solid/Bio" plot ( count houses  with [ heat = 6 ] ) / count houses
  set-current-plot-pen "Community" plot ( count houses  with [ heat = 7 ] ) / count
houses
  set-current-plot-pen "Heat pump"  plot ( count houses  with [ heat = 8 ] ) / ( count
houses )
  set-current-plot-pen "ASHP"  plot ( count houses  with [ heat = 9 ] ) / ( count houses )
  set-current-plot-pen "PV"  plot ( count houses  with [ pv = 1 ] ) / ( count houses )
  set-current-plot-pen "Solar HW"  plot ( count houses  with [ hw = 1 ] ) / ( count
houses )
  set-current-plot-pen "Loft Insul"  plot ( count houses with [ roof = 1 ] ) / count houses
with [ roof > 0 ]
  set-current-plot-pen "CWI"  plot ( count houses with [ wall = 3 and solidwall = 0 ] ) / (
count houses with [ wall > 1.5 ] )
  set-current-plot-pen "Solid Wall Ins"  plot ( 1 - ( count houses with [ wall = 3 and
solidwall = 1 ] ) / ( count houses with [ solidwall = 1 ] ) )
```

set-current-plot-pen "CO2pc" plot (co2tot / co2init) set-current-plot-pen "DG" plot dgtot / count houses

set-current-plot "CO2 per Tech"
set-current-plot-pen "Total CO2" plot saving1 + saving6 + saving8 + savingpv + savingshw + savingcwi + savingloft + savingwall + saving9
set-current-plot-pen "Cond" plot saving1 set-current-plot-pen "Solid/Bio" plot saving6 set-current-plot-pen "Heat Pump" plot saving8
set-current-plot-pen "PV" plot savingpv set-current-plot-pen "Solar HW" plot savingshw set-current-plot-pen "CWI" plot savingcwi
set-current-plot-pen "Loft Insul" plot savingloft set-current-plot-pen "Solid Wall Ins" plot savingwall set-current-plot-pen "ASHP" plot saving9

set-current-plot "£/CO2"
set-current-plot-pen "Total" plot totalcostperco2 set-current-plot-pen "Cond" plot costpersav1 set-current-plot-pen "Solid" plot costpersav6
set-current-plot-pen "Heat Pump" plot costpersav8 set-current-plot-pen "PV" plot costpersavpv set-current-plot-pen "Solar HW" plot costpersavshw
set-current-plot-pen "CWI" plot costpersavcwi set-current-plot-pen "Loft" plot costpersavloft set-current-plot-pen "Solid Wall" plot costpersavwall
set-current-plot-pen "ASHP" plot costpersav9

set-current-plot "No. of installations"
set-current-plot-pen "Cond" plot count houses with [sav1 > 0 and heat = 1] set-current-plot-pen "Solid/Bio" plot count houses with [sav6 > 0 and heat = 6]
set-current-plot-pen "Heat Pump" plot count houses with [sav8 > 0 and heat = 8] set-current-plot-pen "PV" plot count houses with [savpv > 0 and pv = 1]
set-current-plot-pen "Solar HW" plot count houses with [savshw > 0 and hw = 1] set-current-plot-pen "CWI" plot count houses with [savcwi > 0 and wall = 3]
set-current-plot-pen "Loft Insul" plot count houses with [savloft > 0 and roof = 1] set-current-plot-pen "Solid Wall Ins" plot count houses with [savwall > 0 and solidwall = 1]
set-current-plot-pen "DG" plot dgtot - dgold set-current-plot-pen "ASHP" plot count houses with [sav9 > 0 and heat = 9]

set-current-plot "Heating Absolute"
set-current-plot-pen "Cond" plot (count houses with [heat = 1])   set-current-plot-pen "Combi" plot (count houses with [heat = 2])
set-current-plot-pen "Regular" plot (count houses with [heat = 3])   set-current-plot-pen "Oil/LPG" plot (count houses with [heat = 4])
set-current-plot-pen "Electric" plot (count houses with [heat = 5]) set-current-plot-pen "Solid" plot (count houses with [heat = 6])
set-current-plot-pen "Community" plot (count houses with [heat = 7])   set-current-plot-pen "Heat pump" plot (count houses with [heat = 8])
set-current-plot-pen "ASHP" plot (count houses with [heat = 9]) set-current-plot-pen "PV" plot (count houses with [pv = 1])

```
  set-current-plot-pen "Solar HW"  plot ( count houses  with [ hw = 1 ] ) set-current-plot-pen "Loft Insul"  plot ( count houses with [ roof = 1 ] )
  set-current-plot-pen "CWI"  plot ( count houses with [ wall = 3 ] )  set-current-plot-pen "Solid Wall Ins"  plot count houses with [ wall = 3 and solidwall = 1 ]


set-current-plot "Annual Cost and Tax"
  set-current-plot-pen "heattax" plot heattaxtot
  set-current-plot-pen "electax" plot electaxtot
  set-current-plot-pen "Subsidy" plot totalcost

set-current-plot "Total Cost and Tax"
  set-current-plot-pen "Total Cum Tax" plot revenuetot
  set-current-plot-pen "Cum Subsidy" plot subsidycost

set-current-plot "Cumulative CO2"
  set-current-plot-pen "cumco2" plot cumco2

set-current-plot "kwh/dwelling"
 set-current-plot-pen "totalkwh" plot totalkwh / count houses set-current-plot-pen "electrictotal" plot totalelectrickwh / count houses
 set-current-plot-pen "heattotal" plot totalheatkwh / count houses
 set-current-plot-pen "coolpotent" plot totalcoolkwh / count houses

set-current-plot "cluster"
 set-current-plot-pen "clust1" plot count people with [cluster = 1] ; clust1
 set-current-plot-pen "clust2" plot count people with [cluster = 2] ; clust2
 set-current-plot-pen "clust3" plot count people with [cluster = 3] ; clust3
 set-current-plot-pen "clust4" plot count people with [cluster = 4] ; clust4
 set-current-plot-pen "clust5" plot count people with [cluster = 5] ; clust5
 set-current-plot-pen "clust6" plot count people with [cluster = 6] ; clust6
 set-current-plot-pen "clust7" plot count people with [cluster = 7] ; clust7

set-current-plot "clustertechpv"
 set-current-plot-pen "clust1" plot clust1pv
 set-current-plot-pen "clust2" plot clust2pv
 set-current-plot-pen "clust3" plot clust3pv
 set-current-plot-pen "clust4" plot clust4pv
 set-current-plot-pen "clust5" plot clust5pv
 set-current-plot-pen "clust6" plot clust6pv
 set-current-plot-pen "clust7" plot clust7pv

set-current-plot "clustertechshw"
 set-current-plot-pen "clust1" plot clust1shw
 set-current-plot-pen "clust2" plot clust2shw
 set-current-plot-pen "clust3" plot clust3shw
 set-current-plot-pen "clust4" plot clust4shw
```

```
 set-current-plot-pen "clust5" plot clust5shw
 set-current-plot-pen "clust6" plot clust6shw
 set-current-plot-pen "clust7" plot clust7shw

set-current-plot "clustertechloft"
 set-current-plot-pen "clust1" plot clust1loft
 set-current-plot-pen "clust2" plot clust2loft
 set-current-plot-pen "clust3" plot clust3loft
 set-current-plot-pen "clust4" plot clust4loft
 set-current-plot-pen "clust5" plot clust5loft
 set-current-plot-pen "clust6" plot clust6loft
 set-current-plot-pen "clust7" plot clust7loft

set-current-plot "clustertechcwi"
 set-current-plot-pen "clust1" plot clust1cwi
 set-current-plot-pen "clust2" plot clust2cwi
 set-current-plot-pen "clust3" plot clust3cwi
 set-current-plot-pen "clust4" plot clust4cwi
 set-current-plot-pen "clust5" plot clust5cwi
 set-current-plot-pen "clust6" plot clust6cwi
 set-current-plot-pen "clust7" plot clust7cwi

set-current-plot "clustertechwall"
 set-current-plot-pen "clust1" plot clust1wall
 set-current-plot-pen "clust2" plot clust2wall
 set-current-plot-pen "clust3" plot clust3wall
 set-current-plot-pen "clust4" plot clust4wall
 set-current-plot-pen "clust5" plot clust5wall
 set-current-plot-pen "clust6" plot clust6wall
 set-current-plot-pen "clust7" plot clust7wall

set-current-plot "clustertech6"
 set-current-plot-pen "clust1" plot clust16
 set-current-plot-pen "clust2" plot clust26
 set-current-plot-pen "clust3" plot clust36
 set-current-plot-pen "clust4" plot clust46
 set-current-plot-pen "clust5" plot clust56
 set-current-plot-pen "clust6" plot clust66
 set-current-plot-pen "clust7" plot clust76

set-current-plot "clustertech7"
 set-current-plot-pen "clust1" plot clust17
 set-current-plot-pen "clust2" plot clust27
 set-current-plot-pen "clust3" plot clust37
 set-current-plot-pen "clust4" plot clust47
 set-current-plot-pen "clust5" plot clust57
 set-current-plot-pen "clust6" plot clust67
```

```
 set-current-plot-pen "clust7" plot clust77

set-current-plot "clustertech8"
 set-current-plot-pen "clust1" plot clust18
 set-current-plot-pen "clust2" plot clust28
 set-current-plot-pen "clust3" plot clust38
 set-current-plot-pen "clust4" plot clust48
 set-current-plot-pen "clust5" plot clust58
 set-current-plot-pen "clust6" plot clust68
 set-current-plot-pen "clust7" plot clust78

set-current-plot "clustertech9"
 set-current-plot-pen "clust1" plot clust19
 set-current-plot-pen "clust2" plot clust29
 set-current-plot-pen "clust3" plot clust39
 set-current-plot-pen "clust4" plot clust49
 set-current-plot-pen "clust5" plot clust59
 set-current-plot-pen "clust6" plot clust69
 set-current-plot-pen "clust7" plot clust79

end
```

Appendix C SAP Worksheet

This appendix provides a copy of the blank SAP worksheet from SAP 2009 (BRE, 2011a)

SAP WORKSHEET (Version 9.90)

1. Overall dwelling dimensions

	Area (m^2)			Average storey height (m)			Volume (m^3)	
Basement		(1a)	×		(2a)	=		(3a)
Ground floor		(1b)	×		(2b)	=		(3b)
First floor		(1c)	×		(2c)	=		(3c)
Second floor		(1d)	×		(2d)	=		(3d)
Third floor		(1e)	×		(2e)	=		(3e)
Other floors *(repeat as necessary)*		(1n)	×		(2n)	=		(3n)
Total floor area TFA = (1a)+(1b)+(1c)+(1d)+(1e)...(1n) =		(4)						
Dwelling volume				(3a)+(3b)+(3c)+(3d)+(3e)...(3n)		=		(5)

2. Ventilation rate

	main heating		secondary heating		other		total		m^3 per hour	
Number of chimneys		+		+		=		× 40 =		(6a)
Number of open flues		+		+		=		× 20 =		(6b)
Number of intermittent fans								× 10 =		(7a)
Number of passive vents								× 10 =		(7b)
Number of flueless gas fires								× 40 =		(7c)

		Air changes per hour	
Infiltration due to chimneys, flues, fans, PSVs	(6a)+(6b)+(7a)+(7b)+(7c) = ÷ (5) =		(8)

If a pressurisation test has been carried out or is intended, proceed to (17), otherwise continue from (9) to (16)

Number of storeys in the dwelling (n_s)			(9)
Additional infiltration	[(9) – 1] × 0.1 =		(10)
Structural infiltration: *0.25 for steel or timber frame or 0.35 for masonry construction* *if both types of wall are present, use the value corresponding to the greater wall area (after deducting areas of openings); if equal use 0.35*			(11)
If suspended wooden floor, *enter 0.2 (unsealed) or 0.1 (sealed)*, else enter 0			(12)
If no draught lobby, enter 0.05, else enter 0			(13)
Percentage of windows and doors draught stripped			(14)
Window infiltration	0.25 - [0.2 × (14) ÷ 100] =		(15)
Infiltration rate	(8) + (10) + (11) + (12) + (13) + (15) =		(16)
Air permeability value, q_{50}, expressed in cubic metres per hour per square metre of envelope area			(17)
If based on air permeability value, then (18) = [(17) ÷ 20]+(8), otherwise (18) = (16)			(18)

Air permeability value applies if a pressurisation test has been done, or a design or specified air permeability is being used

Number of sides on which dwelling is sheltered			(19)
Shelter factor	(20) = 1 - [0.075 × (19)] =		(20)
Infiltration rate incorporating shelter factor	(21) = (18) × (20) =		(21)

Infiltration rate modified for monthly wind speed:

Monthly average wind speed from Table 7

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$(22)_m$ =	$(22)_1$	$(22)_2$	$(22)_3$	$(22)_4$	$(22)_5$	$(22)_6$	$(22)_7$	$(22)_8$	$(22)_9$	$(22)_{10}$	$(22)_{11}$	$(22)_{12}$

Wind Factor $(22a)_m = (22)_m \div 4$

$(22a)_m$ =	$(22a)_1$	$(22a)_2$	$(22a)_3$	$(22a)_4$	$(22a)_5$	$(22a)_6$	$(22a)_7$	$(22a)_8$	$(22a)_9$	$(22a)_{10}$	$(22a)_{11}$	$(22a)_{12}$

Adjusted infiltration rate (allowing for shelter and wind speed) = $(21) \times (22a)_m$

$(22b)_m$ =	$(22b)_1$	$(22b)_2$	$(22b)_3$	$(22b)_4$	$(22b)_5$	$(22b)_6$	$(22b)_7$	$(22b)_8$	$(22b)_9$	$(22b)_{10}$	$(22b)_{11}$	$(22b)_{12}$

Calculate effective air change rate for the applicable case:

If mechanical ventilation: air change rate through system	0.5	(23a)
If exhaust air heat pump using Appendix N, (23b) = (23a) × F_{mv} (equation (N4)) , otherwise (23b) = (23a)		(23b)
If balanced with heat recovery: efficiency in % allowing for in-use factor (from Table 4h) =		(23c)

a) If balanced mechanical ventilation with heat recovery (MVHR) $(24a)_m = (22b)_m + (23b) \times [1 - (23c) \div 100]$

$(24a)_m$ =	$(24a)_1$	$(24a)_2$	$(24a)_3$	$(24a)_4$	$(24a)_5$	$(24a)_6$	$(24a)_7$	$(24a)_8$	$(24a)_9$	$(24a)_{10}$	$(24a)_{11}$	$(24a)_{12}$	(24a)

b) If balanced mechanical ventilation without heat recovery (MV) $(24b)_m = (22b)_m + (23b)$

$(24b)_m$ =	$(24b)_1$	$(24b)_2$	$(24b)_3$	$(24b)_4$	$(24b)_5$	$(24b)_6$	$(24b)_7$	$(24b)_8$	$(24b)_9$	$(24b)_{10}$	$(24b)_{11}$	$(24b)_{12}$	(24b)

c) If whole house extract ventilation or positive input ventilation from outside

if $(22b)_m < 0.5 \times (23b)$, then (24c) = (23b); otherwise $(24c) = (22b)_m + 0.5 \times (23b)$

$(24c)_m$ =	$(24c)_1$	$(24c)_2$	$(24c)_3$	$(24c)_4$	$(24c)_5$	$(24c)_6$	$(24c)_7$	$(24c)_8$	$(24c)_9$	$(24c)_{10}$	$(24c)_{11}$	$(24c)_{12}$	(24c)

d) If natural ventilation or whole house positive input ventilation from loft

if $(22b)_m \geq 1$, then $(24d)_m = (22b)_m$ otherwise $(24d)_m = 0.5 + [(22b)_m^2 \times 0.5]$

$(24d)_m$ =	$(24d)_1$	$(24d)_2$	$(24d)_3$	$(24d)_4$	$(24d)_5$	$(24d)_6$	$(24d)_7$	$(24d)_8$	$(24d)_9$	$(24d)_{10}$	$(24d)_{11}$	$(24d)_{12}$	(24d)

Effective air change rate - enter (24a) or (24b) or (24c) or (24d) in box (25)

$(25)_m$ =	$(25)_1$	$(25)_2$	$(25)_3$	$(25)_4$	$(25)_5$	$(25)_6$	$(25)_7$	$(25)_8$	$(25)_9$	$(25)_{10}$	$(25)_{11}$	$(25)_{12}$	(25)

If Appendix Q applies in relation to air change rate, the effective air change rate is calculated via Appendix Q and use the following instead:

Effective air change rate from Appendix Q calculation sheet:

$(25)_m$ =	$(25)_1$	$(25)_2$	$(25)_3$	$(25)_4$	$(25)_5$	$(25)_6$	$(25)_7$	$(25)_8$	$(25)_9$	$(25)_{10}$	$(25)_{11}$	$(25)_{12}$	(25)

3. Heat losses and heat loss parameter

Items in the table below are to be expanded as necessary to allow for all different types of element e.g. 4 wall types.
The κ-value is the heat capacity per unit area, see Table 1e

Element	Gross area, m²		Openings m²		Net area A, m²		U-value W/m²K	=	A × U W/K	κ-value kJ/m²·K	A × κ kJ/K	
Door						×						(26)
Window						×	* below	=				(27)
Roof window						×	* below	=				(27a)
Basement floor						×		=				(28)
Ground floor						×		=				(28a)
Exposed floor						×		=				(28b)
Basement wall		-		=		×		=				(29)
External wall		-		=		×		=				(29a)
Roof		-		=		×		=				(30)
Total area of external elements ΣA, m²						(31)						
Party wall						×		=				(32)
(party wall U-value from Table 3.6, κ according to its construction)												
Party floor												(32a)
Party ceiling												(32b)
Internal wall **												(32c)
Internal floor												(32d)
Internal ceiling												(32e)

* *for windows and roof windows, use effective window U-value calculated using formula 1/[(1/U-value)+0.04] as given in paragraph 3.2*
** *include the areas on both sides of internal walls and partitions*

Fabric heat loss, W/K = Σ (A × U) (26)…(30) + (32) = [ ] (33)

Heat capacity C_m = Σ(A × κ) (28)…(30) + (32) + (32a)…(32e) = [ ] (34)

Thermal mass parameter (TMP = C_m ÷ TFA) in kJ/m²K = (34) ÷ (4) = [ ] (35)

For design assessments where the details of the construction are not known precisely the indicative values of TMP in Table 1f can be used instead of a detailed calculation. Also TMP calculated separately can be used in (35).

Thermal bridges : Σ (L × Ψ) calculated using Appendix K [ ] (36)

if details of thermal bridging are not known (36) = 0.15 × (31)

Total fabric heat loss (33) + (36) = [ ] (37)

Ventilation heat loss calculated monthly $(38)_m = 0.33 \times (25)_m \times (5)$

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(38)_m$ =	$(38)_1$	$(38)_2$	$(38)_3$	$(38)_4$	$(38)_5$	$(38)_6$	$(38)_7$	$(38)_8$	$(38)_9$	$(38)_{10}$	$(38)_{11}$	$(38)_{12}$	(38)

Heat transfer coefficient, W/K $(39)_m = (37) + (38)_m$

$(39)_m$ =	$(39)_1$	$(39)_2$	$(39)_3$	$(39)_4$	$(39)_5$	$(39)_6$	$(39)_7$	$(39)_8$	$(39)_9$	$(39)_{10}$	$(39)_{11}$	$(39)_{12}$	

Average = $\Sigma(39)_{1\ldots12}/12$= [ ] (39)

Heat loss parameter (HLP), W/m²K $(40)_m = (39)_m \div (4)$

$(40)_m$ =	$(40)_1$	$(40)_2$	$(40)_3$	$(40)_4$	$(40)_5$	$(40)_6$	$(40)_7$	$(40)_8$	$(40)_9$	$(40)_{10}$	$(40)_{11}$	$(40)_{12}$

Average = $\Sigma(40)_{1\ldots12}/12$= [ ] (40)

Number of days in month (Table 1a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(41)_m$ =	$(41)_1$	$(41)_2$	$(41)_3$	$(41)_4$	$(41)_5$	$(41)_6$	$(41)_7$	$(41)_8$	$(41)_9$	$(41)_{10}$	$(41)_{11}$	$(41)_{12}$	(41)

4. Water heating energy requirement

kWh/year

Assumed occupancy, N (42)

if TFA > 13.9, N = 1 + 1.76 × [1 - exp(-0.000349 × (TFA -13.9)²)] + 0.0013 × (TFA -13.9)

if TFA ≤ 13.9, N = 1

Annual average hot water usage in litres per day $V_{d,average}$ = (25 × N) + 36 (43)

Reduce the annual average hot water usage by 5% if the dwelling is designed to achieve a water use target of not more that 125 litres per person per day (all water use, hot and cold)

Hot water usage in litres per day for each month $V_{d,m}$ = factor from Table 1c × (43)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(44)_m$ =	$(44)_1$	$(44)_2$	$(44)_3$	$(44)_4$	$(44)_5$	$(44)_6$	$(44)_7$	$(44)_8$	$(44)_9$	$(44)_{10}$	$(44)_{11}$	$(44)_{12}$	

Total = $\Sigma(44)_{1...12}$ = (44)

Energy content of hot water used - calculated monthly = 4.190 × $V_{d,m}$ × n_m × ΔT_m / 3600 kWh/month (see Tables 1b, 1c, 1d)

$(45)_m$ =	$(45)_1$	$(45)_2$	$(45)_3$	$(45)_4$	$(45)_5$	$(45)_6$	$(45)_7$	$(45)_8$	$(45)_9$	$(45)_{10}$	$(45)_{11}$	$(45)_{12}$

Total = $\Sigma(45)_{1...12}$ = (45)

If instantaneous water heating at point of use (no hot water storage), enter "0" in boxes (46) to (61)

For community heating include distribution loss whether or not hot water tank is present

Distribution loss $(46)_m$ = 0.15 x $(45)_m$

$(46)_m$ =	$(46)_1$	$(46)_2$	$(46)_3$	$(46)_4$	$(46)_5$	$(46)_6$	$(46)_7$	$(46)_8$	$(46)_9$	$(46)_{10}$	$(46)_{11}$	$(46)_{12}$	(46)

Water storage loss:

a) If manufacturer's declared loss factor is known (kWh/day): (47)

Temperature factor from Table 2b (48)

Energy lost from water storage, kWh/day (47) × (48) = (49)

b) If manufacturer's declared cylinder loss factor is not known :

Cylinder volume (litres) including any solar storage within same cylinder (50)

If community heating and no tank in dwelling, enter 110 litres in box (50)

Otherwise if no stored hot water (this includes instantaneous combi boilers) enter '0' in box (50)

Hot water storage loss factor from Table 2 (kWh/litre/day) (51)

If community heating see section 4.3

Volume factor from Table 2a (52)

Temperature factor from Table 2b (53)

Energy lost from water storage, kWh/day (50) × (51) × (52) × (53) = (54)

Enter (49) or (54) in (55) (55)

Water storage loss calculated for each month $(56)_m$ = (55) × $(41)_m$

$(56)_m$ =	$(56)_1$	$(56)_2$	$(56)_3$	$(56)_4$	$(56)_5$	$(56)_6$	$(56)_7$	$(56)_8$	$(56)_9$	$(56)_{10}$	$(56)_{11}$	$(56)_{12}$	(56)

If cylinder contains dedicated solar storage, $(57)_m$ = $(56)_m$ × [(50) – (H11)] ÷ (50), else $(57)_m$ = $(56)_m$ where (H11) is from Appendix H

$(57)_m$ =	$(57)_1$	$(57)_2$	$(57)_3$	$(57)_4$	$(57)_5$	$(57)_6$	$(57)_7$	$(57)_8$	$(57)_9$	$(57)_{10}$	$(57)_{11}$	$(57)_{12}$	(57)

Primary circuit loss (annual) from Table 3 (58)

Primary circuit loss for each month $(59)_m$ = (58) ÷ 365 × $(41)_m$

(modified by factor from Table H5 if there is solar water heating and a cylinder thermostat)

$(59)_m$ =	$(59)_1$	$(59)_2$	$(59)_3$	$(59)_4$	$(59)_5$	$(59)_6$	$(59)_7$	$(59)_8$	$(59)_9$	$(59)_{10}$	$(59)_{11}$	$(59)_{12}$	(59)

Combi loss for each month from Table 3a, 3b or 3c (enter "0" if not a combi boiler)

$(61)_m$ =	$(61)_1$	$(61)_2$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_3$	$(61)_{12}$	(61)

Total heat required for water heating calculated for each month $(62)_m = 0.85 \times (45)_m + (46)_m + (57)_m + (59)_m + (61)_m$

$(62)_m$ =	$(62)_1$	$(62)_2$	$(62)_3$	$(62)_4$	$(62)_5$	$(62)_6$	$(62)_7$	$(62)_8$	$(62)_9$	$(62)_{10}$	$(62)_{11}$	$(62)_{12}$	(62)

Solar DHW input calculated using Appendix G or Appendix H (negative quantity) (enter "0" if no solar contribution to water heating)
(add additional lines if FGHRS and/or WWHRS applies, see Appendix G)

$(63)_m$ =	$(63)_1$	$(63)_2$	$(63)_3$	$(63)_4$	$(63)_5$	$(63)_6$	$(63)_7$	$(63)_8$	$(63)_9$	$(63)_{10}$	$(63)_{11}$	$(63)_{12}$	(63)

Output from water heater for each month, kWh/month $(64)_m = (62)_m + (63)_m$

$(64)_m$ =	$(64)_1$	$(64)_2$	$(64)_3$	$(64)_4$	$(64)_5$	$(64)_6$	$(64)_7$	$(64)_8$	$(64)_9$	$(64)_{10}$	$(64)_{11}$	$(64)_{12}$	

Total per year (kWh/year) = $\Sigma(64)_{1...12}$ = (64)

if $(64)_m < 0$ then set to 0

Heat gains from water heating, kWh/month $0.25 \times [0.85 \times (45)_m + (61)_m] + 0.8 \times [(46)_m + (57)_m + (59)_m]$

$(65)_m$ =	$(65)_1$	$(65)_2$	$(65)_3$	$(65)_4$	$(65)_5$	$(65)_6$	$(65)_7$	$(65)_8$	$(65)_9$	$(65)_{10}$	$(65)_{11}$	$(65)_{12}$	(65)

include $(57)_m$ in calculation of $(65)_m$ only if cylinder is in the dwelling or hot water is from community heating

5. Internal gains (see Table 5 and 5a)

Metabolic gains (Table 5), Watts

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(66)_m$ =	$(66)_1$	$(66)_2$	$(66)_3$	$(66)_4$	$(66)_5$	$(66)_6$	$(66)_7$	$(66)_8$	$(66)_9$	$(66)_{10}$	$(66)_{11}$	$(66a)_{12}$	(66)

Lighting gains (calculated in Appendix L, equation L9 or L9a), also see Table 5

$(67)_m$ =	$(67)_1$	$(67)_2$	$(67)_3$	$(67)_4$	$(67)_5$	$(67)_6$	$(67)_7$	$(67)_8$	$(67)_9$	$(67)_{10}$	$(67)_{11}$	$(67)_{12}$	(67)

Appliances gains (calculated in Appendix L, equation L13 or L13a), also see Table 5

$(68)_m$ =	$(68)_1$	$(68)_2$	$(68)_3$	$(68)_4$	$(68)_5$	$(68)_6$	$(68)_7$	$(68)_8$	$(68)_9$	$(68)_{10}$	$(68)_{11}$	$(68)_{12}$	(68)

Cooking gains (calculated in Appendix L, equation L15 or L15a), also see Table 5

$(69)_m$ =	$(69)_1$	$(69)_2$	$(69)_3$	$(69)_4$	$(69)_5$	$(69)_6$	$(69)_7$	$(69)_8$	$(69)_9$	$(69)_{10}$	$(69)_{11}$	$(69)_{12}$	(69)

Pumps and fans gains (Table 5a)

$(70)_m$ =	$(70)_1$	$(70)_2$	$(70)_3$	$(70)_4$	$(70)_5$	$(70)_6$	$(70)_7$	$(70)_8$	$(70)_9$	$(70)_{10}$	$(70)_{11}$	$(70)_{12}$	(70)

Losses e.g. evaporation (negative values) (Table 5)

$(71)_m$ =	$(71)_1$	$(71)_2$	$(71)_3$	$(71)_4$	$(71)_5$	$(71)_6$	$(71)_7$	$(71)_8$	$(71)_9$	$(71)_{10}$	$(71)_{11}$	$(71)_{12}$	(71)

Water heating gains (Table 5)

$(72)_m$ =	$(72)_1$	$(72)_2$	$(72)_3$	$(72)_4$	$(72)_5$	$(72)_6$	$(72)_7$	$(72)_8$	$(72)_9$	$(72)_{10}$	$(72)_{11}$	$(72)_{12}$	(72)

Total internal gains = $(66)_m + (67)_m + (68)_m + (69)_m + (70)_m + (71)_m + (72)_m$

$(73)_m$ =	$(73)_1$	$(73)_2$	$(73)_3$	$(73)_4$	$(73)_5$	$(73)_6$	$(73)_7$	$(73)_8$	$(73)_9$	$(73)_{10}$	$(73)_{11}$	$(73)_{12}$	(73)

6. Solar gains

Solar gains are calculated using solar flux from Table 6a and associated equations to convert to the applicable orientation. Rows (74) to (82) are used 12 times, one for each month, repeating as needed if there is more than one window type.

	Access factor Table 6d		Area m²		Solar flux W/m²		$g_\perp$ Specific data or Table 6b		FF Specific data or Table 6c		Gains (W)	
North		×		×		× 0.9 ×		×		=		(74)
Northeast		×		×		× 0.9 ×		×		=		(75)
East		×		×		× 0.9 ×		×		=		(76)
Southeast		×		×		× 0.9 ×		×		=		(77)
South		×		×		× 0.9 ×		×		=		(78)
Southwest		×		×		× 0.9 ×		×		=		(79)
West		×		×		× 0.9 ×		×		=		(80)
Northwest		×		×		× 0.9 ×		×		=		(81)
Rooflights	1.0	×		×		× 0.9 ×		×		=		(82)

Solar gains in watts, calculated for each month $(83)_m = \Sigma(74)_m \ldots(82)_m$

$(83)_m$ =	$(83)_1$	$(83)_2$	$(83)_3$	$(83)_4$	$(83)_5$	$(83)_6$	$(83)_7$	$(83)_8$	$(83)_9$	$(83)_{10}$	$(83)_{11}$	$(83)_{12}$	(83)

Total gains – internal and solar $(84)_m = (73)_m + (83)_m$, watts

$(84)_m =$	$(84)_1$	$(84)_2$	$(84)_3$	$(84)_4$	$(84)_5$	$(84)_6$	$(84)_7$	$(84)_8$	$(84)_9$	$(84)_{10}$	$(84)_{11}$	$(84)_{12}$	(84)

7. Mean internal temperature (heating season)

Temperature during heating periods in the living area from Table 9, T_{h1} (°C) | 21 | (85)

Utilisation factor for gains for living area, $\eta_{1,m}$ (see Table 9a)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
$(86)_m =$	$(86)_1$	$(86)_2$	$(86)_3$	$(86)_4$	$(86)_5$	$(86)_6$	$(86)_7$	$(86)_8$	$(86)_9$	$(86)_{10}$	$(86)_{11}$	$(86)_{12}$	(86)

Mean internal temperature in living area T_1 *(follow steps 3 to 7 in Table 9c)*

$(87)_m =$	$(87)_1$	$(87)_2$	$(87)_3$	$(87)_4$	$(87)_5$	$(87)_6$	$(87)_7$	$(87)_8$	$(87)_9$	$(87)_{10}$	$(87)_{11}$	$(87)_{12}$	(87)

Temperature during heating periods in rest of dwelling from Table 9, T_{h2} (°C)

$(88)_m =$	$(88)_1$	$(88)_2$	$(88)_3$	$(88)_4$	$(88)_5$	$(88)_6$	$(88)_7$	$(88)_8$	$(88)_9$	$(88)_{10}$	$(88)_{11}$	$(88)_{12}$	(88)

Utilisation factor for gains for rest of dwelling, $\eta_{2,m}$ (see Table 9a)

$(89)_m =$	$(89)_1$	$(89)_2$	$(89)_3$	$(89)_4$	$(89)_5$	$(89)_6$	$(89)_7$	$(89)_8$	$(89)_9$	$(89)_{10}$	$(89)_{11}$	$(89)_{12}$	(89)

Mean internal temperature in the rest of dwelling T_2

(follow steps 8 to 9 in Table 9c, if two main heating systems see further notes in Table 9c)

$(90)_m =$	$(90)_1$	$(90)_2$	$(90)_3$	$(90)_4$	$(90)_5$	$(90)_6$	$(90)_7$	$(90)_8$	$(90)_9$	$(90)_{10}$	$(90)_{11}$	$(90)_{12}$	(90)

Living area fraction f_{LA} = Living area ÷ (4) = | | (91)

Mean internal temperature (for the whole dwelling) $= f_{LA} \times T_1 + (1 - f_{LA}) \times T_2$

$(92)_m =$	$(92)_1$	$(92)_2$	$(92)_3$	$(92)_4$	$(92)_5$	$(92)_6$	$(92)_7$	$(92)_8$	$(92)_9$	$(82)_{10}$	$(92)_{11}$	$(92)_{12}$	(92)

Apply adjustment to the mean internal temperature from Table 4e, where appropriate

$(93)_m =$	$(93)_1$	$(93)_2$	$(93)_3$	$(93)_4$	$(93)_5$	$(93)_6$	$(93)_7$	$(93)_8$	$(93)_9$	$(93)_{10}$	$(93)_{11}$	$(93)_{12}$	(93)

8. Space heating requirement

Set T_i to the mean internal temperature obtained at step 11 of Table 9b, so that $T_{i,m} = (93)_m$ and re-calculate the utilisation factor for gains using Table 9a

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Utilisation factor for gains, η_m:													
$(94)_m =$	$(94)_1$	$(94)_2$	$(94)_3$	$(94)_4$	$(94)_5$	$(94)_6$	$(94)_7$	$(94)_8$	$(94)_9$	$(94)_{10}$	$(94)_{11}$	$(94)_{12}$	(94)
Useful gains, $\eta_m G_m$, W $= (94)_m \times (84)_m$													
$(95)_m =$	$(95)_1$	$(95)_2$	$(95)_3$	$(95)_4$	$(95)_5$	$(95)_6$	$(95)_7$	$(95)_8$	$(95)_9$	$(95)_{10}$	$(95)_{11}$	$(95)_{12}$	(95)
Monthly average external temperature from Table 8													
$(96)_m =$	$(96)_1$	$(96)_2$	$(96)_3$	$(96)_4$	$(96)_5$	$(96)_6$	$(96)_7$	$(96)_8$	$(96)_9$	$(96)_{10}$	$(96)_{11}$	$(96)_{12}$	(96)
Heat loss rate for mean internal temperature, L_m , W $= [(39)_m \times [(93)_m - (96)_m]$													
$(97)_m =$	$(97)_1$	$(97)_2$	$(97)_3$	$(97)_4$	$(97)_5$	$(97)_6$	$(97)_7$	$(97)_8$	$(97)_9$	$(97)_{10}$	$(97)_{11}$	$(97)_{12}$	(97)
Space heating requirement for each month, kWh/month $= 0.024 \times [(97)_m - (95)_m] \times (41)_m$													
$(98)_m =$	$(98)_1$	$(98)_2$	$(98)_3$	$(98)_4$	$(98)_5$	$(98)_6$	$(98)_7$	$(98)_8$	$(98)_9$	$(98)_{10}$	$(98)_{11}$	$(98)_{12}$	

Total per year (kWh/year) $= \Sigma(98)_{1...5,10...12} =$ | | (98)

Space heating requirement in kWh/m²/year (98) ÷ (4) = | | (99)

For range cooker boilers where efficiency is obtained from the Boiler Efficiency Database or manufacturer's declared value, multiply the results in $(98)_m$ by $(1 - \Phi_{case}/\Phi_{water})$ where Φ_{case} is the heat emission from the case of the range cooker at full load (in kW); and Φ_{water} is the heat transferred to water at full load (in kW). Φ_{case} and Φ_{water} are obtained from the database record for the range cooker boiler or manufacturer's declared values. Where there are two main heating systems, this applies if the range cooker boiler is system 1 or system 2.

8c. Space cooling requirement

Calculated for June, July and August. See Table 10b

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Heat loss rate L_m (calculated using 24°C internal temperature and external temperature from Table 10)													
$(100)_m$ =	0	0	0	0	0	$(100)_6$	$(100)_7$	$(100)_8$	0	0	0	0	(100)
Utilisation factor for loss η_m													
$(101)_m$ =	0	0	0	0	0	$(101)_6$	$(101)_7$	$(101)_8$	0	0	0	0	(101)
Useful loss, $\eta_m L_m$ (Watts) = $(100)_m \times (101)_m$													
$(102)_m$ =	0	0	0	0	0	$(102)_6$	$(102)_7$	$(102)_8$	0	0	0	0	(102)
Gains (internal gains as for heating except that column (A) of Table 5 is always used; solar gains calculated for applicable weather region based on Table 10, not Table 6a)													
$(103)_m$ =	0	0	0	0	0	$(103)_6$	$(103)_7$	$(103)_8$	0	0	0	0	(103)
Space cooling requirement for month, whole dwelling, continuous (kWh) = 0.024 × $[(103)_m - (102)_m] \times (41)_m$ set $(104)_m$ to zero if $(104)_m < 3 \times (98)_m$ with $(98)_m$ calculated using weather data from Table 10													
$(104)_m$ =	0	0	0	0	0	$(104)_6$	$(104)_7$	$(104)_8$	0	0	0	0	
										Total = $\Sigma(104)_{6...8}$ =			(104)
Cooled fraction										f_C = cooled area ÷ (4) =			(105)
Intermittency factor (Table 10b)													
$(106)_m$	0	0	0	0	0	$(106)_6$	$(106)_7$	$(106)_8$	0	0	0	0	
										Total = $\Sigma(106)_{6...8}$ =			(106)
Space cooling requirement for month = $(104)_m \times (105) \times (106)_m$													
$(107)_m$	0	0	0	0	0	$(107)_6$	$(107)_7$	$(107)_8$	0	0	0	0	
										Total = $\Sigma(107)_{6...8}$ =			(107)
Space cooling requirement in kWh/m²/year										(107) ÷ (4) =			(108)

8f. Fabric Energy Efficiency (calculated only under special conditions, see section 11)

Fabric Energy Efficiency	(99) + (108) =		(109)

9a. Energy requirements – Individual heating systems including micro-CHP

For any space heating, space cooling or water heating provided by community heating use the alternative worksheet 9b.

Space heating:

Fraction of space heat from secondary/supplementary system (Table 11)	*"0" if none*		(201)
Fraction of space heat from main system(s)	(202) = 1 – (201) =		(202)
Fraction of main heating from main system 2	*if no second main system enter "0"*		(203)
Fraction of total space heat from main system 1	(204) = (202) × [1 – (203)] =		(204)
Fraction of total space heat from main system 2	(205) = (202) × (203) =		(205)

Efficiency of main space heating system 1 (in %) (206)
(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c; for gas and oil boilers see 9.2.1)

If there is a second main system complete (207)
Efficiency of main space heating system 2 (in %) (207)
(from database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'space efficiency adjustment' column of Table 4c; for gas and oil boilers see 9.2.1)

Efficiency of secondary/supplementary heating system, % *(from Table 4a or Appendix E)* (208)

Cooling System Energy Efficiency Ratio (see Table 10c) (209)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	kWh/year
Space heating requirement (calculated above)	$(98)_1$	$(98)_2$	$(98)_3$	$(98)_4$	$(98)_5$	0	0	0	0	$(98)_{10}$	$(98)_{11}$	$(98)_{12}$	

Space heating fuel (main heating system 1), kWh/month
$(211)_m = (98)_m \times (204) \times 100 \div (206)$

$(211)_m$	$(211)_1$	$(211)_2$	$(211)_3$	$(211)_4$	$(211)_5$	0	0	0	0	$(211)_{10}$	$(211)_{11}$	$(211)_{12}$

Total (kWh/year) $= \Sigma(211)_{1...5,10...12} =$ (211)

Space heating fuel (main heating system 2), kWh/month, omit if no second main heating system
$(213)_m = (98)_m \times (205) \times 100 \div (207)$

$(213)_m$	$(213)_1$	$(213)_2$	$(213)_3$	$(213)_4$	$(213)_5$	0	0	0	0	$(213)_{10}$	$(213)_{11}$	$(213)_{12}$

Total (kWh/year) $= \Sigma(213)_{1...5,10...12} =$ (213)

Space heating fuel (secondary), kWh/month
$(215)_m = (98)_m \times (201) \times 100 \div (208)$

$(215)_m$	$(215)_1$	$(215)_2$	$(215)_3$	$(215)_4$	$(215)_5$	0	0	0	0	$(215)_{10}$	$(215)_{11}$	$(215)_{12}$

Total (kWh/year) $= \Sigma(215)_{1...5,10...12} =$ (215)

Water heating

Output from water heater (calculated above)

$(64)_1$	$(64)_2$	$(64)_3$	$(64)_4$	$(64)_5$	$(64)_6$	$(64)_7$	$(64)_8$	$(64)_9$	$(64)_{10}$	$(64)_{11}$	$(64)_{12}$

Efficiency of water heater (216)

(From database or Table 4a/4b, adjusted where appropriate by the amount shown in the 'DHW efficiency adjustment' column of Table 4c, for gas and oil boilers use the summer efficiency, see 9.2.1)

if water heating by a hot-water-only boiler, $(217)_m$ = value from database record for boiler or Table 4a

otherwise if gas/oil boiler main system used for water heating, $(217)_m$ = value calculated for each month using equation (8) in section 9.2.1

otherwise if separate hot water only heater (including immersion) $(217)_m$ = applicable value from Table 4a

otherwise (other main system 1 or 2 used for water heating) $(217)_m$ = (216)

$(217)_m$ =	$(217)_1$	$(217)_2$	$(217)_3$	$(217)_4$	$(217)_5$	$(217)_6$	$(217)_7$	$(217)_8$	$(217)_9$	$(217)_{10}$	$(217)_{11}$	$(217)_{12}$	(217)

Fuel for water heating, kWh/month

$(219)_m = (64)_m \times 100 \div (217)_m$

$(219)_m$	$(219)_1$	$(219)_2$	$(219)_3$	$(219)_4$	$(219)_5$	$(219)_6$	$(219)_7$	$(219)_8$	$(219)_9$	$(219)_{10}$	$(219)_{11}$	$(219)_{12}$

Total = $\Sigma(219a)_{1...12}$ = (219)

(for a DHW-only community scheme use (305), (306) and (310a) or (310b), with (304a)=1.0 or (304b)=1.0, instead of (219)

Space cooling

Space cooling fuel, kWh/month

$(221)_m = (107)_m \div (209)$

$(221)_m$	0	0	0	0	0	$(221)_6$	$(221)_7$	$(221a)_8$	0	0	0	0

Total = $\Sigma(221)_{6...8}$ = (221)

Annual totals	kWh/year	kWh/year	
Space heating fuel used, main system 1		(211)	
Space heating fuel used, main system 2		(213)	
Space heating fuel used, secondary		(215)	
Water heating fuel used		(219)	
Space cooling fuel used (if there is a fixed cooling system, if not enter 0)		(221)	
Electricity for pumps, fans and electric keep-hot (Table 4f):			
mechanical ventilation fans - balanced, extract or positive input from outside			(230a)
warm air heating system fans			(230b)
central heating pump			(230c)
oil boiler pump			(230d)
boiler flue fan			(230e)
maintaining electric keep-hot facility for gas combi boiler			(230f)
pump for solar water heating			(230g)
Total electricity for the above, kWh/year	sum of (230a)…(230g) =		(231)
Electricity for lighting (calculated in Appendix L)			(232)
Energy saving/generation technologies (Appendices M ,N and Q)			
Electricity generated by PVs (Appendix M) (negative quantity)			(233)
Electricity generated by wind turbine (Appendix M) (negative quantity)			(234)
Electricity used or net electricity generated by micro-CHP (Appendix N) (negative if net generation)			(235)
Appendix Q items: annual energy (items not already included on a monthly basis)	Fuel	kWh/year	
Appendix Q, <item 1 description>			
energy saved or generated (enter as negative quantity)			(236a)
energy used (positive quantity)			(237a)

Appendix Q, <item 2 description>		
energy saved or generated (enter as negative quantity)		(236b)
energy used (positive quantity)		(237b)
(continue this list if additional items)		

10a. Fuel costs – Individual heating systems including micro-CHP

	Fuel kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating - main system 1	(211)	×		× 0.01 =		(240)
Space heating - main system 2	(213)	×		× 0.01 =		(241)
Space heating - secondary	(215)	×		× 0.01 =		(242)
Water heating (electric off-peak tariff)						
High-rate fraction (Table 13, or Appendix F for electric CPSU)				(243)		
Low-rate fraction	1.0 – (243) =			(244)		
High-rate cost	(219) × (243)	×		× 0.01 =		(245)
Low-rate cost	(219) × (244)	×		× 0.01 =		(246)
Water heating cost (other fuel)	(219)	×		× 0.01 =		(247)
(for a DHW-only community scheme use (342a) or (342b) instead of (247)						
Space cooling	(221)	×		× 0.01 =		(248)
Pumps, fans and electric keep-hot	(231)	×		× 0.01 =		(249)
(if off-peak tariff, list each of (230a) to (230g) separately as applicable and apply fuel price according to Table 12a						
Energy for lighting	(232)	×		× 0.01 =		(250)
Additional standing charges (Table 12)						(251)
Energy saving/generation technologies (233) to (235) as applicable, repeat line (252) as needed						
<description>	one of (233) to (235)	×		× 0.01 =		(252)
Appendix Q items: repeat lines (253) and (254) as needed						
<description>, energy saved	one of (236a) etc	×		× 0.01 =		(253)
<description>, energy used	one of (237a) etc	×		× 0.01 =		(254)
Total energy cost				(240)...(242) + (245)...(254) =		(255)

11a. SAP rating – Individual heating systems including micro-CHP

Energy cost deflator (Table 12):		0.47	(256)
Energy cost factor (ECF)	[(255) × (256)] ÷ [(4) + 45.0] =		(257)
SAP rating (Section 13)			(258)

12a. CO_2 emissions – Individual heating systems including micro-CHP

	Energy kWh/year		Emission factor kg CO_2/kWh		Emissions kg CO_2/year	
Space heating - main system 1	(211)	×		=		(261)
Space heating - main system 2	(213)	×		=		(262)
Space heating - secondary	(215)	×		=		(263)
Energy for water heating	(219)	×		=		(264)
(for a DHW-only community scheme use (361) to (373) instead of (264)						
Space and water heating	(261) + (262) + (263) + (264) =					(265)
Space cooling	(221)	×		=		(266)
Electricity for pumps, fans and electric keep-hot	(231)	×		=		(267)
Electricity for lighting	(232)	×		=		(268)
Energy saving/generation technologies	(233) to (235) as applicable, repeat line (269) as needed					
<description>	one of (233) to (235)	×		=		(269)
Appendix Q items	repeat lines (270) and (271) as needed					
<description>, energy saved	one of (237a) etc	×		=		(270)
<description>, energy used	one of (237a) etc	×		=		(271)
Total CO_2, kg/year	sum of (265)...(271) =					(272)
Dwelling CO_2 Emission Rate	(272) ÷ (4) =					(273)
EI rating (section 14)						(274)

13a. Primary energy – Individual heating systems including micro-CHP

Same as 12a using primary energy factor instead of CO_2 emission factor to give primary energy in kWh/year

Community heating

9b. Energy requirements – Community heating scheme

This part is used for space heating, space cooling or water heating provided by a community scheme.

Fraction of space heat from secondary/supplementary heating (Table 11)	*"0" if none*		(301)
Fraction of space heat from community system	1 – (301) =		(302)

The community scheme may obtain heat from several sources. The procedure allows for CHP and up to four other heat sources; the latter includes boilers, heat pumps, geothermal and waste heat from power stations. See Appendix C.

Fraction of heat from community CHP	*(fractions obtained from operational records or plant design specification; omit line if not applicable)*		(303a)
Fraction of community heat from heat source 2			(303b)
Fraction of community heat from heat source 3			(303c)
Fraction of community heat from heat source 4			(303d)
Fraction of community heat from heat source 5			(303e)
Fraction of total space heat from community CHP	(302) × (303a) =		(304a)
Fraction of total space heat from community heat source 2 <description>	(302) × (303b) =		(304b)
Fraction of total space heat from community heat source 3 <description>	(302) × (303c) =		(304c)
Fraction of total space heat from community heat source 4 <description>	(302) × (303d) =		(304d)
Fraction of total space heat from community heat source 5 <description>	(302) × (303e) =		(304e)
Factor for control and charging method (Table 4c(3)) for community space heating			(305)
Factor for charging method (Table 4c(3)) for community water heating			(305a)
Distribution loss factor (Table 12c) for community heating system			(306)

Space heating

		kWh/year	
Annual space heating requirement		(98)	
Space heat from CHP	(98) × (304a) × (305) × (306) =		(307a)
Space heat from heat source 2	(98) × (304b) × (305) × (306) =		(307b)
Space heat from heat source 3	(98) × (304c) × (305) × (306) =		(307c)
Space heat from heat source 4	(98) × (304d) × (305) × (306) =		(307d)
Space heat from heat source 5	(98) × (304e) × (305) × (306) =		(307e)
Efficiency of secondary/supplementary heating system in % *(from Table 4a or Appendix E)*			(308)
Space heating fuel for secondary/supplementary system	(98) × (301) × 100 ÷ (308) =		(309)

Water heating

Annual water heating requirement		(64)	
If DHW from community scheme:			
Water heat from CHP	(64) × (303a) × (305a) × (306) =		(310a)
Water heat from heat source 2	(64) × (303b) × (305a) × (306) =		(310b)
Water heat from heat source 3	(64) × (303c) × (305a) × (306) =		(310c)
Water heat from heat source 4	(64) × (303d) × (305a) × (306) =		(310d)
Water heat from heat source 5	(64) × (303e) × (305a) × (306) =		(310e)
If DHW by immersion or instantaneous heater within dwelling:			
Efficiency of water heater			(311)
Water heated by immersion or instantaneous heater	(64) × 100 ÷ (311) =		(312)
Electricity used for heat distribution	0.01 × [(307a)…(307e) + (310a)…(310e)] =		(313)
Cooling System Energy Efficiency Ratio			(314)
Space cooling (if there is a fixed cooling system, if not enter 0)	= (107) ÷ (314) =		(315)
Electricity for pumps and fans within dwelling (Table 4f):			
mechanical ventilation - balanced, extract or positive input from outside			(330a)

warm air heating system fans				(330b)
pump for solar water heating				(330g)
Total electricity for the above, kWh/year	(330a) + (330b) + (330g) =			(331)
Energy for lighting (calculated in Appendix L)				(332)
Energy saving/generation technologies (Appendices M and Q)				
Electricity generated by PVs (Appendix M) (negative quantity)				(333)
Electricity generated by wind turbine (Appendix M) (negative quantity)				(334)
Appendix Q items: annual energy (items not already included on a monthly basis)		Fuel	kWh/year	
Appendix Q, <item 1 description>				
energy saved or generated (enter as negative quantity)				(336a)
energy used (positive quantity)				(337a)
Appendix Q, <item 2 description>				
energy saved or generated (enter as negative quantity)				(336b)
energy used (positive quantity)				(337b)
(continue this list if additional items)				

10b. Fuel costs – Community heating scheme

	Heat or fuel required kWh/year		Fuel price (Table 12)		Fuel cost £/year	
Space heating from CHP	(307a)	×		× 0.01 =		(340a)
Space heating from heat source 2	(307b)	×		× 0.01 =		(340b)
Space heating from heat source 3	(307c)	×		× 0.01 =		(340c)
Space heating from heat source 4	(307d)	×		× 0.01 =		(340d)
Space heating from heat source 5	(307e)	×		× 0.01 =		(340e)
Space heating (secondary)	(309)	×		× 0.01 =		(341)
Water heating from CHP	(310a)	×		× 0.01 =		(342a)
Water heating from heat source 2	(310b)	×		× 0.01 =		(342b)
Water heating from heat source 3	(310c)	×		× 0.01 =		(342c)
Water heating from heat source 4	(310d)	×		× 0.01 =		(342d)
Water heating from heat source 5	(310e)	×		× 0.01 =		(342e)
If water heated by immersion heater:						
High-rate fraction (Table 13)					(343)	
Low-rate fraction	1.0 - (343) =				(344)	
			Fuel price			
High-rate cost, or cost for single immersion	(312) × (343)	×		× 0.01 =		(345)
Low-rate cost	(312) × (344)	×		× 0.01 =		(346)
If water heated by instantaneous water heater	(312)	×		× 0.01 =		(347)
Space cooling (community cooling system)	(315)	×		× 0.01 =		(348)
Pumps and fans	(331)	×		× 0.01 =		(349)
(if off-peak tariff, list each of (330a) to (330g) separately as applicable and apply fuel price according to Table 12a						
Electricity for lighting	(332)	×		× 0.01 =		(350)
Additional standing charges (Table 12)						(351)
Energy saving/generation technologies	(333) to (334) as applicable, repeat line (352) as needed					
<description>	one of (333) to (334)	×		× 0.01 =		(352)
Appendix Q items:	repeat lines (253) and (259) as needed					
<description>, energy saved	one of (336a) etc	×		× 0.01 =		(353)
<description>, energy used	one of (337a) etc	×		× 0.01 =		(354)
Total energy cost	= (340a)…(342e) + (345)…(354) =					(355)

11b. SAP rating – Community heating scheme

Energy cost deflator (Table 12):		0.47	(356)
Energy cost factor (ECF)	[(355) × (356)] ÷ [(4) + 45.0] =		(357)
SAP rating (Section 13)			(358)

12b. CO_2 Emissions – Community heating scheme

CO_2 from CHP (space and water heating) *Omit (361) to (366) if no CHP*

Electrical efficiency of CHP unit (e.g. 25%) *from operational records or design spec.*		(361)
Heat efficiency of CHP unit (e.g. 50%) *from operational records or design specification*		(362)

		Energy used kWh/year		Emission factor $kgCO_2/kWh$		CO_2 emission $kgCO_2/year$	
Space heating from CHP	(307a) × 100 ÷ (362) =		×	*Note A*	=		(363)
less credit emissions for electricity	–(307a) × (361) ÷ (362) =		×	*Note B*	=		(364)
Water heated by CHP	(310a) × 100 ÷ (362) =		×	*Note A*	=		(365)
less credit emissions for electricity	–(310a) × (361) ÷ (362) =		×	*Note B*	=		(366)

Note A: factor for CHP fuel. Note B: factor for electricity generated by CHP

CO_2 from other sources of space and water heating (not CHP)

Efficiency of heat source 2 (%)		*If there is CHP using two fuels repeat (361) to (366) for the second fuel*	(367b)
Efficiency of heat source 3 (%)			(367c)
Efficiency of heat source 4 (%)			(367d)
Efficiency of heat source 5 (%)			(367e)

CO_2 associated with heat source 2	[(307b)+(310b)] × 100 ÷ (367b) ×		=		(368)
CO_2 associated with heat source 3	[(307c)+(310c)] × 100 ÷ (367c) ×		=		(369)
CO_2 associated with heat source 4	[(307d)+(310d)] × 100 ÷ (367d) ×		=		(370)
CO_2 associated with heat source 5	[(307e)+(310e)] × 100 ÷ (367e) ×		=		(371)
Electrical energy for heat distribution	(313) ×		=		(372)
Total CO_2 associated with community systems	(363)…(366) + (368)…(372)		=		(373)
if it is negative set (373) to zero (unless specified otherwise, see C7 in Appendix C)					(373)
Space heating (secondary)	(309) ×		=		(374)
Water heating by immersion heater or instantaneous heater	(312) ×		=		(375)
Total CO_2 associated with space and water heating	(373) + (374) + (375)		=		(376)
Space cooling	(315) ×		=		(377)
Electricity for pumps and fans within dwelling	(331) ×		=		(378)
Electricity for lighting	(332) ×		=		(379)
Energy saving/generation technologies	(333) to (334) as applicable, repeat line (380) as needed				
<description>	one of (333) to (334) ×		=		(380)
Appendix Q items	repeat lines (381) and (382) as needed				
<description>, energy saved	one of (336a) etc ×		=		(381)
<description>, energy used	one of (337a) etc ×		=		(382)
Total CO_2, kg/year	sum of (376)…(382)		=		(383)
Dwelling CO_2 Emission Rate	(383) ÷ (4)		=		(384)
EI rating (section 14)					(385)

13b. Primary energy – Community heating scheme

Same as 12b using primary energy factor instead of CO_2 emission factor to give primary energy in kWh/year