Dynamic Modelling of the Socio-Technical Systems of Household Energy Consumption and Carbon Emissions

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ABSTRACT

There is a growing need to curtail the carbon emissions in the globe in order to achieve the climate stabilisation goals based on the climate change threat. And as such, different initiatives and schemes of Government have targeted a number of policies at reducing energy and carbon emissions targets with the housing sector of the economy not an exception. In order to explore the feasibility of achieving carbon emissions reduction targets within the housing sector of the UK, the research views the issue of household energy consumption and carbon emissions as complex socio-technical problem involving the analysis of both the social and technical variables. This thesis therefore describes the development of the system dynamics based model to capture and solve the problem relating to the future profiles of household energy consumption and carbon emissions by providing a policy advice tool for use by the policy makers.

In order to investigate the problem, the research adopts the pragmatist research strategy involving collection of both qualitative and quantitative data to develop the model. The developed model has six modules, which are: population/household, dwelling internal heat, occupants' thermal comfort, climatic-economic-energy efficiency interaction, household energy consumption, and household CO_2 emissions. In addition to the 'baseline' scenario, the developed model was used to develop four illustrative scenarios of household energy consumption and carbon emissions; which are: 'efficiency' scenario, 'behavioural change' scenario, 'economic' scenario, and 'integrated' scenario. The 'efficiency' scenario generally considers the effects of improvements in energy efficiency measures on household energy consumption and ultimately on household carbon emissions. Additionally, the 'behavioural change' scenario tries to model the effects of occupants' change of energy consumption behaviour on household energy consumption and carbon emissions profile. The 'economic' scenario assumes a case of policy change by Government favouring energy prices reduction, thereby reducing the energy bills payable by the householders and its consequences on household energy consumption and carbon emissions. And the 'integrated' scenario combines the assumptions in the first three scenarios and then analyses its effects on household energy consumption and carbon emissions.

The 'baseline' results indicate that about 49% savings in carbon emissions by the year 2050 below the base year of 1990 are possible. Additionally, the results of the developed model for all the illustrative scenarios indicate that carbon emissions savings of 46%, 55%, 58%, and 63% below the base year of 1990 are possible from the 'economic', 'efficiency', 'behavioural change', and 'integrated' scenarios respectively.

The research concludes that it is unlikely for any of the scenarios by its own to meet the required legally binding reductions of 80% cut in carbon emissions by 2050 unless this is vigorously pursued. The unique contribution of the research is the development of a model that incorporates socio-technical issues that can be used for decision making over time.

DEDICATION

In loving memory of my mother

Madam Comfort Tinuola Oladokun

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ACADEMIC REGISTRY

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ACRONYMS AND ABBREVIATIONS

ANT	Actor Network Theory
ABM	Agent-Based Modelling
BBN	Bayesian Belief Network
BRE	Building Research and Establishment
BREDEM	Building Research and Establishment’s Domestic Energy Model
BREHOMES	Building Research and Establishment’s Housing Models
BSRIA	Building Services Research Information Association
CDEM	Community Domestic Energy Model
CHM	Cambridge Housing Model
CLD	Causal Loop Diagram
CM	Configuration Modelling
CREEM	Canadian Residential Energy End-use Model
DDM	Domestic Dwelling Model
DECarb	Domestic Energy and Carbon Model
DECC	Department of Energy and Climate Change
FL	Fuzzy Logic
HECCE	Household Energy Consumption and Carbon Emissions
IEA	International Energy Agency
MA	Morphological Analysis
ONS	Office for National Statistics
SAP	Standard Assessment Procedure
SD	System Dynamics
SFD	Stock and Flow Diagram
SNA	Social Network Analysis
STS	Socio-Technical Systems
TPB	Theory of Planned Behaviours
UKDCM	United Kingdom Domestic Carbon Model
UNDESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1

INTRODUCTION

1.1 Rationale for the research

Governments at different levels around the globe are urgently seeking solutions to the problems emanating from energy consumption and carbon emissions in all spheres of economy. This is because of the challenge of climate change and other related effects as a result of carbon emissions. For example, the evidence from the United Nations Department of Economic and Social Affairs (UNDESA, 2010) suggests that the climate change effects due to carbon emission could cause increase in global temperature of up to 6^{o}C. This invariably results in extremes weather conditions. To this end, different initiatives and schemes of Government have targeted a number of policies at reducing energy and carbon emission, and housing sector of the economy is not an exception. In the United Kingdom (UK), based on the evidence from the Office for National Statistics (ONS) (ONS, 2009), energy consumption in buildings alone is about 42.3% of which domestic sector accounts for around 27.5% of the total UK's energy consumption in the year 2008. Correspondingly, domestic carbon emissions stand at about 26% of the total UK carbon emissions (Natarajan *et al.*, 2011). It is against this background that the domestic sector of the economy is chosen as a focal point for mitigation and adaptation agendas. As such, the UK Government has initiated quite a number of strategies aimed at reducing household energy consumption and carbon emissions (HECCE). This is mainly due to the importance accorded this sector of the economy in realising a target of 80% reduction by 2050 based on 1990 level as enshrined in the Climate Change Act of 2008.

From the foregoing, the menace posed by carbon emissions and other climate change related effects have created extreme difficulty to accurately predict the energy and carbon emissions performance of dwellings once occupied (Stevenson and Rijal, 2010; Bordass *et al.*, 2004). Way and Bordass (2005) posit that dwellings are not only becoming more complex, but also tighter energy and other environmental regulations are increasing pressure regarding their greater predictability. Further to this, outcomes of several studies have indicated that design predictions are not just the same as operational outcomes of dwellings once occupied. One of the reasons advanced by Building Services Research Information Association (BSRIA) (2011) is because of the complex technology currently in use in order to allow dwellings hit their targets of energy and carbon emissions reductions. Mahdavi and Pröglhöf (2009) submitted that "the presence and actions of dwellings occupants have a significant impact on the energy and carbon emission performance of dwellings". Additionally, a number of researchers now attach much importance to occupants[1] and their behaviour in and around dwellings and advocate their inclusion while evaluating the energy and carbon emissions performance of dwellings (Hitchcock, 1993; Nicol and Roaf, 2005; Soldaat, 2006; Dietz *et al.*, 2009; Okhovat *et al.*, 2009; Gill *et al.*, 2010; Stevenson and Rijal, 2010; Yun and Steemers, 2011).

Therefore, it has been established that there are still more to do regarding household energy when it comes to dwellings-occupants-environment interactions. Stevenson and Rijal (2010) argue that one of the areas of uncertainty researchers are still struggling with is in finding means to establish a concrete methodology that links the technical aspect of dwellings energy consumption with that of dwellings occupants. This is with a view to capturing the effects of occupants on household energy consumption. Previous studies in this area of dwellings-occupants-environment interactions mainly focused on occupants' interactions with the control systems and devices put in place in dwellings (Hunt, 1979; Fritsch *et al.*, 1990; Newsham, 1994; Humphreys & Nicol, 1998; Bourgeois *et al.*, 2005; Herkel *et al.*, 2005; Bourgeois *et al.*, 2006; Mahdavi *et al.*, 2006; Soldaat, 2006; Kabir *et al.*, 2007; Borgeson & Brager, 2008; Humphreys *et al.*, 2008; Haldi & Robinson, 2009; McDermott *et al.*, 2010; Prays *et al.*, 2011; Rijal *et al.*, 2011). The main thrust of majority of these studies is on occupants'

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[1] Occupant(s) and householder(s) are interchangeably used throughout this thesis to mean the same thing.

behaviour towards the control of windows for thermal comfort as well as lighting and shades for proper illumination in dwellings. Various models were recommended for use to predict these actions of occupants based on quantitative data collected and analysed. Generally, dwellings need to be acknowledged as being dynamic and interactions of operators, occupants, and designers all influence the way they perform in terms energy consumption and carbon emissions.

It is noteworthy to state that dwellings as a system on its own is engineered using tested components and generally reliable systems, whereas the occupants aspect of it can be unreliable, variable, and perhaps even irrational. Borgeson and Brager (2008) claim that due to complexity, in terms of energy consumption and carbon emissions, dwellings are now behaving in a non-linear and irrational way that then calls for an approach that is able to cope with this kind of complexity. Hitchcock (1993) and Borgeson and Brager (2008) argue that researchers are finding it difficult to predict occupants' behavioural aspect of energy consumption in dwellings. This is mainly because the fundamental approach on which energy consumption models are based is quite different from that of occupants' aspect. While energy models that try to capture the behaviour of occupants towards the opening of windows (Borgeson and Brager, 2008), for example, make use of a linear relationship of temperature difference; the actual action consequently posed by the occupants follow a non-linear and unpredictable way, which make modelling difficult.

One of the breakthroughs proposed by Borgeson and Brager (2008) is to model occupants' behaviour using stochastic algorithms and map this with climate data. These models are deficient in the sense that they still face the challenge of integrating the occupants' behavioural aspect with energy models. Further to this, the UK Government's Standard Assessment Procedure (SAP) for energy rating of dwellings [Building Research Establishment (BRE), 2011] that tries to assign energy rating to dwellings incorporates a number of variables into their calculations. Unfortunately, SAP fails to capture the variables related to the individual characteristics of the household occupying the dwelling *i.e.* household size, occupants behaviour, and so on (BRE, 2011). This then shows that the calculation may be deficient because of the lack of inclusion of these occupants' related variables. There is then the need to explore ways of improving greater predictability of dwellings energy consumption and carbon emissions by demonstrating a novel approach that takes into consideration the challenge of occupants' aspect of energy consumption in dwellings.

Undoubtedly, integration of dwellings occupants' aspect with that of dwellings characteristics/parameters regarding energy consumption in buildings sits squarely within the socio-technical systems (STS) approach of systems-based methodology of scientific inquiry. As pointed out earlier, dwellings as a system is seen to comprise two subsystems: physical subsystem that relates to dwellings characteristics/parameters (technical system) and human subsystem regarding occupants actions within the dwelling (social system). Dwellings as a system is affected should there be any change to both the technical and social systems. Invariably, any change to technical system will have effects on physical subsystem; likewise any change in social system will have corresponding effects on the human subsystem (Figure 1.1). On one hand some changes to technical system may have an indirect influence on the human subsystem, while on the other hand some changes to the social system may have an indirect influence on the physical subsystem as well (Figure 1.1).

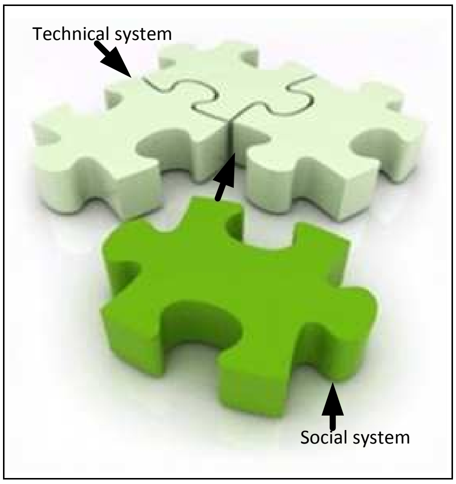

Figure 1.1: Interactions between the social and technical systems

It should not be forgotten that dwellings as a system relates with the outer environment, which have both direct/indirect influence on both the technical and social systems. Any change in the outer environment elements will definitely influence the behaviour of these technical and social systems. This will consequently have effects on household energy consumption and associated carbon emissions. This then presents a kind of complex system that calls for an approach that is able to cope with this type of situation. It needs to, however, be noted that engineering models can only deal with the changes to technical system alone and social models can as well cope with the changes to social system alone. For example, within the energy sector, modelling energy consumption and carbon emissions has been purely based on econometric (FitzGerald *et al.,* 2002), statistical (Fung, 2003), or building physics (Shorrock & Dunster, 1997) method. One of the main thrusts of this research, therefore, is to present an approach that links this phenomenon together, aids in its understanding, and offers ways of testing different strategies for reducing household energy consumption and carbon emissions. This is in order to contribute to the carbon emissions reduction target of the UK Government. Notably, there are quite a number of variables at play here. These variables are interrelated and depend on one another. Among them are the variables that are related to the interaction of dwellings themselves with outer environment as well as the interaction of occupants with the systems put in place to operate dwellings in a sustainable way. All these present a kind of complex system.

Climatic variables (outer environment element), for example, are unpredictable as any change in these (*e.g.* in terms of external temperature, rainfall, *etc.*), may have effects on heating, ventilation, *etc.* They are then likely to trigger a response from the occupants to appropriately react to this situation in terms of heating, use of hot water, *etc.* The reactions from occupants too still largely depend on a number of determinants (*e.g.* demographic, cultural, and economic variables; behaviour; *etc*). Analysis of this scenario presents a kind of complex system that has multiple interdependencies with multi-causal relationships. The variables at play here are both “soft” and “hard” and their behaviour changes in a non-linear way over time with multiple feedback loops. These variables are, however, difficult to predict and keep under control. The situation described above illustrates an example of the STS of household energy consumption and carbon emissions. This research then intends to dwell into this issue of STS of household energy consumption and carbon emissions with a view to adding to the understanding of complex nature of household energy consumption issues. This is by proposing a novel approach to policy makers capable of testing different strategies and interventions for reducing household energy consumption and carbon emissions.

It is on this basis that the research seeks to answer the following questions:

1. What are the social and technical variables influencing household energy consumption and carbon emissions?
2. What are the modelling approaches in use to forecast household energy consumption and carbon emissions?
3. What is the most suitable modelling approach to conceptualise the complex socio-technical systems of household energy and carbon emissions?
4. How could the influence of these socio-technical systems variables on household energy consumption and carbon emissions be modelled and predicted using a pragmatic approach?
5. What are the effects of energy efficiency measures, occupants' behavioural change, and energy prices on household energy consumption and carbon emissions?

1.2 Research Aim and Objectives

The aim of this research is to develop a dynamic model of the socio-technical systems of energy consumption and carbon emissions of the UK housing stock with a view to providing a tool to policy makers capable of testing a range of possible futures regarding household energy consumption and carbon emissions. This will improve the understanding of complex nature of household energy consumption and carbon emissions. In an attempt to develop and evaluate the model, a number of scenarios are constructed to illustrate the possible futures of energy consumption and carbon emissions for the UK housing stock. These scenarios are used to explore the possibility of achieving carbon emission reductions of about 80% by 2050 as enshrined in the Climate Change Act of 2008.

The specific objectives to achieve the aim of this research are to:

1. Identify the social and technical variables influencing household energy consumption and carbon emissions.
2. Review the modelling approaches used in forecasting household energy consumption and carbon emissions.
3. Identify the most suitable modelling approach to conceptualise the complex Socio-Technical Systems (STS) of household energy consumption and carbon emissions.
4. Develop the dynamic model of the socio-technical systems of household energy consumption and carbon emissions.
5. Use the developed model to evaluate the effects of energy efficiency, occupants’ behavioural change, and energy prices on household energy consumption and carbon emissions.

1.3 Scope of the Research

The scope of this research is discussed based on the domain of investigation and the level of aggregation/disaggregation.

1.3.1 Domain of Investigation

Generally, dwellings can either be domestic (residential) or non-domestic. Regarding energy consumption and associated carbon emissions, much importance has been accorded to the dwellings in general, either domestic or non-domestic (Steemers, 2003). This may be due to the fact that dwellings generally share a chunk of total annual energy consumption and associated carbon emissions as ONS (2009) report suggests. A further probe into the consumption and emissions profile of dwellings reveals that the domestic sector retain the lion share of these consumption and emissions, especially in the UK (Steemers, 2003; ONS, 2009). To buttress the above, Hitchcock (1993) argues that the domestic sector is an important component of the energy economy of most countries. Additionally, the policy of the UK government to make all new homes zero carbon as a way of meeting the carbon reductions target as stipulated in the Climate Change Act further reinforces the importance of domestic sector to policy formulation. It is equally important to note in-depth of how domestic buildings respond to social (occupants aspect), technical (physical aspect), and environmental (social or technical) changes when it comes to energy consumption and related carbon emissions. Taking into consideration all the above arguments regarding the domestic sector and coupled with the fact that it is practically impossible for this research to dwell into and study all different arrays of buildings, it is against this backdrop that this research aims to limit the scope of this study to domestic sector and investigate issues regarding household energy consumption and carbon emissions. Also, it is necessary to highlight that modelling the occupants' aspect, especially occupants' behaviour, requires special modelling. As such, occupants' behaviour is treated as exogenous variable within this thesis.

1.3.2 Level of Aggregation/Disaggregation

Johnston (2003) argues that the level of disaggregation within any model of energy consumption and associated carbon emissions in dwellings is large, especially if such a model utilised a bottom-up approach (see Section 2.4.3). This is to mean that the degree of this disaggregation could get down to the level of energy consumption for individual dwellings' end-uses in terms of space heating, hot water consumption, cooking energy, *etc.* or this could include a considerable amount of detail regarding the effects of dwellings thermodynamics to energy consumption. Similarly, the level of aggregation within the top-down energy models, for example, is large as well. In this regard, economic variables, for example, may be used to forecast energy consumption in dwellings.

In order to therefore streamline the scope of this research, it is necessary to determine the level of aggregation/disaggregation to be incorporated into the model. This would then give the explanatory power[2] of the model output. Johnston (2003) relates the level of aggregation/disaggregation and the explanatory power together as shown in Figure 1.2 with the theoretical optimum level. This research will then strike a balance by using variables in both the levels of aggregation and disaggregation since the target audience for the research is energy policy makers.

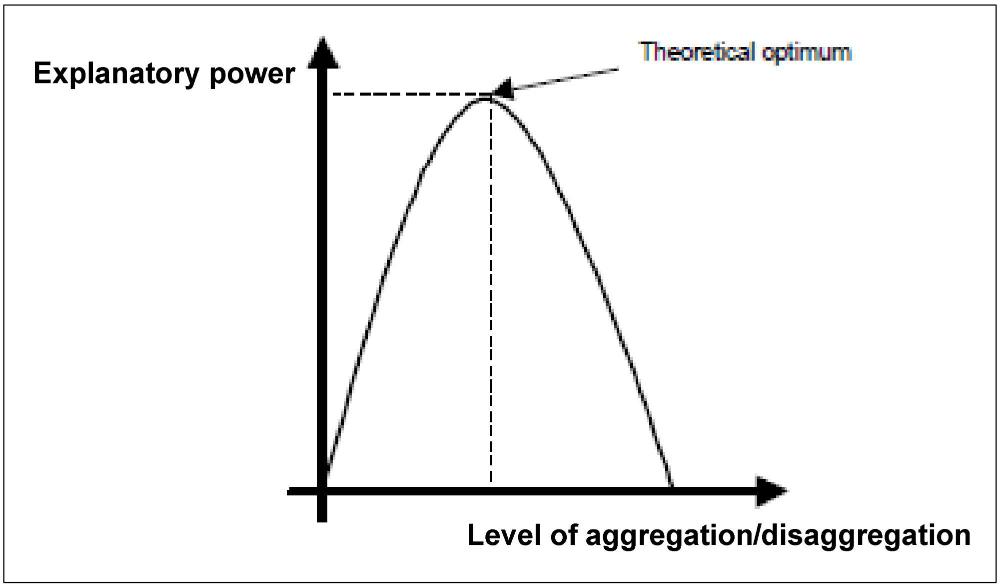

Figure 1.2: Level aggregation/disaggregation and explanatory power

(Adapted from Johnston, 2003)

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[2] Within the context of this thesis, explanatory power is defined based on Johnston (2003) to be the model's ability to give the required insights into the issue of energy consumption and associated carbon emissions in the UK housing stock.

1.4 Methodological Approach Designed for the Research

This research uses a mixed-method research design drawn from the pragmatist philosophical view in order to achieve its objectives stated in Section 1.2. The reason for adopting the mixed-method research design is motivated based on three main reasons that include the nature of the research problem, the data and the methods of collecting these data and the purpose of the research (see Section 4.3). The research problem involves answering questions relating to '*what*' and '*how*', which means a single approach cannot be used to answer those questions. This then informed the decision to use a method that complements both the qualitative and quantitative research strategies. The system dynamics (SD) used as the modelling approach, on its own merit, is hinged on a pluralistic approach that considers both the qualitative and quantitative approaches to modelling. It is also evident that the nature of the research in this thesis entails capturing both the qualitative and quantitative data, which by implication means triangulation of data collection methods (see Section 4.4).

The research starts with a review of extant literature in the area of energy consumption and carbon emissions in housing sector. This involves identification of social and technical variables influencing energy consumption and carbon emissions in dwellings. Also, a review of extant literature on the methods used in forecasting household energy consumption and carbon emissions was conducted with a view to assessing their possibility of being used to conceptualise the research problem (see Chapter two). The review therefore revealed their unsuitability for the research and the need to use the socio-technical systems approach to capture the problem. This then leads to a review of extant literature regarding the modelling techniques for capturing the socio-technical systems (see Chapter three). The review favours the system dynamics as the most suitable approach to capture the problem in the research.

Developing models using the system dynamics approach involves using both the qualitative and quantitative data sources. In this research, the qualitative data sources are based on the literature review and interview. Interviews were conducted in order to capture the views of the experts and practitioners during the model conceptualisation (see Sections 5.6.2, 6.2, and 6.5) and validation (see Chapter eight) stages of the research. Also, quantitative data like household energy consumption based on end-uses, population, number of households, *etc.* were used for the development of the model in this thesis (see Sections 4.4.2, 5.6.3, and 6.6).

1.5 Structure of the Thesis

In a bid to achieve the objectives of the research, Figure 1.3 shows the logical structure of how the research was conducted and reported in this thesis.

Chapter two contains a review of extant literature about energy consumption and carbon emissions in housing sector. The chapter analyses issues relating to energy consumption in domestic buildings together with energy policy and carbon emissions targets in the UK. Additionally, the chapter reviews the theoretical frameworks underpinning the household energy consumption and carbon emissions. The social and technical variables influencing household energy and carbon emissions are identified. The chapter also critically reviews the extant literature to reveal the epistemological issues relating to HECCE models in order to critique different energy models that are previously or currently in use by assessing their strengths and weaknesses. This is with a view to achieving the first and second objectives of the research.

The main thrust upon which this thesis is based is in modelling the STS of HECCE. Chapter three of the thesis then presents an overview of the systems-based approach of scientific inquiry from where the STS theory emanates. This chapter therefore critically examines the tenets of the systems-based approach of scientific inquiry as overall umbrella under which the STS theory is hanging. Further to this, the STS theory is critically reviewed. This was followed by a critical appraisal of different techniques to model the STS as identified in extant literature. The critiques of these different approaches are undertaken in a bid to identifying the most suitable modelling technique to conceptualise the problem under study. This chapter therefore fulfils the objective three of the research.

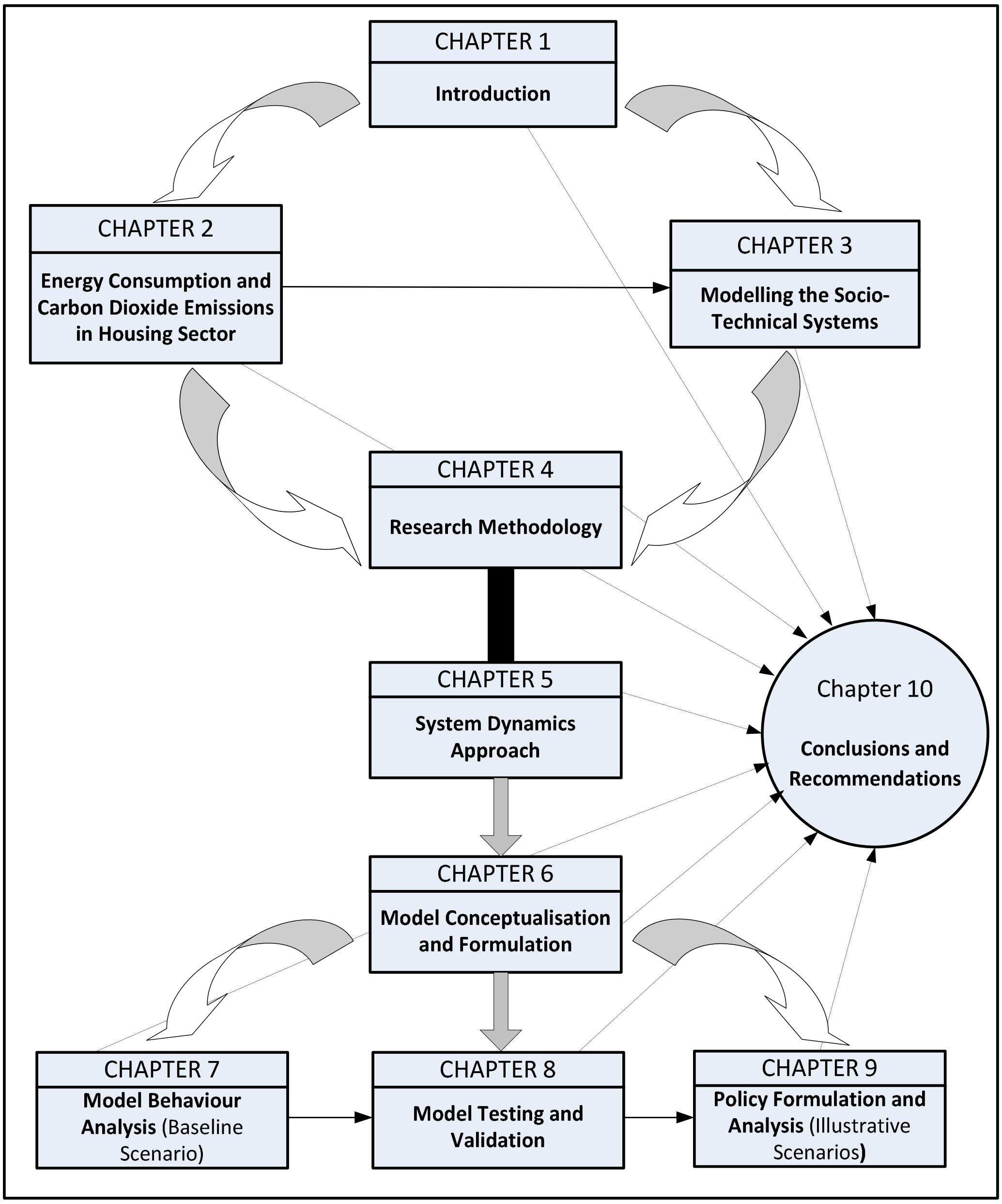

Figure 1.3: Thesis structure

Chapter four provides the methodological approach to the study. The chapter draws together and integrates information presented in chapters two and three to provide the research methods for fulfilling the objectives of the study. The chapter discusses the philosophical knowledge base underpinning the research in general and positions the research method in one of the research paradigms. Further, the chapter discusses the method of data collection. Discussion of model development and validation concludes the chapter.

Chapter five discusses the system dynamics approach as firmed up for the research. The philosophical knowledge base underpinning the research in general discussed in Chapter four was linked to the epistemological and ontological issues of system dynamics approach as modelling technique to conceptualise the HECCE issues addressed in the thesis. Moreover, issues regarding the system dynamics research process firmed up for the study and development of the model algorithms are all discussed in this chapter.

Chapter six reports the model conceptualisation stage of the system dynamics approach as firmed up for the study. The chapter first explains the boundary of the model and illustrates this with the use of a model boundary chart. Reference modes of key variables in the model are illustrated as well. Furthermore, the chapter establishes the causal relationships among the variables hypothesised to influence HECCE. This was arranged into six different modules to reflect the causal loop diagram (CLD) for population/household module, CLD for dwelling internal heat module, CLD for occupants’ thermal comfort module, CLD for climatic-economic-energy efficiency interaction module, CLD for household energy module, and CLD for household carbon emissions module. Following on, the chapter provides the report of transformation of the CLDs produced under the model conceptualisation to stock and flow diagrams (SFDs). The chapter shows how the variables in the model are related to each other in the form of equations in readiness for simulation. The equations developed in this chapter are for baseline simulation. The SFDs are arranged based on the six different modules of the model as explained in chapter five.

Chapter seven gives a discussion of the behaviour of variables in the model based on the baseline simulation performed. That is, the chapter reports the behaviour of key variables in the population/household module, dwelling internal heat module, occupants' thermal comfort module, climatic-economic-energy efficiency interaction module, household energy module, and household carbon dioxide emissions module. It is worthy of note that the behaviour exhibited by the main outputs of this model in terms of household energy and carbon dioxide emissions are explicitly discussed in this chapter based on end-uses of HECCE.

In chapter eight, issues relating to model testing and validation are discussed. The model testing and validation process developed for the research are discussed by appraising the test and validation types as well as giving some background information of experts and professionals that took part in the validation exercise. This was then closely followed by describing and showing the results of each test performed.

Chapter nine carries out a discussion of energy policy formulations and analysis. The chapter presents for different scenarios formulated to include 'efficiency', 'behavioural change', 'economic', and 'integrated' scenarios. The chapter also compares the results of some of these scenarios with some past studies.

Chapter ten concludes the thesis by giving the key findings of the research and the contributions to the field of study. Also, the limitations of the study were also highlighted. Further, the chapter addresses the recommendations for further study based on the limitations of the present study in this thesis.

Chapter 2

ENERGY CONSUMPTION AND CARBON DIOXIDE EMISSIONS IN THE HOUSING SECTOR

2.1 Introduction

Within the research community, there is a general consensus that the threat of global warming as a result of climate change will increase. As a result, different strategies have evolved targeting carbon emissions reductions. The housing sector is therefore at the centre of this reduction targets. This chapter discusses issues of energy consumption and carbon emissions in housing sector together with how energy policy has evolved over the years. Also, the chapter reviews previous studies that are serving as the theoretical framework underpinning the HECCE models. This serves as the basis for reviewing the social and technical variables influencing household energy consumption and carbon emissions.

The chapter also identifies the arrays of energy models that have evolved over the years together with their capability of analysing energy consumption and their associated carbon emissions trends in housing sector of the economy. This is as a result of the growing need to curtail the carbon emissions in the globe in order to achieve the climate stabilisation goals based on the climate change threat as enunciated above. For example in the UK, the need to realise the target of carbon emissions as stipulated in the Climate Change Act of 2008 has rapidly spurred the emergence of many energy models, especially in the domestic sector of the economy, to analyse different strategies and schemes of the government. These kinds of models are therefore required in order to guide in understanding the effects of different strategies and schemes of the government before they are implemented.

2.2 Energy and Carbon Emissions in Housing Stocks

There is a general consensus within the research community regarding the threat of global warming as a result of climate change that is due to an increase in greenhouse gases emitted into the atmosphere because of profligate use of fossil fuels (Harris, 2012; IPCC, 2007). Majorly, the greenhouse gases include carbon dioxide (CO_2), methane (CH_4), hydrofluorocarbons (HFCs), nitrous oxide (N_2O), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). The contribution of each of these emissions to climate change in the form of global warming varies considerably. For example, carbon dioxide emission is adjudged to be the most worrying of these gases as its levels in the atmosphere are rising so very quickly (Terry, 2011). Therefore, the concentration of carbon dioxide emissions in the atmosphere has profoundly increased from approximately 280 parts per million (ppm) in 1750 to about 380 ppm in 2005 with potential of reaching about 540 to 970 ppm by the end of 21st century (IPCC, 2007). IPCC (2007) lists the effects of these increases in carbon dioxide emissions on the global climate to include the following:

- An increase in the globally averaged surface temperature of 1.4 to 5.8ºC.
- An increase in global mean sea level of 9 to 88 centimetres.
- A decrease in snow cover and sea-ice extent in the Northern Hemisphere.
- Changes in weather patterns, which are likely to result in an increase in globally averaged precipitation and the occurrence of extreme weather events.
- The possibility of famines and population migrations.
- The extinction of rare species and the loss of habitats.

The contributing factor to these emissions is not different from the assertion of Harris (2012) of profligate use of fossil fuels. However, burning forest is also a significant contributor according to Terry (2011). Importantly, Terry (2011) posits that emissions from both methane and nitrous dioxide are the most potent emissions when compared to all other greenhouse gases. However, they are in traces amount in the atmosphere compared to carbon dioxide with high concentration, which eventually made them to have less overall impact. This then explains the reason why the term carbon emission is used to always mean greenhouse gases.

Obviously, if the concentration of carbon emissions is allowed to continue to grow unabated, it will undoubtedly have substantial repercussions politically and socio-economically (Johnston, 2003). It is therefore a general consensus reached within the world’s governments to significantly reduce what the carbon emissions will be in this 21st century. This is reflected in the Rio summit of 1992 where the United Nations Framework Convention on Climate Change (UNFCCC) was signed committing developed nations to significantly reduce their carbon emissions profiles (Kashyap *et al.*, 2003). Subsequently, there was series of follow ups regarding the UNFCCC agreement of 1992 and ratified in 1993. For example, the World Climate Conference of 1997 in Kyoto, Japan and that of Copenhagen summit in 2009. At Kyoto conference, a legally binding agreement was reached to cut mainly the emissions from the six aforementioned causes of climate change. Among the developed countries committed to significantly reduce their carbon emissions profile is the UK. And as such, the UK has since then followed the path aiming at reducing its carbon footprints. In this regard, the housing sector in the UK contributes substantially to the UK’s total carbon emissions, which in this case is about 26% of UK’s total emissions (Natarajan *et al.*, 2011). Since then reductions in energy consumption within the housing sector has been a target.

2.2.1 Energy Consumption in Domestic Buildings

Within the housing sector, Harris (2012) argues that approximately 50 per cent of energy use, and carbon dioxide emissions into the atmosphere, are as a result of energy used for heating, cooling and lighting in buildings. Similarly, Urge-Vorsatz *et al.* (2012) and International Energy Agency (IEA) (2012) point out that buildings worldwide account for 122EJ of final energy in 2010, which translates to 33% of total final energy and 54% of electricity. Accordingly, this amount of final energy corresponds to about 9Gt of carbon dioxide emissions (Jennings, Hirst, & Gambhir, 2011; UNEP, 2011).

The figure of energy consumption in buildings, basically for heating, cooling and lighting, has been estimated to be around 30 to 60 per cent of primary energy, especially in Western Europe with about half of this amount used in housing within the UK (Harris, 2011). The end uses (*i.e.* space and water heating, cooking, lighting, and appliances) of delivered energy in the UK housing sector suggest that they considerably vary within different dwelling types. Harris (2011) and Terry (2011) argue that about 58 per cent of delivered energy is used for space heating and when combined with water heating rise to about 82 per cent within the UK housing sector. This suggests that space and water heating has the potential of shaping household energy consumption and any carbon emissions reductions policy are required to target these end uses.

2.2.2 Energy Policy and Emissions Targets within the United Kingdom

Over the years, the UK energy sector has witnessed tremendous improvements and changes in energy policy. Principally, energy policy has been shaped by two major factors. Firstly, as a result of market liberalisation of 1980s, which sees the State controlled energy companies privatised and the Department of Energy dismantled. Secondly, the rising threats of climate change effects as brought to limelight by Rio summit of 1992 (Kashyap *et al.*, 2003) has also significantly shaped energy policy within the UK. This singular factor has risen up the agenda in the UK, as a signatory to Rio submit of 1992, to commit to reduction of carbon emissions (DTI, 2005). As a result of this, the UK Government published its white paper on energy in 2003 entitled “Our Energy Future – creating a Low Carbon Economy”. In this white paper, the UK Government is committed to a 60% reduction in carbon emissions by the year 2050 (DTI, 2003). Undoubtedly, the world of energy is changing rapidly and as such a constant review of energy policy is inevitable. For example, Energy Review Report of 2006, Energy White Paper of 2007, Climate Change Act of 2008, UK Low Carbon Transition Plan of 2009, and Energy Bill of 2012 – 2013. All these policy frameworks tend to shape energy policy mainly to stem the rising tide of carbon emissions and to its drastic reductions.

As a result of this, the Climate Change Act provides the legally binding pathway towards carbon emissions reductions by reducing 22 per cent of carbon emissions between 2008 and 2012 relative to the base year 1990. In addition, the Act stipulates that reductions of 28 per cent are to be achieved between 2013 and 2017, while 34 per cent reductions are required between 2018 and 2022. Additionally, the Act puts it that 50 per cent of carbon emissions reductions are envisaged for between the year 2023 and 2027, while 80 per cent is to be achieved by the 2050 relative to the base year 1990. These savings are to be achieved within all sphere of the economy.

Different studies have, however, highlighted the potential of the housing sector to contribute significantly to these reductions (Levine *et al.,* 2007; Elforgani & Rahmat, 2010; McManus *et al.,* 2010, Baba *et al.,* 2012). And as such, some of these studies have shown the areas of possible policy targets. For example, Levine *et al.* (2007) highlights the importance of technological developments, cultural, and behavioural choices as possible areas of policy formulation. In the UK, however, a number of policy targets are in place within the housing sector. These policies are targeting both the new and existing homes. For example, Ko and Fenner (2008) argues that there are a range of policy frameworks on energy efficiency for new homes in the UK as shown in Table 2.1. The frameworks are as a result of different energy policy reviews as previously highlighted above. The Table shows the programmes that have been firmed up that has the capability of improving energy efficiency profile of new built homes in the UK. The next section discusses empirical studies relating to the household energy consumption and carbon emissions.

Table 2.1: UK Government Policy Framework on Energy Efficiency in New Homes

Policies	**Plans**	**Programmes**
• Energy Bill, 2012 - 2013 • UK Low Carbon Transition Plan, 2009 • Climate Change Bill 2008(draft 13 March 2007) • Energy White Paper 2007 • Pre-Budget Report 2006 • Climate Change and Sustainable • Energy Act 2006 • EU Energy Performance of Buildings Directive 2002 • Housing Act 2004 • Electricity Act 1989 • Gas Act 1986	• Building A Greener Future: Towards Zero Carbon • Development (December 2006 consultation paper) • Climate Change Programme (revised in 2006) • Energy Efficiency: The Government's Plan for Action 2004 • Sustainable Communities Plan 2003	• Building Regulations, Part L1A 2006 • Code for Sustainable Homes • Government funding for social housing and developers only if they meet CSH level 3 or better. New houses by English Partnerships to comply with CSH level 3 or better • Energy Efficiency Commitment 2 (2005–2008), succeeded by Carbon Emissions Reduction • Target Energy Efficiency Commitment (2008–2011) for electricity and gas suppliers (usually relates to energy efficiency in existing houses) • Energy performance certificates and housing information packs • Improved metering and billing information for homeowner. In 2008–2010, free real-time electricity displays for homeowners who request one • Energy Saving Trust product endorsement (energy labels) and building design information Low Carbon Buildings Programme (funding for energy supply technologies but has energy efficiency requirements) • Stamp duty land tax exemption for zero-carbon homes • Reduced VAT rate of 5 per cent for energy-saving materials like insulation, draught stripping, hot water and central heating controls • Research and dialogue programmes including Carbon vision programme (buildings) and Foresight (sustainable energy management and the built environment)

(Adapted with some extension from Ko & Fenner, 2008)

2.3 Previous Empirical Studies on the Socio-technical Systems of Household Energy Consumption and Carbon Emissions

The preceding section laid the foundation on issues relating to energy and carbon emissions in housing sector generally. This section therefore reviews previous empirical studies on the socio-technical systems of household energy consumption and carbon emissions. The social and technical variables influencing energy and carbon emissions in dwellings will be identified.

2.3.1 The Theoretical Framework of Household Energy Consumption and Carbon Emissions

In energy studies literature, there has been a superfluity of framework[3] serving as the theoretical knowledge-base to conceptualise HECCE and these have contributed in no small measure to the tools for the analysis and policy formulation regarding HECCE. Keirstead (2006) argues that this framework fall within two domains – disciplinary and integrated domains. In his submission, he argues that for years "disciplinary" framework has been the dominant guiding approach for policy makers. For example, the frameworks developed from either engineering or economic perspective has been the dominant framework shaping energy policies for years. He then submits that this kind of approach may not be suitable to capture the kind of complex problems plaguing energy sector now and hence the limitation of the disciplinary approach.

In yet another study, Natarajan *et al.* (2011) also acknowledges the limitation of purely disciplinary approaches to analysis of HECCE which reflects in their inability to give a proper explanation to the disjunction between actual and predicted HECCE. In an attempt to work round these limitations and improve on the conceptual framework of HECCE, a small number of literatures have

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[3] "Framework" here refers to a conceptualisation of household energy consumption and carbon emissions and not a model in terms of computer simulation.

identified alternative means to capture energy issues by introducing "integrated" framework that cuts across many disciplines. The framework uses interdisciplinary approach to capture interactions between the complex technology, society, economics, culture and a host of others. The following sub-sections then review literature along the direction of the two afore-mentioned approaches together with some empirical studies previously conducted.

Disciplinary Framework

Over the years, studies relating to HECCE have been championed principally by four major disciplines with each discipline illustrating its own approach/framework for solving HECCE problems. These disciplines are engineering, economics, psychology, and sociology and anthropology. Engineering framework, for example, illustrates mainly the technology of HECCE by estimating HECCE based on the physical laws with little or no attention to economic, sociology, or even behavioural aspects of HECCE. This shows the limitation in this type of framework for their inability to capture a web of interactions between different disciplines. For example, the studies of Anderson (1985) illustrates framework for energy consumption of heating based on heat transfer method; Stokes, Rylatt, and Lomas (2004) give the framework for domestic energy demand; Hart and Dear (2004) provide the framework for weather sensitivities regarding household appliances use, and the host of other studies. The point here is that behavioural responses to technical improvements of HECCE (Keirstead, 2006), for example, are quite beyond the ambit of any purely engineering framework and this may then portends to mean that such engineering framework might be inadequate.

Further, the economic framework as one of the disciplinary framework conceptualises HECCE when it comes to understanding HECCE due to the effects of income levels, energy prices and taxes, *etc* (Ruffell, 1977; Baker, 1991; Greening *et al.,* 1995; Ironmonger *et al.,* 1995). As a social science based framework, however, it introduces some behavioural aspects. Interestingly, Wheelock and Oughton (1994) argue based on the available evidence that the concept depicts by economic approach is not complete in aiding the understanding of HECCE. To this end, Lutzenhiser and Hackett (1993) submit that the combination of the approaches as provided by both the engineering and economic theories forms the physical – technical – economic framework of HECCE which, undoubtedly, immensely helped in shaping energy policies around the globe. This feat achieved was grossly criticised for its inability to properly account for the human behavioural aspect of HECCE in the framework.

It is against this background that the studies in the area of psychology took up this challenge and contribute to the understanding of household energy consumption behaviour. Notably in this circle is the Theory of Planned Behaviours (TPB) of Ajzen (1991), which immensely contributed to the behavioural aspect of HECCE by serving as theoretical knowledge-base to many studies. However, the TPB framework cannot be used as a standalone framework for explaining HECCE because the theory only used personal constructs like attitudes and beliefs without any recourse to other aspects like social and cultural contexts. This then led to studies in the field of sociology and anthropology in a bid to conceptualize energy and society.

Reflecting on all these approaches, it is evident that they are unlikely to capture the kind of complex problems plaguing the energy sector now and hence the need for a more robust approach capable of integrating a number of disciplinary approaches together. It is on the basis of this that a small number of literatures suggest “integrated” frameworks that cut across many disciplines.

Integrated Framework

The argument from the foregoing reinforces the need for a more robust interdisciplinary framework to conceptualise the HECCE. This then led to a combination of different disciplines to conceptualise the issue of HECCE in order to aid a better understanding of energy issues and proffer adequate solutions. In this regard, a number of "integrated" frameworks have, therefore, been used to conceptualise the HECCE. Among those studies is the work of van Raaij and Verhallan (1983), which provides a novel approach to conceptualising energy behaviour. His framework made use of both the physical parameters of dwellings and behavioural characteristics of households. While this work has been continually cited by many studies in the area of consumer behaviour and economic psychology, the framework is yet to be fully developed into simulation model by both the researchers and industry practitioners. Further to the work of van Raaij and Verhallan (1983), the research of Lutzenhiser (1992) proposes a cultural framework of HECCE by conducting a survey of existing approaches in the fields of engineering, economics, psychology, and sociology and anthropology. The framework highlights how the householders ("consumers") make some decisions regarding their choices that are "culturally sensible" and "collectively sanctioned" containing engineering and economic aspects as sub-systems in the framework. However, the framework remains a theoretical framework without any further work to turn the idea into simulation models.

Another study by Hitchcock (1993) uses the systems theory to provide an integrated framework of energy use and behaviour in dwellings. He argues that the energy consumption patterns in dwellings needs to be fully understood from the systems perspective because of the complexity involved in integrating both the technical and social phenomenon together. He further contends that while the engineering models used in capturing the physical processes of dwellings and their effects on energy consumption do give a better understanding of the physical characteristics of dwellings; they, however, fail to capture the effects of human aspect on dwellings. Additionally, he contends that the social models are used in capturing the human aspect effects and as such, can influence energy consumption in dwellings. The study used the concept of socio-technical systems to conceptualise HECCE and came up with a framework. Yet, no modelling technique was proposed to capture these socio-technical systems. There are, however, some previous studies that have empirically studied the interactions among the socio-technical variables influencing the HECCE. The next sub-section discusses this.

2.3.2 Empirical Studies on the Social and Technical Variables Influencing Household Energy Consumption and Carbon Emissions

The work of Hitchcock (1993) sees household as a system being defined by both a physical and a social sense. This implies that the physical household is in form of materials and devices, whereas the social household is in the form of occupants living within the dwelling. Further, the combination and the way these two systems interact that determine energy consumption in dwellings (Hitchcock, 1993). There is therefore a third system that plays a very important role in the relationship, which is the household environment. It is universally accepted that domestic dwellings are basically to provide comfortable environment for human activities by providing space heating, lighting, hot water, and the host of others. Hitchcock (1993) contends that the amount of energy consumed in dwellings depends on the level of service required and the efficiency with which the dwelling can provide such a service. As a result, energy consumption is driven by the needs or behaviour of occupants and/or by the physical characteristics of dwelling (Hitchcock, 1993).

Within this clime, there are various empirical studies that have explored the socio-technical interactions that influence HECCE such as: Hitchcock (1993), Moll *et al*. (2005), Bartiaux & Gram-Hanssen (2005), Bin & Dowlatabadi (2005), Yun & Steemers (2011), Abrahamse & Steg (2011), Kelly (2011), CIBSE (2013), Tweed *et al.* (2014), Gram-Hanssen (2014), *etc*. These studies generally cover the identifications of affecting variables, ranking these variables based on importance, defining the causal effects of variables on the HECCE.

For example, the study of Hitchcock (1993) identifies three elements within the household system to include physical, human, and environmental components. Within the physical elements, Hitchcock (1993) posits that this subsystem consists of physical parameters and variables that influence energy consumption like physical characteristics of dwellings in the form of its size, materials, heating system, stock of appliances and so on; and physical variables in the form of dwelling internal temperature, ventilation rates, amount of hot water, appliances use, and so on. Additionally, Hitchcock (1993) argues that the human subsystem consists of variables relating to the biophysical, demographic, psychological aspects. For example, the biophysical aspect consists of variables like occupants thermal comfort in the form of metabolic rate, respiration, clothing and so on. He refers to demographic variables as household income, socio status, and number of occupants, and so on; whereas psychological variables relate to the individual beliefs, attitudes, knowledge, and personalities. Furthermore, Hitchcock (1993) highlights that the environmental aspect of household consist three major elements of the climate system, the economic system, and the cultural system. For example, the climate system consists of external temperatures, insulations, and wind levels. Interaction of these affects the demand for heating and lighting. The economic system involves variables like energy prices, energy tax, and the likes; whereas the cultural system embraces the general beliefs held by society, consumption habits and the likes. His studies posit that all these variables seamlessly work together to influence household energy consumption.

Yun and Steemers (2011) identified six categories of variables that influence energy consumption in dwellings. These are variables that are related to: climate (cooling degree days), building (total floor area, number of windows, year of construction, and type of housing unit), occupant (number of household members, total annual income, and age of householder), equipment (type of air conditioning equipment), behaviour (number of cooled rooms and frequency of air conditioning equipment use), and energy (total energy for space cooling). The study carried out a path analysis to identify the significant direct/indirect effect on cooling energy use and revealed that climate is the most significant variable influencing cooling energy use.

In another study, Moll *et al*. (2005) posits that the household energy consumption is strongly related to socio-demographic variables, such as income and household size. They argue that households with higher incomes or with larger sizes tend to consume more energy. Moll *et al.*, (2005) used the hybrid energy analysis of household consumption as the methodological approach based on the concept of household metabolism. This approach involves some statistical analyses. The study of Bartiaux and Gram-Hanssen (2005) consider some soicio-political variables influencing household electricity consumption by comparing Denmark and Belgium. The work of Abrahamse and Steg (2011) highlight some psychological and socio-demographic variables influencing HECCE. The research of Bin and Dowlatabadi (2005) illustrate a series of variables influencing HECCE in the US. Another study by Gatersleben *et al.* (2002) and Poortinga *et al.* (2004) investigate some attitudinal and socio-demographic variables and found that household income and size are better explanatory variables of HECCE, while environmental attitudes are weaker predictor.

There are quite a number of studies that have empirically explored the importance of occupants' behaviour regarding HECCE. For example, the research of Barr and Gilg (2006) examine "the ways in which environmental action is constructed in everyday life and related to everyday practices" and "the extent to which there are identifiable groups of individuals with different behavioural properties that exemplify alternative environmental lifestyles and consequently from lifestyle groups". The study used the socio-psychological approach to investigate the problem via a questionnaire survey. This study identified four clusters of individuals as "committed environmentalists", "mainstream environmentalist", "occasional environmentalists", and "non-environmentalists". The study also investigated some variables relating to social and environmental values of group of individuals involved in the research. Variables included in the social value are "altruistic", "openness to change", "conservative", and "egoism". Also environmental value variables included in the research are “faith in growth: anthropocentrism”, “spaceship earth: biospherism”, and “ecocentrism-technocentrism”. Further to these variables, the research sought to know the environmental attitudes of the respondents and included the following factors by framing the questions posed in a pro-environmental direction way: “concern and commitment”, “moral motives”, “outcome beliefs”, “price”, “satisfactions”, “logistics”, “green consumer attitudes”, “comfort”, “environmental rights”, “awareness of norms”, “trust and responsibility”, “extrinsic motivation”, “personal instinct”, “brand loyalty”, and “personal threat”.

Isaacs *et al.,* (2010) carried out surveys on occupants’ behaviour in New Zealand. This study according to Stevenson and Leaman (2010) was adjudged to be the largest surveys in housing. The results of the study reveal that the occupants of the studied area are more comfortable living with a very low temperature. This is highly puzzling and surprising! Probing further by this study to know the cause(s) of this behaviour indicates that culture coupled with the lack of heating appliances is responsible for this behaviour. That is, the lack of central heating may suggest that rooms are heated on one-by-one basis thereby enabling the occupants to set the temperatures of each room according to their expectations. This then suggests that a room-by-room monitoring of comfort level provision will then be worth researching on.

Of interest to this study is the work of Gill *et al.,* (2010) entitled: Low-energy dwellings: the contribution of behaviours to actual performance. The theoretical knowledge base underpinning this study is the work of Ajzen (1985) on the Theory of Planned Behaviour. Gill’s *et al.,* (2010) work gives a simple statistical computation on how to actually estimate the contribution of occupants’ behaviour to variations witnessed on the dwelling performance when the performance of heat, electricity and water consumption were carried out. The study used high-performing dwellings as their case study and a detailed post-occupancy evaluation was undertaken to reveal energy and water consumption performance, and the comfort and satisfaction of the occupants. The results of the study indicate that resource-conscious behaviours account for 51%, 37% and 11% of the variance in heat, electricity and water consumption respectively between dwellings studied. The study then shows the importance and significance that has to accord to human factor as the study demonstrates how the behaviour of occupants can influence the use of energy. Premise on the above, Stevenson and Leaman (2010) then argues that designers should not use the behaviour of occupants as an excuse for the lack of performance of dwellings. They contend that designers need to understand the influence of occupants' behaviour on the dwellings performance and incorporate same appropriately in their designs.

The study of Williamson *et al.* (2010) is another thought provoking study that challenged the failure of regulatory provisions to capture behaviours of occupants in reality. The study investigates five award-winning dwellings in Australia for their ability/inability to meet relevant regulatory standards. The results of the study reveal that the regulatory concept of 'meeting generic needs' fails to account for the diversity of socio-cultural understandings, the inhabitants' expectations and their behaviours. As a result of this, however, comfort levels and low-energy consumption was unable to be predicted by the so-called standards and regulations. The study then suggests that occupants' behaviours and goals needed to be captured by the standards and regulations.

Reflecting on the above reviews it has been established that there are still more to do as relates to the relationship between environment and behaviour in and around dwellings. Stevenson and Rijal (2010) argue that researchers are still wrestling with this relationship and finding means to establish a concrete methodology that links the technical assessment of dwellings with that of occupants. This debate therefore sits squarely within the socio-technical approach which recognises the fact that technological development in the built environment is influenced by human aspects. This problem can then be viewed as a socio-technical problem, which is the main crux of this thesis.

2.3.3 Energy Consumption Behaviours

Different studies (Yu *et al.,* 2011; Hoes *et al.*, 2009) have established that energy consumption can change significantly under different consumption behaviours. These studies highlight the importance of accounting for different occupants' behaviour for it will aid in reliable and accurate estimation of dwellings energy (Azar & Menassa, 2012). A number of studies have established the classification of different energy behaviours. For example, a survey conducted by the Scottish Environmental Attitudes and Behaviour (SEAB) (2008) classifies environmental behaviour into five as deep greens, light greens, shallow greens, distanced, and disengaged. In another study, the research of Accenture (2010) classifies energy consumers in different countries around the world into eight different categories. Additionally, the Low Carbon Community Challenge (DECC, 2012) classifies energy consumption behaviour into four as active energy savers, energy aware, energy ambivalent, and energy wasters. The classification of Energy Systems Research Unit (ESRU) (2012) and Azar and Menassa (2012) are similar. For example, ESRU (2012) classifies energy consumption behaviour into profligate, standard and frugal. Azar and Menassa (2012) classify them into high energy consumers, medium energy consumers, and low energy consumers to respectively mean profligate, standard, and frugal consumption behaviour. Profligate energy consumers here mean those occupants who over-consume energy. The standard energy consumers mean those occupants who make little efforts at reducing energy consumption, whereas frugal energy consumers use energy efficiently. Within this research (as we will later see in Chapter 6 and thereafter), the energy consumption behaviour will follow the categories of both ESRU (2012) and Azar and Menassa (2012).

The next section conducts a review of some previous and current methods used in modelling and simulating the issue of HECCE beyond the frameworks and empirical studies provided in this section.

2.4 The Epistemology of Household Energy Consumption and CO_2 Emissions Models

This section of the Chapter provides a review of the underlying approaches to modelling issues relating to HECCE in the domestic sector of economy. It is, however, worthy to acknowledge that there are several researchers that have carried out a full review of the extant literature on HECCE modelling methodologies and techniques as previously used in this domain. Among these researchers are Bohringer and Rutherford (2008), Strachan and Kannan (2008), Tuladhar *et al.* (2009), Swan and Ugursal (2009), and Kavgic (2010). However, there is the need to have these updated and map them to the objectives formulated for this thesis. To this end, the following sub-sections look at these approaches.

2.4.1 Epistemic Modelling Approaches

For decades now there have been a number of studies on modelling approaches/techniques to capture domestic energy consumption especially at the national level. Johnston (2003) and Kavgic *et al.* (2010) argue that these approaches/techniques vary tremendously in terms of requirements, assumptions made, and the predictive abilities of the models. Within the energy studies research circle, it is overwhelmingly agreed that there are basically two epistemic approaches to modelling domestic energy consumption and the resulting CO_2 emissions. According to the IEA (1998), these approaches are either top-down approach or bottom-up approach. Interestingly, both Kelly (2011) and Kavgic *et al.* (2010) acknowledge the recent advances in the development of another modelling approach paradigm derived from both top-down and bottom-up approaches. This development has then seen some cases where a hybrid of the two approaches has been made in order to develop more robust models as suggested by Bohringer (2007). IEA (1998) provides the main epistemological approach to both the top-down and bottom-up techniques of energy models as illustrated in Figure 2.1.

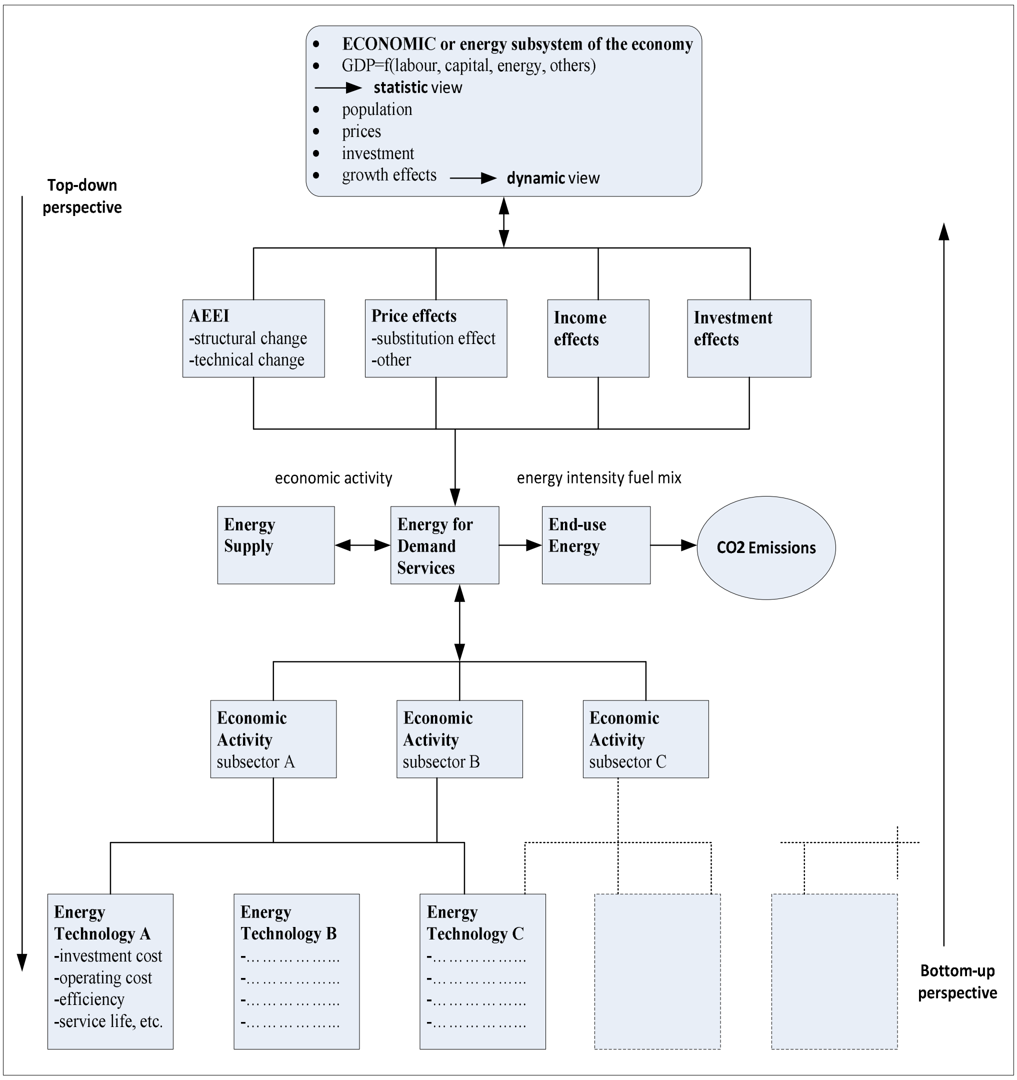

Figure 2.1: Top-down and bottom-up modelling approaches

(Adapted from IEA, 1998)

Basically, the perspective to top-down modelling approach is quite different from that of bottom-up approach as it starts with aggregate data and then disaggregates these down as far as possible in a bid to provide a comprehensive model. Johnston (2003) subsumes that the top-down approach gives a comprehensive approach to modelling and therefore possesses the ability of aiding a high level government's policy and schemes decisions. Conversely, bottom-up approach begins with highly disaggregated data and end up aggregating them up as far as possible. Bottom-up models are seen as incomprehensive when compared to top-down models. This is mainly due to the methodological foundation of the bottom-up approach that models a part/unit of the system under consideration at a time and then aggregates this in a way to provide same information as top-down approach. While it is unarguably true that the two approaches of top-down and bottom-up represent the two main alternatives to modelling energy consumption and carbon emissions in the domestic sector of economy, Johnston (2003) submits that both of them share a degree of commonality. These, according to him, are that (1) they possess the capability to operate at the same level of disaggregation, and (2) they both use the same information, but in different ways. The following further discusses issues regarding the top-down and bottom-up energy models.

2.4.2 Energy and Carbon Dioxide Modelling Using Top - down Approach

As argued above, the top-down modelling approach is a method that is based on aggregate data and works well at an aggregated level. The approach focusses majorly on the relationships between the energy sector and the large scale economy. Generally, top-down modelling approach works in predicting future by fitting the historical time series data on energy and carbon emissions to macroeconomic variables using econometric and multiple regression methods. These are capable of explaining the variance between dependent and independent covariates (Kelly, 2011; Johnston, 2003). Data normally used for the development of such econometric top-down models include fuel prices, gross domestic product, income, average dwelling efficiency.

Within the energy studies research circle, the econometric top-down modelling approach has received quite a degree of criticisms recently. Among the criticisms is in its lack of flexibility in using and incorporating details regarding current and future technological improvement complete with other variables adjudged to influence energy consumption and carbon emissions, as against using only the macroeconomic trends and relationships previously observed (MIT, 1997). The argument of Kelly (2011) follows the line of thought of MIT (1997) when he criticises the approach. He argues that the models from this approach lack details on how best to incorporate the changes in environmental, social and economic dimensions should there be any in them as a result of the challenge of climate change around the globe as being witnessed at the moment. The approach has also been criticised for its failure to consider, more importantly, the socio-technical and behavioural aspects of energy consumption and carbon emissions at the disaggregated level of the household. As previously mentioned under Section 2.3.1, Hitchock (1993) contends that the issue of energy consumption and carbon emissions are to be viewed as a complex technical and social phenomenon that be studied simultaneously from the perspectives of engineering and social science.

In the domestic energy sector, top-down modelling approach has been extensively used and implemented for several household energy consumption and carbon emissions models. For example, the model developed by Hirst *et al.* (1977) to explore the residential energy use sensitivity to demographic, economic, and technological factors. The model they developed is found to be sensitive to major demographic and economic variables that continually need updating annually in a bid to improve the outputs quality. Similarly, Haas and Schipper (1998) used the top-down modelling approach for their study that evaluates the role of efficiency improvements on residential energy demand. The results of their study suggest a non-elastic response to energy consumption due to irreversible improvements in technical efficiency.

In yet another study by FitzGerald *et al.* (2002), a whole economy top-down model for energy demand in Ireland was developed. The output of the model suggests that between 1960 and 2001, electricity demand in the study area increased annually by up to 5% per annum (pa), while within the same period the non-electricity demand witnessed an increase of 1.2% pa. In their model, the effect of cost on energy demand was only considered with no recourse to other important variables affecting electricity consumption.

Further to the above, the work of Summerfield *et al.* (2010) applies a simple top-down approach, based on multiple regression analysis, to model the annual delivered energy price and temperature (ADEPT). This ADEPT model gives annual household energy consumption in the UK since 1970. Lee and Yao (2013) argues that the strength of the model lies in its ability to appropriately predict overall household energy consumption. However, the model was criticised for its inappropriateness for short term overall predictions. Summing up all these limitations, Swan and Ugursal (2009) submit that the top-down approach may not be suitable in identifying key areas for improvements regarding the demand side of energy consumption at household level.

2.4.3 Energy and Carbon Dioxide Modelling Using Bottom - up Approach

The bottom-up approach to modelling has been identified to consist of models that apply a disaggregated approach to model energy consumption and carbon emissions with the use of high resolution data as input (Mhalas *et al.*, 2013; Hoogwijk, *et al.,* 2008). Shorrock and Dunster (1997) and Johnston (2003) argue that the data input required for these kinds of models are heavily reliant on extensive databases of quantitative data of physically measurable variables like the energy efficiency of hot water system, dwellings’ fabric insulation in terms of thermal performance, and the likes. They further contend that these quantitative disaggregated data together with some other information are then used in modelling energy consumption and carbon emissions units like individual dwellings, groups of dwellings, or households. Energy consumption and carbon emissions from these units are then extrapolated to sectorial, regional or national levels in a bid to aggregate the consumption and emissions as the case may be.

Premise on the fact that these models vary considerably in terms of structure and type of data input required, quite a number of researchers (Lee & Yao, 2013; Mhalas *et al.* 2013; Kelly, 2011, Kavgic *et al.*, 2010; Swan & Ugursal, 2009; Johnston, 2003) acknowledge that there are basically two major epistemic methods that have previously used for bottom-up models. These methods are categorised as statistics and building physics[4] methods. However, Kavgic *et al.* (2010) explore the case of mixing both the statistical and building physics approaches to form a more robust and highly sophisticated hybrid bottom-up modelling method. A typical example of this approach is evidenced in the Canadian Hybrid Residential End-use Energy and Emission Model (CHREM) as reported in Swan *et al.* (2008) and Mohmed *et al.* (2008).

Statistical Methods

Within the energy and carbon emissions modelling domain, the statistical modelling methods of bottom-up approach have been extensively explored by different researchers. They have used these modelling methods to generate quite a number of models relating to energy consumption as a function of household characteristics for example. The main driver of this has been attributed to the ease of mapping energy billing data of householders to household characteristics as collected and made available by energy suppliers through the use of statistics. However, these data may not be readily available to public because of the sensitive information of householders contained therein. Swan and Ugursal (2009) identified three major and well-documented methods that have been used over the years by different researches. These methods include regression analysis (RA), conditional demand analysis (CDA), and neural network (NN).

The RA carries out the analyses of energy consumption and carbon emissions and regress these on the variables and parameters of interest that are identified to influence them (Fung, 2003). The models so developed are assessed and evaluated based on some criteria like goodness of fit. The variables or parameters that are found to contribute insignificantly are removed from the models. In the case of CDA however, the method base its analysis on regressing household energy consumption on available end-uses appliances in the household. The main strength of this approach as argued by Swan and Ugursal (2009) is based on the ease of obtaining relevant information required for the model. This may mean

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[4] Some researchers use physical or engineering for building physics categorisation

conducting a simple survey of occupants’ appliances and map these with energy billing information as collected from the energy suppliers. However, data from many occupants (running into thousands) may be required in order for the model to yield reliable results. The NN method is based on a simplified mathematical model.

Statistical techniques (RA, CDA and NN) have been extensively used within the energy studies research domain, especially at the level of household. For example, Tonn and White (1988) used RA method to develop models of electricity use associated with space heating, appliances and lighting, wood use, and indoor temperature, in which household characteristics played a major role in the models produced. In yet another research conducted by Donthitt (1989) in Canada, the RA approach was used to develop a model of household space heating fuel consumption based on historic fuel price, substitute fuel price, total fuel consumption, and a vector of building structure, climatic, and occupants characteristics. The study of Kavousian, Rajagopal, and Fischer (2012) uses RA method to analyse large data sets regarding household electricity consumption to derive insights for policy makers on effectiveness of energy efficiency measures.

Further to the above studies that utilised the RA approach, another set of studies attempted the use of CDA approach to create bottom-up models regarding household energy consumption. Among those studies are the works of Parti and Parti (1980), Aigner *et al.* (1984), Caves *et al.* (1987), Goldfarb and Huss (1988), Hsiao *et al.* (1994), Mountain and Illman (1995), Lins *et al.* (2002), Aydinalp *et al.* (2003), and Swan and Ugursal (2009). The usage of NN method to model HECCE has been limited. Swan and Ugursal (2009) attribute this to high computational and data requirements of the approach. However, some studies have utilised the approach like Issa *et al.* (2001), Aydinalp *et al.* (2002), Mihalakakou *et al.* (2002), Aydinalp *et al.* (2004), and Yang *et al.* (2005).

Building Physics Methods

The building physics technique of bottom-up modelling approach is recognised as the only modelling technique that do not rely on historical data relating to energy consumption in order to fully develop the energy consumption and carbon emissions models at the level of individual dwellings or households (Swan & Ugursal, 2009). The models produced here are developed based on physical characteristics of the dwellings. Therefore, it needs to emphasise that the energy computation of this technique requires quantitative data on physically measurable variables (Shorrock & Dunster, 1997; Johnston, 2003) like information on dwellings' fabric insulation, efficiency of space heating or hot water systems, internal temperatures and heating patterns, external temperatures, ventilation rates, and the host of others (Mhalas *et al.*, 2013). To this extent, Wilson and Swisher (1993) argue that modellers employing the building physics method in estimating dwellings or households' energy consumption immensely benefit from a combination of dwellings' physically measurable data and empirical data from national database including house condition surveys. According to Swan and Ugursal (2009), three major methods of analysis of energy consumption and carbon emissions based on building physics approach have evolved over the years. These methods are termed: distributions, archetypes, and sample methods.

In the distributions method, appliances ownership distributions of different households or dwellings within the housing stock are mapped to the ratings of those appliances in order to estimate the likely energy consumption and the resultant carbon emissions based on end-uses of those households or dwellings. The regional or national energy consumption and carbon emissions can then be estimated by aggregating appliances consumption for each households or dwellings as the case may be. Archetypes method on the other hand base its estimation of energy consumption and carbon emissions on the housing stock classification according to dwelling type, size, age, or even tenure. The consumption and emissions for each dwelling type representatives, for example, are therefore scaled up and then aggregated to form the regional or national energy consumption and carbon emissions. For sample method, the approach models regional or national energy consumption and carbon emissions based on the actual sample dwellings data collected and serve as the input to the model. Here, the methodology firmed up for the sampling exercise is rigorous and scientifically proven to be the true representative of the population as adopted in English or Scottish house condition survey for example. By following this method, the consumption and emissions of different variety of dwelling types are account for and form the basis for the modelling, which again are aggregated to form the regional or national estimate.

There are quite a number of studies that have applied these different building physics techniques (distributions, archetypes, or sample) of bottom-up modelling approach to model energy consumption and carbon emissions of the housing stock. For example, the distributions technique has been utilised by both the developing and developed nations to estimate the regional or national energy consumption and/or carbon emissions of their respective nations. The study of Saidur *et al.* (2007) applied distributions method of appliances ownership to model a non-space heating household energy in Malaysia. The output of the model generates the annual energy consumption for the nation. In yet another study in India, Kadian *et al.* (2007) developed a model of energy-related emissions for households in Delhi by combining the distributions and micro-level data sources. For household energy in Italy, the study of Capaso *et al.* (1994) utilised the appliance use profile of householders based on the distributions technique to generate an outlook of energy consumption for the entire housing stock. The model combined the data of householders’ lifestyle and engineering data of different types of appliances as input for the model. Similarly, the work of Jaccard and Baille (1996) in Canada demonstrate the application of distributions method to model carbon emissions reduction cost of householders based on appliances use behaviour of the householders.

The archetypes technique of building physics modelling method has been extensively utilised by many modellers within the household energy domain. As such, a considerable number of publications have emerged in the literature. The model of Parekh (2005) in Canada was developed based on archetypes of dwellings characteristics in a bid to simplify the analysis and evaluation of household energy use. Another study from the United States of America (USA) models space heating and cooling loads of the USA housing stock (Huang & Broderick, 2000) for 16 different regions using 16 multifamily and 45 single-family archetypes of dwellings. The outcome of this study produced energy simulation results for space heating and cooling loads for 16 different dwelling archetypes for the USA housing stock. The results were disaggregated in a way that the contributions of thermal conductivity of walls, roof, windows, and others could be seen.

In the study of Petersdorff *et al.* (2006), three different archetypes of dwellings (terrace, small apartment, and large apartment) were used when the European Union (EU)-15 building stock was modelled. The study examines and considers five standard dwellings and eight insulation standards using the built environment analysis model. The results produced the heating demand based on the archetypes for 15 different EU countries. Similarly in the UK, the study of Johnston (2003) develops energy consumption and carbon emissions for the UK housing stock to represent different types of dwellings. The model was further disaggregated to include two types of dwellings according to construction date (*i.e.* pre-1996 and post-1996). This disaggregation hence reflects the entire housing stock. Other studies that have utilised archetypes approach for their models include Clarke *et al.* (2008), Jenkins (2008), Gupta (2009), Firth *et al.* (2010), Natarajan *et al.* (2011), Mhalas *et al.* (2013), *etc.*

In contrast to archetypes method, the application of sample method as one of the techniques of building physics modelling approach has been limited. This is likely due to the huge amount of data requirement of the method. And as such, not many studies have used the approach in the literature. Among these few studies are Shorrock and Dunster (1997), Farahbakhsh *et al.* (1998), Larsen and Nesbakken (2004), Boardman *et al.* (2005), and Natarajan and Levermore (2007a). The Building Research Establishment's Housing Model for Energy Studies

(BREHOMES) (Shorrock & Dunster, 1997) developed in the early 1990s used 1000 dwellings types (defined by age group, built form, tenure type and ownership of central heating) as the sample upon which the annual household energy consumption of UK housing stock is based. 8787 dwellings (defined by type, space heating fuels, vintage and province) were used in Canada (Farahbakhsh *et al.*, 1998) to provide the Canadian residential energy end-use model (CREEM) in a bid to test the effect of different strategies of carbon reductions based on two standards.

The model developed by Larsen and Nesbakken (2004) used 2013 dwellings to produce the model of household energy consumption of the Norway's housing stock. The UK domestic carbon model (UKDCM) developed by the Environmental Change Institute of Oxford University (Boardman *et al.*, 2005) made use of 20,000 dwelling types using national statistics to produce the monthly HECCE. The model produced three different scenarios until 2050. In concluding this section, the domestic energy and carbon (DECarb) model (Natarajan & Levermore, 2007a) developed by the research unit for the Engineering and Design of Environments, Department of Architecture and Civil Engineering, University of Bath in 2007 used 8064 unique combinations for six age bands of the UK housing stock to produce the monthly energy consumption for the UK.

2.4.4 Benefits and Limitations of the Top-down and Bottom-up Modelling Approaches

Undoubtedly from the foregoing, it has been revealed that both the top-down and bottom-up approaches have their strengths and at the same time weaknesses. It is therefore imperative to have them summarised before critically reviewing some notable energy consumption models in the domestic sector of the UK economy.

Table 2.2 therefore gives some benefits and limitations of the top-down and bottom-up approaches as evidenced from the work of Kavgic *et al.* (2010). It is necessary to add that both the top-down and bottom-up approaches have not utilised the advantage of incorporating qualitative data input. Unfortunately, Kavgic *et al.* (2010) fails to recognise this as one of the limitations of those approaches. This, however, limits the capability of those approaches. Importantly, incorporating both the qualitative and quantitative data sources to any modelling efforts improves the robustness of such approaches as its lack undermines their capabilities.

2.5 The Notable UK Household Energy Consumption and CO_2 Emissions Models

As can be noted from Section 2.4 that several models have evolved over the years in the UK to estimate and forecast the current and future trends of HECCE for the UK housing stock, it is therefore imperative to discuss in details some of the notable HECCE models that are specifically developed for the UK. Some of these models include:

- The BREHOMES (Shorrock & Dunster, 1997; Shorrock *et al.*, 2005).
- The Johnston model (Johnston, 2003).
- The UKDCM (Boardman *et al.*, 2005).
- The DECarb model (Natarajan & Levermore, 2007a).
- The Community Domestic Energy Model (CDEM) (Firth *et al.*, 2010).
- The Cambridge Housing Model (CHM) (Huges, 2011; Huges & Palmer, 2012).
- The Domestic Dwelling Model (DDM) (Mhalas *et al.*, 2013).

Table 2.2: Benefits and limitations of top-down and bottom-up modelling approaches

Characteristics	Top-down	Bottom-up statistical	Bottom-up building physics
Benefits	- Focus on the interaction between the energy sector and the economy at large - Capable of modelling the relationships between different economic variables and energy demand - Avoid detailed technology descriptions - Able to model the impact of different social cost-benefit energy and emission policies and scenarios - Use aggregated economic data	- Include macroeconomic and socioeconomic effects - Able to determine a typical end-use energy consumption - Easier to develop and use - Do not require detailed data (only billing data and simple survey)	- Describe current and perspective technologies in detail - Use physically measurable data - Enable policy to be more effectively targeted at consumption - Assess and quantify the impact of different combination of technologies on delivered energy - Estimate the least-cost combination of technological measures to meet given demand
Limitations	- Depend on past energy economy interactions to project future trends - Lack the level of technological detail - Less suitable for examining technology-specific policies - Typically assume efficient gaps	- Do not provide much data and flexibility - Have limited capacity to assess the impact of energy conservation measures - Rely on historical consumption data - Require large sample - Multi-collinearity	- Poorly describe market interactions - Neglect the relationships between energy use and macroeconomic activity - Require a large amount of technical data - Do not determine human behaviour within the model but by external assumptions

(Adapted from Kavgic *et al.*, 2010)

2.5.1 The Building Research Establishment's Housing Model for Energy Studies

The BREHOMES as developed by Shorrock and Dunster (1997) is seen as the earliest UK household energy model that is based on the building physics method of the bottom-up modelling approach (Section 2.3.3) to estimate the HECCE of UK housing stock. The model is highly disaggregated model and used weighted average stock transformation method to convert over 18,000 households surveyed to over 1000 different dwelling types in a bid to build this dwelling types profile. The core calculation engine for the model is based on the Building Research Establishment's Domestic Energy Model (BREDEM) in order to establish energy use for dwellings. It needs to state that BREDEM energy model accepts input on different areas of dwelling elements to include dwellings' thermal characteristics, number of occupants or household size, internal and external temperatures, solar gains, heating patterns, *etc*. The BREHOMES model architecture as adapted from the work of Shorrock and Dunster (1997) is shown in Figure 2.2.

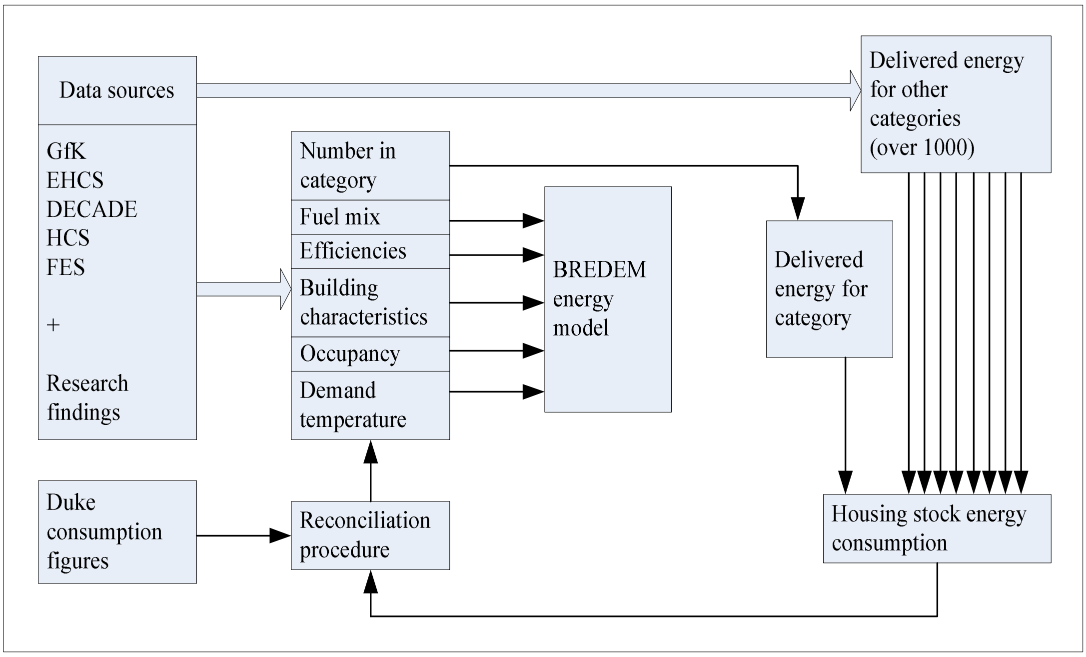

Figure 2.2: BREHOMES model architecture

(Adapted from Shorrock & Dunster, 1997)

The output of the model produces the annual energy consumption and carbon emissions at the national level of aggregation. Two different scenarios are explored by the model to include (1) the baseline model termed ‘Reference’ (business-as-usual) scenario, and (2) ‘Efficiency’ scenario. The earlier version of this model as reported in Shorrock and Dunster (1997) produces the output from a base year of 1990 to 2020. However, a more recent version of the model as reported in Shorrock *et al.* (2005) used a base year of 1993 and extends the output trends till 2050. The model has been extensively applied as policy advice tool for the Department for Environment, Food and Rural Affairs (DEFRA). However, the model is not transparent as it is difficult to replicate the study. Also, the model lacks the capability of capturing qualitative data as input data source as it is heavily rely on highly disaggregated quantitative data source.

2.5.2 The Johnston Model

The Johnston model is another one of the notable HECCE for the UK housing stock. As for BREHOMES, it is also a model based on building physics technique of bottom-up modelling approach. As previously mentioned in Section 2.3.3 above, the Johnston model has the capability of reflecting the different types of dwellings of the entire UK housing stock. However, the model basically disaggregated the overall housing stock into two by using dwellings’ year of construction as the main criterion for the disaggregation. Here, the entire UK housing stock is represented in the model as (1) pre-1996, and (2) post-1996. In like manner to BREHOMES, the model adapted the BREDEM’s calculation algorithm for each dwelling types in order to calculate energy and emissions of these individual dwelling types. The architecture of Johnston model is shown in Figure 2.3 as adapted from Johnston (2003).

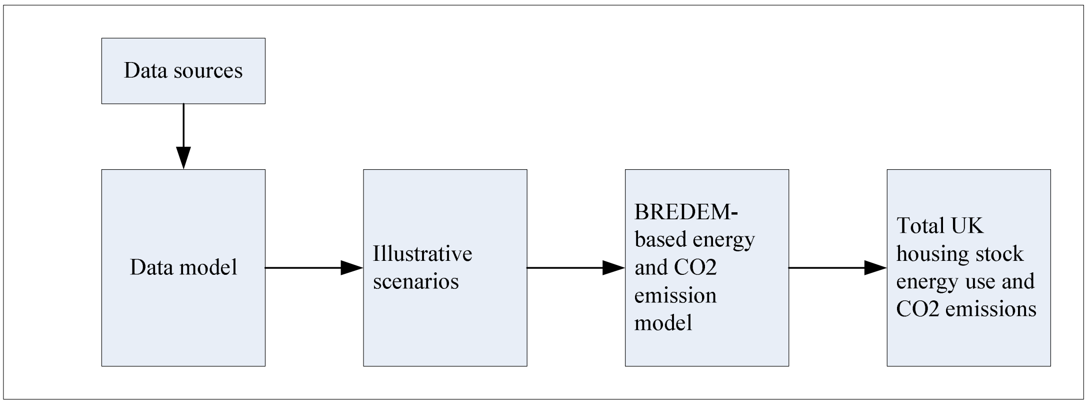

Figure 2.3: Johnston's model architecture

(Adapted from Johnston, 2003)

The overall output of the model appropriately produces the total annual energy consumption and carbon emissions for the entire UK housing stock with 1996 as the base year and this continues until 2050. This is in a bid to give the previous, current, and then project into the future regarding household consumption and emissions level. In order to explore the effects of changes to certain assumptions (like uptake of new technology, trends in population, energy usage changes, *etc.*) made in the model, three major scenarios as typical applicability of the model were produced. The first scenario termed the 'business-as-usual (BAU)' looks at the current trends and projects these until 2050 with an assumption that there won't be any further action or intervention from government to reduce the emissions. With these trends, the output of the scenario reveals that about 33% of the emissions could be reduced by the year 2050 when compared to the emissions level of 1996, which was used as the base year.

The second scenario termed the 'demand side' is based on BAU and extends it in order to incorporate some other measures should new evidence regarding the climate change, for example, emerges in the near future. This scenario explores improvements in energy efficiency of the demand side of household energy. The output of the model predicted a 58% reduction in carbon emissions for this scenario. Additionally, the third scenario termed the 'integrated' scenario combines both the supply and demand sides of the UK housing stock and explores their effects on carbon emissions of the entire housing stock. The results show that about 74% reduction is achievable. Johnston (2003) notes the limitations of the model. That is the model suffers from usability and transparency as he recommends transferring the model to a more suitable platform. Regarding the application of the model, it is capable of being used as a policy advice tool. However, the application of the model has been limited to its developer alone. Therefore, it has not been extensively used in practice.

2.5.3 The UK Domestic Carbon Model

The UKDCM model (Figure 2.4) was developed by the Environmental Change Institute of the Oxford University in the year 2005 in order to explore and investigate how 60% reduction in carbon emissions could be achieved in the UK housing sector. The model is based on building physics. The model processes a huge amount of data that include those obtained from the English Housing Condition Survey and its equivalents in Scotland and Northern Ireland. Among the data input required by the model are population figures, levels of insulation, efficiency of heating equipment, *etc.* as contained in the 40% House report (Boardman *et al.*, 2005). The model contains highly disaggregated datasets for nine geographical areas, seven age classes and ten types of construction of some 20,000 UK dwellings. Additionally, the model has the capability to process different combinations of these datasets in order to further sub-divide the dwellings based on tenure, construction method and number of floors. In like manner as the BREHOMES and Johnston models, the model made use of the BREDEM calculation engine to estimate the emissions of these dwellings. The structure of UKDCM is shown in Figure 2.4 as adapted from Boardman *et al.* (2005).

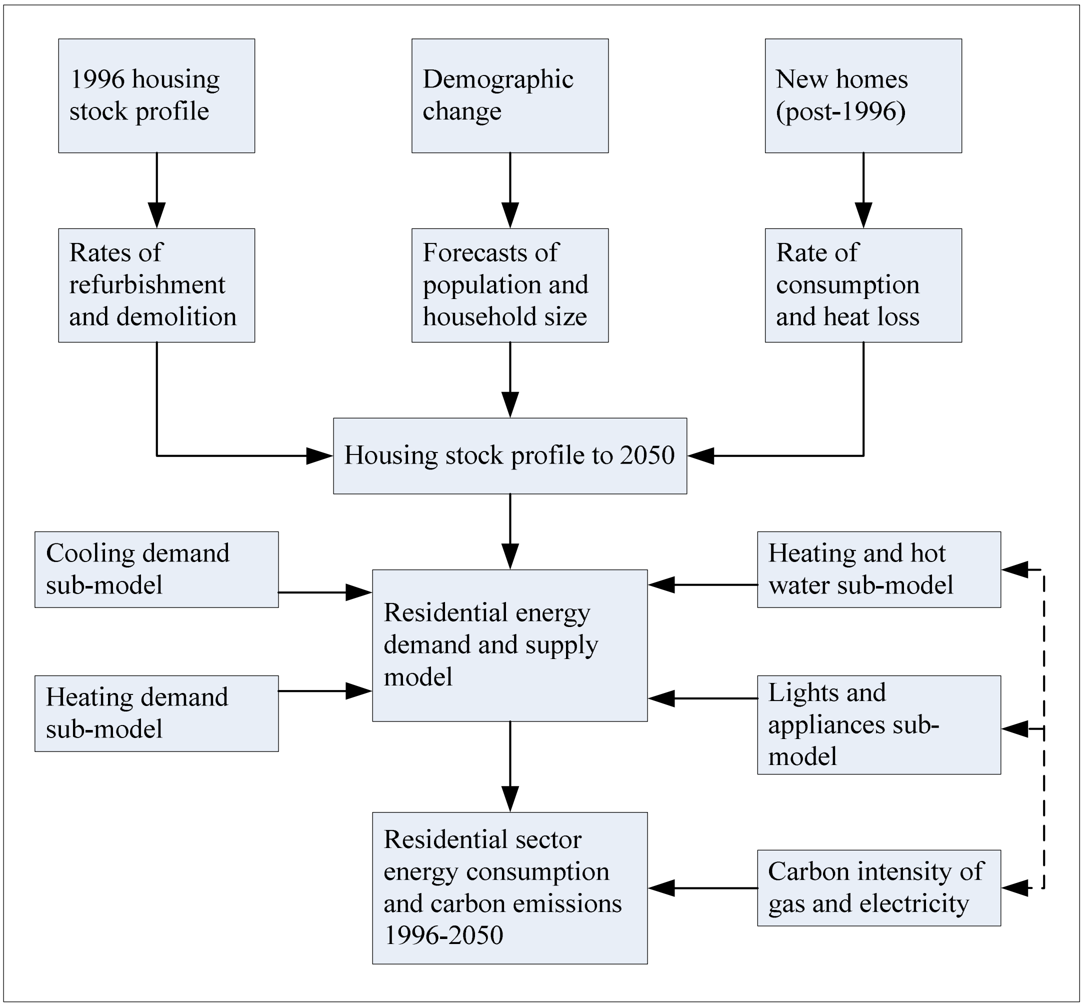

Figure 2.4: UKDCM architecture

(Adapted from Boardman *et al.*, 2005)

The output and temporal resolution of the model gives the monthly energy consumption and carbon emissions of the UK housing stock. The model performed three different scenarios to explore the effects of some policy formulations regarding energy use. The scenarios tested are (a) BAU, (b) 44% emission reduction, and (c) 25% emission reduction below 1990 levels. This model in general together with the scenarios tested was improved upon by another version of the model termed ‘UKDCM2’ (Hinnells *et al.*, 2007). According to Boardman (2007), this newer version was used to prepare the Home Truths report, where the analysis of different scenarios regarding reduction in future carbon emissions were conducted and explored. The scenario A of this newer version represented a plausible scenario to reflect what would happen should there be *"a continuation of current and near-terms trends, technologies, policies and practices, with changes occurring slowly into the future"* (Hinnells *et al.*, 2007). Scenario B updates the scenario B of '40% House report' and this now investigates the way Government's target of 60% emissions reduction by the year 2050 could be achieved through the assumption that members of the society now know more about the issue of energy use and carbon emissions with attendant technological change and societal change to bring about reduction in carbon emissions. In the other hand, Scenario C explores how a further reduction in carbon emissions in excess of 60% could be achieved by assuming higher uptake of renewable and other efficient energy sources, additional demolition and new build, *etc*. The model is being used generally as policy advice tool and it is freely available over the internet.

2.5.4 The Domestic Energy and Carbon Model

The DECarb is another notable model of the HECCE for the UK housing stock with the capability of mapping different technical and climate scenarios in order to generate future trends and options regarding consumption and emissions. The model is an object oriented one that is capable of running on any of the operating systems and it is user friendly in terms of selecting input data. The model is based on building physics approach. Figure 2.5 shows the structure of the model as adapted from the work of Natarajan and Levermore (2007a). Similarly to other models in Sections 2.5.1, 2.5.2, and 2.5.3, DECarb model uses a highly disaggregated housing stock approach that has unique 8064 combinations of six historical age classes of the UK housing stock. Likewise other previous models discussed above, DECarb made use of the BREDEM algorithm for the calculation of consumption and emissions profiles for individual dwellings in the model. There are six different files for the dataset with each to represent each of the six different age classes and these dataset consists of different variables that include dwelling type, insulation characteristics, *etc.* The model is then used to run future scenarios regarding UK housing stock.

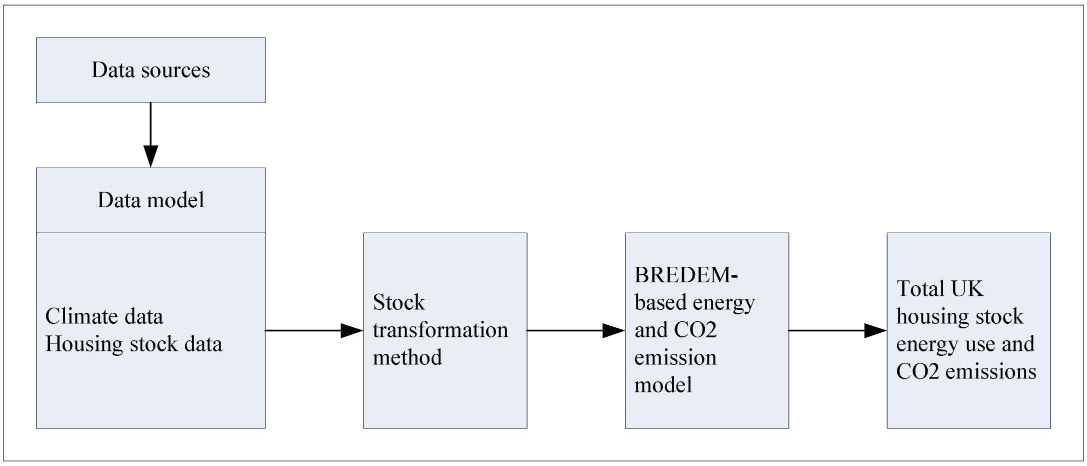

Figure 2.5: DECarb model architecture
(Adapted from Natarajan & Levermore, 2007a)

As the overall output, the model calculates the annual energy consumption and carbon emissions in a bid to perform a forecast of their trends from the base year 1996 until 2050. Interestingly, the model has the capability of performing a back-cast analysis from 1996 backwards. This is embedded into the model in order to serve as a way of validating the model. The model was then used to test climate change scenarios according to UKCIP02 in addition to the BREHOMES, Johnston, and UKDCM scenarios. For example, using the Johnston's model scenarios, the results suggest that it is unlikely to meet the target of up to 50% reduction in carbon emissions for all these scenarios run (Natarajan & Levermore, 2007b). As for other models discussed above, the model is being used as a policy advice tool and readily available online as open framework. As noted above, the model is user friendly in selecting the input data; however, the mode of output data presentation is poor as they are displayed in text file. This then presents difficulty in reading the results of the model.

2.5.5 The Community Domestic Energy Model

The CDEM is another notable model of energy consumption and carbon emissions of the UK housing stock that was developed by the Department of Civil and Building Engineering, Loughborough University in the year 2009 (Firth *et al.*, 2010) based on building physics approach. In like manner to other previous models above, this model is highly disaggregated, but with 47 house archetypes that are derived from unique combinations of built form type and dwelling age. For house architecture calculation engine, the model requires input from many sources to include English House Condition Survey (EHCS), BREDEM-8 calculation engine, SAP rating, *etc.* (Figure 2.6).

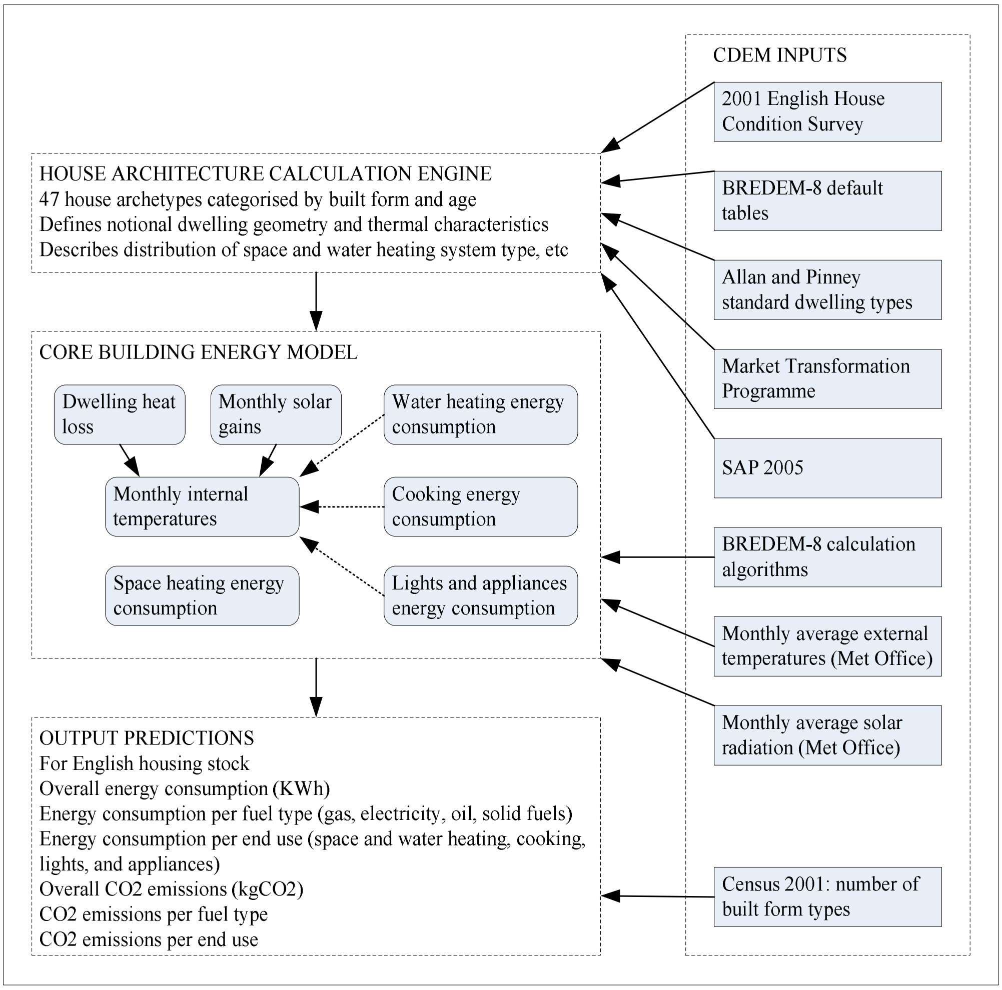

Figure 2.6: CDEM model architecture

(Adapted from Firth *et al.*, 2010)

Regarding the core dwelling model, the main data requirement comes from the BREDEM-8 calculation engine, monthly average external temperatures and monthly average solar radiation as obtainable from the Met Office. The output of the model produces monthly energy consumption and carbon emissions of the whole UK housing stock. Also, the model is capable of producing output based on city or neighbourhood housing stock. Apparently, the model fail to test any scenarios, instead used the model to estimate and predict energy consumption and carbon emissions of the 2001 English housing stock alone.

2.5.6 The Cambridge Housing Model

The CHM model was developed by the Cambridge Architectural Research in a bid to forecast energy consumption and carbon emissions for housing stock in England, Scotland, Great Britain, and the UK in general. It is another building physics-based bottom-up model that uses the calculations formulated and established by SAP 2009 (BRE, 2011) and BREDEM engine (Shorrock & Dunster, 1997) in order to perform all its internal calculations. The model has three basic data input components as shown in Figure 2.7 to include climate data, housing data, and building physics data. For climate data input, the model uses SAP’s monthly solar declination and regional latitude data, BREDEM-8’s monthly/regional solar radiation data, and monthly/regional year-specific wind speed and external temperature data as taken from quite a number of different stations across the UK.

Regarding the housing data input, the main source here is based on 16,670 dwellings as contained in English Housing Survey of 2010 (Palmer & Cooper, 2012) with an adjustment to scale this up to reflect the UK housing stock. However, the building physics data input are the direct results of the calculations performed in SAP and BREDEM. The model then reads in data for individual representative dwelling in order to perform building physics calculations. The

CHM is one of the most transparent models because the model is built and all its calculations performed in Microsoft Excel.

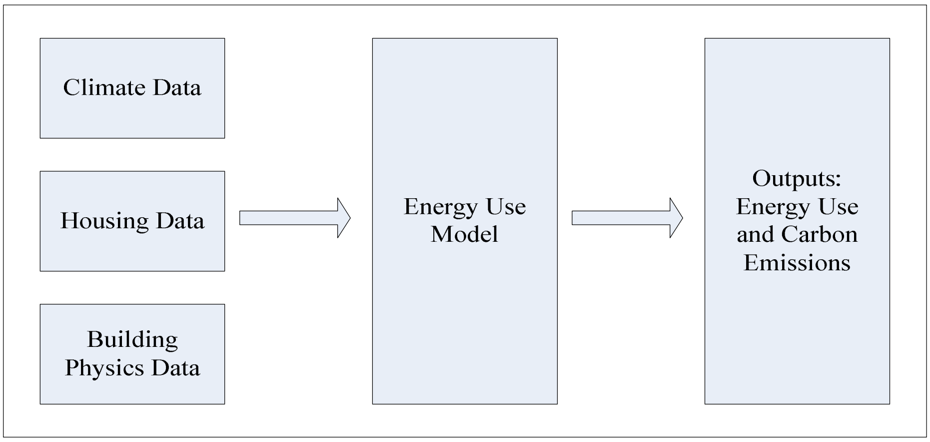

Figure 2.7: CHM model architecture

(Adapted from Huges, 2011)

The output of the model therefore gives the energy consumption together with associated carbon emissions according to fuel and end-use. These are presented for representative of each dwelling type, English housing stock, Scotland housing stock, *etc.* as well as for the entire UK housing stock. It is worthy of note that the output of this model is one of the studies that made up the UK housing fact file domicile in the Department of Energy and Climate Change (DECC) (Palmer & Cooper, 2012).

2.5.7 The Domestic Dwelling Model

The DDM is a new approach being proposed by the Technology Futures Institute of the Teesside University (Mhalas *et al.*, 2013) to model energy consumption and carbon emissions of dwellings and neighbourhood based on visualisation. The model is highly disaggregated as it estimates each dwelling independently within the neighbourhood. The model uses the SAP/BREDEM energy calculation engine. As input to the SAP core calculation engine, the model utilises information from aerial and terrestrial imagery, digital maps, household surveys, census, and ONS. As a first step in the development of this approach, models of the dwellings in the neighbourhood are developed (Mhalas *et al.*, 2013).

Following this is to undertake energy performance calculation of the models according to the SAP algorithms. The carbon emissions reduction capability of the dwelling is hence quantified based on the existing characteristics of the dwelling before using a decision support system to implement the effectiveness of energy improvement measures. This model is implemented on a GIS platform. Figure 2.8 shows the architecture of the model.

2.6 Summary and Critique of the Notable UK Housing Stock Energy Models

By considering the contribution of emissions from domestic dwellings, it can be deduced from Section 2.5 that considerable efforts have been invested into energy models for dwellings in the UK. One thing that is common and central to all the reviewed models under Section 2.5 is that they all share the same BREDEM algorithms in estimating and forecasting energy consumption and carbon emissions. BREDEM has been adjudged as a well-established method to accurately predict UK dwelling energy consumption (Natarajan *et al.*, 2011) as it forecasts dwellings’ energy consumption and carbon emissions at highly disaggregated level based on deterministic building physics. Additionally, domain of application of these models is common as they all applied as policy advice tools. However, the models are varied in terms of their level of disaggregation, resolution of output, output aggregation level, scenario analysis performed, model validation, and their availability to the members of public for scrutiny, as shown in Table 2.3.

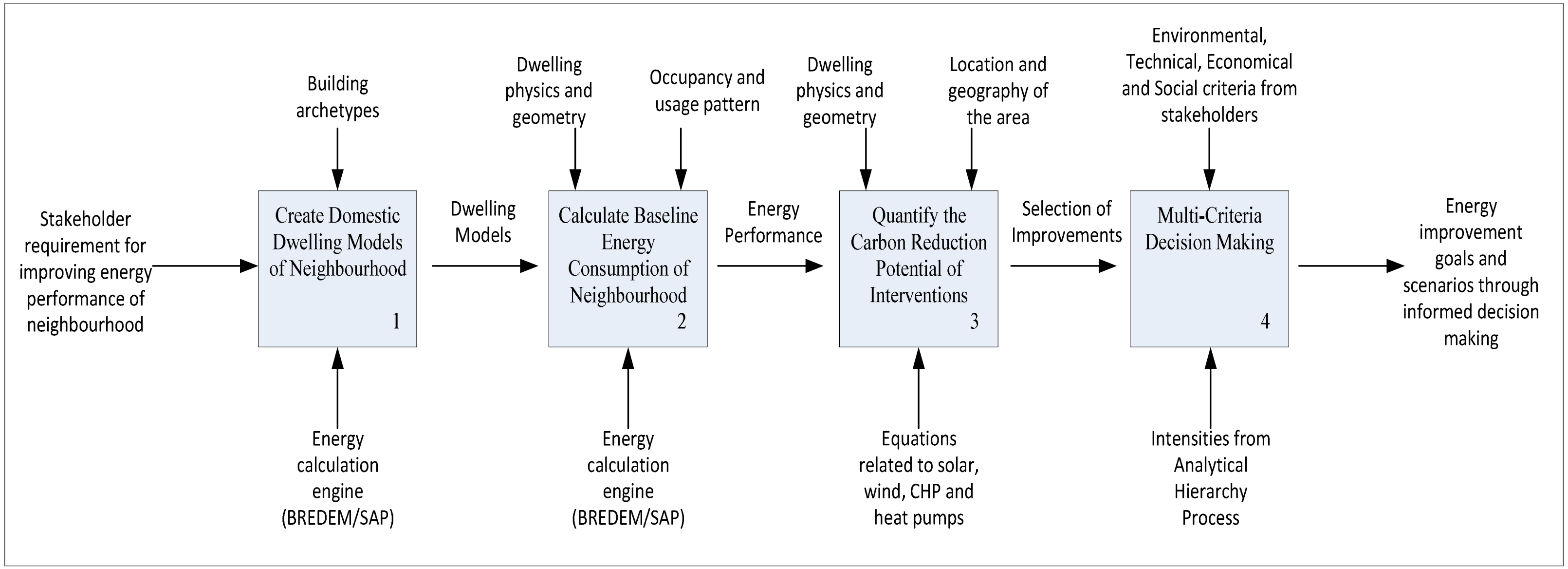

Figure 2.8: Domestic Dwelling Model architecture

(Adapted from Mhalas *et al.*, 2013)

Unfortunately, these models have been criticised due to a number of limitations in them. Firstly, all the models have been criticised for their low level of transparency. Kavgic *et al.* (2010) and Mhalas *et al.* (2013) argue that the models transparency, in terms of the architecture and data sources, is seen as one of the most essential issue worth considering for future deployment of the models. Regrettably, some of these models are not available to the members of public; even those that are made available to public contain little information about their structure and operational details. As such, the models could not be scrutinised as getting access to raw input data or the algorithms used by the models has been a mirage for the majority of them. This is because it is unclear on how the relationships among the different variables making up the models are formulated and built up. Consequently, the outputs of these models are extremely difficult to replicate.

Secondly, the models fail to take into consideration the complex, interdependencies, and dynamic nature of the issue of energy consumption and carbon emissions, especially in households. This is because the modelling approaches of these models are based on static and deterministic method, which is classified as reductionist paradigm that uses linear orientation to give the forecast of a system, which; for example; is just for a particular point in time. These models therefore work with particular sets of data inputs in a bid to produce particular sets of outputs that have little or no room to accommodate uncertainty in input datasets. This is because the approaches for the models are hinged on the notion that exact relationships exist between the variables in the models without uncertainty. For example, some of them employ the use of simple regression analysis that relies on historical data. Here, the future trends are predicted based on the historical without putting into consideration any undesirable or chaotic events that may occur in the near future.

Table 2.3: Comparative analysis of notable UK energy models

Characteristics Models	Developer	Year	Calculation model embeded	Output resolution	Disaggregation level	Scenario analysis	Data output aggregation level	Validation with historical data	Application	Availability
BREHOMES	Building Research Establishment (BRE)	Early 1990s	BREDEM-12	Annual energy consumption	1000 dwelling types used based on age group, tenure type, etc.	Two scenarios until 2020: (a). Reference (b). Efficiency	National	Extensive	Policy advice tool	Available to the developer only
Johnston	Johnston's PhD Thesis at Leeds University	2003	Modified version of BREEDEM-9	Annual energy consumption and carbon emissions	Two dwelling types separated into pre- and post-1996	Three scenarios until 2050: (a). Business-as-usual (b). Demand (c). Integrated	National	Comparison with historical data from the BRE Domestic Energy Fact File	Policy advice tool	Available to the developer only
UKDCM	Environmental Change Institute (ECI), Oxford University	2006	BREDEM-8	Monthly energy consumption and carbon emissions	20000 dwelling types by 2050	Three scenarios until 2050: (a). Business-as-usual (b). 44% emission reduction (c). 25% emission reduction below 1990 levels	National	Validated with regional historical data provided by BERR	Policy advice tool	Open
DECarb	Research Unit for the Engineering and Design of Environments, Department of Architecture and Civil Engineering, University of Bath	2007	BREDEM-8	Monthly energy consumption	8064 unique combinations of six age bands of different dwelling types	(a). UKCIP02 scenarios (b). BREHOMES scenarios (c). Johnston scenarios (d). UKDCM scenarios (e). Back-cast scenario (1970 – 1996)	National	Validated with historical data provided by BERR and BRE Domestic Energy Fact File	Policy advice tool	Open
CDEM	Department of Civil and Building Engineering, Loughborough University	2009	BREDEM-8	Monthly energy consumption and carbon emissions	47 dwelling archetypes based on unique combinations of age band and dwelling built form types	A scenario to predict 2001 housing stock	National, City, Neighbourhood	Validated with 2001 DEFRA aggregate figure of domestic space heating consumption	Policy advice tool	Open

Table 2.3: *Continued*

Characteristics / Models	Developer	Year	Calculation model embeded	Data output resolution	Disaggregation level	Scenario analysis	Data output aggregation level	Validation with historical data	Application	Availability
CHM	Cambridge Architectural Research, University of Cambridge	2010	BREDEM-8 and SAP 2009	Annual energy consumption and carbon emissions	16,670 dwelling types	Conducted sensitivity analysis for the 15 most sensitive parameters in the model	National, Regional	Extensive	Policy advice tool	Open
DDM	Technology Futures Institute, Teesside University	2013	BREDEM-8 and SAP 2009	Annual energy consumption and carbon emissions	756 dwelling types	Illustrative scenarios of (a). Fabric change (b). Solar PV (c). μ-CHP (d). Condensing boiler (e). ASHP (Under-floor) (f). ASHP (radiator)	Individual, Neighbourhood	Validated with energy performance certificate of some social housing dwellings in Middlesbrough	Policy advice tool	Available to the developer only

Thirdly, the importance of occupants-dwelling interaction cannot be over emphasised regarding energy consumption in homes. Therefore, special attention needs to be accorded to this aspect as well. This is evidenced from the assertion made on the report of the Inter-governmental Panel on Climate Change (IPCC) mitigation (IPCC, 2007) that "*occupant behaviour, culture and consumer choice and use of technologies are also major determinants of energy use in buildings and play a fundamental role in determining carbon emissions*". Conversely, IPCC (2007) report further suggests that there is limited evidence to show that these determinants are being incorporated into energy models. While it is evident that BREDEM, for example, incorporates some degrees of occupants' aspect like number of occupants into their model, Natarajan *et al.* (2011) confirms that the behavioural aspect has been limited and not explicitly considered.

Fourthly, it is evident that the issue of energy and carbon emissions remain increasingly complex and difficult to manage. This is due to the fact that quite a number of issues regarding energy sector of the economy are evolving on a daily basis. For example, in order to accurately predict and forecast energy consumption and carbon emissions, energy sector would undoubtedly interact with other sectors like economic and environment sectors and the host of others. These sectors are difficult to manage on their own merit. However, dynamically integrating these external sectors to energy sector further compounds the problem of household energy issues. As such, all the models reviewed in Section 2.5 have not demonstrated enough capacity to dynamically accommodate additional systems that utilise both the quantitative and qualitative data inputs and where some variables may interact in a non-linear way. This then portends to mean that the models are profoundly limited for their lack of ability to incorporate the feedback from these external sectors.

From the forgoing, it is apparent that there is the need to look both inwardly and outwardly for sophisticated modelling approaches capable of dealing with the limitations above and then model the kind of complexity and challenges that are facing the HECCE. This may mean to further broaden the scope and level of interaction of different HECCE drivers and the capacity to expand this should the need arise in the near future. In order to further reinforce this, several researchers advocate and propose the use of the STS as an approach to model this complexity due to high inter-dependencies, chaotic and non-linearity of the variables involved, such as: Hitchcock, 1993; Kohler & Hassler, 2002; Shipworth, 2005; 2006; Motawa & Banfill, 2010. It needs to emphasise that STS is one of the methodologies of the systems-based approach of scientific inquiry. This methodology has previously been used as an approach to model the complexity of real systems' elements and relationships (as will be discussed in Chapter three). Modelling complexity enables capturing the interdependent and multi-causal correlation structure of the elements of STS and determining the efficacy of different change strategies. This helps in analysing the non-linear behaviour of the studied systems where changes in input are neither proportional to changes in output, nor is the input to output relationship fixed over time. This thesis will then use the STS approach to model HECCE. The theoretical backgrounds and the modelling techniques for the STS are covered in Chapter three of this thesis with previous attempts in energy sector.

2.7 Chapter Summary

This chapter has shown that there are a wide range of frameworks that previous studies have formulated to conceptualise the issue of energy consumption and carbon emissions, which are now serving as the theoretical backgrounds underpinning energy models. They are therefore principally fall within two major domains: disciplinary and integrated frameworks. Disciplinary framework focuses on how individual disciplines illustrate the approach to solving energy and carbon emissions problems by formulating a framework. For example, engineering approach looks at the technology of energy consumption and carbon emissions. On the hand, integrated framework uses a holistic approach to combine a number of disciplines together and provide a framework capable of shaping the issue of energy consumption and carbon emissions based on the limitations of disciplinary framework. Within the body of literature, it was established that the social and technical variables influencing household energy consumption and carbon emissions come basically from three interacting systems comprising of the dwellings, occupants, and external environment. The variables identified within the dwellings system are related to dwellings' physical characteristics. Also, variables related to occupants system are in terms of household characteristics, occupants' thermal comfort, and occupants' behaviour. And finally, the variables related to external environment system are in terms of climatic, economic, and cultural influences. The variables used for model conceptualisation in Chapter six are drawn from these frames of variables and mapped into six different modules.

Further to this, the chapter has demonstrated that quite a number of energy and carbon emissions models have evolved over the years with the capability of forecasting and estimating energy consumption and carbon emissions, especially in the domestic sector of the economy. These models are found to vary considerably based on the levels of disaggregation, complexity, resolution of output, output aggregation levels, scenario analysis performed, model validation, and their availability to the members of public for scrutiny, using basically two major epistemic approaches that include: top-down or bottom-up approaches. The top-down techniques rely on the kind of interaction subsisting between the energy sector and the economy in general at aggregated level in order to predict and forecast the behaviour of energy consumption and carbon emissions, especially at the household level, when some changes are made to the policy parameters within such models. On the other hand, bottom-up techniques mainly focus on only the energy sector utilising a disaggregated approach of either statistical or building physics method that contain a high level of details to model energy consumption and carbon emissions, especially at household level.

After a careful appraisal of the existing modelling approaches, the chapter concludes that there are a number of limitations in the existing modelling techniques that prevent them from being used in this thesis. These are (1) lack of transparency in the model algorithms, (2) inability to account for the complex, interdependencies, and dynamic nature of the issue of energy consumption and carbon emissions, (3) limited evidence to show for the occupants-dwelling interactions, and (4) lack of enough capacity to accommodate qualitative data input. And as such, there is the need to scout for more robust and sophisticated modelling approaches that take into consideration the kind of complexity involved and bedevilling the issue of HECCE due to high inter-dependencies, chaotic, non-linearity, and qualitative nature of some of the variables involved.

Chapter 3

MODELLING THE SOCIO–TECHNICAL SYSTEMS

3.1 Introduction

In Chapter two it was concluded that there is the need for more robust approaches that have the capability of modelling the kind of complexity involved in household energy consumption and carbon emissions by taking into consideration the limitations of existing modelling approaches as discussed in Section 2.6. It was argued in Section 1.1 of Chapter one that the problem under investigation in this thesis sits squarely within the domain of STS. In this chapter systems idea that brought about the STS is first discussed by reviewing the rationale, historical backgrounds as well as the basic concepts of the systems-based approach. Further to this, the chapter discusses the theory of STS together with its basic concepts. Literature on the domain of application and modelling techniques of STS will be also reviewed. Additionally, the literature study specifically assesses and critiques the identified STS modelling techniques against a set of criteria that meets the requirements of the problem under investigation as highlighted in Sections 1.1, and 2.6 of this thesis. Finally, the choice of the most suitable STS modelling technique concludes the chapter.

3.2 Systems-based Approach of Scientific Inquiry

The systems idea of scientific inquiry came into limelight not until in the fifties, when the main concepts and principles relating to the general systems theory were formulated. Banathy (2000a) noticed that the systems ideas of different fields share a common ground on systems orientations as those ideas embrace research/professional activities in the area of *"system engineering, operations* *research, system dynamics, cybernetics and information science, general theory of systems, living systems and evolutionary theory, soft systems and critical systems theory, and chaos and complex systems theory"* (Banathy, 2000a). As a result of this, these researchers now recognise the necessity of an interdisciplinary research field with capability of coping with ever increasing complexities that fall beyond the scope of a single discipline. The systems-based approach of scientific inquiry that emphasised the intrinsic order and interdependence of the complex problem in all its ramifications is therefore born.

Systems-based approach of scientific inquiry, however, incorporates systems theory, systems philosophy, and systems methodology; as three main inter-related domains of disciplined scientific inquiry. While the systems theory and philosophy provide the philosophical basis for the systems-based approach, systems methodology gives the sets of methods, strategies, models and tools for systems-based approach of scientific inquiry. The rest of this section discusses the rationale behind the systems-based approach of scientific inquiry, historical background of the systems-based approach, its concepts, components and characteristics, and types of systems.

3.2.1 Rationale Behind the Systems-based Approach to Scientific Inquiry

Science is a way of acquiring testable knowledge about the world (Clayton & Radcliffe, 1996). The classical method of scientific inquiry has played prominent role in understanding and treating complexities in the 'world of science' and came into luminance during the last 17th and 18th centuries based on Descartes' analytic-deductive method which was used in studying complex phenomena. Clayton and Radcliffe (1996) argue that science has a number of defining characteristics of which three are particularly important to include 'replicability', 'refutability', and 'reductionism'. Descartes, however, bolstered reductionism by publishing 'Discourse on Method' in 1637 and this publication gives four precepts which influence science for years (Capra, 1996). According to Capra (1996), these precepts are:

- Accept only that which you are certain of,
- Divide topic into as small parts as possible,
- Solve simplest parts first,
- Make as complete lists as possible.

This method breaks down the complex entities into small parts and studies them separately in order to gradually have the understanding of the whole, which forms the philosophical basis of classical view of scientific inquiry that born the technological and industrial revolutions in the globe (Panagiotakopoulos, 2005).

Panagiotakopoulos (2005) reports that by the end of the 19th century and during the 20th century complexity in 'real world' expanded in such a way that classical method of scientific inquiry reached its limits in explaining the world. Due to this fact, Banathy (2000a) contends that the reductionist approach was no longer able to explain 'wholeness' which results from the mutual interaction of 'parts'. Premise on this, Skyttna (2006) submits that to have a full understanding of the reason why a particular problem occurs and still persists, there must be a savvy of the parts in relation to the whole. This argument is, however, absolutely against the classical view of scientific reductionism and philosophical analysis as promulgated by Descartes (Capra, 1996). In view of this, there is no doubt that simple tools cannot be used to capture ever increasing complex problems in the world that is embedded in interconnected systems which are operating in dynamically changing environments (Banathy, 2000a). This therefore necessitates the needs for a shift in classical approach paradigm to systems approach of scientific inquiry.

Systems approach of scientific inquiry therefore represents a kind of paradigm shift which is now changing the emphasis from 'parts' to the study of 'whole' (Banathy, 2003) since it is difficult to observe properties of the whole bit by bit. Systems approach of scientific inquiry, hence, provides a multi-dimensional framework in which information from different disciplines and domains can be integrated without being forced into a one-dimensional mapping, which is not possible from the view of classical approach.

3.2.2 Historical Background of the Systems-based Approach

The account of historical background of the systems-based approach of scientific inquiry has been widely reported in the literature. This subsection therefore gives a summary of how the approach has evolved over the years as reported by Decleris (1986).

Banathy (2000b) reports the pioneer work of Ludwig von Bertalanffy in the area of biology in 1932 as being the first to develop the systemic idea on general systems theory in early 20th century. This work spurs research activities in many areas of scientific endeavours as it is capable of dealing with messy complex problems. Table 3.1 depicts how the systems approach has transcended over the years and this is complete with the major actors within those years. Also, Table 3.2 shows how the ideas of the systems researchers have expanded due to more and more complex problems being confronted with.

In Decleris (1986), it was reported that the **first phase** of the systems-based approach evolution marks the start of the systems theory formulation between 1916 and 1940. This emanates as a result of the fact that the classical method of scientific inquiry finds it difficult to cope with ever increasing complex problems and the need to depart from the thinking of traditional analytic-deductive approach. This is where the basic systemic ideas are then defined and announced as depicted in Table 3.2. The **second phase** of this evolution is termed the *practical orientation* phase as the period witnessed a more practical relevance of the technological revolution. This is the period when the technological advancement skyrocketed mainly due to the need to tackle many complex problems that arose from World War II. The main complex problem that developed then was that of coordination of complex actions (Table 3.2), which brought about the main idea of compilation of optimum theoretical models based on the Operations Research and Policy Science disciplines (Tables 3.1 & 3.2).

The **third phase** witnessed the development of highly sophisticated systems-based technological advancement that contributed in no small measure to the birth of new scientific disciplines. This causes the systems approach to be reoriented and refined in order to accommodate these developments. The phase saw the emergence of Mathematical Theory of Communication, Cybernetics, Network and Linear Systems Theory, Systems Analysis, and Systems Construction. In fact, the phase is known for the formation of *hard* systems (Table 3.1). The major problem of this phase is in the area of Information Transmission and Construction of Complex Artefacts, which brought about the ideas of Information and Control Systems (Table 3.2). Decleris (1986) argues that subsequent inventions in the fields of Cybernetics and Mathematical Theory of Communication had a remarkable impact in the world of science today, especially in the area of human-machine systems (*i.e.* STS).

The **fourth phase** is seen as the formation of *soft* systems. This is because the period saw an enormous expansion in the systems approach across many fields of study in a bid to solve complex social problems. Principally, problems in human systems are solved by this approach. During this period, the problem of uncertainty and change in complex systems behaviour grew and difficult to manage due to the *soft* nature of the problem. The main ideas communicated here to solve these were the ideas of dynamic systems and information processing systems (Table 3.2). These ideas were seen to be effective is disciplines like Systems Management, Spatial Planning, Education, Transportation, *etc.*

Arguably, the world is in the **fifth phase** of systems approach where complex problems due to global climate change have surfaced in the last two decades involving *soft* and *hard* systems. The main idea here in order to solve the problem of climate change is sustainability, especially issues of carbon emissions, under purview of which the study in this thesis falls. This problem then necessitated the use of systems approach to capture the problem.

Table 3.1: Systems approach evolution

Systems Approach Evolution	Main Contributors
First Phase (1916-1940): *Precursors*	• **Biology:** Bertalanffy (1932) • **Linguistics:** Saussure (1916) • **Psychology:** Kohler (1929) • **Anthropology:** Malinowsky (1926), Radecliffe-Brown (1935) • **Sociology:** Parsons (1937)
Second Phase (1940-1945): *Practical Orientiation*	• **Operations Research:** Rowe (1941), Rand (1946) • **Policy Science:** Lasswell (1951)
Third Phase (1945-1970): *Formation – "Hard" Systems*	• **Mathematical Theory of Communication:** Shannon (1948) • **Cybernetics:** Wiener (1948), Ashby (1952) • **Network and Linear Systems Theory:** Guillemin (1957) • **General Systems Theory:** Bertalanffy (1956) • **Society for General Systems Research:** Boulding (1954) • **Systems Analysis:** Riemann (1953) • **Systems Construction:** Riemann (1953)
Fourth Phase (1970-1992): *Spreading – "Soft" Systems*	• **Systems Management:** Churchman (1979) • **Social Systems Construction:** Pinch *et al.* (1984) • **Human Systems:** Rosenstiel et al. (1991) • **National Systems Organisations – International Institutes:** Trist (1981)
Fifth Phase (1992-): *"Hard" and "Soft" Systems*	• **Climate Change:** IPCC (2010) • **Sustainability:** Redclift (2005)

(Adapted with extension from Decleris, 1986)

Table 3.2: Systemic ideas evolution

Systems Approach Evolution Phases	Problem	Idea
First Phase (1916-1940)	Description of Complex Objects/ Phenomena	Definition and Announcement of Basic Systemic Ideas
Second Phase (1940-1945)	Coordination of Complex Actions	Compilation of Optimum Theoretical Model (Modelling/Optimisation)
Third Phase (1945-1970)	Information Transmission, Construction of Complex Aretefacts	Information (Information and Control Systems)
Fourth Phase (1970-1992)	Uncertainty and Change in Complex Systems Behaviour	Dynamic Systems, Information Processing Systems
Fifth Phase (1992-)	Global Climate Change	Sustainability

Banathy (2000b) regards researchers like Ashby, Bertalanffy, Boulding, Fagen, Gerard, and Rappoport as the pioneers that set forth the basic concepts and principles of the general theory of systems that metamorphosed into systems-based approach today. The concept of systems approach advocates that the properties and characteristics of the *whole*, which is the *systems* itself, is quite different from summing up the *parts* in such a way that properties of a *whole* cannot be observed bit by bit as against the view of classical, traditional method of scientific inquiry that studies *parts* with linear *cause and effect*. Banathy (2000a) argues that deterministic, linear *cause and effect* is practically inadequate in dealing with many interactive variables of complex, dynamic systems. In contrast, systems-based approach is able to capture the dynamics of multiple, mutual and recursive complex causation (Banathy, 2000a) and sees the behaviour of the systems as non-linear, non-deterministic and expansionist in nature as negates the reductionist approach of classical science. Based on the ideas of the pioneers of the systems-based approach, Banathy (2000a) proposes an overview of the key distinctions between the classical view of scientific inquiry and systems view of scientific inquiry. These distinctions are based on what they ‘focus on’, their ‘mode of inquiry’, the way they ‘reason’, the ‘rule’ guiding them, ‘goal’ and finally ‘control’ as shown in Figure 3.1.

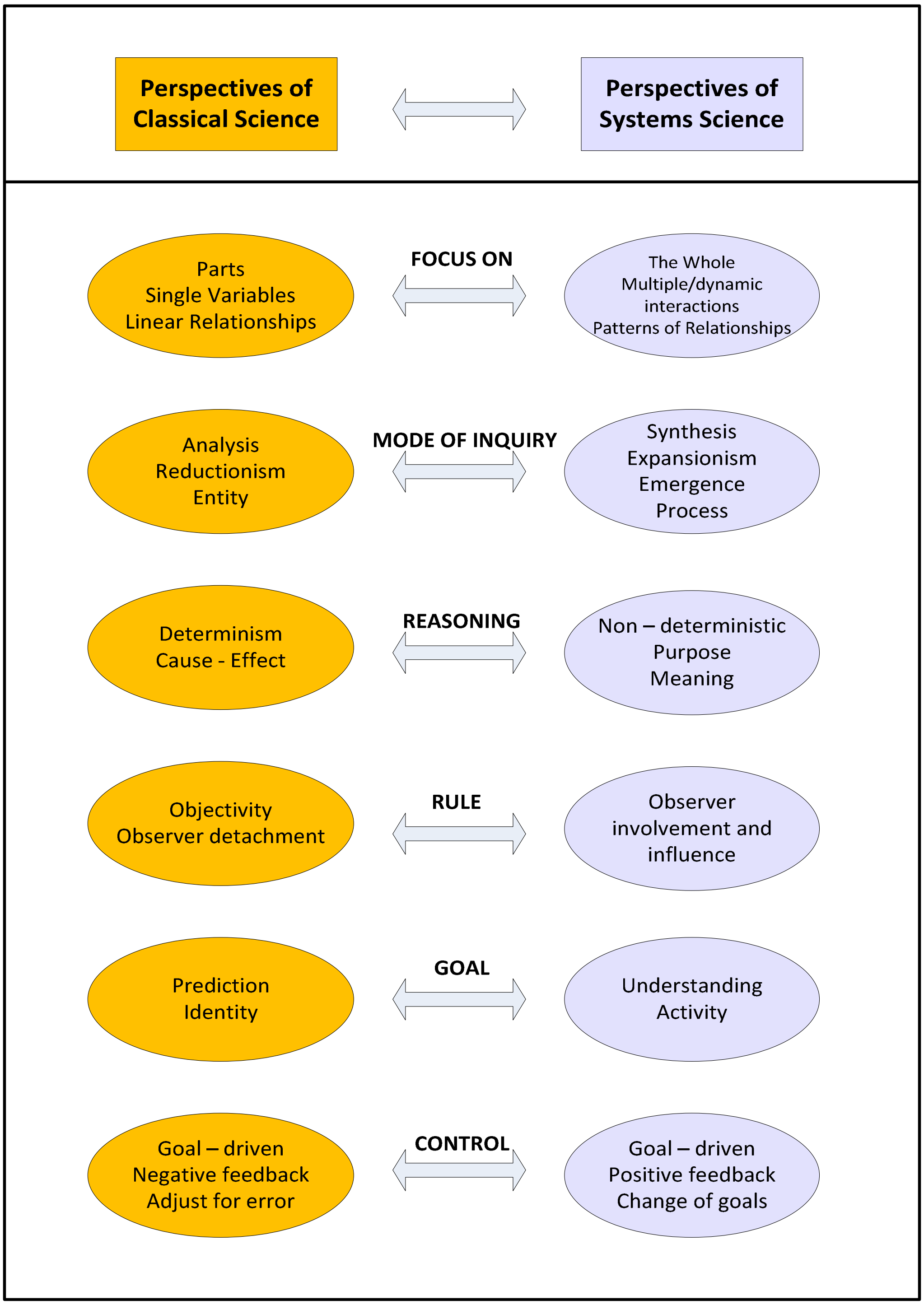

Figure 3.1: Key distinctions between classical and systemic orientations

(Adapted from Banathy, 2000a)

3.2.3 Components and Characteristics of Systems-based Approach

Based on the basic concepts of systems-based approach enunciated above and the works of researchers like Turner (1978), Capra (1996) and Blockley (1998), it is undoubtedly evident that the systems-based approach encapsulates many interrelated components, the properties of which are altered should the systems cloaked in any way (Waterson, 2009). These components are the main anchor of the systems-based approach. To this end, adopting a systems approach to solving the problem relating to HECCE in the context of this thesis entails getting insights into the effects of interactions among different variables hypothesised to influence household energy consumption as reported in Chapter five of this thesis.

By drawing from the studies of Turner (1978) and Blockley (1998), Waterson (2009) was able to capture those components and their characteristics that are the central idea being communicated by the systems-based approach as shown in Figure 3.2. The characteristics are therefore similar to the problem under investigation by this thesis (Chapter 1). The three main components given by Waterson (2009) (Figure 3.2) are:

- Input-output processes – this aspect gives the relationships that exist between the systems inputs and their corresponding outputs containing elements like multifinality, equifinality, *etc.*
- Whole-part relationships – the main idea being communicated by this component is hinged on the fact that the working of the systems as a whole needs to be firstly analysed in parts as suggested by Gibson (1979). The component further suggests that the whole is quite more than just summing up the parts (Banathy, 2000a) as this kind of relationships existing between them are argued to be complex, dynamic, and chaotic in nature (Sinclair, 2007). Holism, entropy, and system elements are therefore expressed as the major elements of this component.

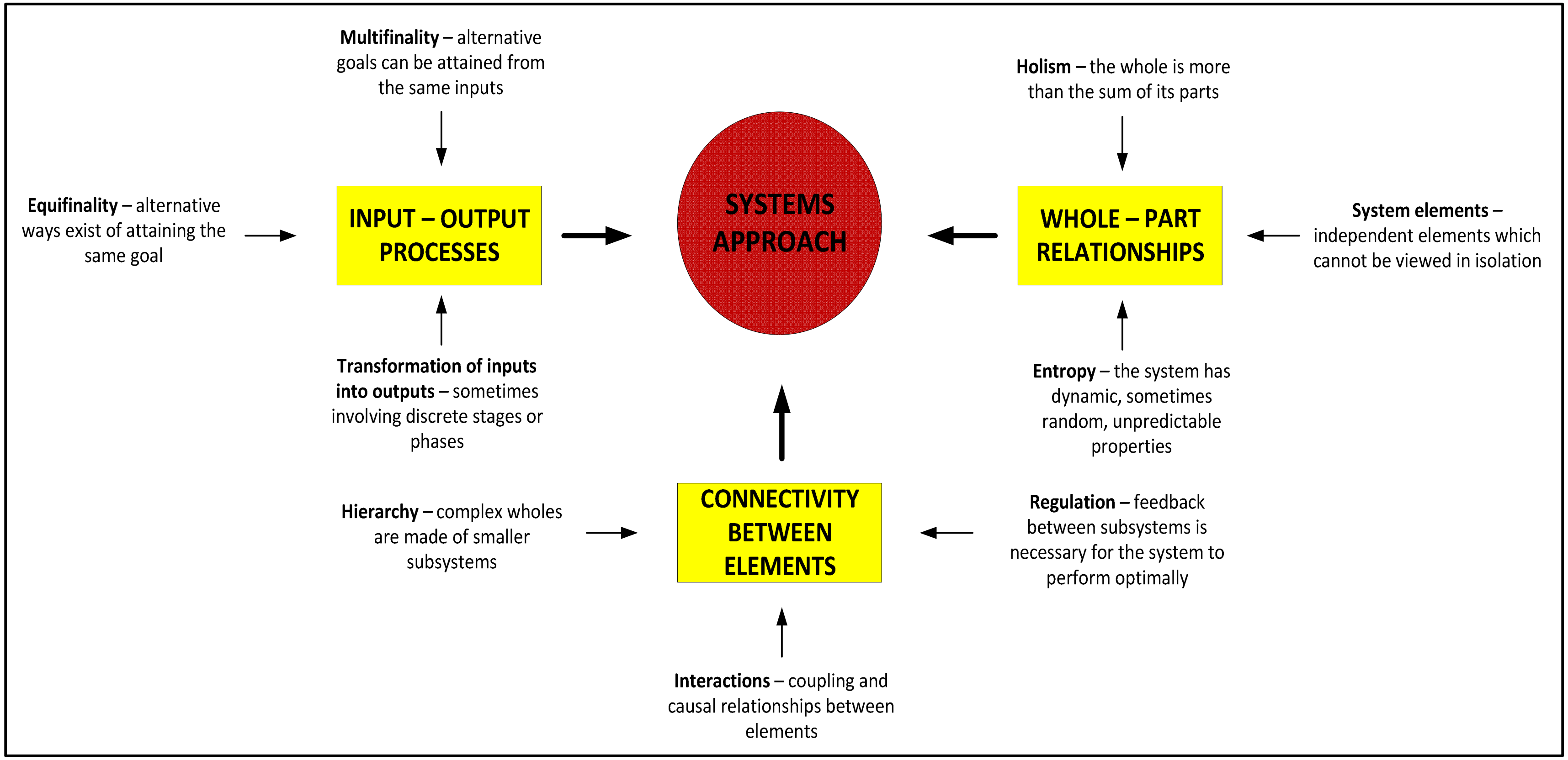

Figure 3.2: Components and characteristics of the systems approach

(Adapted from Waterson, 2009)

- Connectivity between elements – this component expresses the interrelationships among different elements within the systems in terms of hierarchy, interactions and regulation. The complexity of the systems here are hence elaborated based on causal relationships and feedback structure among these elements (Katz & Kahn, 1966).

Additionally, Wilson *et al.* (2007) and Walker *et al.* (2008) offer the description of behaviour exhibited by the system in order to further capture its characteristics. They argue that a systems as a dynamic and complex whole containing an integrated interacting functional parts has energy, material, and information flowing through it. These energy, material, and information of the studied systems are placed within an environment that is surrounded by permeable boundaries, which is capable of exhibiting erratic behaviour while its elements seek equilibrium.

3.2.4 Types of Systems

The study of Decleris (1986) classified systems into *hard* and *soft* systems as evidenced from Table 3.1 in Section 3.2.2. *Hard* systems, for example, are described as technical and physical systems that can be quantified while its behaviour can be fully controlled at the same time (Panagiotakopoulos, 2005). However, these cannot easily take unquantifiable variables into consideration. Different from the *hard* systems, *soft* systems are good at capturing and understanding unquantifiable variables like people’s opinions, cultures, viewpoints and the likes. In short, it will address qualitative aspects of any problem situations. To this end, the classification brought about the concept of STS as a systems-based approach capable of handling the complexity posed by the interaction of ‘human’ and ‘machine’, which is good at combining the quantitative and qualitative research strategies together. The next section then discusses the STS theory.

3.3 The Socio-Technical Systems Theory

STS theory has evolved over the years as a kind of coaction among the sociologists that specialised in a new area of academic endeavour termed the “sociologists of technology” (Dwyer, 2011). There was a general belief that engineers/technologists, for example, tend to ignore the importance of socio aspect of their work; while on the other hand, the social scientists tend not knowing much about the technology and therefore reluctant at considering the artificial reality of technical objects (Ropohl, 1999). STS theory has then been used as the theory that combines the two divides together. Therefore, the STS theory serves as the theoretical basis for this study. The rest of this section discusses the basic concepts of the STS theory and its domain of application.

3.3.1 Basic Concepts of Socio-Technical Systems Theory

The origin of the concepts of STS as a methodology for the systems-based approach of scientific inquiry could be traced to the studies undertaken by the Tavistock Institute, London especially during the post-war reconstruction of industry (Trist, 1981; Cartelli, 2007). Cartelli (2007) reports that the emergence of the concepts is highly necessary in pursuit of a fit between the work force and machine during the introduction of technological systems for work automation when it was found out that workers are resistant to technological innovation. Since then, the concept has come into luminance and serves as the theoretical framework underpinning many studies.

According to Walker *et al.* (2008), STS as a concept is founded on two main principles. The first one is the interaction between the social and technical sub-systems that set the conditions for successful (or unsuccessful) systems performance. They argued that the interactions are comprised partly of linear “*cause and effect*” relationships, the relationships that are normally “*designed*”, and partly from “*non-linear*”, complex, and even unpredictable relationships; which are those that are often unexpected. *Soft*, which is socio, does not necessarily behave like the *hard*, which is technical (Walker *et al.*, 2008). Additionally, Walker *et al.* (2008) contends that the growth in complexity and interdependence makes the “technical” systems, for example to start to exhibit non-linear behaviours. And as such, the STS as a technique of the systems-based approach of scientific inquiry is used to handle this kind of complexity as both the methodology and tools. The second of the two main principles, is founded on “*joint optimisation*” of the two systems.

Interestingly, Dwyer (2011) illustrates the concept of STS by the use of a generic model as shown in Figure 3.3. According to her, STS is seen to contain *components* that are referred to as *social structures* and *artifacts* that are called *technical elements*, which contribute directly or through other *components* to a common *system goal*. It was shown that both the *components* and *artifacts* interact with each other. What is guiding the overall behaviour of the system is the system goal.

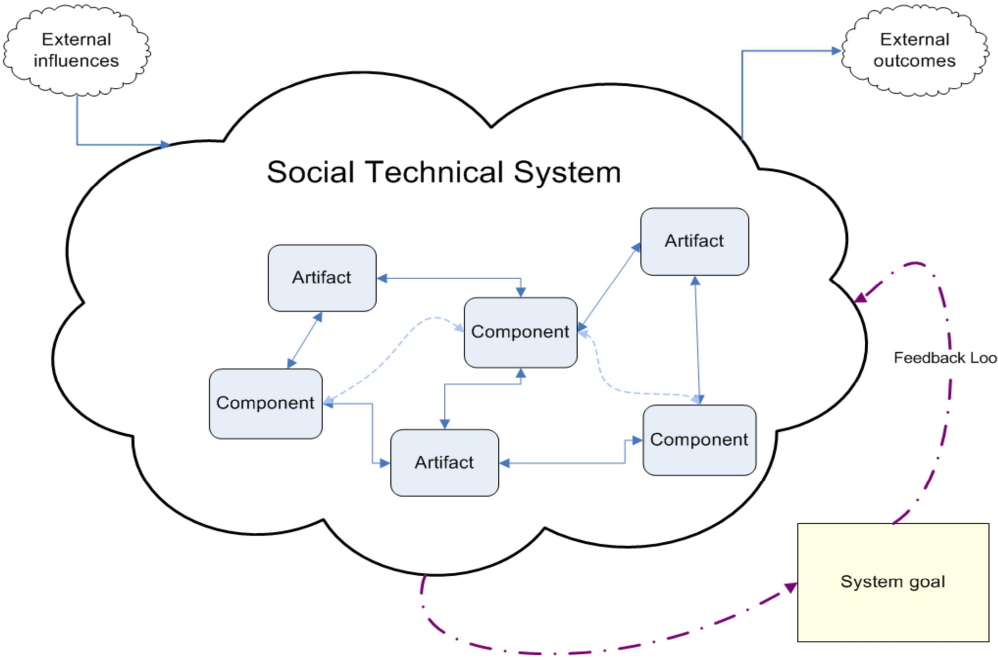

Figure 3.3: A model of a socio-technical system
(Adapted from Dwyer, 2011)

The feedback loop enables the actual output of the system to be compared to the system goal. Hughes (2000) argues that it is only through the feedback loop that errors are detected and thereby corrected in order to have an improvement in system performance.

The central idea from the concepts of the STS can be applied to the issue of HECCE in order to put the discussion here in context. As presented under Section 1.1 in Chapter 1 of this thesis, household systems consists of an interplay among the dwellings systems (in terms of dwellings' physical characteristics and technological systems put in place within it) refers to as technical systems (*artifacts*), occupants systems (in terms of behaviour towards energy consumption, for example) refers to as socio systems (*components*), and external environment systems (in terms of external temperature, energy prices, *etc.*) refers to as technical and/or socio systems. These systems are then interrelate and appropriately influence energy consumption and associated carbon emissions.

A detailed analysis of all the variables in the systems suggests that they all depends one another thereby making the systems to be a complex one. This is so mainly because the variables within each of the systems have multiple interdependencies with multi-causal feedback structure considering their effect on energy consumption and carbon emissions. Further, they are interconnected, chaotic in nature, and difficult to understand, predict and keep under control, thereby calling for a pragmatic approach like STS approach to handle the situation under consideration. An appraisal of the thesis problem suggests that the STS approach is adequate in capturing it. Hence, STS theory serves as the theoretical background to the research.

3.3.2 Domain of Application of Socio-Technical Systems

A review of domain of application of STS by different researchers is undertaken. During the review, it was noted that the concept of STS means slightly different things to researchers in different fields of study, for example: in engineering, it means that organisational form follows technical function, while technical function too follows organisational form; in computer science, the technical system consists of hardware and software that make an information system, while the users of this system and the organisation in which it is embedded form the social system; *etc.* However, similarities in the use of this concept is stronger and more than the differences. Literature search was then conducted irrespective of the definition used for the STS by different researchers.

Based on the review, STS has been successfully implemented in human-computer interaction studies, information technology, software engineering, engineering (general), business and management, medicine and the host of others. For example, de Greene (1988) used STS in the context of organisational design management. Likewise, Appelbaum (1997) used STS in the context of organisational development where it was argued that integration of organisational development with technological advancement into a total system could prove difficult, but the use of STS will make it possible. Also, STS was used in the context of innovation which predisposes systemic changes in any organisation (Geels & Kemp, 2007). Williams and Edge (1996), Rohracher (2003) and Geels (2004) used STS in the context of diffusion of technology in an organisation.

Further, STS has been used in energy supply and demand, especially when it was necessary to study the socio-technical influences on energy use, *e.g.* Shipworth (2005), Shipworth (2006), and Motawa and Banfill (2010). STS has been used in the computer/software engineering as well as communication and telecommunication engineering (Patnayakuni & Rupple, 2010). This concept of STS has also been found application in the domain of water management while considering irrigation project (Jayanesa & Selka, 2004) and in the domain of agriculture and food (Marques *et al.*, 2010). The above then shows how research has transcended using STS in solving real life problems.

STS has, therefore, been previously used as methodology to model the complexity of real systems' elements and relationships as indicated above. STS is difficult to model because of its complex nature. It is complex because its elements are with multiple interdependencies and have multi-causal correlation structure. Further, STS exhibits a kind of non-linear behaviour where changes in input are neither proportional to changes in output, nor is the input to output relationship fixed over time (Motawa & Banfill, 2010). The ability of STS to integrate both "hard" and "soft" data together under the conditions described above makes it different from other complex systems.

3.4 Modelling Techniques for Socio-Technical Systems

This section covers the techniques utilised by different researchers, under different themes, in order to model STS. Based on the review conducted in Section 3.3.2 above, a detailed analysis of selected articles from the pool of articles reviewed was undertaken. Specifically, these articles were analysed for the modelling techniques utilised in the context of STS. The articles were then analysed according to the STS domain, STS definition, whether or not modelling/simulation was performed, the modelling/simulation techniques that was utilised, whether or not the results produced are reproducible, whether or not the techniques presented are capable of being generalised to another domains of application, and whether or not the model can be easily extended and if it can be, to what extent can this be done? The main aim of this exercise is to identify the major techniques that have been used by different studies to conceptualise STS problems. Table 3.3 shows the results of this review. As shown in Table 3.3, the articles reviewed were assessed to indicate any presence of evidence to suggest within their body that there is a match or no match or unclear in STS application domain, STS definition, modelling/simulation, modelling/simulation technique, reproducible, generalizable, and extendable. The (+) sign indicates that there is a match, whereas a (-) sign shows that there is no match. The (?) sign signifies that evidence of those criteria is unclear.

Table 3.3: Review of modelling techniques for socio-technical systems

Article Authors	STS Application Domain	STS Definition	Modelling/ Simulation	Modelling/ Simulation Technique	Reproducable	Generalisable	Extendable
Bergman *et al.* (2008)	+	+	+	ABM	?	+	?
Carley (2002)	+	+	-	?	-	+	-
Iivari & Hirschheim (1996)	-	-	-	?	-	+	-
Jarman & Kouzmin (1990)	-	-	-	?	-	+	-
Shipworth (2005)	+	+	-	-	+	?	?
Sterman (1989)	+	-	+	SD	+	+	+
Olla et al. (2003)	+	-	+	ANT	-	?	-
Cai et al. (2009)	+	-	+	FL	+	?	-
Li et al. (2010)	+	-	+	FL	+	-	-
McNeese *et al.* (2000)	-	+	-	-	-	+	-
Ramanna *et al.* (2007)	-	-	-	-	-	?	-
Shah & Pritchett (2005)	-	+	+	ABM	-	+	+
Johnson (2008)	-	+	-	?	-	+	-
Shipworth (2006)	+	+	+	BBN	+	+	+
Smajgl et al. (2008)	?	?	-	-	-	-	-
Masys (2006)	+	?	-	?	-	+	-
Sterman (2000)	+	-	+	SD	+	+	+
Sutcliffe *et al.* (2007)	-	+	-	-	-	?	-
Thissen & Herder (2003)	+	+	-	-	-	+	-
Yahja & Carley (2005)	-	-	+	ABM	?	+	?
Lock (2005)	+	-	+	CM	-	?	-
Ritchey (2011)	+	-	+	MA	-	?	-
McIntosh *et al.* (2005)	+	+	-	?	-	+	-
Lock (2004)	+	-	+	CM	-	?	-
Wu & Xu (2013)	+	-	+	SD & FL	+	+	+
De Waal & Ritchey (2007)	+	-	+	MA	-	?	-

Table 3.3: *Continued.*

Article Authors	STS Application Domain	STS Definition	Modelling/ Simulation	Modelling/ Simulation Technique	Reproducable	Generalisable	Extendable
Jensen (2001)	+	-	+	BBN	+	+	+
Callon (1986)	+	-	+	ANT	-	?	-
Natarajan *et al.* (2011)	+	+	+	ABM	+	-	+
Feng *et al.* (2013)	+	-	+	SD	+	+	+
Carroll *et al.* (2010)	+	+	+	SNA	-	-	-
Carroll (2012)	+	+	+	ANT/SNA	+	+	-

ANT – Actor Network Theory, ABM – Agent-based Modelling, BBN – Bayesian Belief Network, CM – Configuration Modelling, FL – Fuzzy Logic, MA – Morphological Analysis, SNA – Social Network Analysis, SD – System Dynamics. '+' means there is a match, '-' means there is no match, '?' means unclear.

The result of the review conducted shows that most of the articles analysed explicitly indicate STS as the domain of application for their studies. Also, about half of those articles claim that the STS method presented can be generalised. Furthermore, the analysis shows that just some of the STS approach presented can be reproduced and further extended to accommodate additional modules/sub-systems. It was also concluded from the review that out of 32 articles analysed, 20 of them provided the modelling/simulation techniques utilised for their different studies within the context of STS. Therefore, the output of the study shows some of the techniques that have served as decision support tools/platforms under which STS of real problems are modelled. To this extent, this study therefore identified the following as the techniques for modelling STS.

1. Actor Network Theory (ANT)
2. Agent-Based Modelling technique (ABM)
3. Bayesian Belief Network (BBN)
4. Configuration Modelling (CM)

5. Fuzzy Logic (FL)
6. Morphological Analysis (MA)
7. Social Network Analysis (SNA)
8. System Dynamics (SD)

The next section therefore summarises and critiques these modelling techniques.

3.5 Summary and Critique of the Modelling Techniques

For any of those techniques to be adequate in the context of this thesis, there are some criteria they must fulfil based on the nature of the problem under investigation in this thesis. For example, different researchers have criticised the energy models in the housing sector for the lack of transparency (Kavgic *et al.*, 2010; Mhalas *et al.*, 2013) as discussed in Chapter two. Also, Hitchcock (1993), Kohler and Hassler (2002) and Shipworth (2005; 2006) established that the complex socio-technical systems are highly interdependent, chaotic, and non-linear, and problems involving these are better solved using a pluralistic approach.

Therefore, it is important to set the criteria upon which the STS modelling techniques will be compared. And as such, the modelling techniques are compared to one another based on (1) transparency, (2) multiple interdependencies (3) dynamic situations (4) feedback processes (5) non-linear relationships (6) *hard* and *soft* data (7) uncertainties of the variables involved, (8) chaotic assumptions and (9) the use of the model as learning laboratory. It is against this background the techniques were all assessed, compared, and critiqued in order to decide on which one of them will be able to capture the problem under investigation based on the above criteria. Table 3.4 summarises and compares all the STS modelling techniques. The tenets as well as strengths and weaknesses of each of the STS modelling techniques are therefore discussed accordingly in the following sub-sections. This exercise would, undoubtedly, help in identifying which of them is best for conceptualising the problem under investigation in this thesis.

Table 3.4: Comparative analysis of STS modelling techniques

Criteria	**ANT**	**ABM**	**BBN**	**CM**	**FL**	**MA**	**SNA**	**SD**
Transparency	√	√	√				√	√
Multiple interdependencies	√	√	√				√	√
Dynamic situations		√						√
Feedback processes								√
Non-linear relationships	√	√	√	√	√	√	√	√
Considering “hard” and “soft” data	√	√	√	√	√	√	√	√
Chaotic assumptions	√	√	√	√	√	√		√
Uncertainties		√	√	√	√	√		√*
Learning laboratory tool			√					√

** Limited capability in handling uncertainties.*

3.5.1 Actor Network Theory

Actor Network Theory (ANT) was first proposed by Michel Callon and Bruno Latour (Callon & Latour, 1981; Callon, 1986). Olla *et al.*, (2003) argues that ANT provide a platform for understanding the creation of networks of aligned interests where, according to Olla *et al.*, (2003), the world is full of hybrid entities containing both human and non-human elements. Carroll (2012) contends that the greatest strength of ANT lies in its ability to integrate both *hard* and *soft* data together (Table 3.4). Also, the approach is capable of modelling problems containing variables that have multiple interdependencies with non-linear relationships under chaotic assumptions. It, therefore, has some merit in modelling STS problems. However, the approach has been criticised for its inability to provide the means of differentiating between humans and non-humans elements within the model (Carroll, 2012).

3.5.2 Agent-Based Modelling

According to Jennings (2000), an agent is seen to be an entity or component that is autonomous, reactive, pro-active and capable of social interaction. Agent-Based Modelling (ABM) aims to model the global consequences of each of the entities/components of a system including their behaviour and interactions. This is then the main distinguishing element that sets agent-based models apart from other models (van Dam *et al.*, 2009). In general, the ABM approach is applicable for modelling of complex systems if the following conditions are satisfied (van Dam and Lukszo 2006):

- The problem has a distributed character;
- The subsystems operate in a highly dynamic environment;
- The subsystems have to interact in a flexible way; and
- The subsystems are characterised by reactivity, pro-activeness, cooperativeness and social ability.

As shown in Table 3.4, ABM seems to be a suitable approach to create models of STS because of its capability to handle both *hard* and *soft* data with multiple interdependencies and treat non-linear behaviour of such data set under small uncertainties (Bergman *et al*, 2008; Natarajan *et al.*, 2011). To this end, a number of studies have utilised the approach for modelling complex problems. For example, the study of Yahja and Carley (2005) used the approach to model improvement in multi-agent social-network systems. Also, Natarajan *et al.* (2011) found the approach useful in modelling energy consumption and carbon emissions of the UK housing stock. However, the approach has some drawbacks. For example, its weakness lies in its inability to handle multiple feedback processes and difficulty in being used as a learning laboratory.

3.5.3 Bayesian Belief Networks

Bayesian Belief Networks (BBN) was developed around late 1980’s and its applicability didn’t come into luminance until 1990s. According to Jensen (2001), BBNs emerged as an intuitive technique for reasoning under uncertainty. This technique combines different data types as well as learning from new observations as they become available. Advantages (Table 3.4) of using BBNs as opined by Gill (2002) are:

- The ability to learn as new information is received or population variables change
- The capacity to systematically integrate a wider variety of data types and any prior available knowledge
- Allow predictions about the likely future state of the system based on what is currently known about the system and assumptions about future data
- The capability to learn causal relationships and gain understanding of a problem domain and then predict the consequences of intervention
- Overt and clear model assumptions
- Straightforward sensitivity testing.

This approach has been successfully used in a number of applications. Application of BBN in the field of environmental management include: management of fisheries (Fernandez *et al.*, 2002), land use change (Bacon *et al.*, 2002), agricultural land management (Cain *et al.*, 2003), and integrated water resource management (Bromley *et al.,* 2004). This approach has also been applied to modelling the socio-technical influences on domestic energy consumption in one of the UK’s Carbon Vision programme: Carbon Reduction in Buildings (CaRB) project (Shipworth, 2005; Shipworth, 2006). As argued by Shipworth (2005), however, BBN is used as decision support systems mainly because of their capability to integrate different array of data together, as well as synthesise relevant factors in social, economic, ecological and technical fields which then makes it particularly useful in the complex socio-economic/socio-technical environments of sustainable development. However, BBN approach is not without its own drawbacks. De Waal and Ritchey (2007) argue that using BBN may prove a little bit difficult during the initial problem formulation phase of the modelling process and difficult to deal with time dependent data set with feedback processes.

3.5.4 Configuration Modelling

Configuration Modelling (CM) is another technique and decision support tool recently proposed by Simon Lock (Lock, 2004; 2005) for modelling the STS. Lock (2005) acknowledges that managing the evolution of large systems is a complex and difficult task where the full social and technical implications of any proposed changes must be fully appreciated before a decision is made whether or not to proceed with their implementation. He contends that the task becomes challenging and difficult to manage since the interplay between the technical and non-technical components is often complex and the various human factor that are involved inject much variability and unpredictability into the system. It is against this backdrop that a new decision support tool that permits the investigation and exploration of different configurations of socio and technical components is needed in order to fully predict how changes made to the individual components or the overall configuration of a system will affect operational behaviour of that system during the real world operation (Lock, 2005). Lock (2004), however, argues that this modelling paradigm is a novel approach in the sense that it is easy and quick to construct and can as well help to promote understanding of different stakeholders. However, there is lack of evidence from the body of literature to suggest that this approach has the capability to capture multiple interdependencies of data set under dynamic situation. Furthermore, the domain of application of this approach has been limited to the area of software engineering as this has not gained a wider application, but has some merits in modelling STS.

3.5.5 Fuzzy Logic

The capability of Fuzzy Logic (FL) to model STS has been highlighted in literature. FL began with the 1965 proposal of fuzzy set theory by Lotfi Zadeh (Zadeh, 1979). It is a mathematical approach that is used to represent uncertain and imprecise information. Cai *et al.* (2009) argues that this method deals with reasoning that is approximate rather than fixed and exact, but effective in describing highly complex, ill-defined mathematical systems. Furthermore, the approach can effectively support linguistic imprecision and vagueness (Li *et al.*, 2010). A number of studies have used this approach to model complex systems under different themes. For example, Cai *et al.* (2009) used the approach to identify optimal strategies within energy sector planning under multiple uncertainties of variables involved. Also, under the same theme as Cai *et al.* (2009), Li *et al.* (2010) combined the approach with stochastic programming to model energy and environmental planning systems. Further to this, Wu and Xu (2013) combined FL with SD to predict and optimise energy consumption of world heritage areas in the People's Republic of China. While the major strength of the approach lies in its ability to model systems under varying degrees of uncertainties, it does have some limitations that may debar it from being used within the context of this thesis. It lacks the ability to handle multiple interdependencies of variables under dynamic situations. Also, it does not support feedback processes and cannot be used as learning laboratory. As can be seen, the strengths and limitations of this technique are profound as succinctly summarised in Table 3.4.

3.5.6 Morphological Analysis

Morphological Analysis (MA) was developed by Zwicky – the Swiss-American astrophysicist and aerospace scientist – as a general method for structuring and investigating the total set of relationships contained in multi-dimensional, usually non-quantifiable, complex problems (Zwicky, 1969; Ritchey, 2011). The concept and application of MA as strategic decision support is closely related to BBNs. According to de Waal and Ritchey (2007), it allows small groups of subject specialists to define, link and internally evaluate the parameters of complex problem spaces easily, thus creating a solution space and flexible inference. They, however, argued that MA cannot easily treat hierarchal structure and causal relationships, but when combine with BBNs the benefits of both of these techniques can be optimised. This technique has previously applied to diverse fields based on the work of Zwicky. Among them are astrophysics, the development of propulsive power plants and propellants, the legal aspects of space travel and colonisation (de Wall and Ritchey, 2007). Suitability of this approach to the area of application of this thesis is limited, though it has some potential when combined with other suitable approaches as shown in the Table 3.4 above.

3.5.7 Social Network Analysis

Social Network Analysis (SNA) views social relationships in terms of network theory that consists of *nodes* and *ties* (also called *edges*, *links*, or *connections*). Nodes, according to (Freeman, 2006), are individual actors within the networks, and ties are the relationships between the actors. The resulting graph-based structures are often very complex. There can be many kinds of ties between the nodes. Research in a number of academic fields has shown that social networks operate on many levels, from families up to the level of nations, and play a critical role in determining the way problems are solved, organisations are run, and the degree to which individuals succeed in achieving their goals. Most importantly, SNA has the capability of modelling non-linear, multiple interdependent quantitative and qualitative variables (Carroll *et al.*, 2010). Therefore, it has some merits in modelling STS, but its strength could be improved upon when combined with other approaches.

3.5.8 System Dynamics

System Dynamics (SD) emerged in the 1950s as introduced by Jay Forrester as multi-disciplinary field of study that has the capability to deal with complex systems. SD, as a systems-based approach, is seen as a methodological approach and set of analytical tools for modelling STS (Motawa & Banfill, 2010).

Ogunlana, Lim and Saeed (1998) mention that the SD is an approach useful for managing processes with two major characteristics:

- They involve changes over time,
- They allow feedback, the transmission and receipt of information.

Interestingly, Coyle (1997) offers a robust definition of SD as a method "*that deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding through a qualitative and quantitative model, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation*".

Over the years, the approach has developed itself into a very powerful tool for modelling complex systems. To this extent, it has found a wider application in quite an array of different fields. For example, Ogunlana *et al.* (1998) used it in the field of project management, Feng *et al.* (2013) in the area of energy consumption and carbon emissions, and the host of other applications. The approach was able to garner use in different capacities based on its strength. Accordingly, Sterman (1992) justifies the application of SD to modelling complex problems in the sense that:

- SD models are well suited in capturing multiple interdependencies.
- SD was developed to deal with dynamics.
- SD is the modelling method of choice where there are significant feedback processes.
- SD, more than any other modelling technique, stresses the importance of non-linearities in model formulation, therefore, is able to capture any form of non-linear relationships.
- SD modelling permits both "hard" and "soft" data.

However, SD has limited capability of handling situations under uncertainties. This weakness has received due attention from the SD research circles and significant improvements have been made on this as some of the SD software now incorporate optimisation and sensitivity analysis of uncertain parameters.

3.5.9 Conclusion from the STS Modelling Techniques for the Research

The above summary and critique of different STS modelling techniques give the appropriateness of each of the techniques to conceptualise the problem under investigation in this thesis. Of the nine criteria used in appraising the techniques, the analysis done suggests that SD almost meets all the nine criteria, except for its inability to fully handle parameters under uncertainties, of which a full scale improvement on this aspect is underway. As argued in Section 3.5.8, SD was specifically introduced by Jay Forrester in order to handle complex problems that have multiple interdependencies and are dynamic in nature with many feedback structures. The tools for this technique have in-built functions to capture the non-linear relationships existing among different variables making up the model with the capability of accepting both qualitative and quantitative data and convert same to simulation. The technique can also handle chaotic situations by invoking the delay functions in-built in the tools. It is necessary to mention that the technique is undergoing a constant review and over the years, the transparency aspect of it has been greatly enhanced and improved upon. This means that all the model variables including the algorithms can be assessed and scrutinised by third parties. Summing up all these characteristics of SD makes it more appropriate to conceptualise the problem under investigation in the context of this thesis.

However, there are other techniques that meet substantial parts of the criteria of assessment of the techniques. For example, both ABM and BBN met seven each of those criteria. In ABM, the models developed using the technique can be easily scrutinised for its algorithms. The major drawback is in its inability to handle feedback processes which has been argued as germane to the dynamic characteristic of any of the techniques. Also, the approach cannot be used as learning laboratory where policies can be tested for results of implementation before being actually implemented in reality. In the case of BBN, the technique is transparent as well. Clearly, it is unsuitable for this thesis because of its inability to handle dynamic situations involving feedback processes.

3.6 Chapter Summary

The main aim of this chapter was to identify the most suitable modelling approach to conceptualise the complex socio-technical systems of household energy consumption and carbon emissions. This chapter identified this modelling approach. Before the review of literature for modelling techniques of STS, the chapter first reviewed literature on systems-based approach of scientific inquiry as they form the theoretical knowledge base underpinning the STS. This is mainly to give the philosophical backgrounds of STS.

Literature search was then conducted and the review results revealed that the domain of application of STS has been in the area of human-computer interaction studies, information technology, software engineering, engineering (general), business and management, medicine and the host of others. Also, the review was analysed for modelling techniques for STS. The following techniques were identified to include: actor network theory, agent-based modelling technique, Bayesian belief network, configuration modelling, fuzzy logic, morphological analysis, social network analysis, and system dynamics. These techniques were further probed for their capability in capturing the problem under investigation in the thesis against a set of criteria. After a careful appraisal of all the techniques, the study identified system dynamics as the most suitable technique in conceptualising the problem under investigation in the context of this thesis. The next chapter discusses the research methodology developed for this study.

Chapter 4

RESEARCH METHODOLOGY

4.1 Introduction

The research methodology is seen as a roadmap of any research undertaken that is firmed up to direct the research in terms of theoretical underpinning of the approach, data collection methods, and modelling technique used in solving the problem. The preceding Chapters two and three present the literature review towards solving the research problem as directed by the study objectives. It is therefore necessary to discuss and describe the methodology adopted and used to achieve the objectives of the research in the context of this thesis. The chapter first discusses the philosophical foundations guiding any research in attempt to underpin the methodology used for this research in philosophically. The rest of the chapter therefore provides details regarding the methodological approach developed for the research including the method of data collection, and model development and validation.

4.2 Philosophical Background Underpinning Any Research

Pruyt (2006) argues that what constitute different research *paradigms* are rooted in and consistent with the sets of basic assumptions about epistemology[5], ontology[6], axiology[7], human nature, methodology, causality and logic. And these *paradigms* frame *philosophies, meta-methodologies, multi-methodologies, methodologies, methods, techniques, tools,* and their interpretations (Pruyt, 2006).

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[5] An epistemological issue concerns the question of what is (or should be) regarded as acceptable knowledge in a discipline (Bryman, 2008).

[6] Ontology answers the question: what is the nature of reality?

[7] Axiology answers the question: what is the role of values? Values here reflect either the personal beliefs or the feelings of a researcher (Bryman, 2008).

Table 4.1 illustrates the interconnectivity among these different concepts by giving their meaning and examples as used within this thesis.

Therefore, for a researcher to arrive at a research methodology decision, the decision needs justification by considering the philosophical underpinning of the approach, procedures of inquiry, and specific methods of data collection, analysis, and interpretations. Additionally, Creswell (2009) posits that the selection of adequate research methodology still largely depends on the research problem or issues being addressed, the researchers’ personal experiences, and the audiences for the study. Different researchers, however, admit that an adequate understanding of the philosophical *paradigm* of any research is a necessity as this forms the basis for researchers’ understanding of the research method to utilise at any point in time.

Table 4.1: Basic concepts of philosophical paradigms

Concept	**Meaning**	**Examples**
Paradigm	Coherent set of meta-theoretical (ontological, epistemological, praxiological, methodological, nature-of-society, human-nature, …) assumptions which constitutes a distinct worldview	Positivism
↓↑ (Philosophical or sociological) theory	Coherent explanations of (social, material, personal, …) life by a distinct philosophical or sociological school of thought	Giddens’ structuration theory
↓↑ Meta-methodology	Framework for choosing between methodologies and for matching and mixing methodologies	Multimethodology
↓↑ Multi-methodology	A (new) methodology consisting of the combination of (parts of) other existing methodologies	Adaptive control methodology
↓↑ Methodology	Structured set of guidelines or activities to assist people in undertaking research or interventions	Mainstream SD methodology
↓↑ Method	Structured set of processes and activities that includes tools, techniques, and models, that can be used in dealing with the problem or problem situation	Mainstream SD method
↓↑ Technique	Specific activity that has a clear and well-defined purpose within the context of a methodology	Stock-flow diagram, numerical simulation
↓↑ Tool	Artefact, often computer software, that can be used in performing a particular technique	Vensim, Stella, …

(Adapted from Pruyt, 2006)

Before further discussion, it is imperative to define the term *paradigm*. To this effect, Bogdan and Biklen (1998) define *paradigm* as *"a loose collection of logically related assumptions, concepts, or propositions that orient thinking and research"*. In a more straightforward manner, Cohen and Manion (1998) view it as *"the philosophical intent or motivation for undertaking a study"*. It is equally important to clarify that different authors at different times used distinct interpretive words to depict the word *paradigms*. For example, Creswell (2009) expresses this as *worldviews*, Crotty (1998) – *epistemologies and ontologies*, and even Neuman (2000) – *research methodologies.*

Philosophical research paradigms have been therefore discussed extensively in literature. While some of these authors argue that the philosophical *paradigms* underpinning any research are positivism, interpretivism or pragmatism (Amaratunga and Baldry, 2001; Bryman, 2003; Punch, 2005); others have gone beyond these three *paradigms*. For example, Creswell (2009) views the philosophical *paradigms* underpinning any research from four different schools of thought to include: postpositivism, constructivism, advocacy/participatory, and pragmatism. Blaikie (2009) extends these four schools of thought to ten under two covers of *classical research paradigms*: positivism, critical rationalism, classical hermeneutics, interpretivism; and *contemporary research paradigms*: critical theory, social science realism, contemporary hermeneutics, ethnomethodology, saturation theory, and feminism.

As can be seen from the foregoing, literature suggests that authors have used diverse terms with wide-ranging claims regarding philosophical paradigms underpinning any research. It then makes this aspect look occasionally more confusing to early career researchers. To this end, the following common philosophical research paradigms are further discussed here: positivism, interpretivism, and pragmatism. These are linked to the research strategy and method of data collection used in this research.

4.2.1 The Positivist Philosophical Research Paradigm

Bryman (2008) observes that the doctrine of positivism is extremely difficult to pin down mainly because different authors used it in different ways. This reinforces the assertion made towards the end of the last paragraph of Section 4.2 that authors have used diverse terms to reflect a wide-range of claims regarding philosophical research paradigms. However, the ideas of different authors do converge.

To this extent, Pruyt (2006) therefore argues that the positivist philosophical research paradigm describes the ontological-epistemological position that is realist-objective. Kelly's (2004) position about the positivist philosophical paradigm assumes that *"reality is objectively given and can be described by measuring properties which are independent of the researcher and instrument"*. Bryman (2008) adds to this by describing positivism as an *"epistemological position that advocates the application of the methods of the natural sciences to the study of social reality and beyond"*. The argument subsumes that the principle of positivism could be applied to the world of social sciences based on the assumption that social sciences can be studied in like manner as the natural sciences (Mertens, 2005). This principle is argued to entail the following (Bryman, 2008):

1. Only phenomena and hence knowledge confirmed by the senses can genuinely be warranted as knowledge (the principle of *phenomenalism*).
2. The purpose of theory is to generate hypothesis that can be tested and will thereby allow explanations of laws to be assessed (the principle of *deductivism*).
3. Knowledge is arrived at through the gathering of facts that provide the basis for laws (the principle of *inductivism*).
4. Science must (and presumably can) be conducted in a way that is value free (that is, *objective*).
5. There is a clear distinction between scientific statements and normative statements and a belief that the former are the true domain of the scientist.

> The last principle above by implication depicts the first one mainly because the truth or otherwise of normative statements cannot be confirmed by the senses.

In terms of research strategy, Pruyt (2006) contends that positivism research paradigm adopts methodologies that are purely quantitative and decontextualized, often named '*hard'*; which by implication portends that the paradigm aligned with the data collection and analysis that portrays quantitative methods (Essa, 2008). The methodological approach firm up for this research aligns with some features of this frame as will be discussed in Section 4.3. The next sub-section discusses the *interpretivist* research philosophy.

4.2.2 The Interpretivist Philosophical Research Paradigm

A number of researchers (Creswell, 2009; Schwandt, 2007; Lincoln & Guba, 2000; Neuman, 2000; Crotty, 1998; Lincoln & Guba, 1985; Berger & Luekmann, 1967) bluntly view the interpretivist philosophical research paradigm as an approach to qualitative research that, according to Bryman (2008) and Blaikie (2009), holds a sharp contrasting epistemology to positivism. This research paradigm seeks the understanding or meaning of phenomena subjectively through participants that make up this paradigm (Creswell, 2011). The view of Remenyi *et al.* (1998) is in no way different from that of Creswell (2011) that interpretive research tends to understand and explain a phenomenon, rather than searching for the external cause of fundamental laws.

Additionally, Bryman (2008) opines that it is a paradigm that is *"predicated upon the view that a strategy is required that respects the differences between people and the objects of the natural sciences and therefore requires the social scientist to grasp the subjective meaning of social action"*. Here social scientists are seen to be saddled with the responsibility of gaining access to the 'common-sense thinking' of people and therefore have their actions interpreted from their point of view. Along this same line of thought, Creswell (2009) simply puts the interpretivist philosophical research paradigm as the researcher's intent to make sense of the meanings others have about the world, where the researcher inductively develops a theory rather than starting with a theory.

However, it needs to emphasise that all above submissions are based on the following summarised assumptions by Creswell (2009) as identified by Crotty (1998):

- Meanings are constructed by human beings as they engage with the world they are interpreting. Qualitative researchers tend to use open-ended questions so that the participants can share their views.
- Humans engage their world and make sense of it based on their historical and social perspectives – we are all born into a world of meaning bestowed upon us by our culture. Thus, qualitative researchers seek to understand the context or setting of the participants through visiting this context and gathering information personally. They also interpret what they find, an interpretation shaped by the researcher's own experiences and background.
- The basic generation of meaning is always social, arising in and out of interaction with a human community. The process of qualitative research is largely inductive, with the inquirer generating meaning from the data collected in the field.

As reflected from the foregoing, the interpretivist research paradigm advocates the qualitative research strategy, which invariably involves collecting qualitative data. Again, the methodological approach for this research takes some features of this research philosophy which is further discussed in Section 4.3. The next sub-section discusses the pragmatist research paradigm.

4.2.3 The Pragmatist Philosophical Research Paradigm

Essa (2008) argues that pragmatism is not consecrated to just only one system of philosophy or reality. Both Pruyt (2006) and Creswell (2009) express that pragmatism position is grounded and enormously benefitted from the work of philosophical pragmatists like Peirce, James, Mead, Dawey, Davidson, Bentley, and Rorty as identified in Maxcy (2002) and Cherryholmes (1992). The epistemology and ontology of this research paradigm are founded on the tenets of finding solutions to research problems (Creswell, Guttman, & Plano-Clark, 2002) as raised by the research questions (Tashakkori & Teddlie, 1998), rather than focussing on a specific method or the paradigm or (epistemology/ontology/……) assumptions fundamental to such a method.

Therefore, Creswell (2003) contends that pragmatist researchers mainly focus on the ‘what’ and ‘how’ of the research problem by applying all the methods based on the criterion they think will work best in answering their research questions utilising both qualitative and quantitative approaches (Tashakkori & Teddlie, 1998). Following on from this, Creswell (2009) summarises the following as the assumptions that are central to the pragmatist philosophical research paradigm as identified by Cherryholmes (1992) and Morgan (2007):

- Pragmatism is not committed to any one system of philosophy and reality. This applies to mixed methods research in that inquirers draw liberally from both quantitative and qualitative assumptions when they engage in their research.

- Individual researchers have a freedom of choice. In this way, researchers are free to choose the methods, techniques, and procedures of research that best meet their needs and purposes.

- Pragmatists do not see the world as an absolute unity. In a similar way, mixed methods researchers look to many approaches for collecting and analysing data rather than subscribing to only one way (*e.g.* quantitative or qualitative).

- Truth is what works at the time. It is not based on a duality between reality independent of the mind or within the mind. Thus, in mixed methods research, investigators use both quantitative and qualitative data because they work to provide the best understanding of a research problem.

- The pragmatist researchers look to the *what* and *how* to research, based on the intended consequences – where they want to go with it. Mixed methods researchers need to establish a purpose for their mixing, a rationale for the reasons why quantitative and qualitative data need to be mixed in the first place.

- Pragmatists agree that research always occurs in social, historical, political, and other contexts. In this way, mixed methods studies may include a postmodern turn, a theoretical lens that is reflective of social justice and political aims.

- Pragmatists have believed in an external world independent of the mind as well as that lodged in the mind. But they believe that we need to stop asking questions about reality and the laws of nature (Cherryholmes, 1992). *"They would simply like to change the subject"* (Rorty, 1983).

- Thus, for the mixed methods researcher, pragmatism opens the door to multiple methods, different worldviews, and different assumptions, as well as different forms of data collection and analysis.

From the foregoing, it is evident this research paradigm extends their view of research methodology beyond using a single research approach to achieve the objectives of any research problem. Instead, this strategy takes a holistic view at the problem and uses any method or a combination of methods to solve the research problem. This may mean combining both the qualitative and quantitative research strategies, thereby triangulating data collection methods. The next section therefore discusses the methodological approach developed for this research and how these paradigms align with it based on supported philosophical evidences.

4.3 Methodological Approach Developed for the Research

This section of the thesis provides details on the methodological approaches used to achieve the objectives of the research in this thesis. The preceding section shows the discussion of philosophical paradigms guiding any research upon which the methodology adopted for this research is drawn. This research uses a mixed-method research design drawn from the pragmatist philosophical view in order to achieve its objectives. The reason for adopting the mixed-method research design is motivated based on three main reasons that include the nature of the research problem, the data and the methods of collecting these data, and the purpose of the research. The research problem as discussed in Chapter one of this thesis entails answering quite a number of research questions in order to fulfil the aim and objectives of the research. This includes answering questions relating to '*what*' and '*how*' questions and as such, it portends to mean that no single approach could be used to answer those questions. This then informed the decision to use a method that complements both the qualitative and quantitative research strategies and all-encompassing.

The purpose of this research is to develop a dynamic model of the socio-technical systems of energy consumption and carbon emissions of the UK housing stock and provide a tool to policy makers capable of testing a range of possible futures regarding household energy consumption and carbon emissions. As discussed in Chapter three, the modelling platform adopted for this research to implement the purpose of this study is system dynamics. As will be seen in Chapter five, the system dynamics approach, on its own merit, is hinged on a pluralistic approach that considers both the qualitative and quantitative approaches to modelling. Let this alone has the capability of informing this research on the choice of research method and design to use. Additionally, it is extremely important to justify that the knowledge claim in this research is valid and highly reliable. And the only way to demonstrate such, according to Awodele (2012), is to desire *complementariness, completeness of ideas, credibility, and diversity of views*, which are tantamount to reliability and validity.

From the foregoing, it is evident that the nature of the research in this thesis entails capturing both the qualitative and quantitative data, which by implication means triangulation of data collection methods (detail is discussed in Section 4.4). Qualitative data, which is majorly collected via interviews (see Section 4.4.1), is necessary in order to capture the views of the experts and practitioners regarding the model conceptualisation (see Sections 5.6.2, 6.2, and 6.5). Also, quantitative data like household energy consumption based on end-uses, population, number of households, *etc.* (see Section 4.4.2), are required for the research problem. All these then justifies the use of mixed-method research.

Johnson and Onwuegbuzie (2004) define mixed-method research as "*the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study*". Philosophically, Johnson and Onwuegbuzie (2004) argue that mixed-method research uses the concept and system of philosophy of pragmatic method. In this regard, de Waal (2001) points out that the logic of inquiry of mixed-method makes use of induction[8], deduction[9], and abduction[10]. Mixed-method research design is all inclusive, pluralistic, and complementary in nature (Johnson & Onwuegbuzie, 2004) as it uses multiple approaches in achieving the research objectives. This means that this research design do not limit the researchers' choice of method to just a single method. Additionally, mixed-method research design suggests that the researchers are in control and use an eclectic approach in

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[8] Induction here refers to discovery of patterns.

[9] Deduction relates to testing of theories and hypotheses.

[10] Abduction pertains to uncovering and relying on the best of a set of explanations for understanding one's results.

conducting the research. Fundamentally, what guide the adoption of mixed-method research design is the research questions/objectives and as such dictates the best way to answer the research questions or achieve the research objectives. The strengths and weaknesses of mixed-method are therefore shown in Table 4.2.

Table 4.2: Strengths and weaknesses of mixed-method

Strengths	**Weaknesses**
• Words, pictures, and narrative can be used to add meaning to numbers. • Numbers can be used to add precision to words, pictures, and narrative. • Can provide quantitative and qualitative research strengths. • Researcher can generate and test a grounded theory. • Can answer a broader and more complete range of research questions because the researcher is not confined to a single method or approach. • The specific mixed *research designs* discussed in this article have specific strengths and weaknesses that should be considered. • A researcher can use the strengths of an additional method to overcome the weaknesses in another method by using both in a research study. • Can provide stronger evidence for a conclusion through convergence and corroboration of findings. • Can add insights and understanding that might be missed when only a single method is used. • Can be used to increase the generalizability of the results. • Qualitative and quantitative research used together produce more complete knowledge necessary to inform theory and practice.	• Can be difficult for a single researcher to carry out both qualitative and quantitative research, especially if two or more approaches are expected to be used concurrently; it may require a research team. • Researcher has to learn about multiple methods and approaches and understand how to mix them appropriately. • Methodological purists contend that one should always work within either a qualitative or a quantitative paradigm. • More expensive. • More time consuming. • Some of the details of mixed research remain to be worked out fully by research methodologists (e.g., problems of paradigm mixing, how to qualitatively analyse quantitative data, how to interpret conflicting results).

(Adapted from Johnson & Onwuegbuzie, 2004)

Figure 4.1 provides the research objectives, the major tasks performed, the methodology to achieve each of the tasks, and the chapters where each of the objectives are achieved as firmed up for the research. The method of data collection is discussed in the next section.

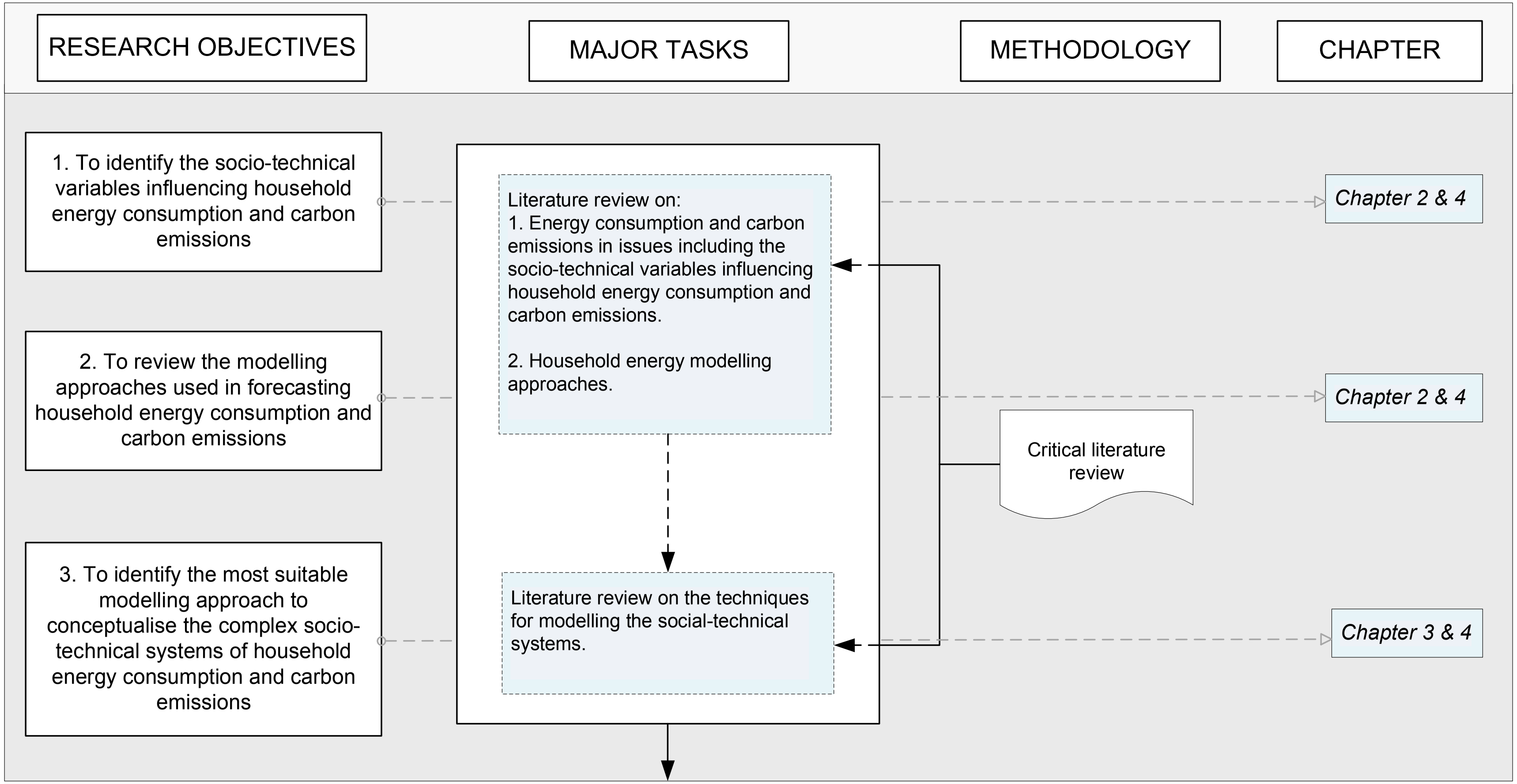

Figure 4.1: Research objectives and methodological approach

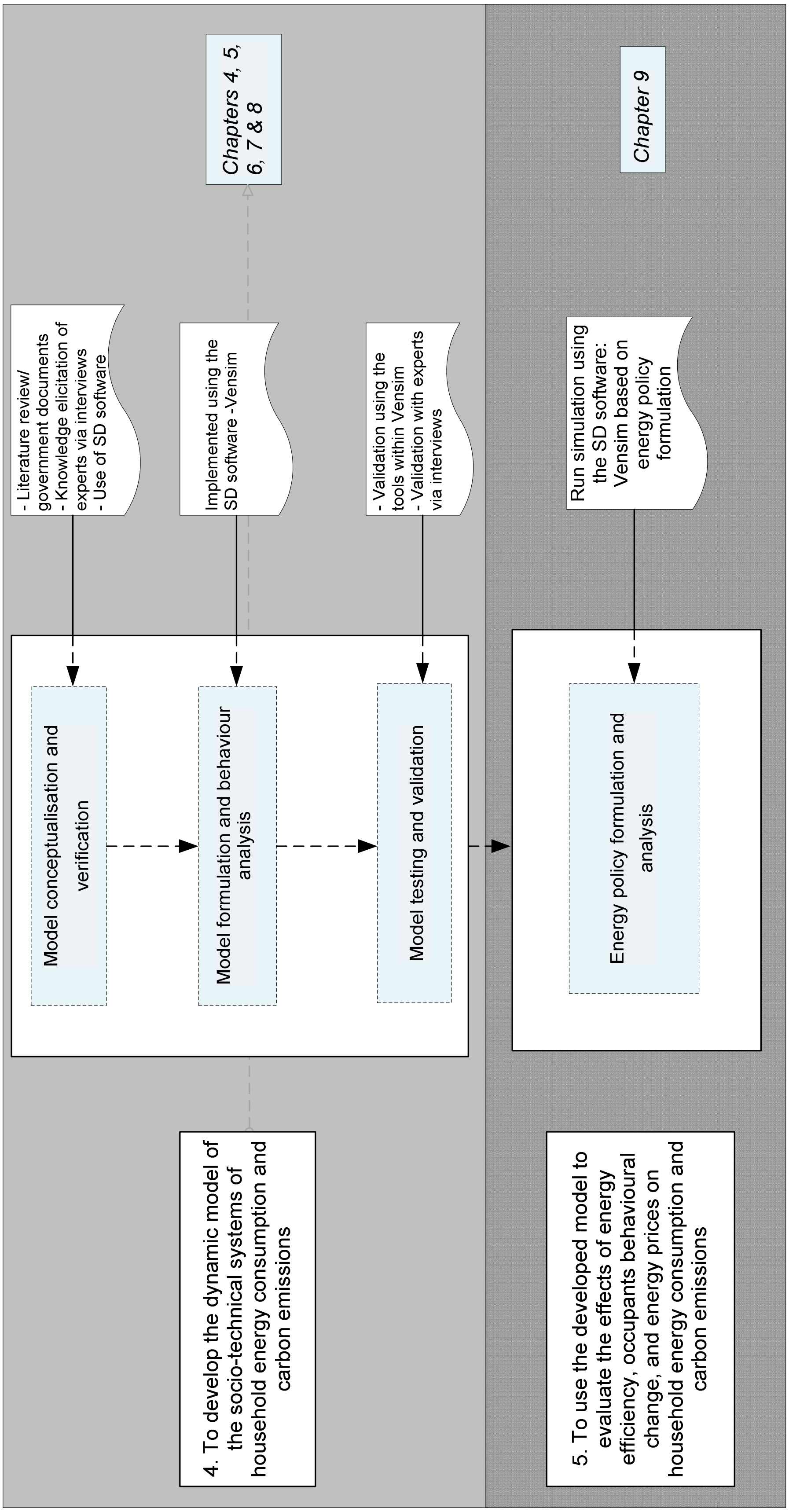

Figure 4.1: *Continued*

4.4 Method of Data Collection for the Research

The methodological approach firmed up for this research, as discussed in the preceding section, suggests that the pragmatic research approach is most suitable and appropriate for this research. The philosophical foundation underpinning this has already been discussed in Section 4.2.3 and this falls within the pragmatist research paradigm. Pragmatic approach entails using a combination of qualitative and quantitative research strategies by collecting both the qualitative and quantitative data. As such, the aim of this research involves developing a dynamic model of the socio-technical systems of household energy consumption and carbon emissions. To this extent, Luna-Reyes and Andersen (2003) state that models, especially SD models (as will be discussed in Chapter five), require moving between qualitative and quantitative research strategies. This is to ascertain that the data mimic reality of the system under study. As a result of this, triangulation of data collection approach is inevitable.

This study employed a number of quantitative and qualitative data for the research. Qualitatively, the research used literature review to achieve some of the objectives of the research even before the modelling efforts. At model development stage of this research, Luna-Reyes and Andersen (2003) argue that qualitative data collection brings about rigour in modelling process and adds to the richness of the process, which quantitative data may not be able to provide. This is by bringing insights into the model from the mental models of experts via interviews. In fact, Forrester (1975c) attaches much importance to qualitative data sources and identifies them as the main sources of data in SD as will be discussed in Chapter five. To this extent, this research collected some qualitative data in order to conceptualise and drive the model via literature review and interview of experts and practitioners in the field of this study.

In order to develop and drive the model, which is the final output of this research, quantitative data were used. The main quantitative data used is sought primarily from three different secondary sources to include DECC, metrological department, ONS, and other sources like Government reports and documents for example SAP. DECC is acknowledged as the main power house for data related to any form of energy and issues concerning climate change in the UK. DECC collates energy and climate change data from different sectors of the UK economy such as: housing, transport, industry, *etc.* The published DECC dataset specifically used for the study is the UK housing energy fact file 2012 (Palmer & Cooper, 2012), which draws together, in a compact form, most of the important data regarding household energy use in the UK since 1970. The rest of this section discusses data collected in details basically as primary and secondary data sources.

4.4.1 Primary Data: Interview

Asika (2009) states that data are classified as either primary or secondary data. The classification is based on two possible data sources as primary data source and secondary data source. He further argues that primary data mainly come from direct observation of the event, manipulation of variables, contrivance of research situations including performance of experiments and responses to questionnaires and interviews.

Interviews with experts and practitioners on a problem, for example, often play a crucial role in modelling process as they enable the modeller to obtain the mental data of these experts/practitioners' mental models. Interviews capture their thoughts, expressions, and understanding of the system under study. Mental data is not directly accessible except it is elicited from the experts via interviews. According to Fellows and Liu (2003), interviews can be structured, semi-structured, or unstructured. The characteristic of each type of interviews is given in Table 4.3 as adapted from the work of Coombs (1999). Both unstructured and semi-structured interviews were employed in this study. That is, unstructured interview method was used to elicit interviewees' mental knowledge and for face validation of the model, whereas the semi-structured interview approach was used at model validation stage alone, especially during model validation based on scoring method (details are provided in Section 8.6 of Chapter 8). Note that majority of the qualitative data used in this model are captured from the experts and industry practitioners that took part in the study.

Table 4.3: Types of interviews

Type	**Characteristics**
Structured	Wording of the questions and the order in which they are asked is the same from one interview to another. Respondents are expected to choose an answer from a series of alternatives given by the interview.
Semi-structured	Interviewer asks certain major questions the same each time, but is free to alter their sequence and probe for more information.
Unstructured	Interviewer prepares a list of topics that they want the respondent to talk about, but is free to phrase the questions as they wish, ask them in any other that seems sensible and even join in conversation by discussing what they think of the topic themselves.

(Adapted from Coombs, 1999)

The interviews were conducted twice. Firstly, at the system conceptualisation stage of the modelling process (as will be discussed in Section 5.5.2 of Chapter five), the mental data of experts and industry practitioners were captured in the form of knowledge elicitation through unstructured interviews. This is basically to ascertain the correctness of the initial causal loop diagrams (CLDs) drawn based on the modellers knowledge of the system under study as elicited through the review of literatures and government documents. Also, at this stage respondents were interviewed on formulation of some of the relationships between certain variables in the model that are with lack of empirical data and/or evidence of relationships existing among them. This method is in line with the approach of Coyle (1997) regarding establishing the causal relationships among the variables in SD models as will be fully explained in Chapter 5.

Secondly, semi-structured interviews were conducted at the validation stage of the modelling stage (as shown in Section 5.5.4 of Chapter 5 and Chapter 8). At this stage, experts and industry practitioners were engaged with in order to validate the output of the model in terms of its behaviour. This is to make sure that the behaviour of the model outputs reflect their expectations or otherwise based on their experience and advance reasons for any plausible behaviour noticed. Additionally, the interviews were conducted with system dynamicists in order for them to assess the model and then validate it. The system dynamicists selected for this exercise were those with requisite experience in modelling SD systems and are conversant with the Vensim software, since the model is implemented using the software. This is to ascertain that all the tenets of such software are duly adhered to and no floatation of the software rules whatsoever.

Those that took part in the first stage of interviews were selected using double sampling method (Asika, 2009). The database of the Scottish Statistic Register for professionals in energy and environment consisting of 365 individuals as at September, 2012 was used. The whole population of those on the register was first sampled by sending an email seeking their participation in the study with brief background information on the research. They were requested to answer some questions relating to their area of expertise, academic qualification, years of experience in energy related issues, and availability to partake in the study. Taking cognisance of the above criteria, only ten of those that were responded were found adequate to partake in the study. And as such, ten of them were interviewed at this stage in order to elicit their knowledge regarding the system under study.

At the second stage of interviews, 15 respondents took part in the exercise. This consists of eight respondents that were interviewed at the system conceptualisation stage. Additional four were sampled from the same database above, all making 12 experts and industry practitioners from energy background. The remaining three experts are drawn from the SD background. They were randomly selected from the list of SD experts from the UK that attended the 31st International Conference of the System Dynamics Society in the US. Their availability were then sought and confirmed accordingly.

4.4.2 Secondary Data

Bryman (2008) argues that the term secondary data source refers to those data sources in which the researcher making use of such data may not have been involved in the collection of such data. Dale *et al.* (1988) advance some reasons why collection of secondary data should be given a thought and seriously considered. Among these are that it saves cost and time as well as having access to high-quality data.

In this study, it is practically impossible to personally collect the required data that will drive the model as they are best collected by the government agencies because they have all the requisite resources to do so. And as such, data for the following variables are extracted from the UK housing energy fact file of the DECC (Palmer & Cooper, 2012): space heating, hot water, lighting, appliances, and cooking energy; carbon emissions; energy efficiency (SAP) ratings; fabric insulation in the form of loft, cavity and solid wall insulation; energy prices in the form average annual gas and electricity bills; abridged version of population and households. The Metrological Department is the home for weather related data in the UK. The main weather related data collected includes external air temperature and humidity. Data extracted from the ONS database include data related to demographic variables, which includes a full version of population, and households' data, average life expectancy, average fertility rate, and reproductive time. These specific data are sought as motivated by the variables included in the model.

Table 4.4, therefore, shows a sample quantitative data of some of the variables used in the model. It is important to state that the data are subjected to further analysis to show the minimum, maximum, mean, standard error and standard deviation of these variables.

Table 4.4: Sample data

Variable	Unit of Measurement	Minimum	Maximum	Mean	Standard Error	Standard Deviation
Households	Households	18791000	26863000	2.2664E7	3.63850E5	2.35802E6
Population	People	55632000	62736000	5.7931E7	3.00346E5	1.94646E6
Space heating	MWh	10.14	15.84	13.54	0.18	1.19
Hot water	MWh	3.03	6.64	4.78	.17	1.10
Average annual gas bill	£	372	659	542.07	12.44	79.66

Literature review

The main qualitative secondary data collected for the study is in the form of literature review. Majorly, the intention of literature review is to show the level of existing knowledge relating to the subject of study, *i.e.* HECCE as the case is in this study. Literature review provides a solid theoretical background regarding the topic under study as it gives the gaps in knowledge (Fellows & Liu, 2003). The literature review needs to be thorough, critical, and up-to-date. In fact, the study of Hart (1998) highlights some of the purposes of literature review as follows:

- Differentiate what has been done from what needs to be done;
- Discover important variables relevant to the research problem;
- Synthesise and obtain a new perspective;
- Identify relationships between ideas and practice;
- Establish the context of the research problem;
- Rationalise the significance of the research problem;
- Improve and obtain the subject vocabularies;
- Develop an understanding of theory and method;
- Communicate ideas and theory to applications;

- Identify the main methodologies and research techniques that have been used; and
- Place the research in a historical context to show familiarity with state of the art developments.

In this study; beyond gathering data for some of the variables involved in the model, a comprehensive literature review was undertaken in order to first gain initial insights into the issues relating to HECCE. This approach of literature review was used to collect relevant information regarding the research problem (Chapter 1), factors influencing household energy consumption and carbon emissions (Chapter two), methods of modelling HECCE (Chapter 2), methods of modelling the STS (Chapter 3) as well as gathering of information on research method for the study (Chapters 4 and 5). This implies that literature review was conducted at different stages of this study and information collected was critically appraised. For example, literature review is the major data source for the initial system conceptualisation in the form of causal loop diagrams as will be discussed in Chapter six.

4.5 Model Development and Validation

As given previously, the platform for modelling in this thesis is system dynamics. Therefore, it is important to discuss in details the approach employed in developing the model as well as in validating it. Details relating to this are provided in a separate chapter dedicated to the system dynamics approach, which is Chapter 5. Specifically, the model development and validation are discussed in Sections 5.6 and 5.7 of Chapter 5.

4.6 Chapter Summary

The epistemology and ontology of research paradigms guiding the methodology of any research endeavour was succinctly discussed in this chapter. It is shown in the chapter that the qualitative and quantitative research strategies emanate from the interpretivist and positivist research paradigm positions respectively, while a combination of both is from the pragmatic research paradigm position. The chapter also established the use of mixed-method research design that is based on the concept and system of philosophy of pragmatic method for the research in this thesis. Due to the fact that the mixed-method research design is all inclusive, pluralistic, and complementary in nature, the chapter discussed different approaches used in collecting data. This involved collecting both the primary data (in the form of interview) and secondary data (literature review and hard data from databases of government agencies). Information on model development and validation of the research was given as well. The next chapter discusses the system dynamics modelling as the approach to implement the modelling task in this research.

Chapter 5

THE SYSTEM DYNAMICS APPROACH

5.1 Introduction

In Chapter three, the system dynamics approach was selected as the most suitable approach to conceptualise the problem under study in the context of this thesis. The research methodology in terms of theoretical underpinning of the methodology and research strategy including the methods of data collection used in solving the research problem are discussed in Chapter four. It is equally important to discuss the system dynamics approach in detail and present how it is applied in this thesis. Therefore, this chapter describes the theoretical background of the system dynamic approach and its philosophical underpinnings. The software used to implement the system dynamics modelling are discussed including description of symbols and conventions used in system dynamics. The details of the SD modelling process firmed up for the research including the step by step approach used in building the model in this thesis are discussed.

5.2 System Dynamics Modelling

The SD approach is the chosen research methodology and tool for this research based on critical appraisal of different approaches as conducted in Chapter three. It is therefore necessary to link this research approach to the philosophical research paradigms as discussed in Section 4.2 above. In order to address the philosophical issues regarding SD, it would be necessary to first ask: what is system dynamics? Is it a paradigm, philosophy, theory, methodology, method, or a set of techniques or tools? Answering these questions has, indeed, generated a high level debate in the SD research circle as different system dynamicists and researchers have attributed different names to it. For example, some system dynamicists see SD as a theory (Flood & Jackson, 1991; Hitchcock & Salmon, 2000), a (group of) method(s) (Coyle, 1979; Meadows, 1980; Wolstenholme, 1990; Sterman, 2000; Lane, 2001), a methodology [Roberts, 1978; system dynamics society (SDS), 2013], a field of study (Richardson, 1991; Coyle, 2000), a tool (Luna-Reyes & Andersen, 2003; Zhao *et al.,* 2011; Ansari & Seifi, 2013), a paradigm (Andersen, 1980; Randers, 1980; Meadows, 1980; Meadows & Robinson, 1985; Forrester, 1994; Richardson & Pugh, 1999; Maani & Maharaj, 2004), and a host lot of nouns.

Historically, SD emanates from MIT’s Sloan School of Management in the 1950s when Jay W. Forrester introduced the approach in his quest to link engineering and management together. This idea was conceived in order to solve complex problems considering Forrester’s background in computers and feedback control systems. His ideas on this methodology were made known in 1956 through a seminar paper presented at the Faculty Research Seminar of the MIT’s Sloan School of Management (Forrester, 2003). Forrester started communicating his ideas by fiercely offer criticism of economic models and its assumptions. Forrester’s main criticism of economic models is hinged on the fact those economic models (Olaya, 2011):

- fail to adequately reflect the loop structure that make up economic systems and as such neglect leads to exclude inherent properties of closed loops such as resistance to change, accumulations and delays;
- are incapable of including flows of goods, money, information, and labour in one single interrelated model;
- exclude changing mental attitudes that affect and explain economic processes;
- use linear equations for describing systems;
- offer a restriction in building models as constrained by the capacity for manipulating numerical data and solving the equations;
- rely on multiple regression analysis for obtaining coefficients for equations that define economic behaviour;

- lack reflection on the very assumptions underlying the models.

After all these arguments, Forrester then went ahead to present his approach that was hinged on servomechanisms and differential equations: the techniques that were argued to be largely underutilised then (Forrester, 1975a). Premise on the above, Forrester considered a new approach to understanding the firm and economy, as reported in Forrester (1975a) by proposing a new kind of models that incorporate (1) dynamic structure; (2) information flows; (3) decision criteria; (4) non-linear systems; (5) differential equations; (6) incremental changes in variables; (7) model complexity (8) symbolism and correspondence with real counterparts; and (9) structure over coefficient accuracy.

Forrester then made more advances on the technique, which led to the publication of an article entitled "Industrial dynamics: A major breakthrough for decision makers" in Harvard Business Review (Forrester, 1975b) in the year 1958. In this article, Forrester was able to shape his ideas and since then, SD has emerged as a multi-disciplinary field of study that deals with the analysis of complex systems. The approach has, indeed, remained a powerful and well-established methodology and tool for modelling and understanding feedback structure in complex systems (Ansari & Seifi, 2013; Zhao *et al.*, 2011; Ranganath & Rodrigues, 2008). The approach, according to Coyle (1997), *"deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation"*, that was grounded in theory of modern feedback control and nonlinear dynamics. Further to this, it is built on 'cause and effect' relations among different variables influencing the system under investigation (Ranganath & Rodrigues, 2008) and indeed a *"method to enhance learning in complex systems"* (Sterman, 2000). The next gives the philosophical underpinnings of SD approach.

5.3 System Dynamics – A Positivist, Interpretivist, or Pragmatist Philosophical Research Paradigm?

The preceding sub-sections in chapter four highlight the philosophical research paradigms guiding any research methodology. It is therefore necessary to place the SD approach within the philosophical research paradigm space. However, correctly placing the SD approach within this space has generated a high level debate within the research circle. And as such, it is important to assess the premises of SD regarding how it is grounded in philosophical foundations. Is it a positivist, interpretivist or pragmatist philosophical research paradigm?

In answering the above question, Jackson (2003), for example, considers SD models to be representation of an assumed "objective" real world; thereby labelling the SD approach as a "hard" approach as further reflects in the work of Flood and Jackson (1991). This means that the SD approach is placed within the one dimensional array of *positivism*. This categorisation cannot be utterly refuted as Zagonel (2004) gives some examples of SD practices that illustrate this position as policy engineering, optimisation based simulation, purely quantitative SD and micro-world modelling. Following this position, Pruyt (2006) contends that the positivist SD assume an ontological position that modelled systems correspond to existing systems in the real world. Also, the epistemological position of this paradigm assumes that stock and flow diagrams and causal loop diagrams are good objective representations of the external reality. This position presumes that the resulting quantitative SD simulation presents an approach to replicate the dynamics of these real-world systems.

In yet another circumstance, some other studies have criticised viewing the SD approach as purely objective (interepretivist) research paradigm. Forrester[11] himself (Forrester, 1961) stressed that "*a model can be useful if it represents only what we believe to be the nature of the system under study…we are forced to commit ourselves on what we believe is the relative importance of various factors.*

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[11] Jay W. Forrester is the pioneer of SD approach

We shall discover inconsistencies in our basic assumptions…Through any of these we learn”. The justification to disproof the arguments of critics who mistakenly placed SD approach within the purely positivism space is apparent from this statement that SD is more than simulations alone. This is because it qualitatively captures the mental models of practitioners involved in SD modelling. Further to this, quite a number of system dynamicists (Forrester, 1975c; Doyle & Ford, 1998; Sterman, 2000) have argued that the central concept driving the SD approach lies on “mental models”, which presumably is purely subjective.

However, the ability and adequacy of “mental models” that is labelled as the core of the SD approach to accurately depict reality have generated a kind of debate within the research circles (Doyle & Ford, 1998). Apparently, it would be necessary to further explore the idea of mental models in order to see on how it has helped shape the SD approach. Sterman (2000), for example, expressly refers to “mental models” as “*our beliefs about the networks of causes and effects that describe how a system operates, along with the boundary of the model (which variables are included and which are excluded) and the time horizon we consider relevant…Most of us do not appreciate the ubiquity and invisibility of mental models, instead believing naively that our senses reveal the world as it is. On the contrary, our world is actively constructed (modelled) by our senses and brain*”. Further, Lane (1999) considers “mental models” as desired systems conceived and existing in the mind of the modeller. Pruyt (2006) describes both the ontological and epistemological positions of interpretivist SD. He sees the ontological position as relativist and the epistemological position as subjective.

From the foregoing, it is yet unclear if it is adequate to place the SD approach in any of the research paradigm divides above or both. This then necessitates the need to assess the pragmatist SD. Pruyt (2006), for example, argues that most SD practices contain pragmatist elements within them as they tend to reflect the characteristics of both the positivist and interpretivist paradigms. That is, the ontological/epistemological assumption of SD approach is more realist/objective

– as the case is during the simulation phase – and sometimes more nominalist/subjective – as the case is during modelling and interpretation phases (Pruyt, 2006). Barton (2002) adds to this by suggesting that the philosophical underpinning of systems thinking stage of SD approach (refers to as modelling phase by Pruyt, 2006) lies on pragmatism.

5.4 System Dynamics as a Multi-disciplinary Modelling Approach

In order to put SD in context as a multi-disciplinary modelling approach, it is important to further discuss its application in addition to the one briefly discussed in Section 3.5.8 of Chapter three. Undoubtedly, SD has developed itself into a unique and very powerful tool that finds applications in a wide range of fields, where the behaviour of a system is to be studied (Ranganath & Rodrigues, 2008). For example, SD has found application in economics and finance (Ghaffarzadegan & Tajrishi, 2010; Forrester, 1971), resource management (Rehan *et al.,* 2011; Dyson & Chang, 2005), education (Homer, 1997), health (Milstein *et al.,* 2010; Homer *et al.,* 2006), production management (Ellis, 2001, Repenning & Sterman, 2001), project management (Ogunlana *et al.,* 1998), public policy and management (Rouwette *et al.,* 2007; Dangerfield, 2006), strategy (Barabba *et al.,* 2002; Homer, 1996) energy and environment (Balnac *et al.,* 2009; Yudken & Bassi, 2009). Within the energy consumption and carbon emissions domain (Feng *et al.,* 2013; Wu & Xu, 2013), SD models have been developed and applied in different contexts and not limited to energy efficiency (Davis & Durbach, 2010; Motawa & Banfill, 2010; Dyner *et al.,* 1995) and energy policy evaluation (Chi *et al.,* 2009; Naill, 1992; Ford, 1983).

It needs to clearly state that within the energy policy evaluation domain, which is the main focus of this research, Ford (1983) used SD to generate different policy analysis scenarios regarding electricity planning in the United States (US). Similarly in the US, Naill (1992) adopted SD approach to model policy related to energy supply and demand for better energy planning in the US economy.

Likewise within the same context in the UK, Chi *et al.* (2009) considers SD as an approach to understand the dynamics of the UK natural gas industry in order to formulate a long time energy policy. While some of these studies reinforce the application of SD approach to energy policy evaluation, there is, however, paucity of sufficient evidence to support that due attention has been paid to the issues relating to HECCE from the SD perspective.

5.5 System Dynamics Software

It is important to note that there is quite a number of software under which SD can be implemented. These include: DYNAMO, Powersim, STELLA/iThink, AnyLogic, Vensim and the host of others. Brief details about some of the software are presented hereunder based on the extension of Eberlein's (2013) work:

- *DYNAMO*: Within the SD modelling, DYNAMO (Dynamic Models) represents the first simulation language developed in the field. The software was developed at Massachusetts Institute of Technology (MIT) by Jack Pugh around 1960s. It can run on personal computers under DOS/Windows platform. It provides an equation-based modelling environment.

- *Powersim*: Powersim came into limelight in the mid – 1980s as a result of the research sponsored by the Norwegian government in a bid to support and improve the quality of high school students in the use of SD models. The output of the research gave birth to the object-oriented simulation-based games that primarily used for education. Powersim can be used in Windows based environment for creating SD models with the ability of facilitating interactive games or learning experiments.

- *STELLA* (Structural Thinking Experimental Learning Laboratory with Animation): STELLA was first inaugurated on the Macintosh in the 1980s, but now available on Windows. The software provides a graphical interface for the development of SD models. It supports a series of tools in the model development which allows easy access to equation writing.

- *AnyLogic*: AnyLogic software was developed in the 2000s as organised by the Distributed Network Computer research group at St. Petersburgh Technical University. The software has the capability of supporting the SD, discrete event simulation, and ABM. The software can as well work on Windows, Macintosh, and Linus.

- *Vensim*: Vensim was developed around the mid-1980s primarily for use in consulting projects by Ventana Systems. The software became commercially available in 1992 and works well in both Windows and Macintosh. Vensim fully supports SD modelling with flexible graphical representations without any form of clustering on the interface. The software contains panoply of tools for model analysis and testing, and the results can be visualised instantly on invoking SyntheSim. Vensim has the capability of using data and calibrating same. The software also has the capability of being linked to other software like C, C++, Visual Basic, *etc.* Also, other SD modelling software like Powersim, STELLA can be easily converted to Vensim.

According to Coyle (1997), before settling for any of the software, there is the need to assess the software package based on: its basis in fundamental SD theory; the ease of which it can be used; the support it gives to model building; the extent to which models can be documented and explained to a sponsor; the facilities it has for debugging a model; the ease of making experiments and producing output; and the scope of its facilities for policy design. When all the identified SD software is assessed against the above set of criteria together with their capabilities as explained above, they all have what it takes to be used. However, Vensim is chosen as the SD software for the modelling in this thesis because of its flexible graphical representations, which aid its clarity in presenting the CLDs. Also, its ability to incorporate optimisation, the method that was derived from numerical mathematics, an added advantage over all other software motivates its use.

Within the Vensim software, there is quite an array of symbols used in creating SD model sketches. Also, it needs to state that Vensim utilises a workbench that allows the modeller to build and analyse a model and its accompanied datasets (Ventana, 2010). According to Ventana (2010), the workbench comprise of a menu, a model, a toolbar, a variable, control panel, one or more toolsets, output windows and model building windows. An example of this workbench is shown in Figure 5.1 displaying different tools and symbols used in Vensim.

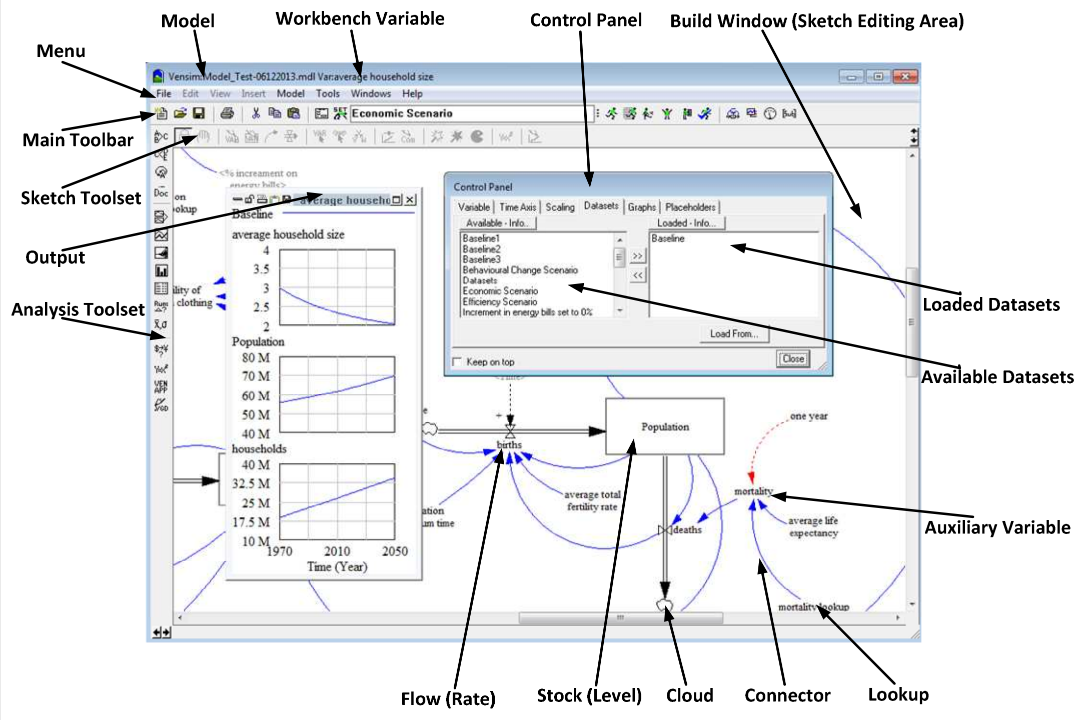

Figure 5.1: Vensim workbench

Within the Title Bar, the Model (Model_Test-06122013.mdl) and Variable (average household size) are named and displayed. Immediately after the Title

Bar is the Menu, which is followed by the Main Toolbar for the software. Below the Main Toolbar is the Sketch Toolset used in sketching the model. To the left of the screen is the Analysis Toolset for performing the analysis of the Model Output as shown in another window in Figure 5.1. Also, the Control Panel is shown in another window displaying the Loaded and Available Datasets. The Build Window reflects the workbench where sketches related to the model are created and edited.

Additionally, Figure 5.1 shows some of the conventions used in Vensim especially in depicting different types of variables within the SD models like stock, flow, *etc.* Some of the other conventions are highlighted too. The description of these terminologies is given in Table 5.1.

Table 5.1: Conventions used in SD modelling

Name	**Description**
Stock (Level)	A stock can be defined as a structural term for anything that accumulates.
Flow (Rate)	If stocks/levels are bathtubs, then flows/rates are pipes that feed and drain them.
Cloud	A cloud is an infinite reservoir representing the boundary. The capacity of cloud is so great that it makes no sense to worry about filling or draining it.
Connector (Arrow)	A connector/arrow is used to link the variables in the model together.
Auxiliary Variables	These are computed from Levels, Constants, Data, and other Auxiliaries. Auxiliary variables have no memory, and their current values are independent of the values of variables at previous times.
Look-ups	They are used in specifying arbitrary non-linear relationships in Vensim.

(Adapted with modifications from Morecroft, 1988)

5.6 System Dynamics Research Process Developed for the Research

In SD literature, different authors suggest different, but overlapping, stages involved in any SD modelling efforts. For example, Wolstenholme (1990) simply identifies two phases to include diagram conceptualisation, and analysis and simulation phases. Randers (1980) however goes beyond the two phases identified by Wolstenholme (1990) to suggest four stages comprising of model conceptualisation, formulation, testing, and implementation. Sterman (2000) gives problem articulation, dynamic hypothesis, model formulation and simulation, testing, and policy formulation and evaluation as the main stages involved in any SD process. Robert *et al.* (1983), Richardson and Pugh (1999), and Ranganath and Rodrigues (2008) are of the opinion that any SD modelling efforts should incorporate the following stages: problem identification, system conceptualisation, model formulation, analysis of model behaviour, model evaluation, policy analysis and improvement, and policy implementation. Martinez-Moyano and Richardson (2013) extends what Robert *et al.* (1983), Richardson and Pugh (1999), and Ranganath and Rodrigues (2008) consider being the main stages of SD modelling efforts.

Due to the nature of the research problem in this thesis, this study firmed up a SD modelling that consists of problem identification and definition, system conceptualisation, model formulation, model behaviour analysis, model behaviour analysis, model testing and validation, and policy formulation and analysis as shown in Table 5.2. These are then mapped into four main stages as Figure 5.2 depicts. The modelling process for the research includes the timeline, major tasks performed, and the methodology employed to achieve each of the tasks performed.

Table 5.2: Approaches to the system dynamics modelling process

Randers (1980)	Roberts et al. (1983)	Wolstenholme (1990)	Richardson and Pugh (1999)	Sterman (2000)	Ranganath and Rodrigues (2008)	Martinez-Moyano and Richardson (2013)	This study
Conceptualisation	Problem definition	Diagram construction and analysis	Problem identification and definition	Problem articulation	Problem identification and definition	Problem identification and definition	Problem identification and definition
	System conceptualisation		System conceptualisation	Dynamic hypothesis	System conceptualisation	System conceptualisation	System conceptualisation
Formulation	Model representation	Simulation phase (stage 1)	Model formulation	Formulation	Model formulation	Model formulation	Model formulation
	Model behaviour		Analysis of model behaviour				Model behaviour analysis
Testing	Model evaluation	Simulation phase (stage 2)	Model evaluation	Testing	Simulation and validation	Model testing and validation	Model testing and validation
			Policy analysis		Policy analysis and improvement	Model use, implementation, and dissemination	
Implementation	Policy analysis and model use	Simulation phase (stage 2)	Model use or implementation	Policy formulation and evaluation	Policy implementation	Design of learning strategy/ infrastructure	Policy formulation and analysis

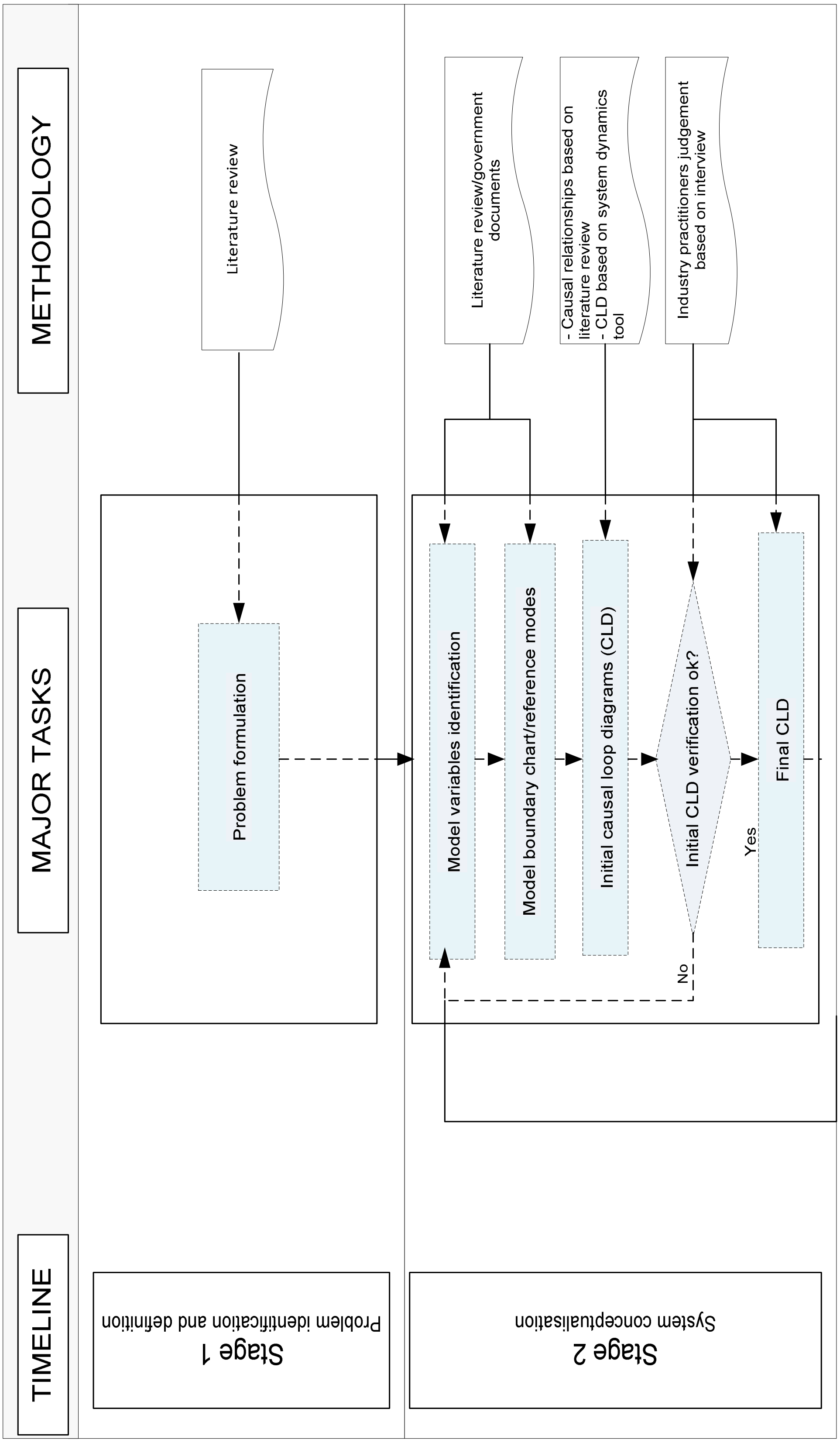

Figure 5.2: Modelling process

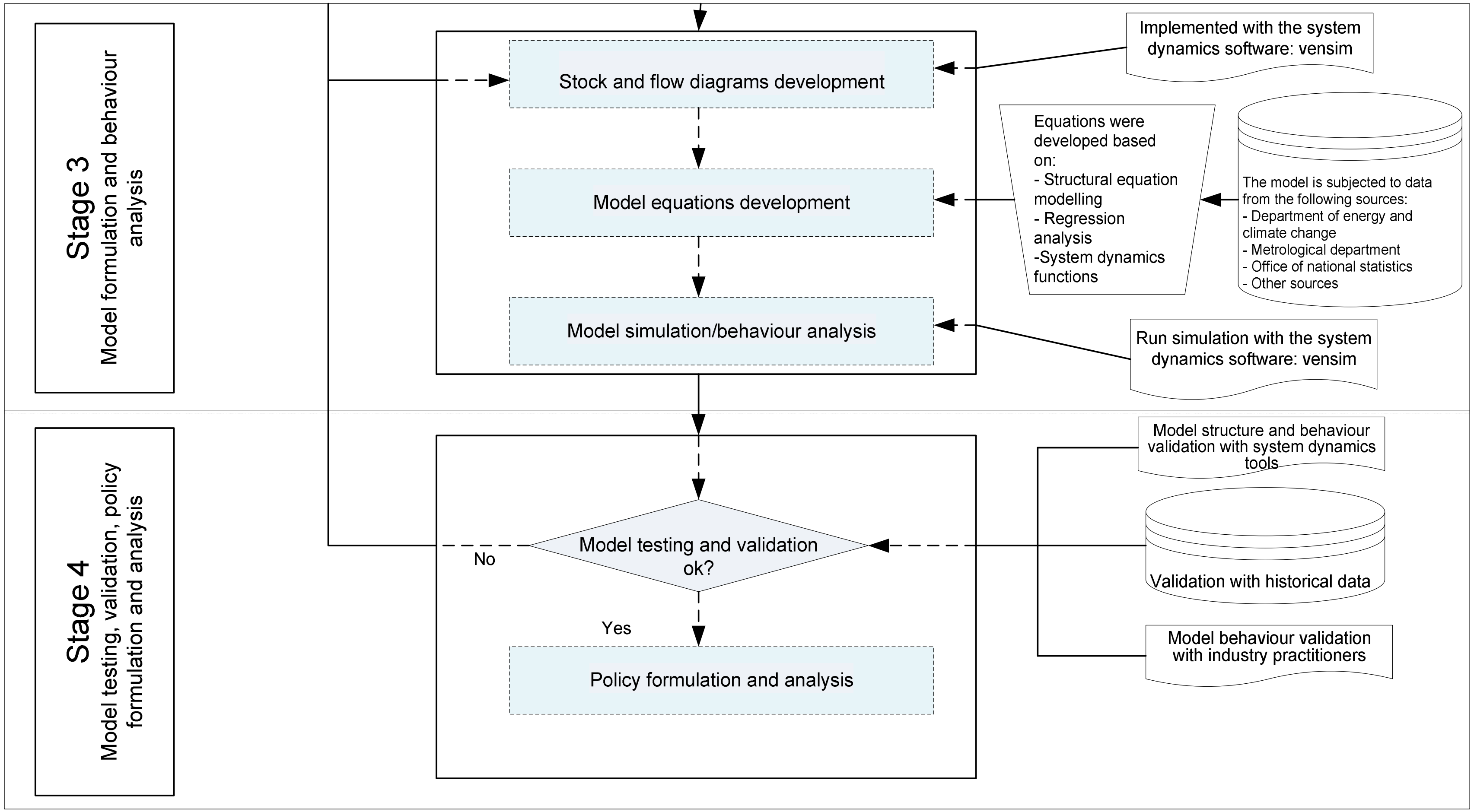

Figure 5.2: *Continued*

5.6.1 Stage 1: Problem Identification and Definition

The first stage (Figure 5.2) identifies the problem for the research and properly defines it by reviewing extant literature in the subject. This is necessary in order to properly put in context the problem SD approach intends to solve. This has been established in Chapter one of this thesis.

5.6.2 Stage 2: System Conceptualisation

The second stage as shown in Figure 5.2 is the system conceptualisation. This stage does not necessarily require the modeller to catalogue quantitative data in order to conceptualise the problem. However, the modeller mainly focuses on extant literature review on the problem and how the mental knowledge of the experts in the field of study can be captured all in a bid to develop the initial characterisation of the problem. Sterman (2000) reinforces the importance of this exercise when he submits that modellers usually have discussions with relevant stakeholders within the frame of the research, which is supplemented by literature review, interviews, and direct observations or participation.

The above exercise performed involves identification of model variables and establishment of model boundary, which includes the reference modes as evidenced from the review of extant literature, reports and documents from different sources including the UK government agencies like department of energy and climate change (DECC). At this stage, the variables identified are related to one another in order to establish the causal relationships and feedback structure within the system under study. This then leads to the initial formulation of the ‘cause and effect’ relationships among those variables in the system and pictorially represented them by what is called ‘causal loop diagrams’ (CLDs). The study achieved the CLDs for the system under study with the use of SD software (Vensim DSS version 5.11).

The CLDs represent sets of dynamic hypotheses for the study. It is necessary to note that the initial CLDs were based on the knowledge elicitation of the modeller (author). Input from the experts on the subject is then captured in the form of knowledge elicitation by having discussions with ten of them (this was fully explained in Section 4.4.1 of Chapter four). The purpose of this exercise is to verify and validate the initial CLDs that were purely based on the knowledge elicitation of the modeller alone as evidenced from the literature review and archival analysis. This exercise witnessed removal and addition of some causal links and variables until the final CLDs were achieved. The experts and industry practitioners that took part in the interview were selected based on double sampling frame as explained in Section 4.4.1 of Chapter 4. It is worth mentioning that at this stage the final CLDs do not indicate the stock or the flow but merely indicate the influence of one variable on the other. Details about the CLDs are explored in Chapter six.

5.6.3 Stage 3: Model Formulation and Behaviour Analysis

In this stage, a detailed model structure is given together with model parameter values. Depending on the research problem, this stage used to mostly contain elements of quantitative data as the case is in this thesis. In some cases, however, formulation of qualitative concepts is done here as well as the case is in this thesis also. In fact, one of the main strengths of the SD approach is in its ability to combine both the qualitative and quantitative research approach together as debated in Section 5.3 of this chapter. Richardson and Pugh (1981) add to the qualitative model formulation by suggesting that "*the modeller may wish to represent a concept explicitly. To do this requires the invention of units and a measurement scale, and consistent treatment throughout the model*".

The use of qualitative data sources for model formulation has received criticism within the research circles as quite a number of researchers have raised some concerns on the applicability of qualitative data in equations formulation. The defence against this query has been that the tenet of SD approach is founded on taking advantage of the mental models of experienced practitioners with the subject area. For example, Richardson (1996) addresses the issue of qualitative mapping and formal modelling. In the same vein, Sterman (2000) contends that "*omitting structures or variables known to be important because numerical data are unavailable is actually less scientific and less accurate than using your best judgement to estimate their values*". Taking all these into cognisance, the model in this thesis is formulated with the use of both qualitative and quantitative data sources as previously enunciated.

Stage three of the research process, as depicted in Figure 5.2, involves model formulation and behaviour analysis. Formulating the model requires representing the model using the stock and flow diagrams (SFDs). The SFDs show a pictorial representation of the behaviour of the system in the form of accumulation (stock) and flow (rate), and it is achieved with the use of SD software. It needs to emphasise that mere CLDs or SFDs do not result in SD. This will constitute SD when the variables in the model are related together in terms of equations and model simulation performed. So, model equations are developed based on a combination of different approaches involving qualitative and numerical data. For example, equations were developed by the use of SD functions in Vensim software to capture qualitative and quantitative data, regression analysis, structural equation modelling, and other means like some equations that were developed by SAP. In building the equations, the model is subjected to various data sourced and collected from a number of different sources in the UK such as: DECC, metrological department, and ONS. Also, data collected via interviews during the knowledge elicitation and from literature are qualitatively inputted into the model through "look-ups" in Vensim software. Once the system configuration is found satisfactory, the simulation is then run based on Vensim SD software from 1970 to 2050 with a year time step and the use of Euler form of integration type. Model behaviour are then analysed and discussed accordingly. A full detail about model formulation is presented in Chapter six and model behaviour analysis is addressed in Chapter seven.

5.6.4 Stage 4: Model Testing and Validation, and Policy Formulation and Analysis

Stage four, as shown in Figure 5.2, concludes the modelling process in building SD model of the problem addressed in this thesis. This stage consists of model testing and validation, and policy formulation and analysis. The studies of Forrester and Senge (1980) and Sterman (2000) provide a comprehensive array of different tests to be performed in order to have SD models validated. The studies broadly divide the tests into two to include (1) structure verification and (2) behaviour verification (Chapter eight lists all the tests based on Sterman, 2000). Forrester and Senge (1980) highlight the importance of this exercise when they commented on structure verification, for example, that "*the model must not contract knowledge about the structure of the real system…In most instances, the structure verification test is first conducted on the basis of the model builder's personal knowledge and is then extended to include criticisms by others with direct experience from the real system*". In the same vein, Randers (1980) establishes how the test should be performed and who should take part in it by suggesting that "*…the modeller should not restrict himself to the small fraction of knowledge available in numerical form fit for statistical analysis. Most human knowledge takes a descriptive non-quantitative form…Model testing should draw upon all sources of available knowledge*". These statements emphasise the importance of model validation with experts and practitioners in the field of study.

In this study, model validation involved testing and verifying the model structure, behaviour and sensitivity analysis with the use of SD functions within the Vensim software. Further to this, validation against historical data was performed based on the available historical data and the predictive ability of the model in its ability to mimic reality in the future was assessed statistically. Additionally, interviews were conducted with 15 experts and industry practitioners, eight of which are among those that were previously contacted at the second stage of the study in order to assess the model structure and output in terms of its behaviour whether or not they meet their expectations based on their experience in the field.

After the model testing and validation were satisfactorily done, policy formulation was done in order to carry out policy analysis based on the policy levers introduced within the model. This then necessitates running a number of policy scenarios with the model upon which decisions regarding HECCE may be based as fully discussed in Chapter nine. The next section discusses how the model algorithms were developed.

5.7 Development of Model Algorithms

Variables (especially levels, rates, auxiliary, *etc.*) are to be related to one another in the form of equations. Developing the main algorithms in contemporary SD paradigm involves using an array of functions embedded in the SD modelling software. For example, within the Vensim software, algorithms are formed with the use of simple functions like addition, subtraction, multiplication, and division. Also, special functions are used within the SD modelling platform software (Vensim for example) to implement some computational tasks in the model. For example, there are functions like DELAY, FORECAST, IF THEN ELSE, RAMP, SMOOTH, STEP, and the host of rest. The ability to utilise these functions is still subject to availability of requisite data or correct parameter assumptions to implement these tasks and then successfully drive the model. Where there is lack of empirical data, qualitative data are gleaned by interviews, for example, through knowledge elicitation of the experts (Sterman, 2000). In this research, SD functions within the Vensim software are used to mimic the reference modes[12] that are illustrating the problem. On the other hand, where there is evidence of empirical data, the modeller explores the advantages of some other methods of establishing the relationships among the variables in the model (*e.g.* regression analysis).

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[12] Reference modes are elaborately discussed in Section 6.4 of Chapter six

In the context of this thesis, both qualitative and quantitative data were used to develop the model algorithms as given in the preceding sections. As a result of this, a combination of regression analysis, structural equation modelling, and pre-defined equations (*e.g.* SAP algorithms) in some aspects are used in addition to some special functions within the Vensim software. Table 5.3 gives an example of regression-based equation developed for relationship between population and households as will be seen in equation 6.5 of Chapter six. Also, an example of algorithm based on structural equation modelling with a combination of Vensim special function developed is shown in equation 6.25 of Chapter six. Furthermore, examples of equations based on SAP algorithms are shown in equations 6.7 to 6.14 of Section 6.7.2 of Chapter six.

Table 5.3: Sample relationship developed from regression analysis

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-3.436E8	4538500.746		-75.712	.000
	Population	.067	.017	.056	3.886	.000
	Time	182057.612	2746.898	.947	66.278	.000

Dependent Variable: Households

5.8 Chapter Summary

The system dynamics approach was selected as appropriate modelling platform for the research problem in this thesis. The chapter then discussed the system dynamics approach employed in the research. The chapter underpinned the system dynamics approach as belonging to one of the philosophical paradigms discussed in Chapter four. And as such, the system dynamics approach was identified within the frame of the pragmatic paradigm. This indicates that any research involving the system dynamics falls within the purview of qualitative and quantitative research strategies which is adopted research strategy for this thesis as discussed in Chapter four. Furthermore, DYNAMO, Powersim, STELLA/iThink, AnyLogic and Vensim as some of the software under which system dynamics can be implemented were briefly discussed. Vensim was chosen as the modelling software for the thesis. This is because of its flexible graphical representations, which aid its clarity in presenting the causal loop diagrams as well as its ability to incorporate optimisation. The chapter also discussed the stages involved in the SD modelling process as adopted for the research to include four stages: problem identification and definition; system conceptualisation; model formulation and behaviour analysis; and model testing and validation, and policy formulation and analysis stages. This is in addition to the methodological approach developed for the research discussed in Chapter four. The discussion of the methods used in the development of the relationships among the model variables concludes the chapter. These methods include the use of SD functions within the Vensim software, regression analysis, and SEM as well as other established equations like those provided in SAP algorithms. The next chapter discusses the development of the model in terms of conceptualisation and formulation.

Chapter 6

MODEL CONCEPTUALISATION AND FORMULATION

6.1 Introduction

This chapter presents the main features and structures of the model in this thesis. The chapter starts by discussing the details of the experts who participated in the model conceptualisation. This is followed by presenting the reference modes of key variables in the model as evidenced from historical data. Further to this, the dynamic hypotheses (casual loop diagrams) for each of the sub-modules in the model are described and discussed. Discussion of the model formulation in terms of stock and flow diagrams for each of the sub-modules concludes the chapter.

6.2 Details of Participants in Model Conceptualisation

The main purpose of this sub-section is to explain in details of those experts who participated in model conceptualisation stage in addition to the information given under the research methodology chapter (see Section 4.4.1 of Chapter four). It needs to mention that prior to this exercise; the modeller had already identified the variables relevant to the scope of the study and linked them together with the use of causal diagramming. Each of the causal diagrams was studied in detail and feedback loop structures within these diagrams were located and labelled appropriately. The developed causal diagrams were used to establish the effect of one variable on the others as hypothesised that they are likely to influence household energy consumption.

After the input from the experts, Section 6.5 therefore contains the final/validated CLDs for the research. In order to validate these CLDs, the research adapted the approach used by Mohammed (2007) by showing all the diagrams to each of the experts who participated in the unstructured interviews (Table 6.1) to perform the following tasks:

- Verify the existence of the link with ‘1’ for ‘there is link’ and ‘0’ for ‘there is no link’.
- Indicate the strength of the link with ‘3’ for ‘strong link’, ‘2’ for ‘reasonable link’, and ‘1’ for ‘weak link’.
- Verify the direction of link with ‘+’ for ‘agree the direction’ and ‘-’ for ‘disagree the direction’.
- Indicate any missing link(s), using the above value.

As explained in the research methodology chapter, ten experts participated in the unstructured interviews. Evidently from Table 6.1, the organisation types the interviewees belong to are either public or private sector (50% are from the public sector and 50% are from the private sector). This mix, therefore, strikes a balance between the public and private sectors interviewees as there may likely be some differences regarding their perception of issues relating to household energy consumption. Table 6.1 further indicates that the lowest academic qualification of the interviewees is bachelor’s degree (50% of the interviewees). 40% of those interviewed hold a master’s degree, while the remaining 10% hold a PhD degree. The implication of this is that all the interviewees have the requisite academic qualification to be presumably knowledgeable about the issues being sought by the study.

Table 6.1 indicates the years of experience of the interviewees to ensure that those interviewed have involved and have deep knowledge on issues relating to household energy consumption. The result indicates that the interviewees have an average of 17.5 years of experience on issues relating to household energy. In addition, the result shows that none of the interviewees have pre-knowledge or experience in SD modelling. From the foregoing background information of experts participated in the causal diagrams validation process, it can be concluded that the evaluation will be made by relevant and qualified experts whose inclusion in producing the final causal diagrams can be relied upon and serve as the true representation of reality in the field of study.

Table 6.1: Background information of experts participated in casual diagrams validation

Category	Classification	Frequency	Percentage (%)
Organisation Type	Public	5	50
	Private	5	50
	Total	**10**	**100**
Academic Qualification	Bachelor's degree	5	50
	Master's degree	4	40
	PhD	1	10
	Total	**10**	**100**
Years of Experience in Household Energy Related Issues	6-10	3	30
	11-15	2	20
	16-20	4	40
	21-25	1	10
	Mean = 17.5		
Experience in System Dynamics Modelling	No	10	100
	Yes	0	0
	Total	**10**	**100**

Having established the reliability of participation of interviewees in the validation of the causal diagrams, the interview of each interviewee began with a brief description of the research by highlighting its aim and objectives. This was then followed by explanation of the methodology adopted for the research and the expected outcome from the unstructured interview. This is necessary in order to ensure that the exercise is clear enough to the interviewee. After this, the interviewee was given the causal diagrams that were produced based on the modeller's (interviewer's) knowledge of the system under study as captured from the review of extant literatures and government documents. The diagrams were explained to the interviewees. Each of the interviewees was then asked to make a review of the variables in the causal diagrams. Following this, they were asked to assess the appropriateness of the causal links for the variables included in the diagram and suggest additional variables and links should there be any need for such. Also, they were asked to strike out some of the variables or links as they deemed fit or alter the direction of the variables links as necessary. This validation exercise therefore ensures that the view of energy experts are captured and reflected in the causal diagrams. The duration of each interview was between 45 minutes and 75 minutes.

6.3 Model Boundary Chart

Energy and CO_2 emissions issues are highly complex systems in which quite a number of decisions need to be made on a continual basis. Considering the amount of details and information required, any attempt to model all the activities within this domain constitute an effort in futility. As such, a model of such would be undesirable mainly because its complexity would obscure the dynamic nature of the parameters being observed. To this end, the research needs to carefully select a level of aggregation in order to ensure that the model built sufficiently gives all the essential parameters and policy levers required. The research combined both the top-down and bottom-up approaches (as explained in Chapter 2) in selecting all the variables and as such, all the variables are aggregated at the level of policy makers in top level management regarding HECCE.

As previously highlighted, the boundary of the model needs to be carefully selected. According to Sterman (2000), a model boundary chart summarises the scope of the model by listing which key variables are included endogenously, which are exogenous, and which are excluded from the model. Therefore, the model requires including all the important variables that need consideration by the policy makers together with some variables beyond the system control. To this end, the variables included in this research are extracted from extant literature, government documents and reports as well as inputs from knowledge elicitation process of the interviews conducted on ten seasoned experts and industry practitioners in the field as explained in Section 6.2. Table 6.2 shows the variables included and those that are excluded from the model at this stage and this list is not exhaustive. It needs to mention that within the SD modelling paradigm, variables that are included in the model are divided into (Sterman, 2000): (1) endogenous – dynamics variables that form the internal structure of the system; and (2) exogenous – variables whose values are not directly affected by the system. As given in Table 5.1 and explained in Section 5.5 of Chapter five, the variables that are designated "S" and "F" illustrate stock and flow variables respectively. However, all other undesignated variables represent auxiliary, data, constant, or lookup variables.

6.4 Reference Modes

In SD modelling, a reference mode is seen as an important element of the modelling process. That is, there is the need to consider the historical behaviour of the key variables in the system under consideration and what their behaviour might be in the future (Sterman, 2000). Therefore, a reference mode depicts a pattern of behaviour that represents the dynamic nature of the problem in question. Consequently, it serves as a reference behaviour upon which the validity of a simulated model is assessed and determined. Sterman (2000) argues that there is the need to identify the time horizon for those variables considered to be of high importance to the problem under consideration. The main output of this research is the trend of household energy consumption and carbon emissions as affected by some key variables and how they respond to changes in some policy parameters. In order to identify the time horizon for the model in this research, it is necessary to consider the time horizon of historical data available on household energy consumption and carbon emissions, as domiciled in DECC (Palmer & Cooper, 2012), which are presented from 1970 and are updated on a yearly basis. Equally, it is of paramount importance to align to this research the time horizon of what carbon emissions reductions would be in the year 2050 as stipulated in the climate change act of 2008 in the UK. As a result of these considerations, the time horizon of 1970 to 2050 is therefore adopted for the model in this research. The following sub-sections therefore present the reference modes for some of the key variables as evidenced from available historical data.

Table 6.2: Model boundary

Endogenous Variables	Exogenous Variables/Parameters	Excluded Variables
heat losses	total floor area	Some variables relating to occupants behaviour *e.g.*:
dwelling heat gain (dhg) due to cooking	area of opening	- occupants' social class influence
dhg due to no of people	solar flux	- occupants' social group influence
dhg due to appliances less cooking	solar transmittance factor for glazing	- occupants' cultural influence
dhg due to artificial lighting	frame factor	- occupants' personal influence
average effect of solar gains	average solar access factor	Some variables relating to dwellings physical parameters e.g.:
total dwelling heat gains	pi	- dwelling exposure
Natural heat transfer (F)	dhg due to water heating	- dwelling orientation
Artificial heat transfer (F)	insulation factor	- air changes
Dwelling Internal Heat (S)	setpoint temperature	Some variables relating to external environment like:
discrepancy in internal and external temperature	temperature conversion factor	- political uncertainties
dwelling internal temperature	growth in occupants activity level	- energy securities
discrepancy in internal and setpoint temperature	external air temperature	
humidex value	relative humidity	
Occupants activity level (F)	SAP rating	
Occupants Metabolic Buildup (S)	average annual gas bill	
Perceived dwelling temperature (F)	average annual electricity bill	
Occupants Comfort (S)	energy to carbon conversion factor	
probability of window opening	carbon depletion factor	
probability of putting on clothing	demand for cooking energy	
effect of energy efficiency standard improvement on dwelling energy efficiency	lighting energy demand	
effect of fabric insulation on energy efficiency	appliances energy demand	
effect of combined fabric insulation and energy efficiency standard on dwelling energy efficiency	population equilibrium time	
effect of energy efficiency standard on cooking energy	reproductive time	
effect of energy efficiency standard on appliances energy	average total fertility rate	
effect of energy efficiency standard on lighting energy	average life expectancy	
effect of energy efficiency on hot water energy	occupants behaviour	

Table 6.2: *Continued.*

Endogenous Variables	Exogenous Variables/Parameters	Excluded Variables
effect of energy efficiency on space heating energy		
effect of dwelling energy efficiency on energy bills		
effect of energy bills on energy consumption		
climatic effects on international energy price		
climatic effects		
average annual energy bills		
space heating demand		
space heating energy rate (F)		
Space Heating Energy Consumption (S)		
Energy to carbon conversion (F)		
Space Heating Carbon Emissions (S)		
Carbon depletion (F)		
rate of hot water energy usage (F)		
hot water energy usage demand		
Hot Water Energy Consumption (S)		
Carbon Emissions due to Hot Water Usage (S)		
Cooking energy rate (F)		
Cooking Energy Consumption (S)		
Carbon Emissions due to Cooking Energy (S)		
rate of lighting energy usage (F)		
Lighting Energy Consumption (S)		
Carbon Emissions due to Lighting Energy (S)		
Appliances Energy Consumption (S)		
rate of appliances energy usage (F)		
Carbon Emissions due to Appliances Energy (S)		
average annual energy consumption per household		
total annual household energy consumption		
average annual carbon emissions per household		
total annual household carbon emissions		
Population (S)		
births (F)		
deaths (F)		
mortality		
households		
household size		

S= stock, F= flow.

6.4.1 Population

The historical data of UK population analysed in Figure 6.1 is based on the UK housing energy fact file published by the Department of Energy and Climate Change (Palmer & Cooper, 2012). The historical data of UK total population suggests that the population is growing. The pattern of growth as evidenced from Figure 6.1 reveals that between the year 1970 and 1982, the growth is minimal and not noticeable. Since the year 1982 therefore, the growth has followed a gentle slope until the year 2004. Thereafter, the slope of the growth trend has been steeper compared to between 1982 and 2004. This trend suggests that in years to come, it is most likely for the UK population to continue to grow. The implication of this growth is profound in that population drives households and households drive household energy consumption, which in turn drives household carbon emissions. The trend therefore highlights the problem posed by the behaviour of UK population.

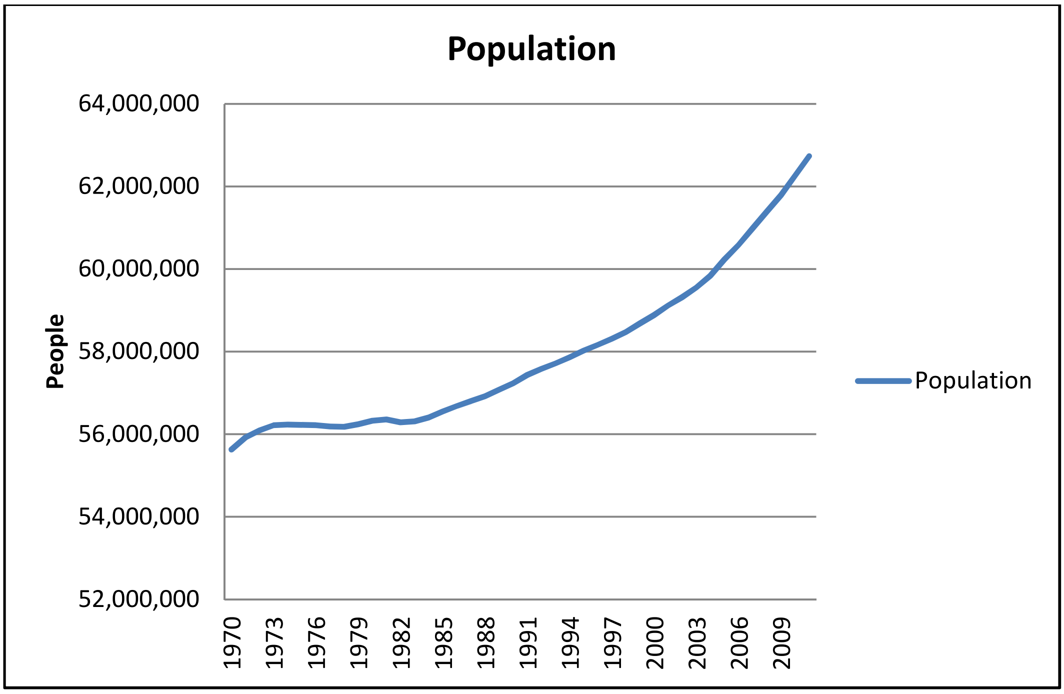


Figure 6.1: Reference mode for population
(Source: Palmer & Cooper, 2012)

6.4.2 Households

The reference mode of UK households' number is shown in Figure 6.2. The trend indicates that a growth in the number of households over the years. If this trend is sustained, it means that the number of households in the UK would continue to grow. The implication of this, as explained in Section 6.4.1, is attendant growth in average household energy consumption, which means average household carbon emissions would witness an increase as well. This then shows that certain policy regarding the number of households could melt household energy consumption and consequently, household carbon emissions. This research will then try to mimic this trend and project the trend into the future.

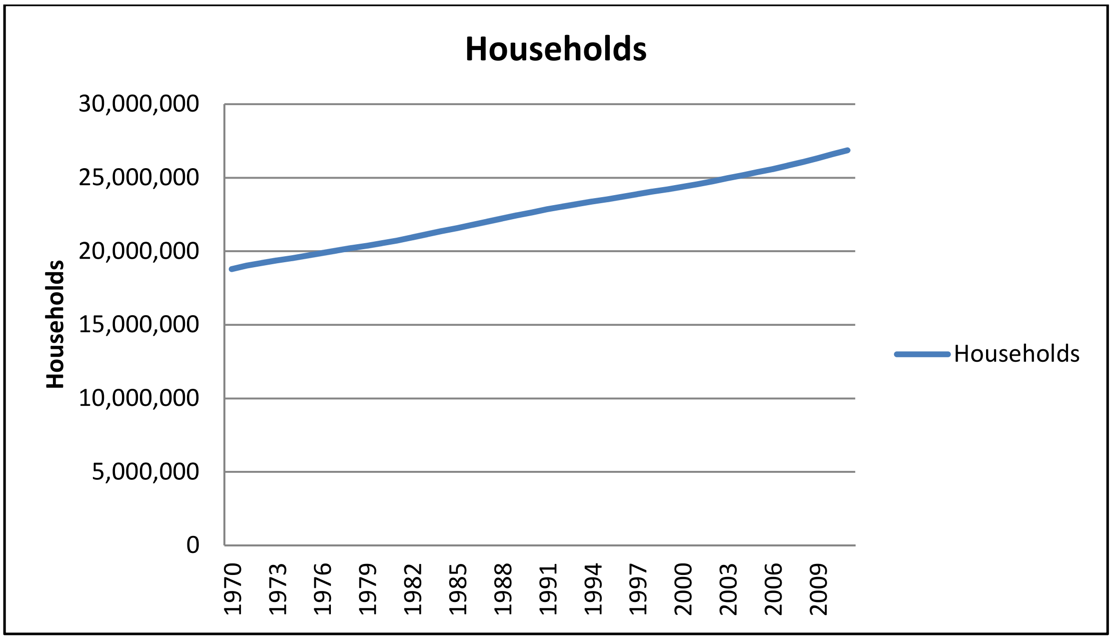


Figure 6.2: Reference mode for households

(Source: Palmer & Cooper, 2012)

6.4.3 Space Heating Energy Consumption

Figure 6.3 shows the behaviour of household space heating energy consumption based on historical data available. It shows that the slice of household energy consumption as a result of space heating has been following an upward direction until the year 2004 when it began to decline a bit. The growth follows a 'lumpy' trend with attendant troughs and peaks indicating the times of mild and severe weather conditions. With this reference mode, the problem associated with household space heating energy is therefore profound. The research will thus attempt to simulate the trend as shown in Figure 6.3, which will serve as the basis for validating the output of the model.

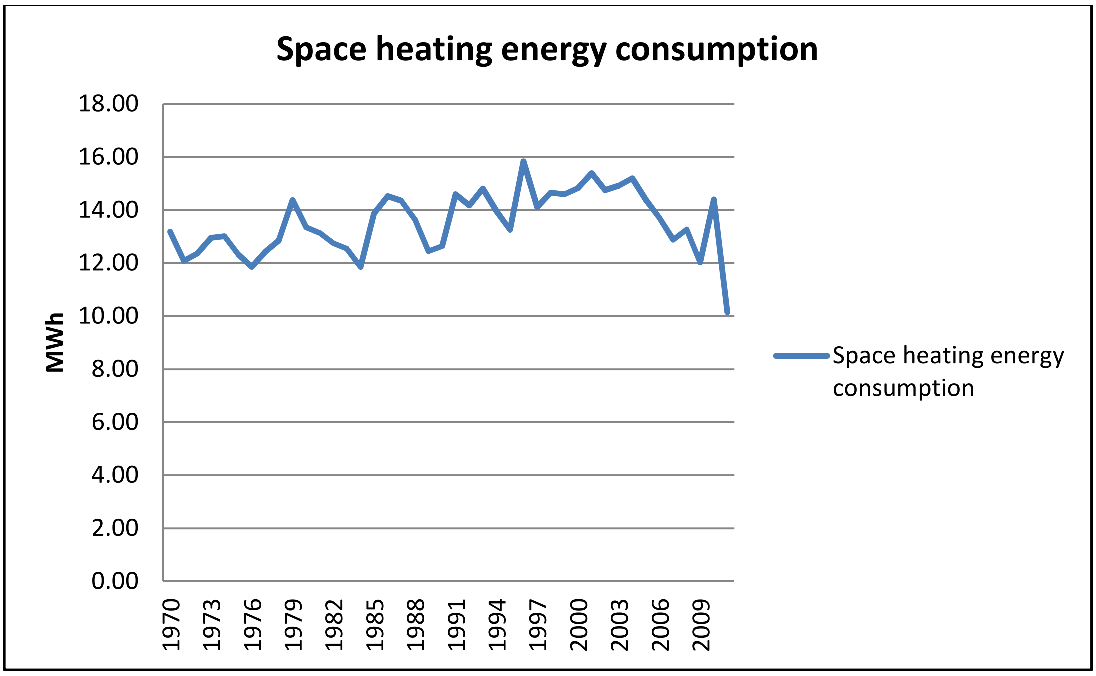


Figure 6.3: Reference mode for household space heating energy consumption (Source: Palmer & Cooper, 2012)

6.4.4 Hot Water Energy Consumption

In Figure 6.4, the time series behaviour of household hot water consumption is shown. The behaviour depicts in the graph is consistent with several improvement attempts at reducing hot water energy consumption in households as the trend shows a decline in consumption since 1970. The graph indicates how hot water energy consumption in households has evolved over the years. The implication of this to this research is that if the trend of hot water energy is sustained, it means that lesser hot water energy will be consumed now than before. The insight from this reference mode will then shape the model in this research.

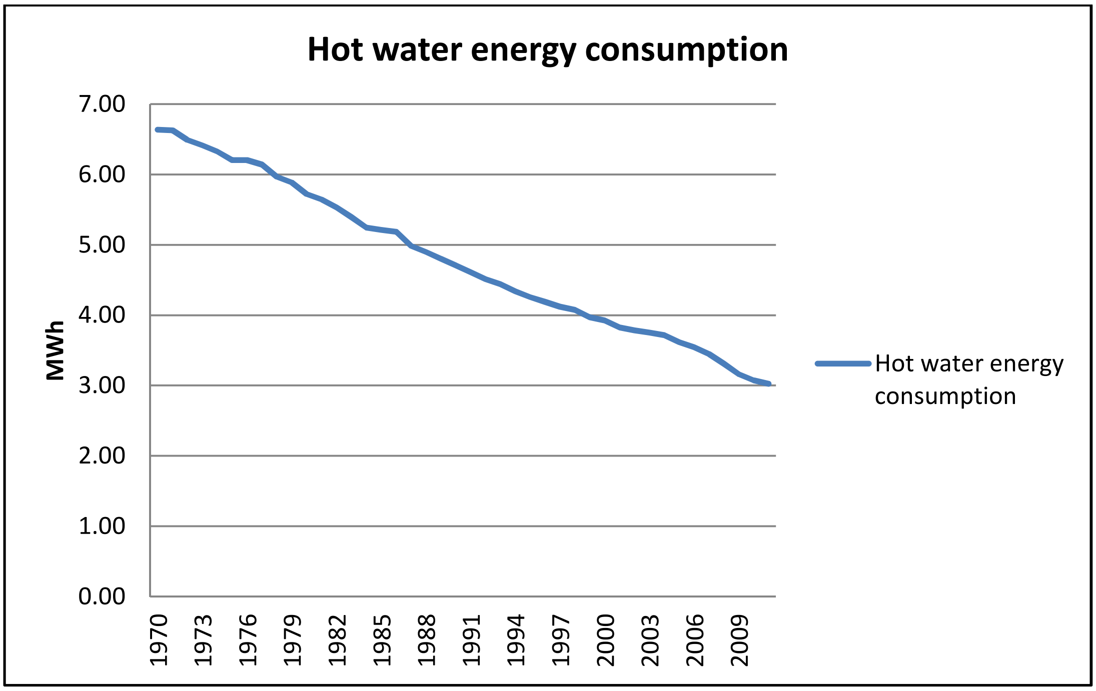


Figure 6.4: Reference mode for household hot water energy consumption (Source: Palmer & Cooper, 2012)

6.4.5 *Cooking Energy Consumption*

The reference mode for cooking energy use in homes as depicts in Figure 6.5 show a more positive changes to occupants' lifestyle as cooking energy consumption has been on the downward trend since 1970. In fact, households cooking energy in 2009 is almost half of what it was in 1970. This shows a tremendous savings in cooking energy. The savings could be attributed to expansion in 'ready-made meals', which made takeaways to thrive. However, the trend shows a significant insight as the decline in cooking energy as from year 2000 appears to be levelling off when compared to the rate of change between 1980s and 1990s.

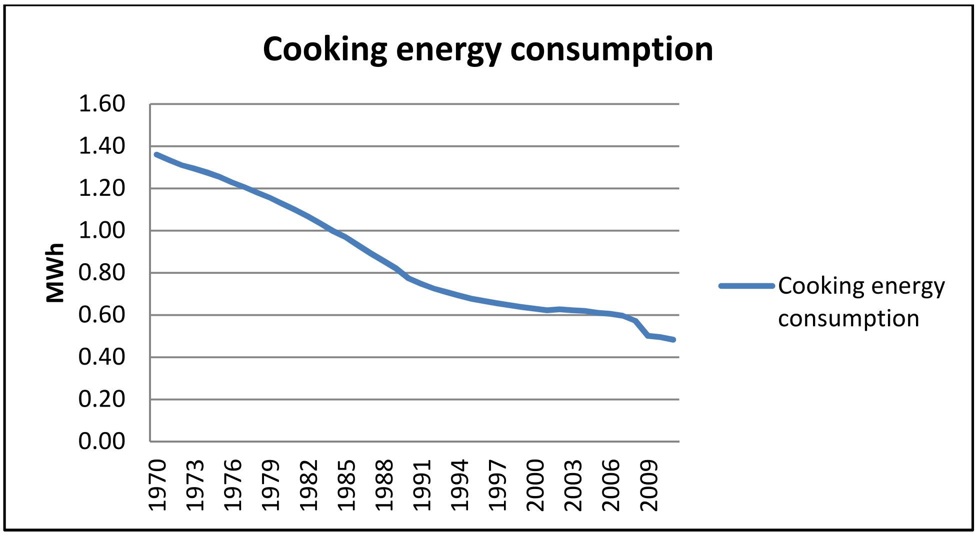


Figure 6.5: Reference mode for household cooking energy consumption

(Source: Palmer & Cooper, 2012)

6.4.6 Lighting Energy Consumption

Undoubtedly, lighting energy has always been a fraction of household total energy. However, the insight from the reference mode as shown in Figure 6.6 indicates that energy use for lighting has been on the increase until year 2002 when it began to decline. The decline reveals attempts by different schemes aimed at reducing household energy use through the use of energy efficient lights in homes.

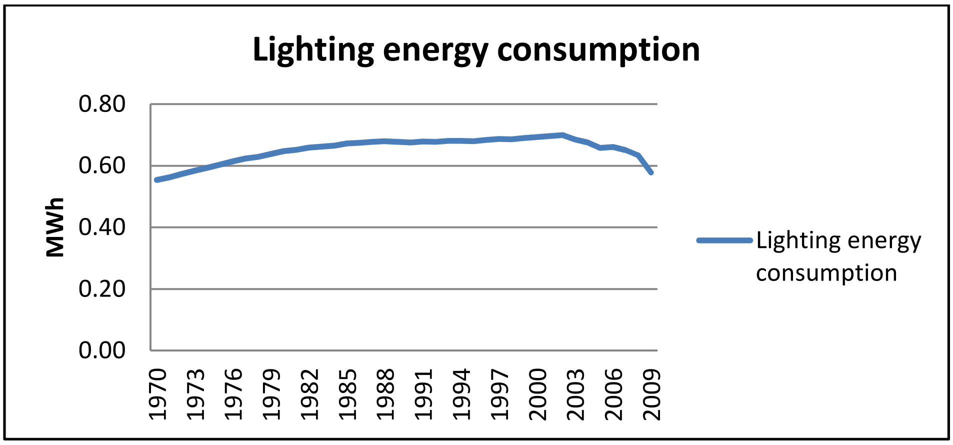


Figure 6.6: Reference mode for household lighting energy consumption

(Source: Palmer & Cooper, 2012)

6.4.7 Appliances Energy Consumption

The reference mode the household appliances energy consumption is shown in Figure 6.7. The trend indicates that since 1970, appliances energy has been on the increase.

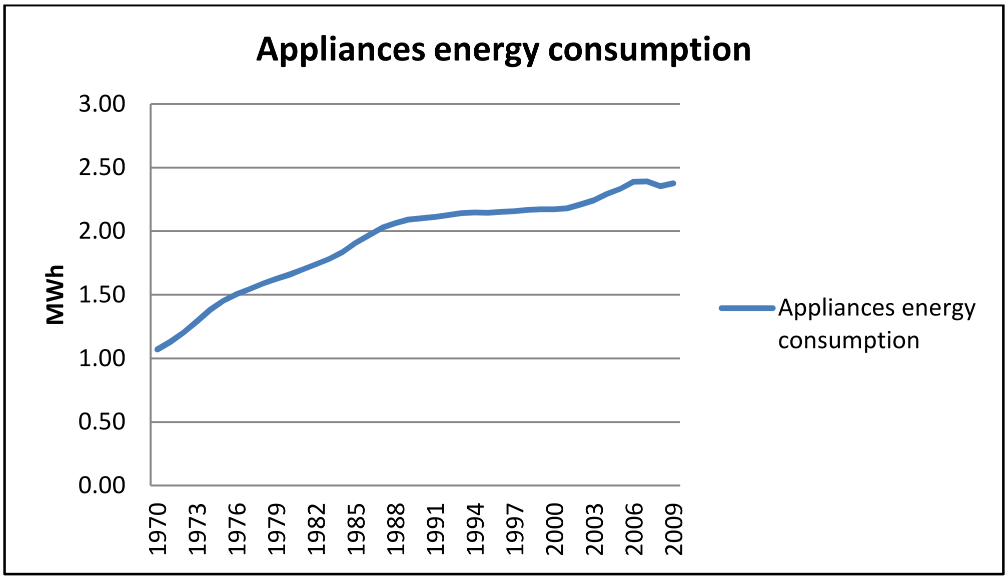


Figure 6.7: Reference mode for household appliances energy consumption

(Source: Palmer & Cooper, 2012)

6.4.8 Average Annual Energy Consumption per Household

The pattern of behaviour of average annual energy consumption per household as shown in Figure 6.8 indicates that it follows the same pattern of behaviour of space heating energy consumption provided in Figure 6.3. This further reinforces the fact that space heating energy actually shapes household energy consumption.

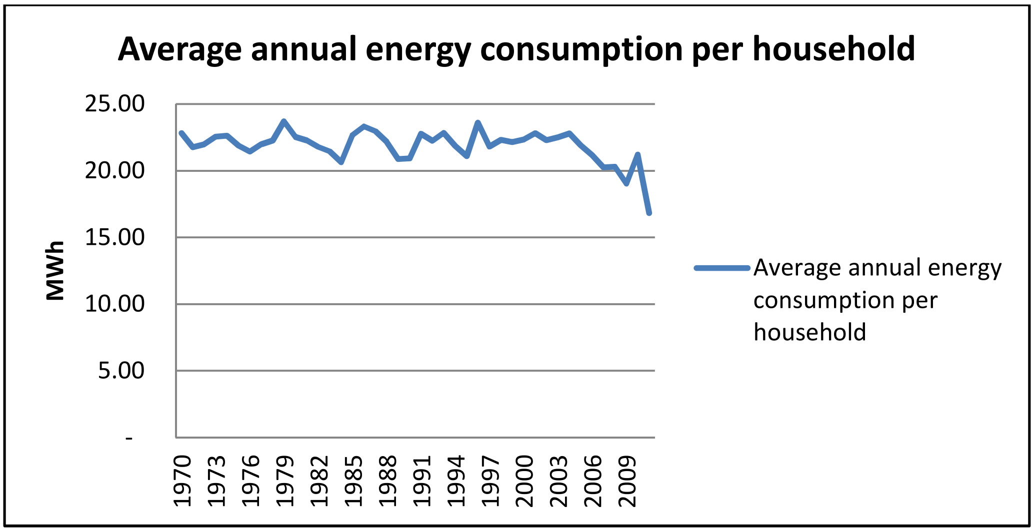


Figure 6.8: Reference mode for average annual energy consumption per household (Source: Palmer & Cooper, 2012)

6.4.9 Average Annual Carbon Emissions per Household

The pattern of behaviour of average annual carbon emissions per household as shown in Figure 6.9 shows that household carbon emission has been on the downward trend since 1970. The profile therefore follows a lumpy trend with peaks and troughs.

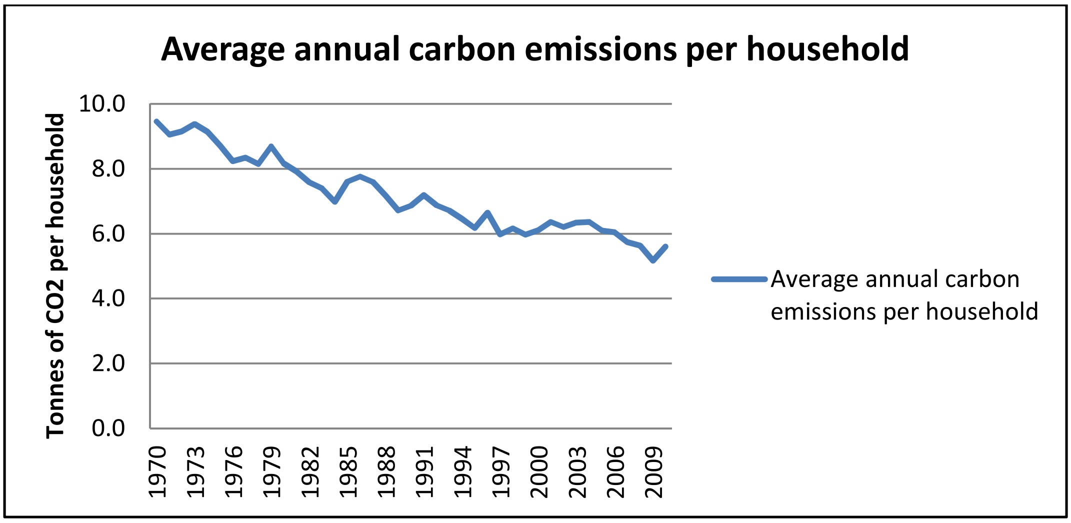


Figure 6.9: Reference mode for average annual carbon emissions per household (Source: Palmer & Cooper, 2012)

6.5 Causal Loop Diagrams (CLDs)

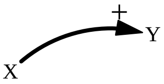
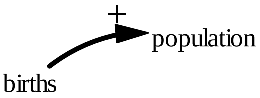
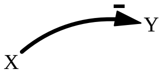
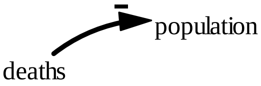
CLDs as dynamic hypotheses are essential tool in SD and they are not only the foundation upon which quantitative models are built but are also a valuable device in their own right for describing and understanding systems (Coyle, 1997). They provide qualitative explanation of the underlying structure operating in a system in the form of 'cause and effect'. According to Sterman (2000), CLDs are used to:

- Quickly capture hypotheses about the causes of dynamics in a system;
- Elicit and capture the mental models of individuals or teams;
- Communicate the important feedbacks believe to responsible for a problem.

CLDs are constructed by incorporating the various variables associated with a system. Casual loops show how each variable relate with one another. That is, the relationship between any two variables is annotated by the use of an arrow connecting them together. A positive relationship means an increase in arrow tail variable would cause an increase in arrow head variable and vice-versa, whereas a negative relationship means an increase in arrow tail variable would cause a decrease in arrow head variable and vice-versa. This relationship polarity is illustrated with symbol, interpretation, mathematics, and examples as shown in Table 6.3 based on the work of Sterman (2000).

Dynamics exhibited by the system under study are achieved based on the feedback loops of the CLDs. As such, feedback loops can be positive or negative. Positive feedback loops (reinforcing loops) denote that the system increase or decrease indefinitely, whereas negative feedback loops (balancing loops) stabilise over time. Loops polarity is achieved by summing up the negative polarity of each of the variables within such a loop.

Table 6.3: Relationship polarity

Symbol	Interpretation	Mathematics	Examples
	All else equal, if X increases (decreases), then Y increases (decreases) above (below) what it would have been. In the case of accumulations, X adds to Y.	$\frac{\partial Y}{\partial X} > 0$ In the case of accumulations, $Y = \int_{t0}^{t} (X + \cdots) ds + Yo$	
	All else equal, if X increases (decreases), then Y decreases (increases) below (above) what it would have been. In the case of accumulations, X subtracts from Y.	$\frac{\partial Y}{\partial X} < 0$ In the case of accumulations, $Y = \int_{t0}^{t} (-X + \cdots) ds + Yo$	

(Adapted with some modifications from Sterman, 2000)

The development of CLDs has its own sets of rules and guidelines to follow. To this extend, Pruyt (2013) provides the guidelines for drawing CLDs as the following:

- Make different types of CLDs for different purposes/audiences/uses (conceptualisation, loop analysis, communication,…) and at different levels of aggregation.
- Choose the right level of aggregation (but never too detailed) dependent on the intended use/goal/audience.
- Iterate, use SD software to redraw your diagrams.

- Use nouns or noun phrases with a clear (positive) sense of direction as variable names. Choose variable names that, together with the causal links and polarities, enable to easily “read the loops”.
- Don’t use/conjugate verbs in variable names. The arrows with their polarities perform the role of verbs when reading a CLD.
- Links between variables are causal and direct, not correlational nor indirect.
- Unambiguously label link polarities (split out links into different effects if polarities are ambiguous).
- Links should be drawn/interpreted under the *ceteris paribus* assumption, *i.e.* that everything else remains the same.
- Links are relative: they tell the value of the variable will be above/below what it would have been without the effect.
- Explicitly include the goals of goal-seeking loops.
- Distinguish between actual versus perceived conditions.
- Trace and unambiguously label loop polarities, and name loops such that they immediately convey their role, and that the names can be used in texts/presentations.
- Indicate important delays on causal links
- Use curved lines, make important loops circular, and minimise crossed lines.
- For communication purposes, don’t use too large a diagram with too many loops.
- Don’t try to make comprehensive or final CLDs: they will never be. They are either conceptualisation tools or tools to communicate (specific) messages.
- Draw CLDs from different angles/perspectives and at different levels of aggregation.
- It is useful to integrate points of view in one and the same CLD, unless the points of view represent fundamentally different or irreconcilable world views. Then, different CLDs need to be draw.

In this study CLDs are constructed for each of the modules in the model based on the methods explained in Chapter four and Section 6.2. All of them are therefore interlinked. CLDs for each of the modules are presented in the next sub-sections.

6.5.1 CLD for Population/Household Module

Figure 6.10 shows a combination of positive and negative loops involving some of the variables hypothesised to drive population and hence households. The positive loop could be read as “the more the people, the more the births there will be; the more births there are, the more people there will be”. Alternatively, this could be read as “the fewer people there are, the fewer births there will be; the fewer births there are, the fewer people there will be”.

The model postulates that the number of births is based on the number of deaths, reproductive time, population equilibrium time, average total fertility rate, and of course population as well. The positive or reinforcing feedback shows that population will continue to grow or decline as births continue to grow or decline respectively. However, the negative or balancing loop involving population and deaths will act to stabilize and balance the system from continual increamemt or decreament as the case may be. It needs to mention that population drives deaths and vice – versa. Also, average life expectancy drives mortality, and mortality in turn drives deaths.

The expected behaviour of the output of this module will be based on the interaction of the loops as we have multi-loops in this module. Some of the loops may be dominant. For example, if the positive loop is a dominant one; it may mean that population will continue to grow, though the rate of growth may vary. However, if the negative loop is the dominant one, it means that as deaths continue to grow, population may decline until such a time that the total population will go into extinction and there will be no households which is the major output of this module.

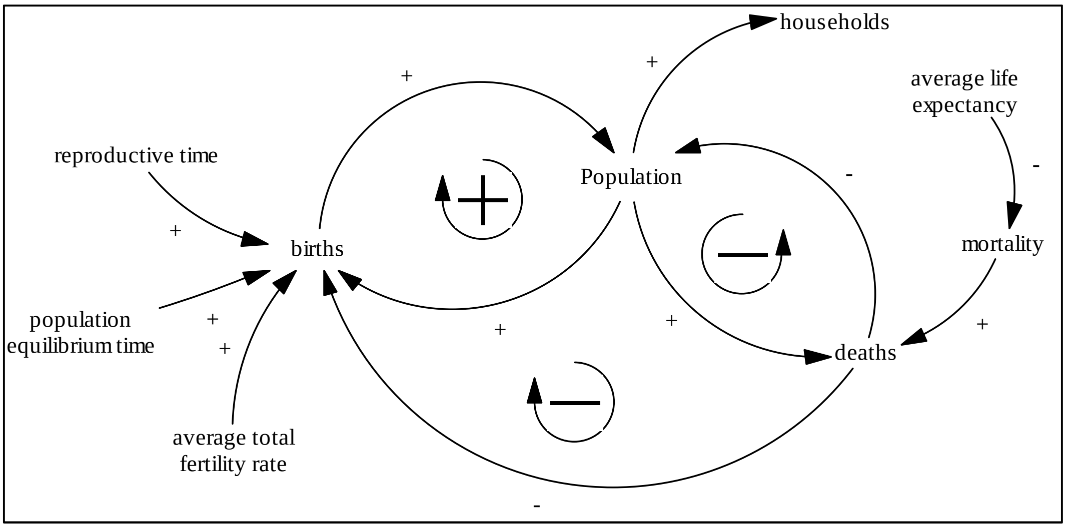


Figure 6.10: CLD for population/household module

6.5.2 CLD for Dwelling Internal Heat Module

CLD for dwelling internal heat module is presented in Figures 6.11. The structure shows the thermodynamics of dwelling internal heat based on interaction and inter-dependencies of different variables hypothesised to be driving it. For example, natural and artificial heat transfers in dwelling as well as Dwelling Heat Gains (DHGs) are identified as the main variables hypothesised to be driving dwelling internal heat. That is, gaps (in terms of change in temperature) identified as a result of change in dwelling internal and external temperature dictate whether or not heat will flow into or out of the dwelling.

Similarly, artificial heat transfer within the dwelling is regulated according to the temperature set-point and dwelling internal temperature and this accordingly drives the dwelling internal heat. Further to these, DHGs is a function of heat gains from many sources as indicated in Figure 6.11 (DHG due to no of people, DHG due to appliances, DHG due to cooking, DHG due to water usage, DHG due to artificial lighting, and solar gains). However, heat losses due to infiltrations and the likes reduce the DHGs.

In needs to emphasise that the dwelling internal heat drives the dwelling internal temperature, which in turn, in combination with some other environmental factors, dictates the perceived dwelling temperature by the occupants. Within this module, two loops of a positive and a negative feedback loops are constructed as shown in Figure 6.11. As previously discussed under Section 6.5.1 above, the positive feedback loop indicates that dwelling internal heat will continue to increase or decline, while the negative feedback loop sets out to stabilise and balance the system over time based on the effect of artificial heat transfer in dwelling.

The expected output behaviour could be S – shaped behaviour due to the interaction of asymptotic growth (negative feedback) with exponential growth (positive feedback). Though, the non-linear behaviour could be shifted and regulated according to loop predominance as discussed in Section 6.5.1 above, and hence the behaviour may not be S – shaped as postulated above.

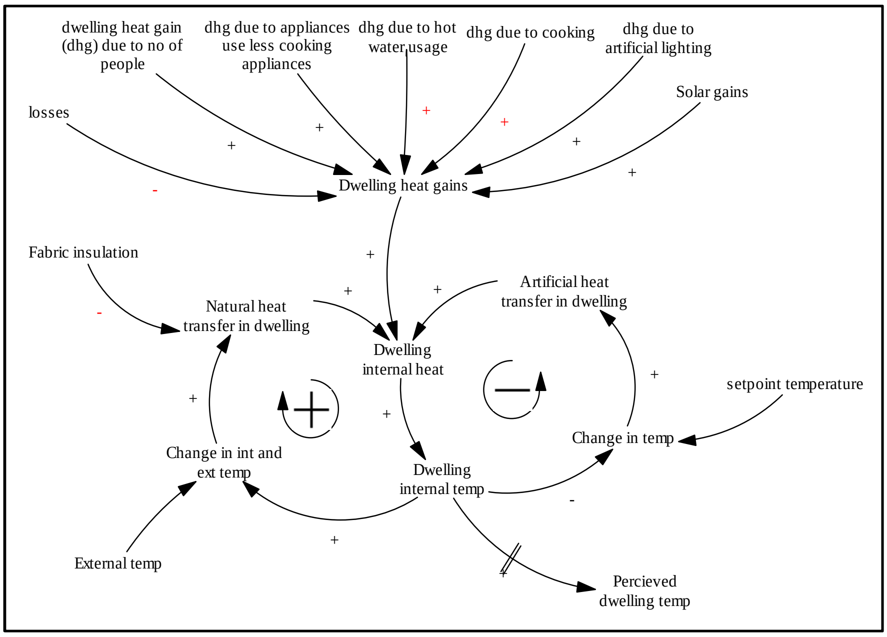


Figure 6.11: CLD for dwelling internal heat module

6.5.3 CLD for Occupants' Thermal Comfort Module

CIBSE (2006a) divides thermal environment of occupants in dwellings into three broad categories to include thermal comfort, thermal, discomfort, and thermal stress. According to the International Standard Organisation (ISO) 7730 (ISO, 1994), the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) (ASHRAE, 2004), and CIBSE (2006a), thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment". That is, the condition when someone is not feeling either too hot or too cold. Thermal discomfort, however, expresses the condition when people start to feel uncomfortable, but without any unwell conditions (CIBSE, 2006a). Similarly, thermal stress gives uncomfortable conditions to occupants which have the potential of causing harmful medical conditions.

The occupants' thermal environment is not straight forward and cannot be expressed in degrees nor can it be satisfactorily defined by acceptable temperature ranges. This is a personal experience dependent on a great number of variables, which is likely to be different from person to person within the same space. These variables can be (1) environmental – air temperature, relative humidity, air velocity, radiant temperature; (2) personal – clothing, metabolic heat; (3) other contributing variables – access to food and drink, acclimatisation, state of health.

In this module, we produce a causal model of different variables hypothesised to affect occupants' thermal comfort herein refers as occupants' comfort. We postulate that the major variables that drive occupants' comfort here are "occupants' activity level" and "perceived dwelling temperature". It needs to mention that "perceived dwelling temperature" is at the heart of this causal model with five different inflows from "relative humidity", "dwelling internal temperature", "occupants' activity level", "probability of putting on clothing", and "probability of windows opening". All these variables are interrelated in a non–linear way and work seamlessly together as shown in Figure 6.12. A total of three different feedback loops (with two negative and a positive feedback loops) are constructed for the module.

The first balancing feedback loop involves [occupants' comfort – probability of putting on clothing – perceived dwelling temperature], while the second one takes the following variables [occupants' activity level – occupants metabolic build-up – probability of putting on clothing]. Additionally, the reinforcing loop involves [occupants' comfort – probability of windows opening – perceived dwelling temperature]. The behaviour of the model is expected to be predominately dictated by the multi-loops within the CLD.

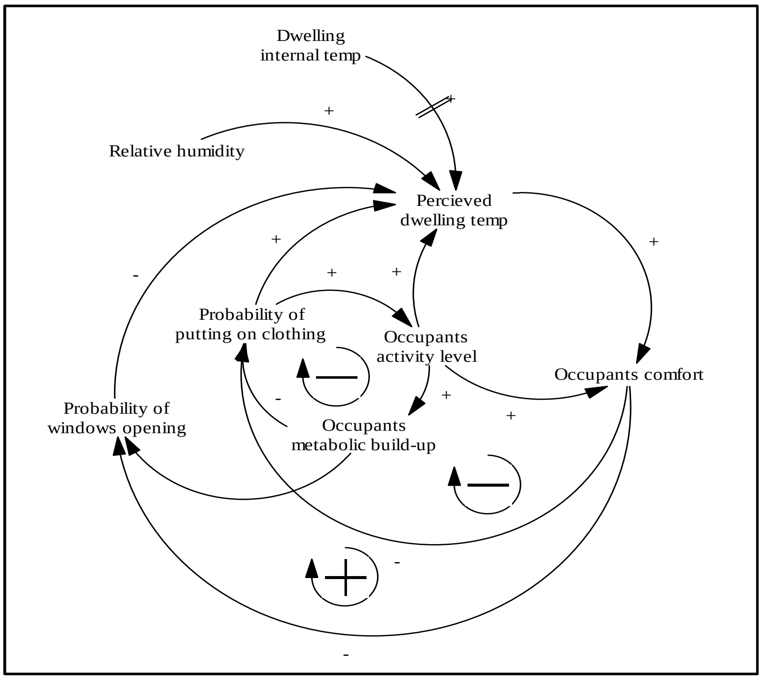


Figure 6.12: CLD for occupants' thermal comfort module

6.5.4 CLD for Climatic – Economic – Energy Efficiency Interaction Module

There are a series of variables in climatic, economic, and energy efficiency domains interacting together in a complex manner to influence and consequently affect household energy. These variables are defined by this research and not limited to climatic effects as a result of adverse weather condition; influence of international fuel prices as a major variable triggering Government's policy regarding energy tax, alternative energy sources, subsidy on alternative energy sources, energy prices, *etc*.; energy efficiency of dwellings, fabric insulation, and household income, and their effects on variables like household fuel poverty.

However, not all the above-mentioned variables are included in this module due to consideration of ease of data for the simulation later and the need to keep the model as simple as possible. To this end, Figure 6.13 shows the interrelationships among the climatic – economic – energy efficiency variables that are included in the model. Dwelling energy are considered from two perspectives of fabric insulation and its effects on energy efficiency, and Government's Standard Assessment Procedure (SAP) rating of dwellings and its effects on dwelling energy efficiency as well. It was assumed that the effect of energy efficiency standard improvement on dwelling energy efficiency will improve energy efficiency standard of cooking energy as well as lighting and appliances energy. This is because it is believed that the efficiency standards of these areas make up the Government's SAP rating of dwellings. Furthermore, it was hypothesised that the combined effect of fabric insulation and energy efficiency standard of dwellings will increase the effect of dwelling energy efficiency on energy bills, which undoubtedly will affect space heating and hot water energy use.

Effect of energy bills on energy consumption generally is postulated to be as a result of three different variables that include average annual energy bills in terms of gas and electricity bills, effect of dwelling energy efficiency on energy bills, and effect of unfavourable climatic effects on energy prices. It is further hypothesised that the accumulation of carbon emissions is likely to trigger unfavourable climatic effects under the assumption that this will not be sudden; hence an introduction of a delay function before this happens. Feedback loops cannot be seen from this structure as represented in Figure 6.13. However, these will definitely show up when this module interrelates with other modules as it will be seen in Section 6.5.5.

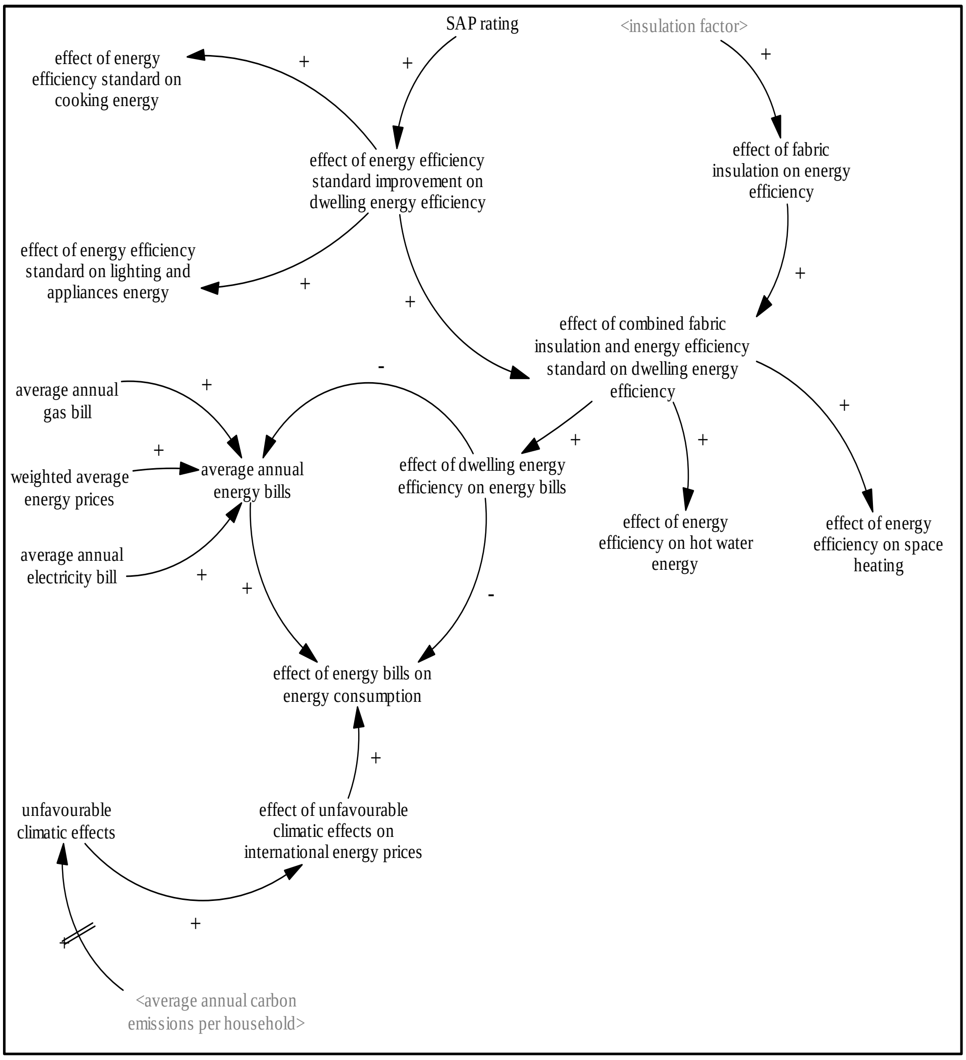


Figure 6.13: CLD for climatic – economic – energy efficiency module

6.5.5 CLD for Household Energy Consumption and CO_2 Emissions Modules

This section combines household energy consumption and CO_2 emissions modules together in order to depict the complex interrelationships ensuing among the variables of these modules. The structure of the CLD for these modules show the variables that are hypothesised to drive household energy consumption and carbon emissions based on five different household energy end–uses. These include energy use for space heating, hot water, appliances, cooking, and lighting. The CLD is therefore developed for each of these household energy end-uses and are interlinked to depict the main feedback loops dictating the behaviour of the outputs.

Figure 6.14 shows the CLD involving all the household energy end-uses considered in the research that include space heating, hot water, cooking, lighting, and appliances energy. By taking the loops involving space heating energy consumption for example, the CLD (Figure 6.14) indicates that there are many variables hypothesised to be driving the rate of space heating by occupants or householders. Obviously, these variables include dwelling internal temperature and set-point temperature from dwelling internal heat module; occupants comfort (from occupants thermal comfort module) driving space heating demand, and space heating demand in turn propelling the rate of space heating; effect of energy efficiency on space heating and effect of energy bills on energy consumption (from climatic – economic – energy efficiency interaction module); and of course, occupants behaviour.

It was hypothesised that rate of space heating drives space heating energy consumption, and the consumption drives space heating carbon emissions. Carbon emissions from different household energy end-uses contribute to average annual carbon emission per household, which is assumed to reinforce unfavourable climatic effects under delay function as discussed under Section 6.5.4. It is important to note that there was an assumption that not all carbon emitted to the atmosphere will cause unfavourable climatic effects as some of them will be depleted from the atmosphere by different means like absorption by plants and the likes. Carbon depletion factor was introduced to take care of carbon depletion as shown in Figure 6.14. Discussions of other household energy end-uses are not much differ from above as discussed for space heating energy.

Obviously, the outcome of the CLD expressed in Figure 6.14 is expected to exhibit a non-linear behaviour because of a combination of different loops as shown. However, loops predominance is likely to moderate the outputs from the model.

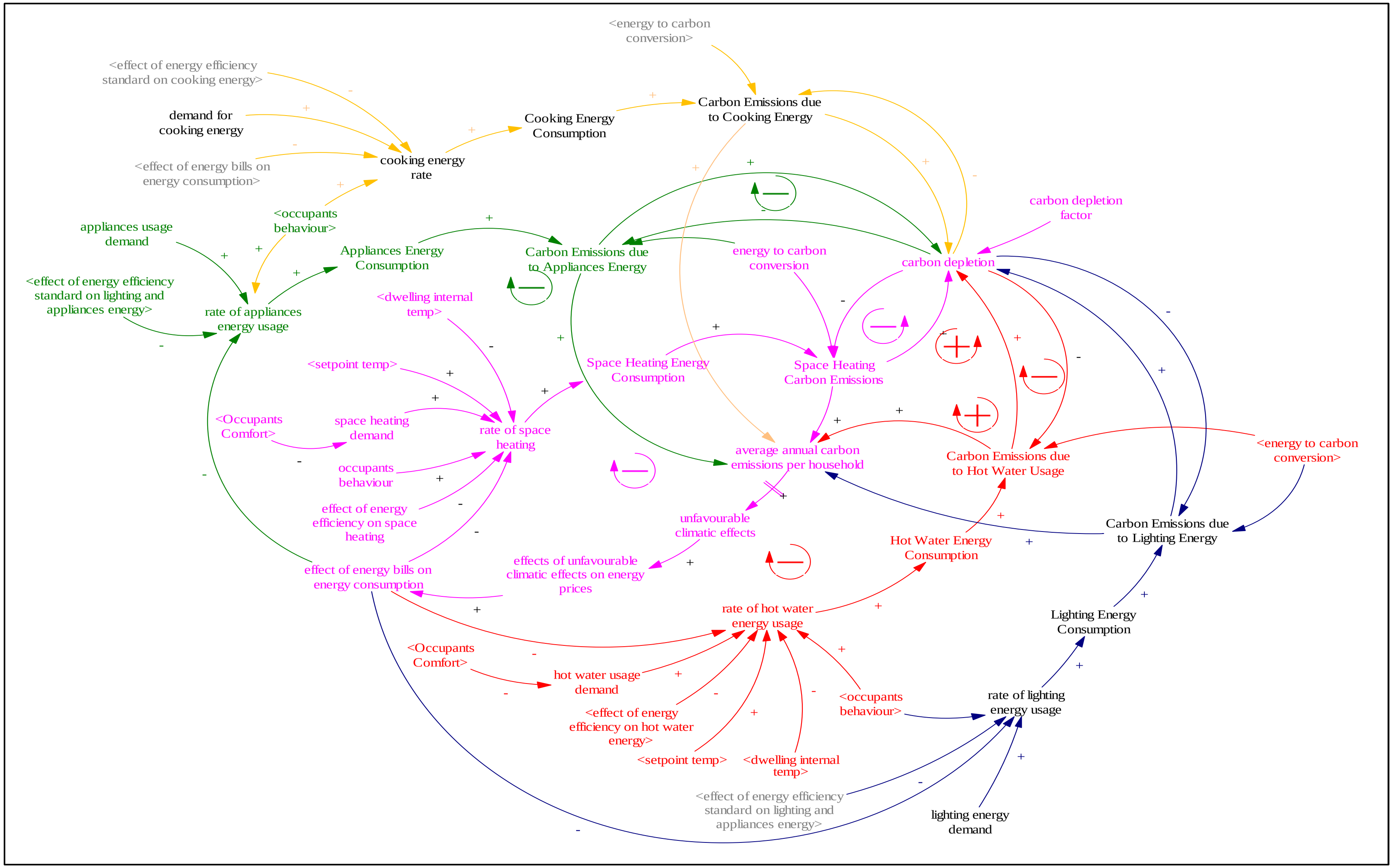


Figure 6.14: CLD for household energy consumption and CO_2 emissions

6.6 Model Formulation

The dynamic hypotheses (CLDs) are useful, without any iota of doubt, in many situations. They capture the mental models of interdependencies and feedback processes of a given modelling exercise. However, they suffer from a number of limitations among which are their inability to capture the stock and flow structure of systems (Sterman, 2000). Hence, there is the need for SFDs for the models as they are, according to Sterman (2000), the two central concepts of dynamic systems theory. At this stage, the variables/parameters in the causal relations developed are transformed into SFDs. The SFDs distinguish the model parameters into the controlling ‘flow’ acting as regulators and ‘stock’ where accumulations take place. Accumulations characterise the state of the system and generate information upon which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. By decoupling rates of flow, stocks are the source of disequilibrium dynamics in systems. The parameters in the model are linked together with equations in preparation for simulation. It is necessary to restate that the models in this research is built and implemented using the SD software Vensim DSS for Windows Version 5.11A produced by The Ventana Simulation Environment. The next sub-sections describe the SFDs for each of the modules in the model.

6.6.1 Population/Household Module

In a bid to estimate energy consumption and CO_2 emissions per household, it is expedient to model the number of households in the UK. Based on the regression analysis performed on historical data of UK population and households, a significant relationship was found between the two. Hence, the research utilised the model of population to estimate the number of households in the UK. Population is being influenced by a number of variables. In this model, a limited number of variables are considered which include, birth and death rates, reproductive time, population equilibrium time, average total fertility rate, mortality and average life expectancy as shown in Figure 6.15.

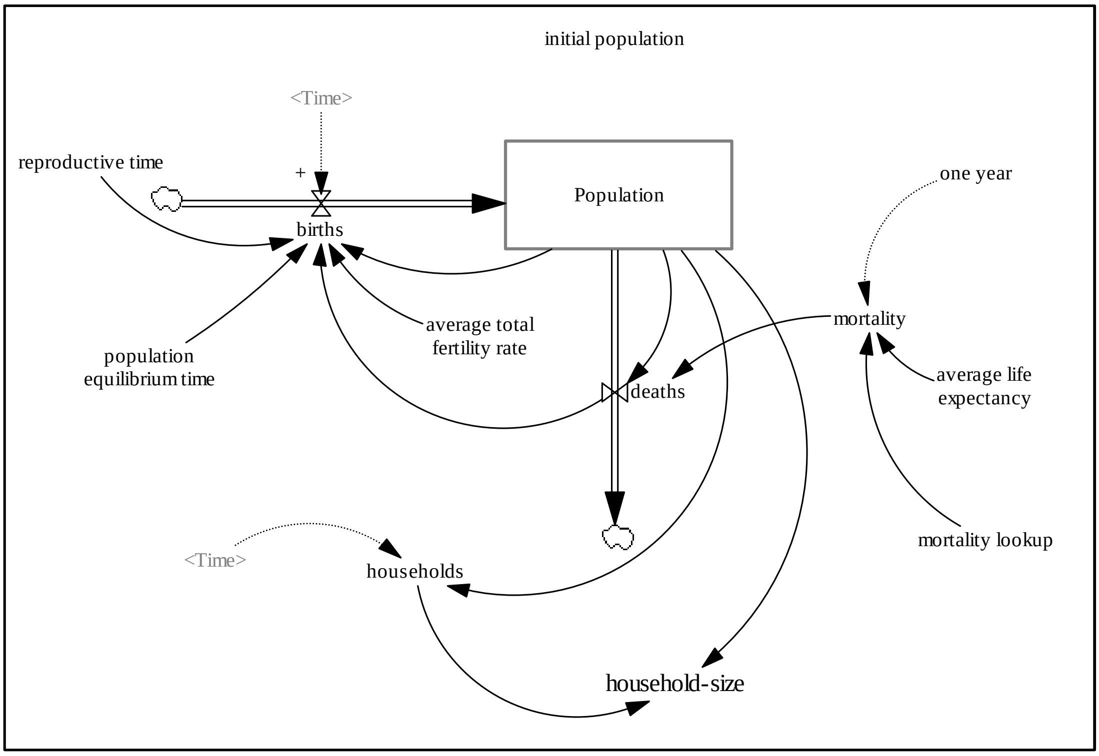
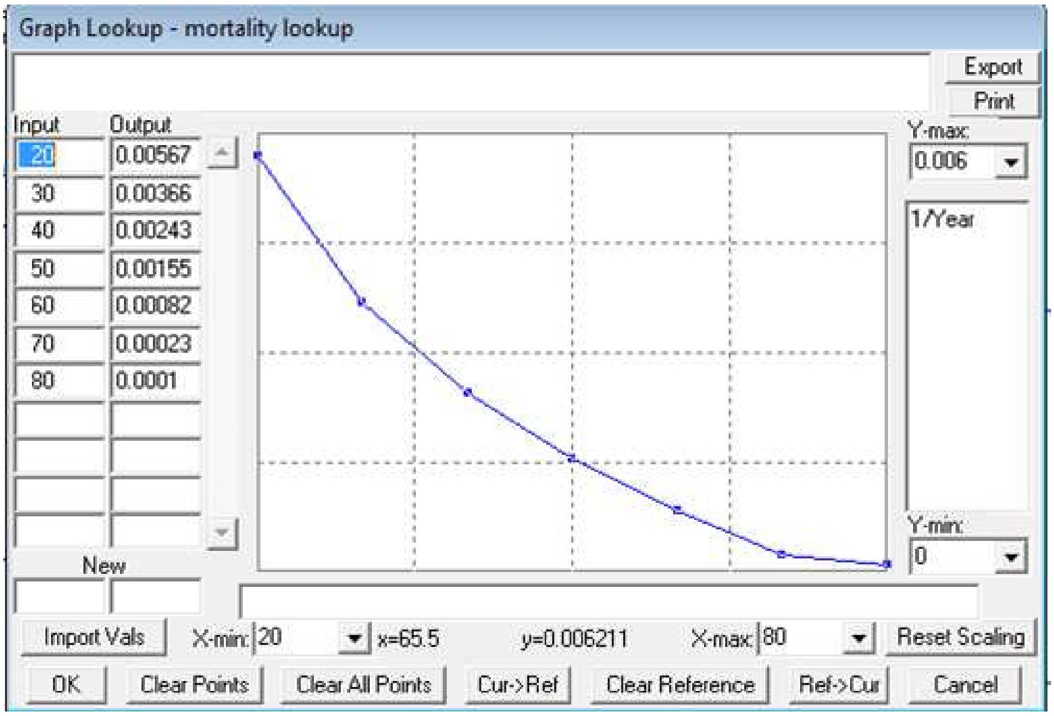


Figure 6.15: SFD for population/household module

Population is modelled as 'stock'. This is being controlled by an inflow (births) and an outflow (deaths). 'Births' is influenced by 'reproductive time', 'population equilibrium time', 'average total fertility rate', and 'deaths'. On the other hand, 'deaths' is determined primarily by 'mortality' rate. 'Mortality' is generated based on 'average life expectancy' and 'mortality lookup' profile. 'Mortality lookup' is one of the variables in the model that is based on qualitative data of relying on experts' judgement as well as information from literature. Relating together different variables in this sector of the model involves generating a set of equations by employing both regression analysis and tools within the system dynamics software (Vensim). For example, equation 6.1 shows the Vensim interpretation of 'Population' acting as the stock with 'births' as inflow (rate) and 'deaths' as outflow (rate). This equation is automatically generated by the software. However, the equation for 'births' (see eq. 6.2) was developed based on little adjustment to the similar equation developed by Forrester (1971) for his World Dynamics model. The adjustment made was mainly to reflect the number of years from the last year of data (which in this case is 2011) and the last year of model run (which in this case is 2050), which translates to 39 years.

Additionally, ‘mortality’ (see eq. 6.4) is determined based on the profile of mortality rate that is qualitatively captured as ‘mortality lookup’ according to available data from the Office of National Statistics as shown in Figure 6.16. ‘Households’ is determined based on regression analysis as shown in Table 6.4. The main data source for the development of this algorithm (population and household) is shown in Table 6.5. Therefore, equations (6.1) to (6.6) give the major equations developed for this module. It needs to further state that the model is run from the year 1970 to 2050 and initial population corresponds to population in the year 1970. The complete set of equations can be found in Appendix A.



Graph Lookup - mortality lookup

Input	Output
20	0.00567
30	0.00366
40	0.00243
50	0.00155
60	0.00082
70	0.00023
80	0.0001

Y-max: 0.006

1/Year

Y-min: 0

X-min: 20

x=65.5

y=0.006211

X-max: 80

Figure 6.16: Mortality lookup

Table 6.4: Relationship developed for households from regression analysis

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-3.436E8	4538500.746		-75.712	.000
	Population	.067	.017	.056	3.886	.000
	Time	182057.612	2746.898	.947	66.278	.000

Dependent Variable: Households

Table 6.5: Sample data for households and population

Variable	**Unit of Measurement**	**Minimum**	**Maximum**	**Mean**	**Standard Error**	**Standard Deviation**
Households	Households	18791000	26863000	2.2664E7	3.63850E5	2.35802E6
Population	People	55632000	62736000	5.7931E7	3.00346E5	1.94646E6

$$Population\ (t) = INTEGRAL\ [births - deaths,\ population\ (t_0)] \qquad (Eq.\ 6.1)$$

$$births = \begin{cases} IF\ THEN\ ELSE\ (Time = population\ equilibrium\ time, deaths, \\ IF\ THEN\ ELSE\ (Time \leq 2011, average\ total\ fertility\ rate * Population \\ * 0.08/reproductive\ time, \\ FORECAST\ (average\ total\ fertility\ rate * Population * 0.08/reproductive\ time, 39, 100))) \end{cases}$$

$$(Eq.\ 6.2)$$

$$deaths = Population * mortality \qquad (Eq. 6.3)$$

$$mortality = mortality\ lookup\ (average\ life\ expectancy/one\ year) \qquad (Eq. 6.4)$$

$$households = -3.436e008+182058 * Time + 0.067 * Population \qquad (Eq.6.5)$$

$$household\ size = Population/households \qquad (Eq.6.6)$$

6.6.2 Dwelling Internal Heat Module

The structure of this module in the form of SFD is shown in Figure 6.17. Dwelling internal heat is modelled as an accumulation of natural and artificial heat transfers (which are modelled as flows). Natural heat transfer is driven by the dwellings' insulation level, internal and external temperature. Similarly, artificial heat transfer is propelled by total dwelling heat gains (DHGs), dwelling's temperature set-point, and internal temperature. Temperature conversion factor was used to convert dwelling internal heat measured in Watts to degree centigrade. However, DHGs were estimated based on the procedure and formulae of the Government's SAP as published by the Building Research Establishment (BRE) on behalf of DECC (BRE, 2012). As such, DHGs due to cooking, number of people, appliances, artificial lighting, hot water, and solar gain effects were included in the calculation. Likewise, heat losses from the dwelling fabric were estimated based on the procedure of SAP and this amount was deducted from the total DHGs. To this extent, equations 6.7 to 6.12 are based on the formulae provided by SAP (equations appear on page 22 and Table 5 of page 145 of BRE, 2012). The remaining equations 6.13 and 6.14 show the equations developed for the level variable 'dwelling internal heat' and 'total dwelling heat gains' respectively. The only data driving this module is 'external air temperature', which is yearly average for the UK as summarily shown in Table 6.6.

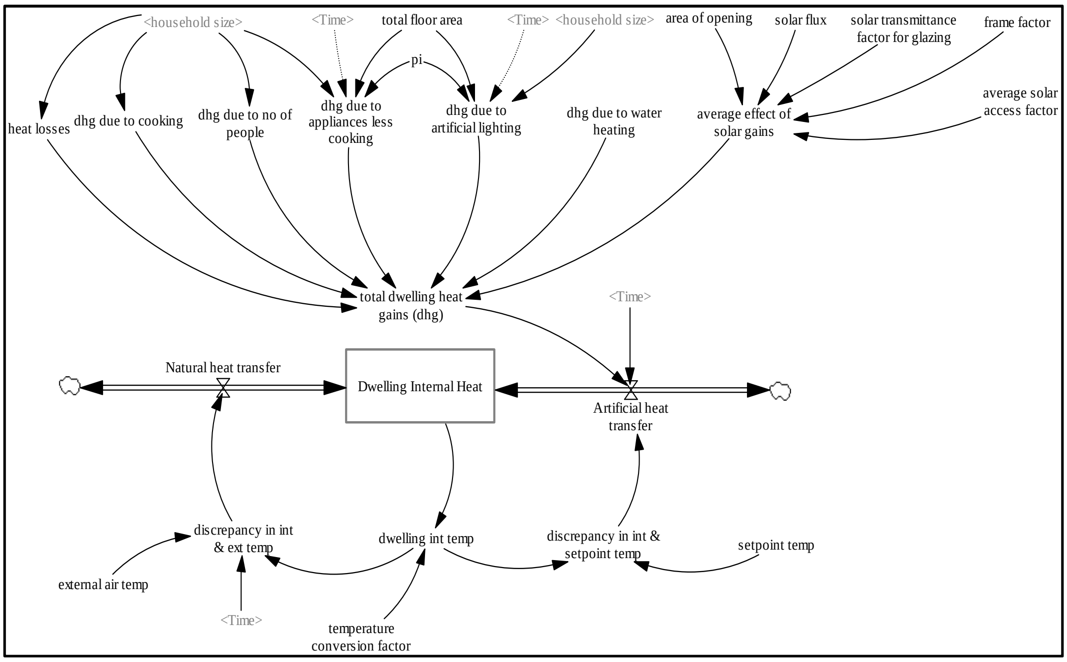


Figure 6.17: SFD for dwelling internal heat module

*heat losses = -40*household size* *(Eq. 6.7)*

*dhg due to cooking = 35+(7*household size)* *(Eq. 6.8)*

*dhg due to people = 60*household size* *(Eq. 6.9)*

dhg due to appliances less cooking = (207.8(total floor area*household size)*EXP(0.4714))*(1+0.157*COS(2*pi*(Time-1.178)))*1000/60* *(Eq. 6.10)*

dhg due to artificial lighting = (59.73(total floor area*household size)^0.4714)*0.96^2*(1+0.5*COS(2*pi*(Time-0.2)))*0.85*1000/(24*30*12)* *(Eq. 6.11)*

*average effect of solar gains = 0.9*area of opening*frame factor*average solar access factor*solar flux*solar transmittance factor for glazing* *(Eq. 6.12)*

Dwelling internal heat (t) = INTEGRAL [natural heat transfer + artificial heat transfer, dwelling internal heat (t_0)] *(Eq. 6.13)*

Total dwelling heat gains = (DHG due to appliances less cooking + DHG due to artificial lighting + DHG due to cooking + DHG due to no of people + DHG due to water heating + average effect of solar gains - heat losses) *(Eq. 6.14)*

Table 6.6: Sample data for external air temperature

Variable	**Unit of Measurement**	**Minimum**	**Maximum**	**Mean**	**Standard Error**	**Standard Deviation**
External air temperature	Degree centigrade	8.06	10.80	9.78	0.10	0.69

(Source: Palmer & Cooper, 2012)

6.6.3 Occupants Thermal Comfort Module

There are a great number of techniques for estimating likely thermal comfort, including; effective temperature, equivalent temperature, wet bulb globe temperature, resultant temperature and so on' and charts exist showing predicted comfort zones within ranges of conditions. However, ISO 7730 (ISO, 1994) suggests thermal comfort can be expressed in terms of predicted mean vote (PMV) and percentage people dissatisfied (PPD). These were developed by Professor Ole Fanger (Fanger, 1970) by using the principles of heat balance equations and empirical studies regarding the skin temperature in order to define thermal comfort. In line with the PMV and PPD, the Chartered Institution of Building Services Engineers (CIBSE) (CIBSE, 2006a; 2006b) recommended comfort criteria for specific applications in certain areas of the dwellings in terms of temperature, occupants' activity, and clothing levels. For example, the guide

(CIBSE, 2006b) stipulates a winter operating temperature of 17 – 19^{0}C, activity of 0.9 met., and clothing level of 2.5 clo., for bedrooms.

In building a SFD for this module, the criteria as set out by CIBSE (2006b) was employed and this is presented in Figure 6.18. Both the ‘occupants comfort’ and ‘occupants’ metabolic build-up’ were modelled as stock based on equations (6.15) and (6.16). Accumulation of ‘occupants comfort’ stock, for example, is driven by the ‘perceived dwelling temperature’ (inflow). This is in turn depends on a number of factors like humidex value, clothing, windows opening within the dwelling as well as occupants metabolic build-up. ‘Humidex value’ was modelled from the dwelling internal temperature and relative humidity based on Figure 6.19 which shows different ranges of humidex value for different degrees of comfort by qualitatively mimic it with the use of lookups within the model. As shown in Figure 6.18, the ‘probability of window opening’ and ‘probability of putting on clothing’ by occupants were determined qualitatively using lookups as shown in Figures 6.20 and 6.21 respectively according to the mental data collected from the interviewees at model conceptualisation stage (see Section 4.4.1). The main data driving this module are from relative humidity (summary shown in Table 6.7), which is externally sourced and internally generated data from the previous module (*i.e.* internal dwelling temperature) Examples of equations developed for this module is shown in equation (6.17- 6.19).

Table 6.7: Sample data for relative humidity

Variable	Unit of Measurement	Minimum	Maximum	Mean	Standard Error	Standard Deviation
Relative humidity	Percentage	67	94	85.09	1.32	8.67

(Source: Met Office, 2013)

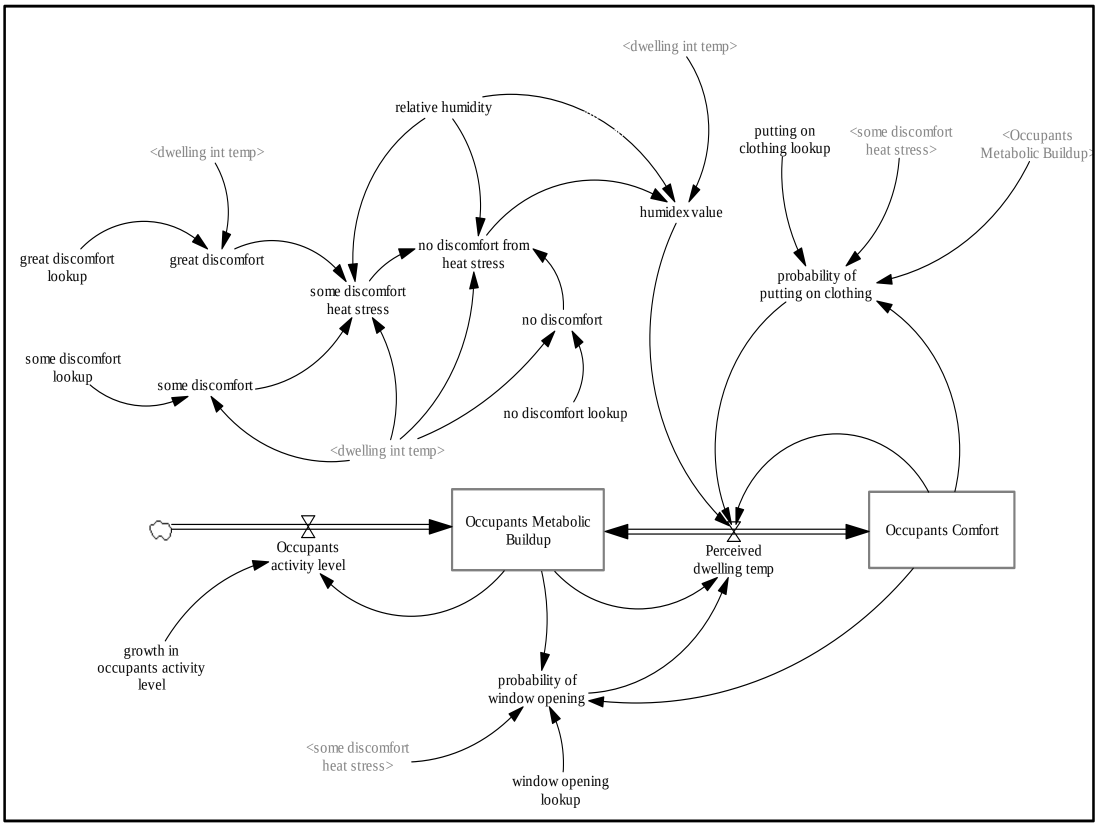
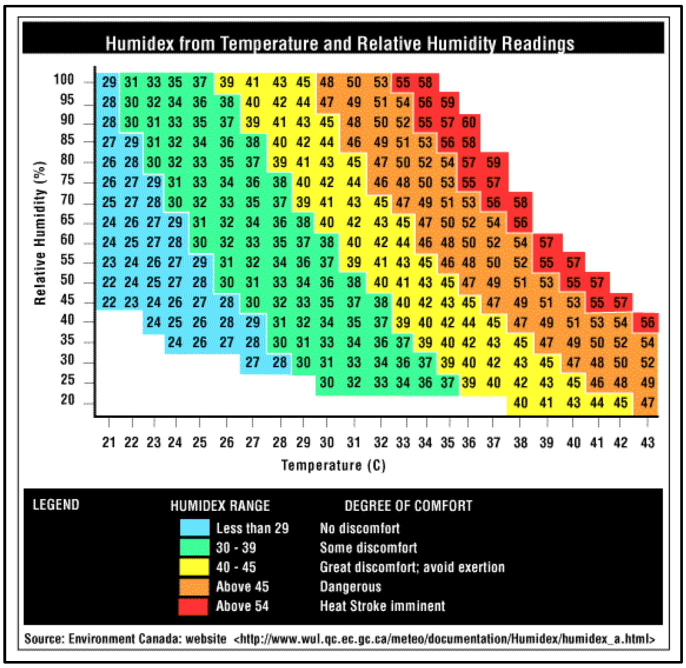


Figure 6.18: SFD for occupants thermal comfort module


Humidex from Temperature and Relative Humidity Readings

Relative Humidity (%)	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
100	29	31	33	35	37	39	41	43	45	48	50	53	55	58									
95	28	30	32	34	36	38	40	42	44	47	49	51	54	56	59								
90	28	30	31	33	35	37	39	41	43	45	48	50	52	55	57	60							
85	27	29	31	32	34	36	38	40	42	44	46	49	51	53	56	58							
80	26	28	30	32	33	35	37	39	41	43	45	47	50	52	54	57	59						
75	26	27	29	31	33	34	36	38	40	42	44	46	48	50	53	55	57						
70	25	27	28	30	32	33	35	37	39	41	43	45	47	49	51	53	56	58					
65	24	26	27	29	31	32	34	36	38	40	42	43	45	47	50	52	54	56					
60	24	25	27	28	30	32	33	35	37	38	40	42	44	46	48	50	52	54	57				
55	23	24	26	27	29	31	32	34	36	37	39	41	43	45	46	48	50	52	55	57			
50	22	24	25	27	28	30	31	33	34	36	38	40	41	43	45	47	49	51	53	55	57		
45	22	23	24	26	27	28	30	32	33	35	37	38	40	42	43	45	47	49	51	53	55	57	
40			24	25	26	28	29	31	32	34	35	37	39	40	42	44	45	47	49	51	53	54	56
35				24	26	27	28	30	31	33	34	36	37	39	40	42	43	45	47	49	50	52	54
30							27	28	30	31	33	34	36	37	39	40	42	43	45	47	48	50	52
25										30	32	33	34	36	37	39	40	42	43	45	46	48	49
20																		40	41	43	44	45	47

Temperature (C)

LEGEND

	HUMIDEX RANGE	DEGREE OF COMFORT
🟦	Less than 29	No discomfort
🟩	30 - 39	Some discomfort
🟨	40 - 45	Great discomfort; avoid exertion
🟧	Above 45	Dangerous
🟥	Above 54	Heat Stroke imminent

Source: Environment Canada: website <http://www.wul.qc.ec.gc.ca/meteo/documentation/Humidex/humidex_a.html>

Figure 6.19: Humidex chart

Graph Lookup - window opening lookup

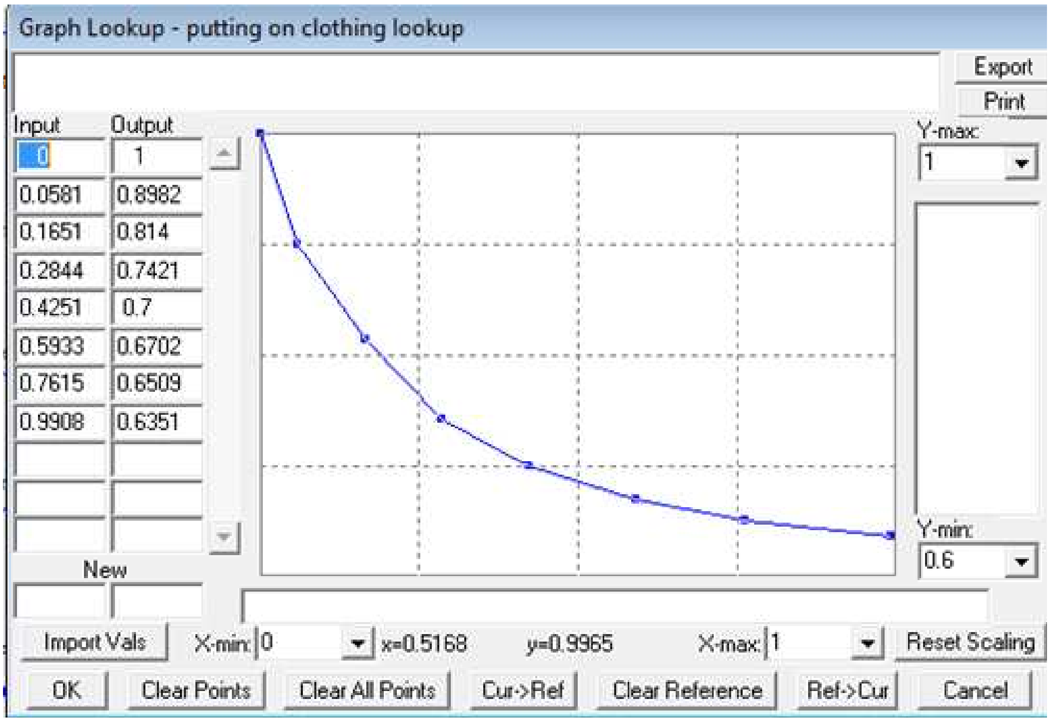
Input	Output
0	0
0.07951	0.2588
0.1988	0.4956
0.4037	0.75
0.6177	0.8904
0.8012	0.9605
1	1

Y-max: 1

Y-min: 0

X-min: 0 x=0.5474 y=1.022 X-max: 1

Figure 6.20: Window opening lookup



Graph Lookup - putting on clothing lookup

Input	Output
0	1
0.0581	0.8982
0.1651	0.814
0.2844	0.7421
0.4251	0.7
0.5933	0.6702
0.7615	0.6509
0.9908	0.6351

Y-max: 1

Y-min: 0.6

X-min: 0 x=0.5168 y=0.9965 X-max: 1

Figure 6.21: Putting on clothing lookup

Occupants comfort (t) = INTEGRAL [perceived dwelling internal temperature, occupants comfort (t_0*)]*

(Eq. 6.15)

Occupants metabolic build-up (t) = INTEGRAL [occupants activity level + perceived dwelling internal temperature, occupants metabolic build-up (t_0*)]*

(Eq. 6.16)

$$humidex\ value = \left\{\begin{array}{l} IF\ THEN\ ELSE\ (dwelling\ internal\ temperature < 21\ :AND: \\ \qquad relative\ humidity < 45, \\ dwelling\ internal\ temperature, no\ discomfort\ from\ heat\ stress) \end{array}\right.$$

(Eq. 6.17)

$$no\ discomfort\ from\ heat\ stress = \left\{\begin{array}{l} IF\ THEN\ ELSE\ (dwelling\ internal\ temperature < 30\ :AND: \\ \qquad relative\ humidity > 25, \\ no\ discomfort\ from\ heat\ stress,\ some\ discomfort\ from\ heat\ stress) \end{array}\right.$$

(Eq. 6.18)

$$some\ discomfort\ heat\ stress = \left\{\begin{array}{l} IF\ THEN\ ELSE\ (dwelling\ internal\ temperature < 36\ :OR: \\ \qquad relative\ humidity > 50, \\ \qquad some\ discomfort,\ great\ discomfort) \end{array}\right.$$

(Eq. 6.19)

6.6.4 Climatic – Economic – Energy Efficiency Interaction Module

The structure of SFD for this module is not much different from its CLD as discussed under Section 6.5.4 apart from establishing the relationships (in form of equations) between different variables in the module. It needs to state that no variable is represented as stock and flow. However, their impact is felt much in order modules like Section 6.6.5. To this end, this module shows the interactions of some energy efficiency, economic, and climatic variables that are included in the model. Other variables of interest could, however, be incorporated into the model by changing the structure of the model.

As shown in Figure 6.22, importance of household energy efficiency measures to household energy bills are highlighted. Also, the effects of unfavourable climatic conditions have on international energy prices and consequently on household energy bills are elaborated. All these work together seamlessly as a system to give effect of energy bills on energy consumption, which ultimately have effects on carbon emissions. An example of sample data driving this module is given in Table 6.6. Examples of major equations in this module are given in equations (6.20 – 6.24).

Table 6.8: Sample data under climatic-economic-energy efficiency interaction module

Variable	Unit of Measurement	Minimum	Maximum	Mean	Standard Error	Standard Deviation
Average annual gas bill	£	372	659	542.07	12.44	79.66
Average annual electricity bill	£	378	578	490.43	8.43	53.96
Weighted average energy prices	-	3.45	6.01	4.74	0.10	1.61
SAP rating	-	17.60	55.00	37.86	1.61	10.31

(Source: Palmer & Cooper, 2012)

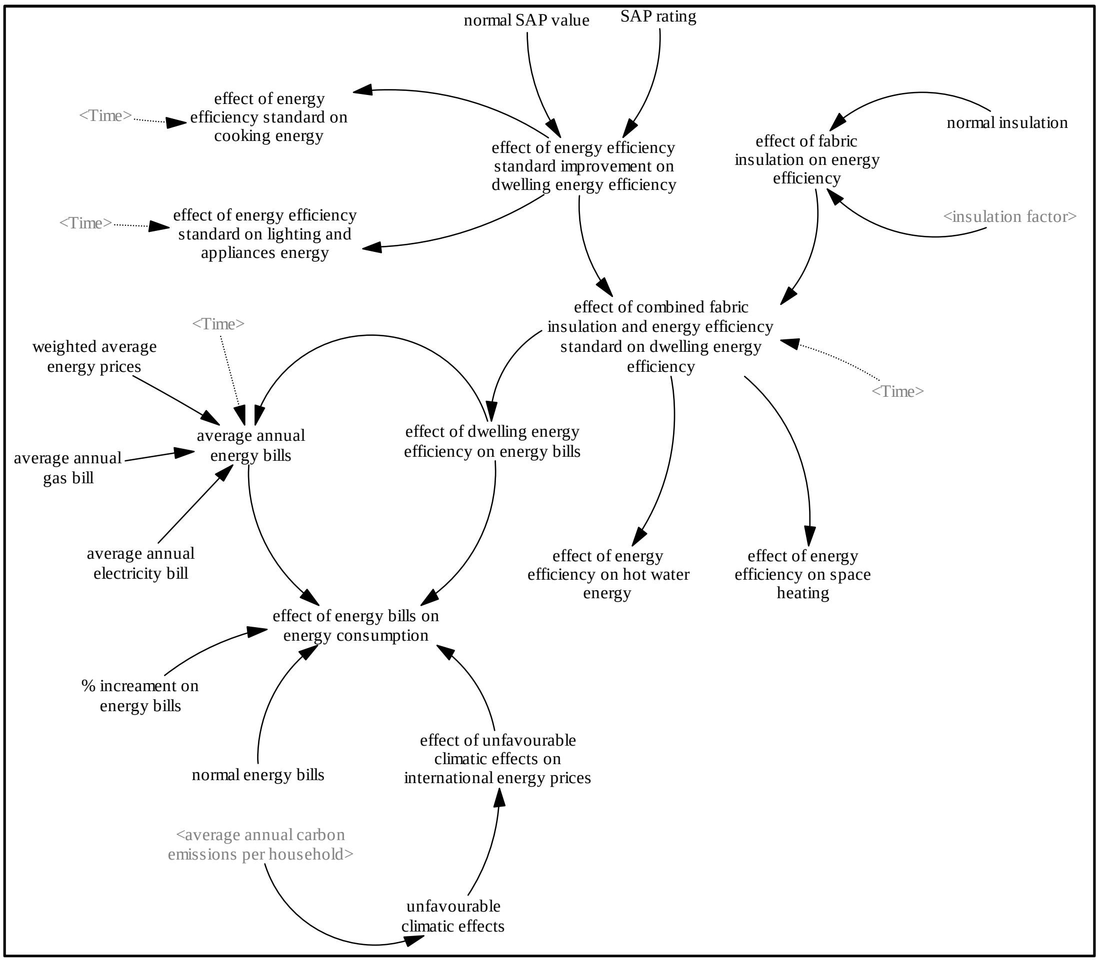


Figure 6.22: SFD for economic – climatic – energy efficiency interaction module

effect of energy bills on energy consumption = 1-(1/((1+(1/average annual energy bills)*100)+effect of dwelling energy efficiency on energy bills)-0.9)*(1-(1/(1+"% increment on energy bills"/normal energy bills)))/(effect of unfavourable climatic effects on international energy prices) _(Eq. 6.20)_

unfavourable climatic effects = SMOOTH((1-(1/average annual carbon emissions per household)), 5) _(Eq. 6.21)_ *effect of dwelling energy efficiency on energy bills = 1/effect of combined fabric insulation and energy efficiency standard on dwelling energy efficiency*

(Eq. 6.22)

effect of energy efficiency standard improvement on dwelling energy efficiency = WITH LOOKUP (SAP rating/normal SAP value) *(Eq. 6.23)*

effect of fabric insulation on energy efficiency = WITH LOOKUP (insulation factor/normal insulation) *(Eq. 6.24)*

6.6.5 Household Energy Consumption Module

In this module, household energy consumption is modelled. This is based on five different end uses of energy (space heating energy consumption, hot water energy consumption, cooking energy consumption, lighting energy consumption, and appliances energy consumption). The details of SFD developed for ‘space heating energy consumption’, ‘appliances energy consumption’, ‘hot water energy consumption’, ‘lighting energy consumption’, and ‘cooking energy consumption’ are shown in Figures 6.23 - 6.27 respectively. As shown in Figures 6.23 - 6.27, it is necessary to state that the ‘space heating carbon emissions’, ‘carbon emissions due to appliances energy’, ‘carbon emissions due to hot water usage’, ‘carbon emissions due to lighting’, and ‘carbon emissions due to cooking’ are systematically modelled as accumulation of ‘space heating energy consumption’, ‘appliances energy consumption’, ‘hot water energy consumption’, ‘lighting energy consumption’, and ‘cooking energy consumption’ respectively converted to carbon emissions through the use of ‘energy to carbon conversion factor’. This method is used for all other household energy consumption end uses. ‘Average annual household energy consumption’ (shown in Figure 6.28) is therefore determined by adding all the household energy consumption stocks: space heating, hot water, cooking, lighting, and appliances energy consumption. Total annual household energy consumption is determined by multiplying the 'average annual energy consumption per household' by 'households'. Example of data driving the module is shown in Table 6.7. As example as well, equations relating to household energy consumption component of Figure 6.23 are given (Eq. 6.25 – 6.29). However, those relating to the carbon emissions component are given in Section 6.7.6 (Eq. 6.30 – 6.31).

Table 6.9: Sample data for household energy by end-uses

Variable	Unit of Measurement	Minimum	Maximum	Mean	Standard Error	Standard Deviation
Space heating	MWh	10.14	15.84	13.54	0.18	1.19
Hot water	MWh	3.03	6.64	4.78	.17	1.10
Cooking	MWh	0.48	1.36	0.86	0.04	0.28
Lighting	MWh	0.55	0.69	0.65	0.01	0.04
Appliances	MWh	1.07	2.39	1.92	0.06	0.37

(Source: Palmer & Cooper, 2012)

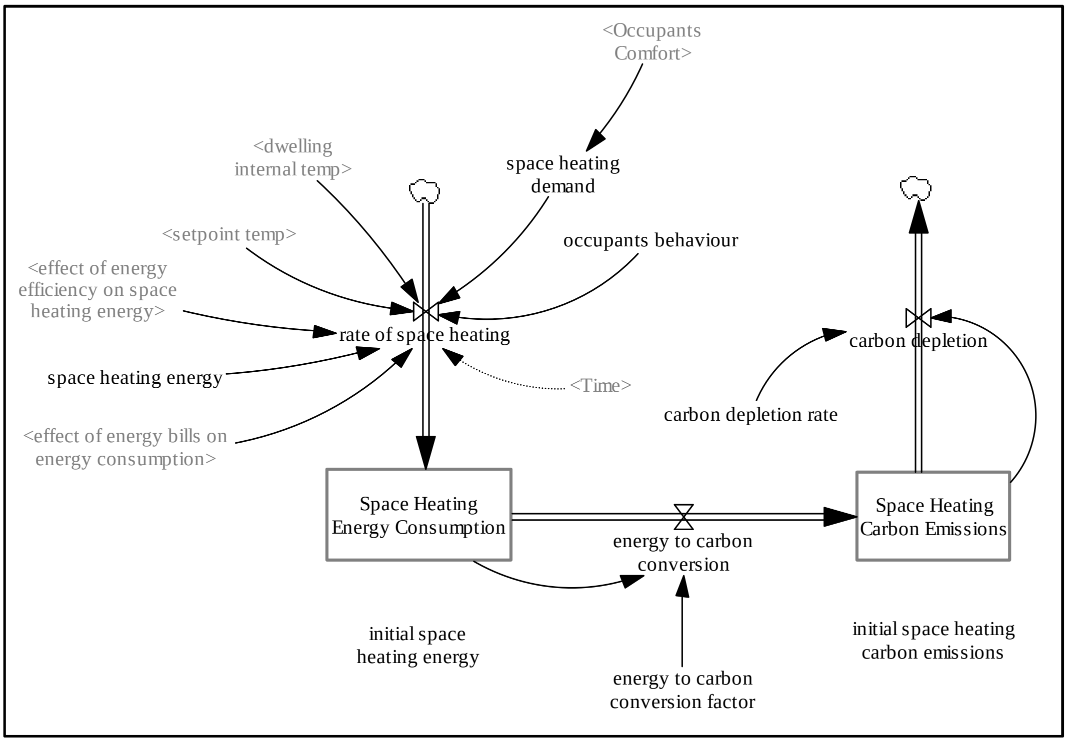


Figure 6.23: SFD for space heating energy consumption and carbon emissions

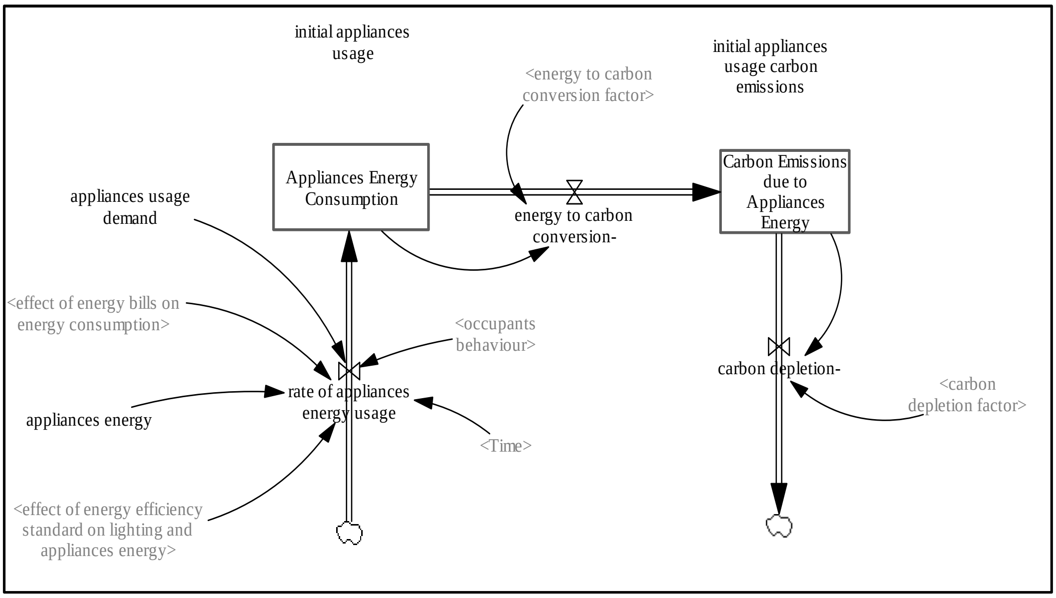


Figure 6.24: SFD for appliances energy consumption and carbon emissions

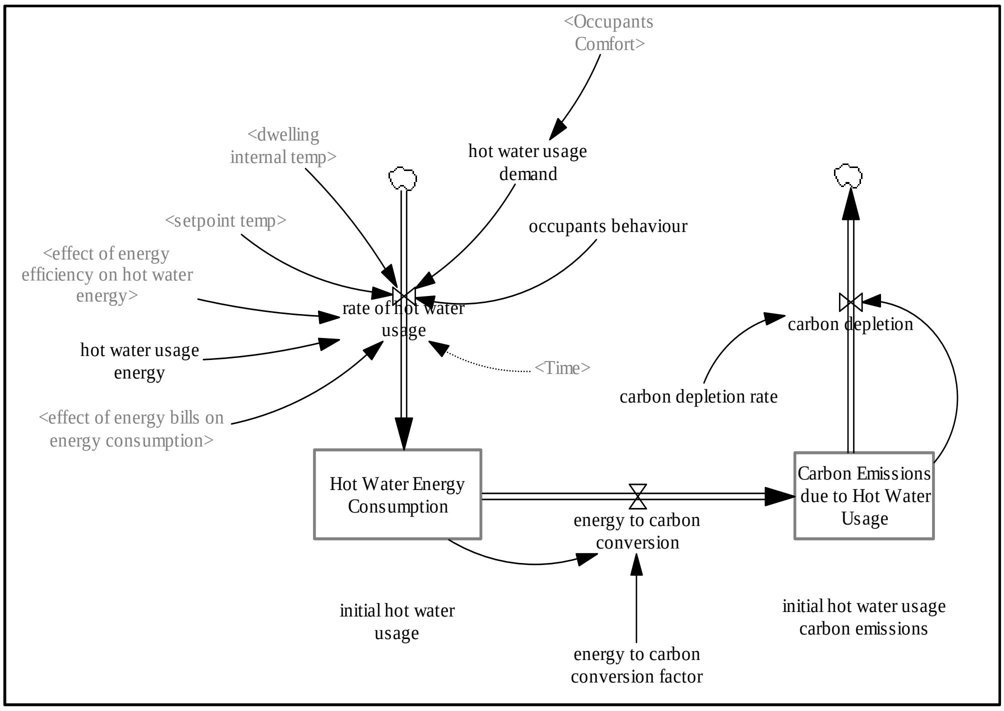


Figure 6.25: SFD for hot water energy consumption and carbon emissions

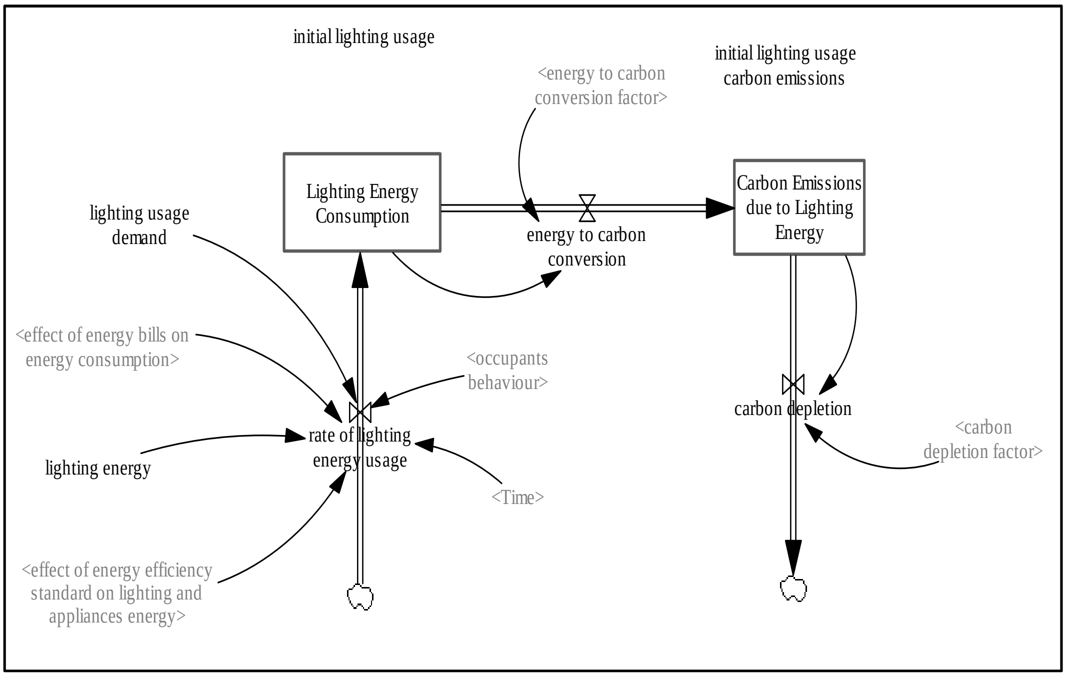


Figure 6.26: SFD for lighting energy consumption and carbon emissions

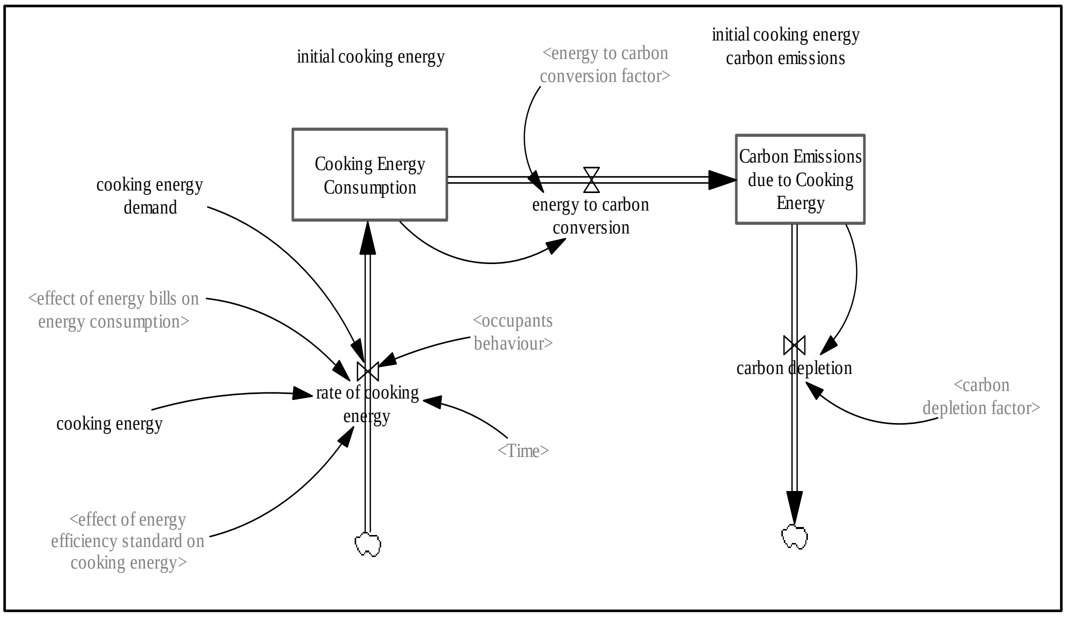


Figure 6.27: SFD for cooking energy consumption and carbon emissions

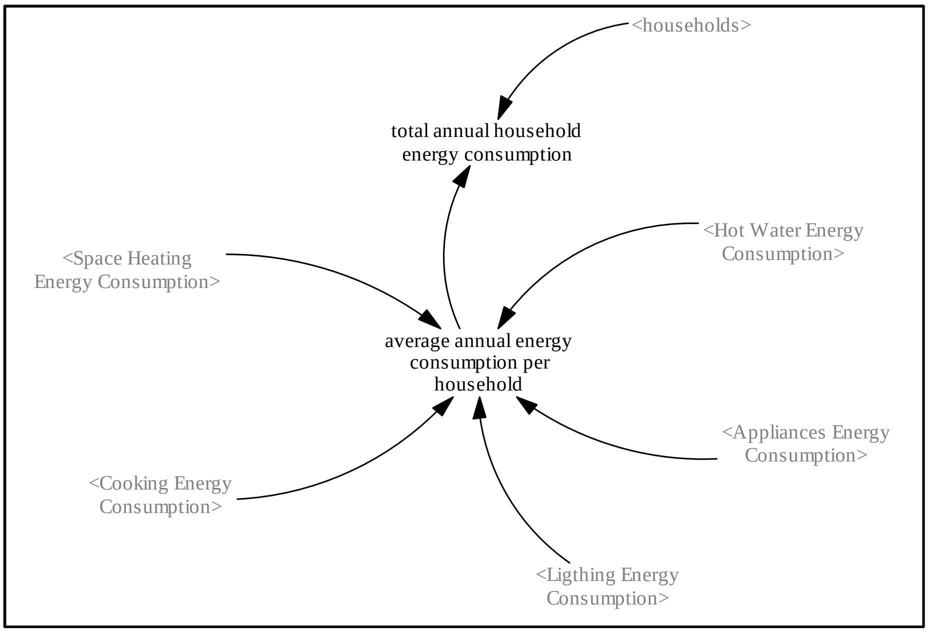


Figure 6.28: SFD for household energy consumption

*rate of space heating = (space heating energy*effect of energy efficiency on space heating/effect of energy bills on energy consumption*1.14-0.15*FORECAST(space heating energy*0.53, 39, 450))*(0.60*setpoint temp)/dwelling internal temp)* *(Eq. 6.25)*

Space Heating Energy Consumption (t) = INTEGRAL [(rate of space heating-energy to carbon conversion), initial space heating energy (t_0)*]* *(Eq. 6.26)*

*energy to carbon conversion = Space Heating Energy Consumption*energy to carbon conversion factor* *(Eq. 6.27)*

average annual energy consumption per household = Cooking Energy Consumption + Hot Water Energy Consumption + Lighting Energy Consumption + Space Heating Energy Consumption + Appliances Energy Consumption *(Eq. 6.28)*

*total annual household energy consumption = average annual energy consumption per household*households/10^6* *(Eq. 6.29)*

6.6.6 Household CO_2 Emissions Module

As previously mentioned in Section 6.6.5 above, carbon emissions are modelled by converting energy consumption to carbon emissions through the use of a conversion factor termed ‘energy to carbon conversion’ (Figure 6.23 – 6.27). It is important to state that the ‘energy to carbon conversion factor’ used in this model is assumed to be the conversion factor of energy to carbon conversion factor of energy from electricity source. This is done for simplicity sake. Ideally, energy conversion factor of different fuels (*i.e.* gas, oil, electricity, *etc.*) to meet household energy consumption by end-uses needs to be determined and applied appropriately. This is however acknowledged as one of the limitations of this model. Average annual carbon emissions per household and total annual household carbon emissions (Figure 6.29) are determined by the same approach as described under household energy consumption module in Section 6.6.5.

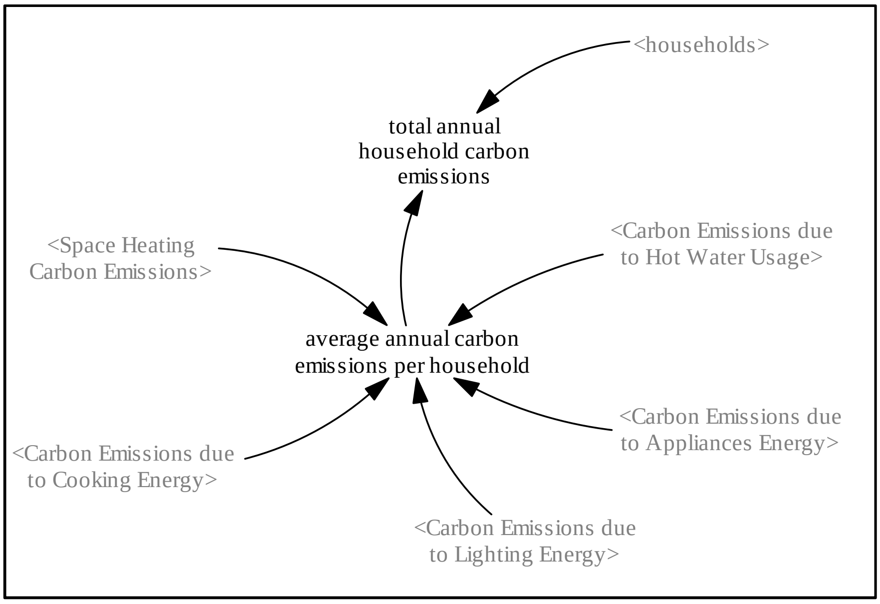


Figure 6.29: SFD for household carbon emissions

Space Heating Carbon Emissions (t) = INTEGRAL [((energy to carbon conversion- carbon depletion), initial space heating carbon emissions (t_0)] *(Eq. 6.30)* *carbon depletion = Space Heating Carbon Emissions*carbon depletion factor* *(Eq. 6.31)*

average annual carbon emissions per household = Carbon Emissions due to Cooking Energy + Carbon Emissions due to Hot Water Usage + Carbon Emissions due to Lighting Energy + Carbon Emissions due to Appliances Energy + Space Heating Carbon Emissions *(Eq. 6.32)*

*total annual household carbon emissions = average annual carbon emissions per household*households/10^6* *(Eq. 6.33)*

6.7 Discussion of the Variables not Considered by the Model

Section 6.3 discusses the boundary for the model in this thesis. It was discussed there that it is necessary to have a model boundary chart that detailed the variables included in the model in the form of endogenous and exogenous variables, and those that are excluded. Considering the type of complexity involved in the system being modelled in this research, some variables relating to occupants' behaviour like "occupants' social class influence", "occupants' cultural influence", *etc.* (Table 6.2) are excluded from the model. This is mainly because of the fact that "occupants' behaviour" in the developed model is currently modelled exogenously based on the assumption that "occupants' behaviour" externally affects household energy consumption. Inclusion of these variables will mean that a lot of time will be committed to conducting social research relating to different influences on "occupants' behaviour" leading to modelling the "occupants' behaviour" endogenously. This is, however, seen as a limitation of this research.

Additionally, some variables relating to the physical characteristics of dwellings like dwelling exposure, air changes, *etc.* are also excluded from the model. These variables are specific to individual dwellings. In Section 1.3.2 of Chapter one, the level of aggregation/disaggregation to be incorporated into the model was discussed. And it was emphasised that there is the need to strike a balance between aggregated and disaggregated variables to be included in the model because of the target audience of the model output, which in this case are the energy policy decision makers. Furthermore, some variables relating to external environment like political uncertainties and energy securities are not modelled considering the scope of the research and non-inclusion of them signifies the potential of the model to explore quite an array of issues.

6.8 Chapter Summary

This chapter has described and discussed the model conceptualisation and formulation. The chapter discussed in details information about those that participated in the model conceptualisation process. The mental model developed by these individuals was captured in the form of knowledge elicitation in order to improve and validate the causal diagrams drawn by the modeller. The final causal diagrams developed for the model were therefore described and discussed for each of the modules in the model. The chapter also described and discussed the model formulation in the form of stock and flow diagrams for all the modules. The key algorithms relating the variables together were also given. The next chapter will discuss the behaviour of the model based on ‘baseline’ scenario.

Chapter 7

MODEL BEHAVIOUR ANALYSIS (‘BASELINE’ SCENARIO)

7.1 Introduction

This chapter presents the model behaviour based on the ‘baseline’ scenario. It communicates the most likely way in which the household energy and carbon emissions of the UK housing stock will evolve over the years starting from 1970 until 2050. The ‘‘baseline’’ scenario assumes the continuation of the trends depicted by historical data based on the current trends of energy efficiency measures, ‘standard’ consumption behaviour, and energy prices. The chapter first describes the general assumption underpinning the ‘baseline’ scenario. This is followed by a discussion of the insights from the model in terms of the behaviour generated. These are discussed based on the modules of the model. Comparison of the results of the model with some previous studies concludes the chapter.

7.2 General Assumptions and Description of ‘Baseline’ Scenario

The ‘baseline’ scenario functions as the reference case to all other scenarios formulated for this research as will be the proposed policies to experiment, which will be discussed in Chapter nine. It serves as the base case upon which these all other scenarios can be compared. The scenario assumes that there are no much substantive changes made to the current trends in energy efficiency policy and efforts with an assumption that no other policy measures are further introduced apart from the continuation of the existing ones currently in operation. In terms of energy efficiency measures of dwellings, efficiency of heating systems, cooking, lighting and appliances as evidenced from historical data available will continue to follow the current trend, without any specific efforts to upturn the trend.

Three behavioural classifications are included within the model. These are ‘frugal’, ‘profligate’ and ‘standard’ behavioural classifications (as discussed in Section 2.3.3). ‘Standard’ here means that the consumption behaviour of occupants is assumed to be a mid-way between the profligate and frugal consumption behaviours. The ‘baseline’ scenario therefore assumes that the energy consumption behaviour of householders in UK is ‘standard’. This is assumed to see the dwelling internal temperature of householders having a set-point of 19ºC. Further, the scenario assumes that any change to energy bills will not significantly affect the energy consumption behaviour of the householders as the ‘standard’ consumption behaviour will be maintained. Both the number of households and average household size in the UK impact on the energy consumption profile of the UK housing stock, and as such there future trends as emanate from the output of UK population are maintained for the scenario.

7.3 Behaviour Analysis of Some Variables in Population/Household Module

It is shown in the preceding chapter that one of the modules that constitute the model of HECCE in this thesis is the population/household module. The importance of this module cannot be over-emphasised as the number of households play a major role in accurately estimating the amount of energy consumption in the entire UK’s housing stock. This is mainly due to the fact that energy consumption in homes is driven by the quest for energy services like comfort by occupants. This is to mean that actual energy required in meeting these services reflects, for example, the type of services required by the occupants and the factors relating to fabric insulation in homes, heating systems, appliances use, *etc.* Invariably, householders consume energy as a result of them seeking comfort at home. With this notwithstanding, it is unsurprising that household energy consumption is strongly influenced by the population, the number of households and the average household size. For example, the amount of household energy consumption attributable to hot water consumption and usage of some appliances is greatly influenced by the household size. However, there is the minimum level of household energy consumption applicable to each household as the operation of some energy consuming appliances like fridge, fridge-freezer, or freezer, *etc*. don't depend on the household size.

The model outputs in this module are presented in Figures 7.1, 7.2, and 7.3 to respectively illustrate the behaviours of total UK population, total number of UK households, and average household size in the UK from 1970 until 2050. The model shows that the total UK population is on an upward trend till 2050 (Figure 7.1). The model indicates that the UK population of 55.63 million in 1970 will grow to 69.78 million by the year 2050. This figure shows a yearly increase of 0.31% on the average. Comparing this figure with data from the Office of National Statistics (2013) suggests that the UK population receive an annual growth of 0.28% averagely between the year 1970 and 2010. Within the same time horizon of 1970 and 2010, the model output shows an average of yearly growth of 0.26% in population. The slight difference in the two estimates can be attributed to the methods used in the development of the models.

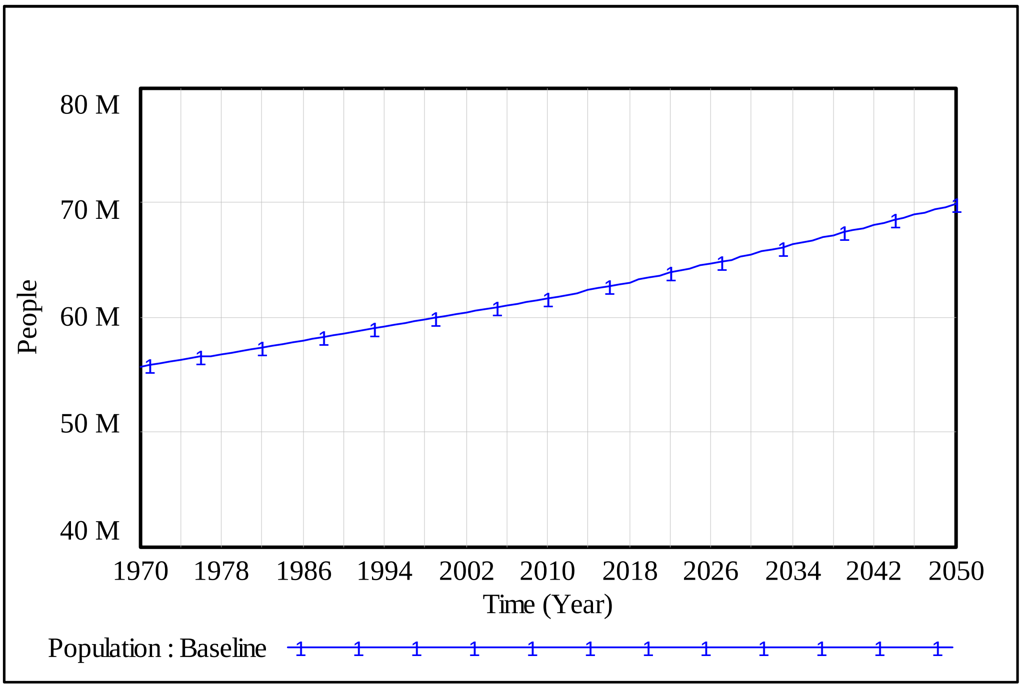


Figure 7.1: Projected total UK population under the 'baseline' scenario

Additionally, Figure 7.2 shows that the average number of households on a yearly basis grows steeply when compared to the steepness of the population output as shown in Figure 7.1. The result of the model indicates the number of households of 18.78 million will grow to 34.10 million by the year 2050. This reflects an overall average yearly increment of about 1.02%. The growth in the number of households is an indication of rising number of smaller households, which reflects that more people tends to live all alone and/or in smaller family sizes. This is not only has implications on adequate provision of housing for the citizenry, but alter the housing stock energy consumption profile of homes. Unsurprisingly, this by implication means that per capital energy consumption will tend to grow as the number of households increases with attendant decrease in the average household size. It then shows that the projection of number of households is key to accurately estimating the household energy consumption and carbon emissions.

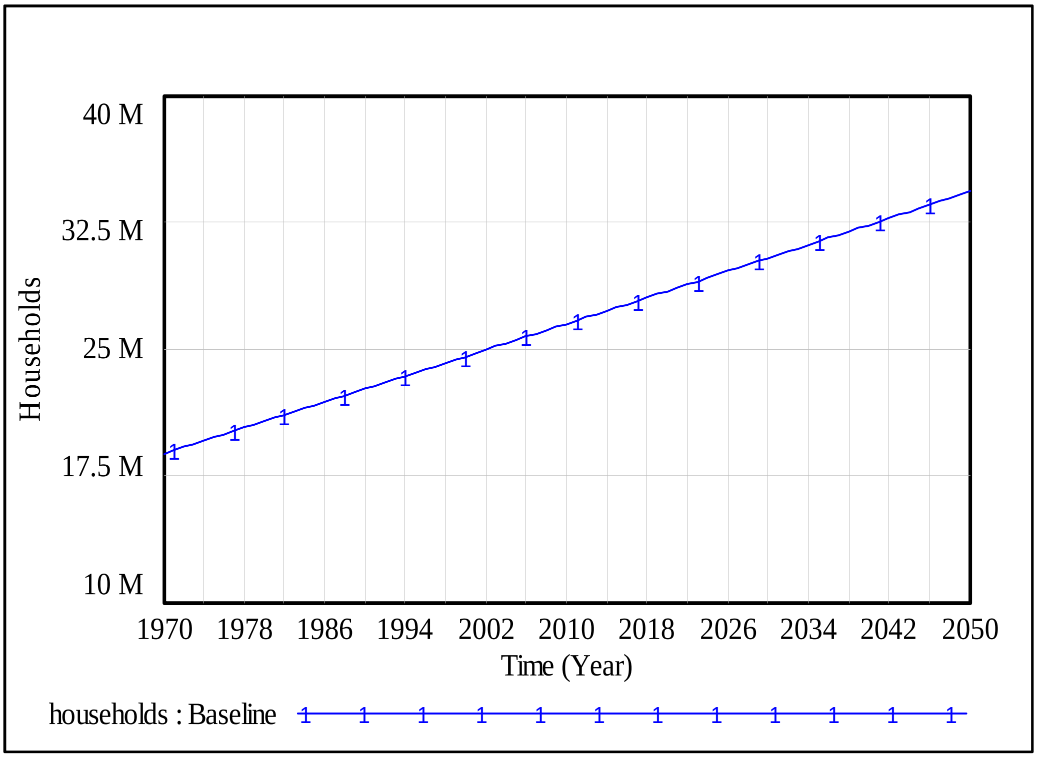


Figure 7.2: Projected total number of UK households under the ‘baseline’ scenario

Furthermore, in order to gain a more insight into the behaviour of the number of households as produced by the model, a further analysis was conducted at an interval of ten years from 1970. The results of this study are compared with that of Johnston (2003) and Palmer and Cooper (2012) as shown in Table 7.1. The behaviour of this study indicates that an increase in the number of households on a yearly basis, but with a decline in the level of this growth until 2050. The result shows almost the same downward trend as the output of Johnston (2003) model. The major difference in the two models lies in the region of 2040 – 2050, where Johnston (2003) specifically stated that he fixed the trend of this region (and not the result of analysis) based on the assumption that the number of households will not change in those years. This assumption then explains the difference in the two models. Correspondingly, when the output of this model is compared with that of Palmer and Cooper (2012), which is based on the ONS available data till 2010, the results follow a 'lumpy' trend with a combination of peaks and troughs, but overall the number of households grow at 0.99% yearly, whereas the results of this model show a growth of 1.02% yearly (Table 7.1).

Table 7.1: Average yearly percentage increase/decrease in the number of households

Year	**Johnston (2003) (%)**	**Palmer and Cooper (2012) (%)**	**This Study (%)**
1970 – 1980	-	0.82	0.93
1980 – 1990	-	0.88	0.84
1990 – 2000	0.76*	0.72	0.77
2000 – 2010	0.70	0.81	0.71
2010 – 2020	0.68	-	0.67
2020 – 2030	0.53	-	0.63
2030 – 2040	0.37	-	0.59
2040 – 2050	-0.09	-	0.55
Overall yearly average	**0.56*†**	**0.99†**	**1.02†**

** The year starts from 1996; †was computed based on [(final year value – base year value)/number of years*100%].*

Equally, it is expedient to explain some insights shown by the behaviour of average household size trend as depicted in Figure 7.3. The model result suggests that the trend of the UK household size averagely follows a downward trend with the slope of graph between 1970 and 2020 a little bit steeper than that of between 2020 and 2050. That is, the average household size declines steadily from 2.96 in 1970 to 2.04 in 2050. The reason for this trend may be attributed to the growth in the number of single person households without children as previously advanced. Traditionally, households, for example, used to comprise of married couples living together with their dependent children, but a decline in this kind of proportion may also likely responsible for the model behaviour. Further to this, it may be that there is growth in the number of households consisting of married couples without dependent children or increase in the proportion of lone parent households. All these factors may be responsible for the decline witness in average household size by the model. The results of this model are consistent with historical data as contained in Palmer and Cooper (2012) and the output of Johnston's (2003) model. The next section discusses the behaviour of key variables within the dwelling internal heat module.

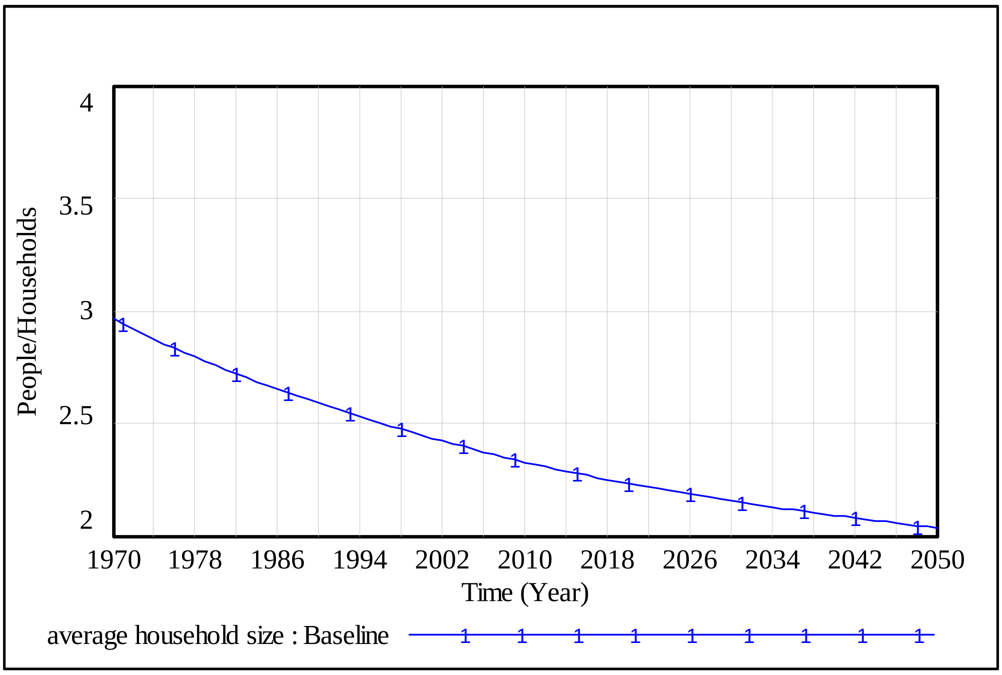


Figure 7.3: Average UK household size under the 'baseline' scenario

7.4 Behaviour Analysis of Some Variables within the Dwelling Internal Heat Module

In this module, the only variable that changes from one scenario to others is the set-point temperature ‘setpoint temp’. The baseline value assumed for this variable is 19ºC. This section, therefore, presents the behaviour of key variables within the dwelling internal heat module. As enunciated in Chapter six, dwelling internal heat is required by the developed model majorly with the aim of modelling its impact on occupants comfort and consequently on space heating and hot water requirements of the householders. The dwelling internal heat is principally influenced by the amount of heat gained into the dwelling and determines the dwelling internal temperature. The total dwelling heat gains (DHGs) for the entire UK housing stock is modelled from six different sources as explained in Chapter six to include: DHGs due to appliances, artificial lighting, cooking, number of people (metabolic heat gains), water heating, and solar gains as advanced in BRE (2012). The degree of infiltration into/out of the dwelling is modelled and captured as heat losses.

Figure 7.4 shows the model behaviour for DHGs due to appliances, artificial lighting, cooking, water heating, heat losses, and number of people. It should be noted that the graph (Figure 7.4) uses a multi-scale approach in the presentation. The values ‘-80’ and ‘-200’ denote upper and lower values respectively for the variable designated ‘1’ in the graph, which in this case is ‘heat losses’. Similarly, the values of ‘400’ and ‘200’ respectively denote the upper and lower values of the second variable designated ‘2’, which in this case is ‘dhg due to appliances less cooking’; and so on. The behaviour exhibit reveals that the DHGs due to appliances, artificial lighting, cooking, number of people, and water heating follow the same trajectory patterns of gentle decline. These patterns are, however, not too distant from the behaviour displayed by the average household size as shown in Figure 7.3 above. The main reason that could be advanced for these insights is the dominant effect of average household size of the UK housing stock that has been on decline trend from an average of 2.96 in 1970 to 2.04 by 2050 as the model results suggest.

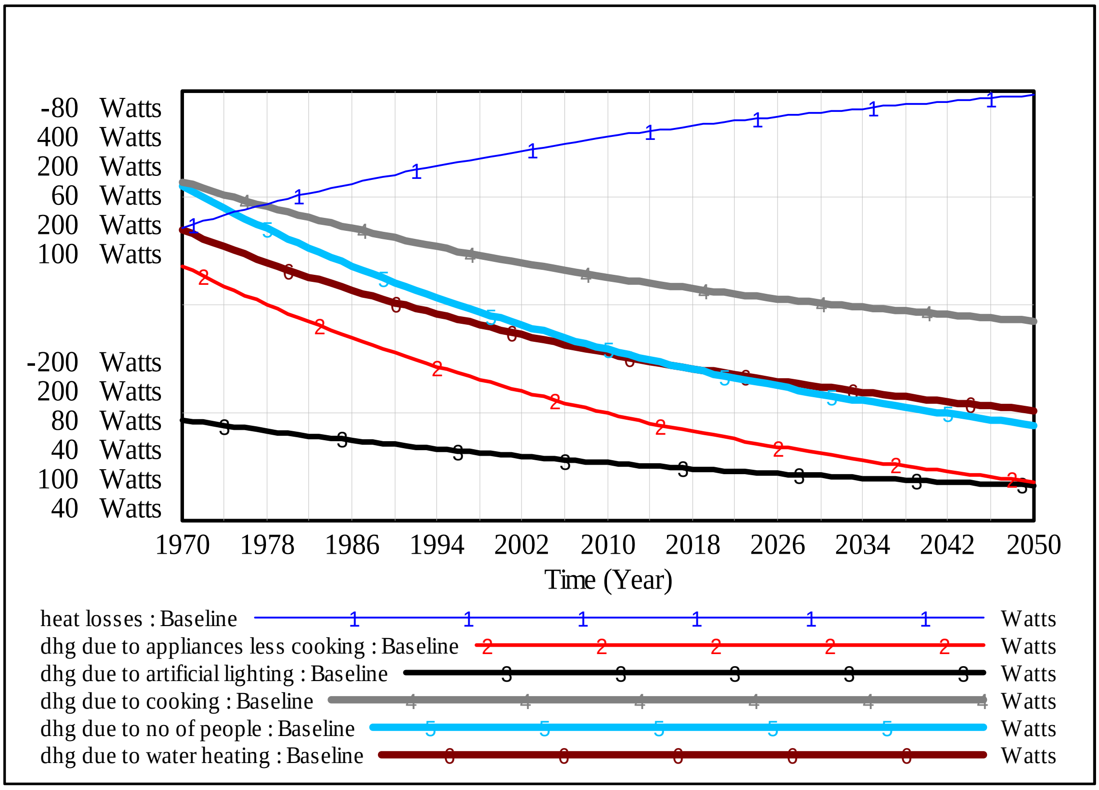


Figure 7.4: Heat losses and dwelling heat gains due to appliances, artificial lighting, cooking, no of people, and water heating under the 'baseline' scenario

Further to these, the results as shown in Figure 7.4 give an insight into the pattern of behaviour expecting from the heat losses from the UK housing stock. The output suggests that heat losses from dwellings would decrease over time. This is as a result of different schemes put in place at improving airtightness in dwellings based on melioration of fabric insulation of dwellings. Correspondingly, another important component of DHGs that is not captured in Figure 7.4 is solar gains due to the limitation of the software that cannot combine more than six variables in a graph. Again, this follows the method described in SAP 2012 (BRE, 2012) as explained in Section 6.6.2 of Chapter 6. Using this method involves making a number of assumptions as presented in BRE (2012) regarding solar flux, solar transmittance factor for glazing, frame factor, average solar access factor, and average area of openings in dwellings. All these parameters are constant and this is why the trend exhibited by solar gains is perfect horizontal trend. The total DHGs as a result of the summation of these different gains produces gentle decline behaviour as illustrated in Figure 7.5.

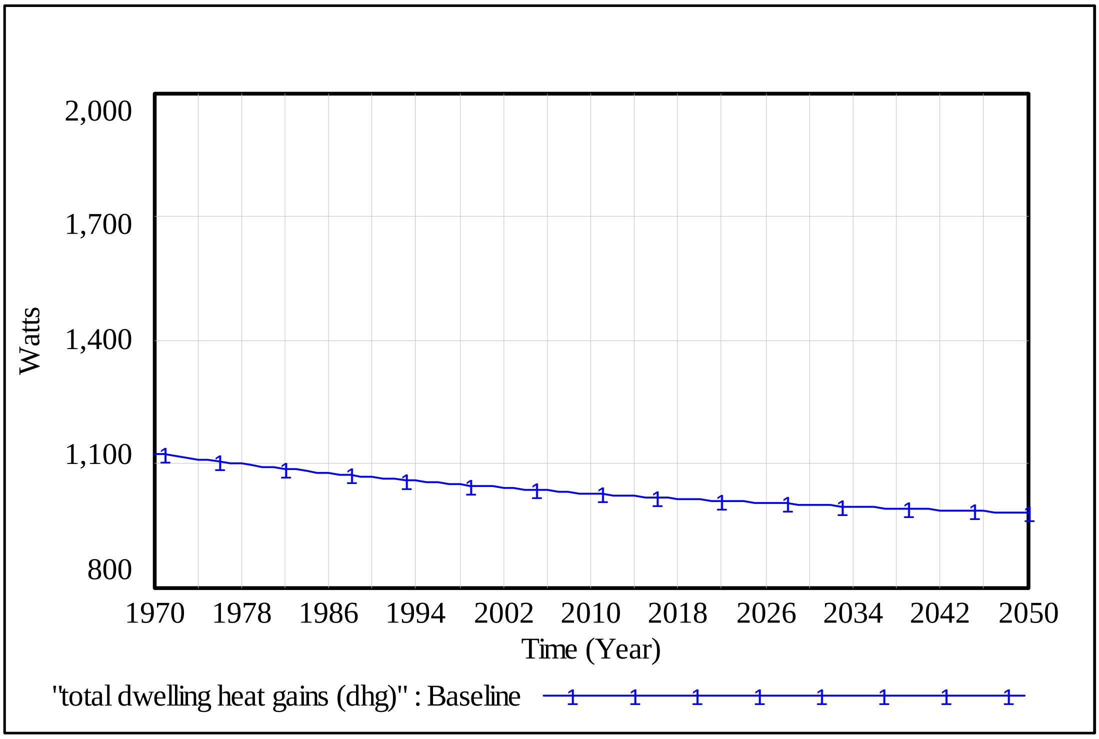


Figure 7.5: Total dwelling heat gains under the ‘baseline’ scenario

From the foregoing, the total dwelling heat gains adds to the artificial heat transfer modelled as a flow as shown in Chapter six and among different variables hypothesised to drive dwelling internal heat that is modelled as an accumulations of natural and artificial heat transfers in and out of dwellings. This then provides the thermodynamics of heat balance within the dwelling. Consequently, the average dwelling internal temperature is modelled as well. The results of the model indicate that there is growth in the dwelling internal heat (Figure 7.6) and average dwelling internal temperature (Figure 7.7) since 1970. The model predicts that these trends would continue until 2050. Another insight from Figures 7.6 and 7.7 suggest that the trends follow the same pattern of growth with 'troughs' and 'peaks' corresponding to the periods of extreme and milder winter weather respectively. For example, there was a drop 'trough' in temperature in the year 2010 due to extreme weather condition of that year, which correspondingly affects 'dwelling internal heat' and 'dwelling internal temperature' (Figures 7.6 and 7.7). The model then suggests that the weather condition will improve. This is, therefore, reflected in picking-up again as the behaviours of these two variables suggest. These results are consistent with the output of a number studies in the UK predicting that in years to come the UK faces the risk of overheating in dwellings especially at summer time (Banfill *et al.*, 2012; CIBSE, 2013) and the concerns raised by the global climate warming as a result of increase in dwelling internal heat and accordingly average dwelling internal temperature. Also, the results are illuminating in the sense that infiltration into the dwellings will decline as a result of improved fabric insulation leading a reduced wind forces, which creates pressure differences within dwellings. This means buildings will be able to retain more internal heat as a result of space heating and internal temperature will rise.

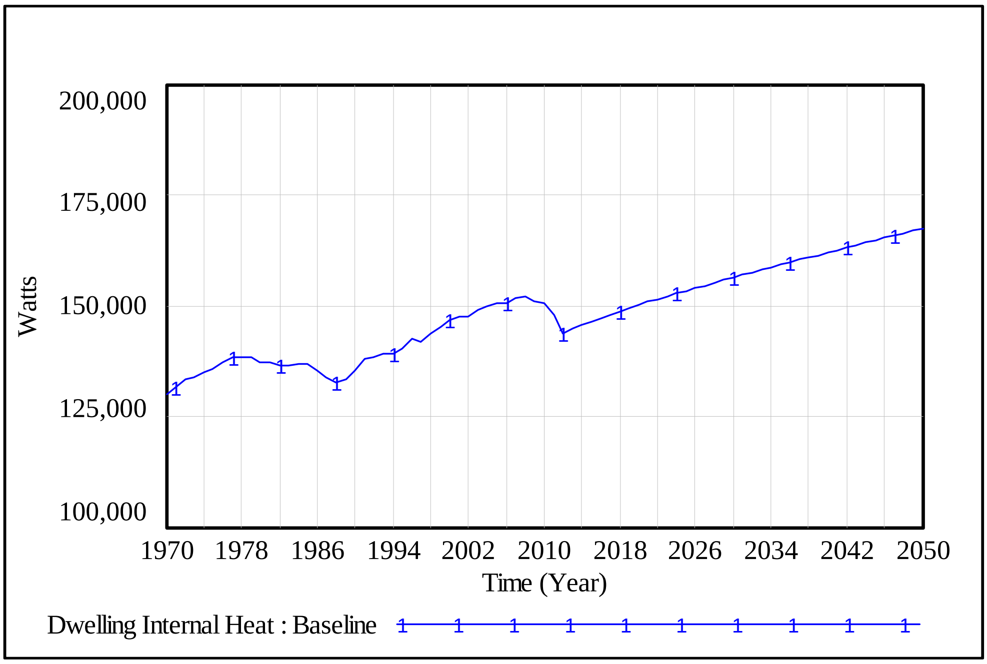


Figure 7.6: Dwelling internal heat under the 'baseline' scenario

For example, the model results envisaged that the average dwelling internal temperature will continue to increase based on the desire of occupants to improve thermal comfort by raising the temperature set-point as long as energy prices are kept low. It needs to emphasise that this will not go on increasing indefinitely. At last, it will get to a saturation level upon which any further increase would constitute a kind of discomfort to occupants.

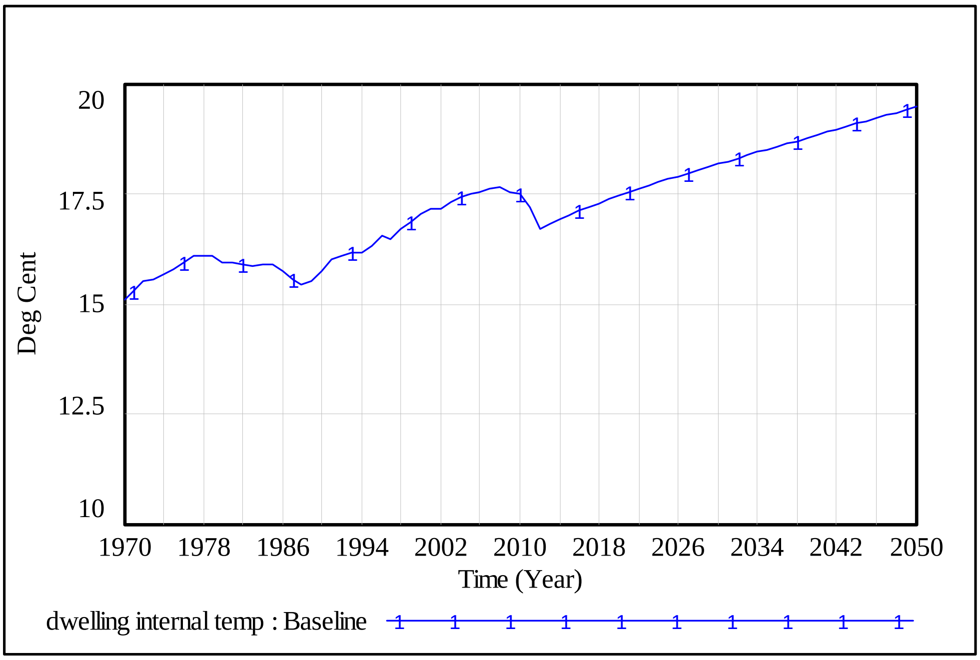


Figure 7.7: Dwelling average internal temperature under the ‘baseline’ scenario

7.5 Behaviour Analysis of Some Variables in Occupants Thermal Comfort Module

In this section, the behaviour of key variables in occupants thermal comfort module of the model is presented and insights generated from the behaviour are discussed as well. The average dwelling internal temperature from the preceding section in combination with the average relative humidity serves as input to this module. This is mainly to model the perceived dwelling temperature in a bid to model occupants’ comfort. As explained in Chapter 6, the perceived dwelling temperature is modelled qualitatively based on humidex chart referred to in Figure 6.18 of Chapter 6. The chart takes the values of average dwelling internal temperature and average relative humidity to estimate the humidex value, which in turn produces the perceived dwelling temperature as shown in Figure 7.8. This is in combination with other variables like the probability of window opening, probability of putting on clothing, occupants' metabolic build-up and occupants comfort as discussed in Section 6.6.3. The pattern exhibited by the perceived dwelling temperature variable resembles that of the average dwelling internal temperature as there is gentle growth in the perceived dwelling temperature. As the value of perceived dwelling temperature increases, it will trigger actions from the occupants. The actions assumed and included in the model are either to open window(s) or put on more clothing with high thermal resistance as the case may be in order to get the required comfort level.

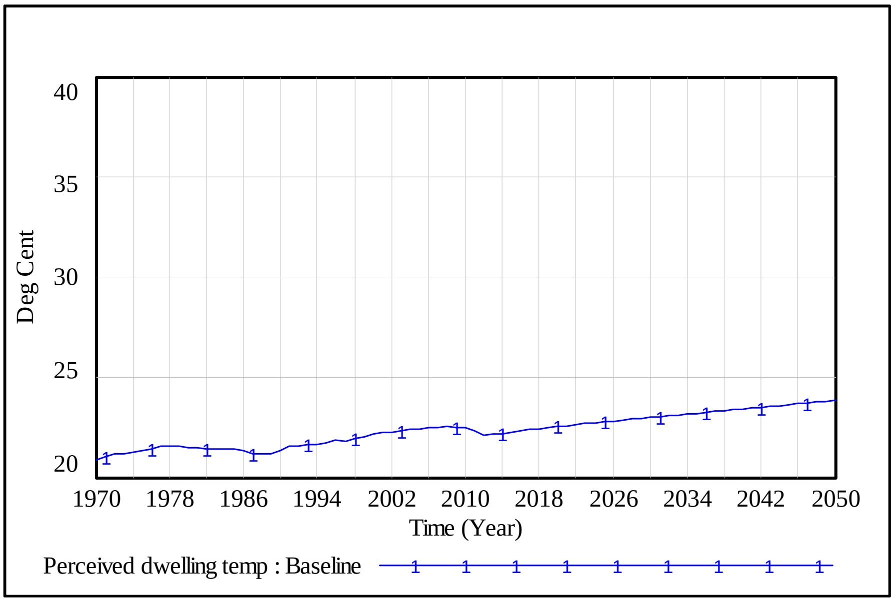


Figure 7.8: Perceived dwelling temperature under the 'baseline' scenario

It is explained in Section 6.6.3 that probabilities of putting on clothing and window opening are qualitatively modelled from the 'putting on clothing lookup' and 'window opening lookup'. Therefore, the insights into the chances of occupants putting on more clothing or opening window(s) that shaped the pattern of behaviour of perceived dwelling temperature (see Figure 7.8), occupants' metabolic build-up (see Figure 7.10), and occupants' comfort (see Figure 7.11) as generated from the model are shown in Figure 7.9. Since the result of the perceived dwelling temperature shows a gentle slope in growth (see Figure 7.9), this implies that occupants will tend to open their dwellings window(s) in order to get the required thermal comfort. Also, it is possible for them to remove dense clothing, which obviously has high thermal resistance and put on light clothing with reduced thermal resistance purposely to regulate their body temperature and get the desired thermal comfort. The insights from the model as shown in Figure 7.9 indicate that over the years, starting from 1970 until 2050, the probability of putting on clothing with increased thermal resistance will tend to decline on the average, while at the same time horizon, the probability of occupants opening windows to get the required thermal comfort will increase as the perceived dwelling temperature increases. Again, these results are profound in that they are consistent with the global climate warming predictions.

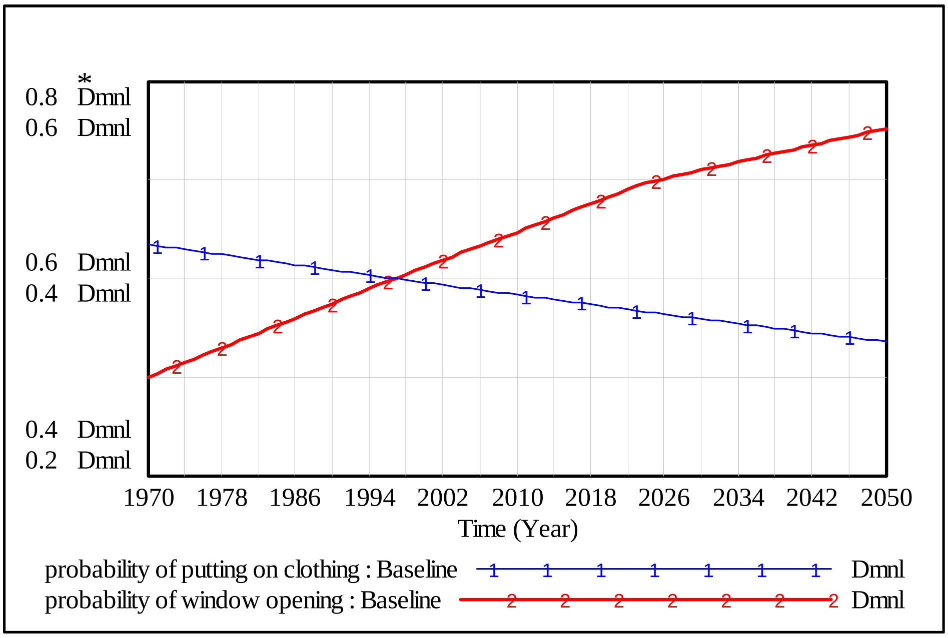


Figure 7.9: Probabilities of putting on clothing and window opening under the 'baseline' scenario

**Dmnl – dimensionless.*

Stemming from the above, the output of the model as shown in Figures 7.10 and 7.11 suggest that the pattern of behaviour of occupants' metabolic build-up and occupants comfort grow over time. It is as a result of rise in perceived dwelling temperature which may lead to a decline in the quest for more space heating and hot water usage. It needs to mention that there will be a time when these growths would reach a saturation level at which time, they tend to decline. Though, this model produces no such plausible insight, may be due to the fact that occupants comfort is being regulated by the two aforementioned actions of the occupants – window opening and putting on of clothing. It is also possible that artificial ventilation may be introduced in future should the value of occupants comfort outrageously increased in such a way that the two aforesaid actions of the occupants as assumed in this model no longer validly hold. This may, however, add to household energy consumption profile.

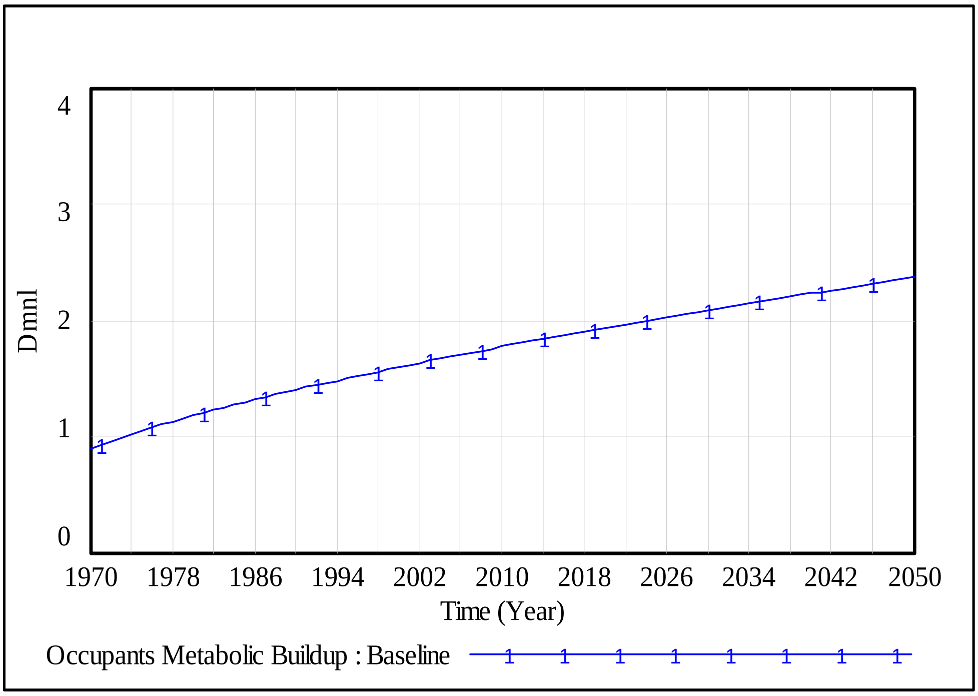


Figure 7.10: Occupants metabolic build-up under the 'baseline' scenario

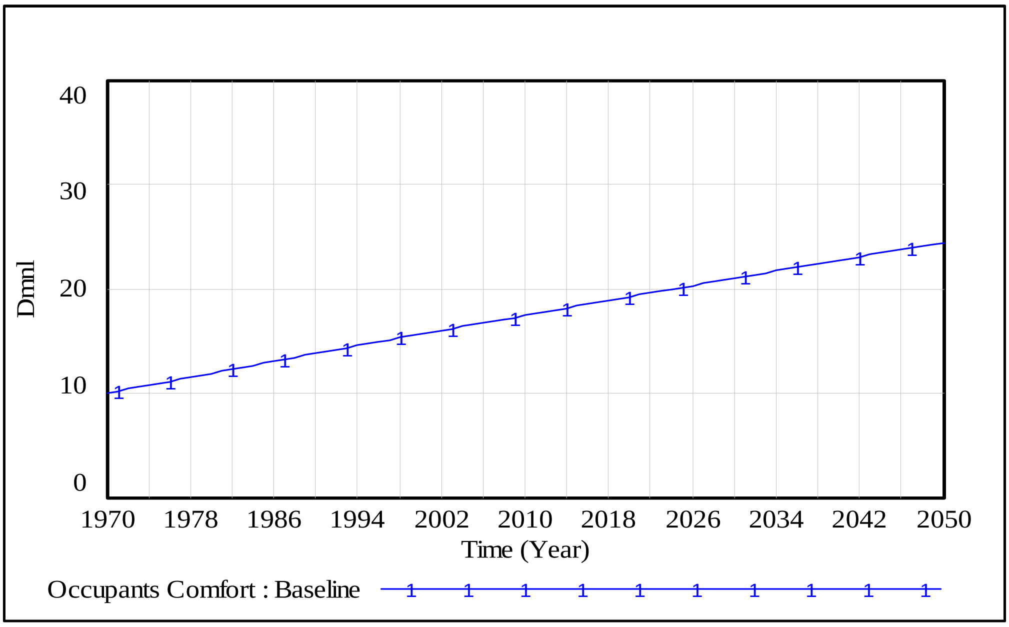


Figure 7.11: Occupants comfort under the ‘baseline’ scenario

7.6 Behaviour Analysis of Some Variables in Climatic-Economic-Energy Efficiency Interaction Module

For this module, there are baseline assumptions considered for some of the variables that changes from one scenario to others in the module. For example, ‘SAP rating’ is based on the historical data and this allowed to follow the historical trend, but does not go beyond 0.75. The ‘insulation factor’ is set at 0% as there is no change to the historical trend. Also, the value of the ‘% increment on energy bills’ is set at 0% as no increment is assumed for the ‘baseline’ scenario. This section of the chapter, therefore, gives the results of ‘baseline’ scenario analysis performed for the climate-economic-energy efficiency interaction module. This is to show the effects of key variables in the module on energy consumption and carbon emissions as will be discussed in Sections 7.7 and 7.8. Figure 7.12 shows the profile of unfavourable climatic effects, which is internally generated based on interaction of different variables in the model. Within the energy related research community, it is widely accepted that changes to the global climate are as a result of increase in carbon emissions in the atmosphere (Rogelj, Meinshausen, & Knutti, 2012). Increase in carbon emissions is then likely to have unfavourable climatic effects. The results of this model shown in Figure 7.12 suggest that unfavourable climatic effects tend to decline. The reason behind this insight is that carbon emissions tend to reduce in atmosphere. This may be due to different efforts geared towards reducing carbon emissions released into the atmosphere.

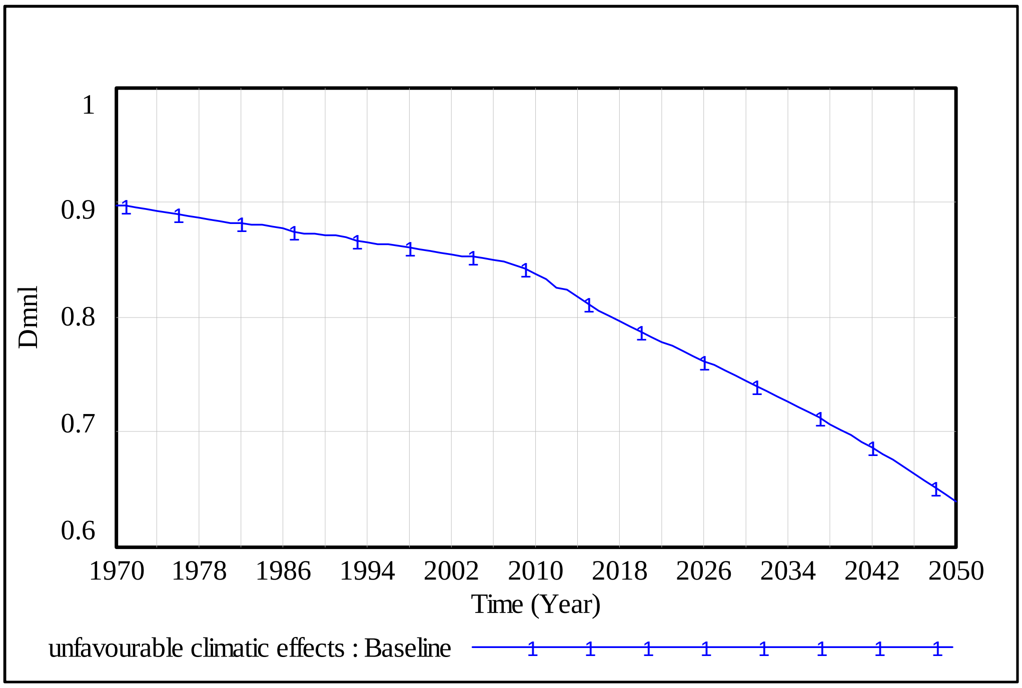


Figure 7.12: The behaviour of unfavourable climatic effects

The effect of energy efficiency standard improvement on dwelling energy efficiency was qualitatively modelled to show how the model will respond to changes in energy efficiency standard as dictated by the values of SAP rating of dwellings. As shown in Figure 7.13, the model result suggests that the effect of energy efficiency standard improvement on dwelling energy efficiency will tend to improve, but will not rise above certain value (0.75) as the model assumption for ‘SAP rating’ suggests.

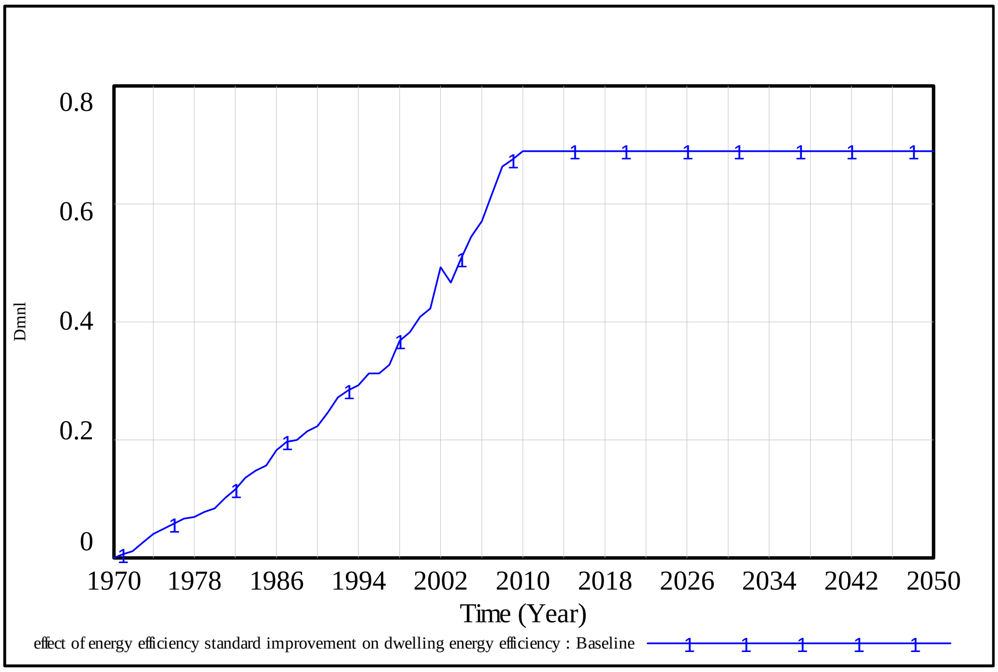


Figure 7.13: The behaviour of effect of energy efficiency standard improvement on dwelling energy efficiency

7.7 Behaviour Analysis of Household Energy Consumption Module

In this module, the only variable that changes for different scenarios is ‘occupants behaviour’. For the ‘baseline’ scenario, this variable is assumed to be ‘standard’, which is designated as ‘2’ within the model. The insights into energy consumption attributable to the ‘baseline’ scenario are therefore presented in this section. These insights are discussed based on the end-use household energy consumption. To this end, the following sub-sections show and discuss the trend of energy use for space heating, hot water, cooking, lighting, appliances (see Table B1 in Appendix B) as well as total household energy consumption for the entire UK housing stock.

7.7.1 Behaviour Analysis of Space Heating Energy Consumption

The behaviour over time of the average space heating energy consumption per household in the UK is shown in Figure 7.14. The graph indicates that the space heating energy is by far took the biggest chunk of UK household energy consumption. This is because its average annual value has been hovering around 15MWh per household for the first four decades. Within this period, space heating energy has been moving in an upward direction until the year 2004 when it begins to fall apart from the year 2010 (which is due to bad weather condition of 2010). The reason that could be advanced for the growth in energy over the first four decades may be due to the behavioural attitude of occupants as they seek more thermal comfort at home thereby raising the internal temperature of their homes. It may also due to homes extension over the years that results in increased heated volume, which significantly adds to the space heating energy.

Based on the assumptions for the 'baseline' scenario, the model forecasts that the space heating energy would continue to follow a downward trend from the year 2004 until 2050 due to improvements in energy efficiency (SAP rating) as a result of stringent building regulations and other areas of government campaign including occupants' behavioural change towards energy consumption. Further to these reasons, the downward trend as revealed by the model results may be due to energy costs that have been on the increase since 2004 as advanced by Summerfield *et al.* (2010) and may be unconnected to milder winters (Palmer & Cooper, 2012).

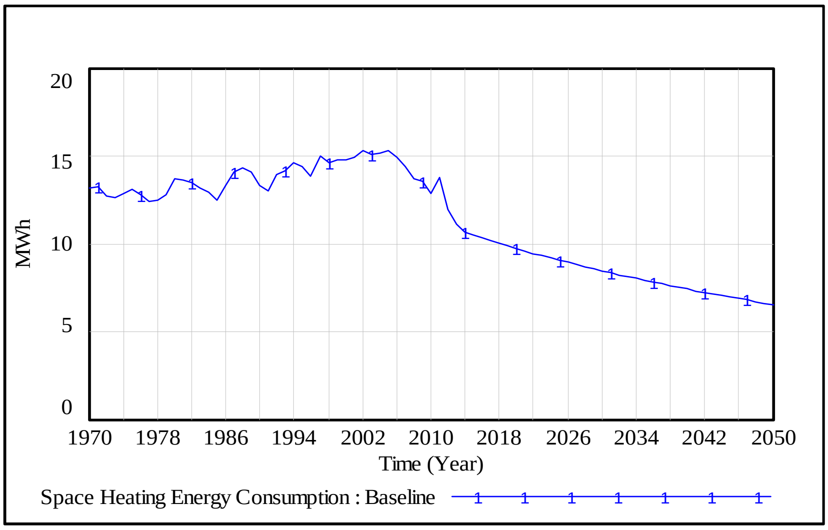


Figure 7.14: Average space heating energy consumption per household

7.7.2 Behaviour Analysis of Hot Water Energy Consumption

The result of the model suggests that hot water energy use for average UK homes has significantly reduced since 1970 and continues in this downward trend as shown in Figure 7.15. The reason that may be adduced for this trend may be connected to reduction in heat loss from hot water tanks (in terms of improvement in energy efficiency 'SAP rating') due to improved lagging of hot water pipes and tanks coupled with improvements in household heating systems that is being witnessed due to changes to building regulations. A further probe into the behaviour of the model indicates that the slope of the trend slightly changed around the year 2014 and follows this new trend until the year 2050. Should the trend follow the slope of the graph since 1970 until 2014 as shown in Figure 7.15, it may mean that by 2040, the average energy consumption for hot water would have net zero, which is practically impossible. It needs to note that irrespective of the demand for cut in household energy consumption, it will not translate to mean that no hot water would be required at homes in years to come as there will be a minimum amount of hot water energy required for each household.

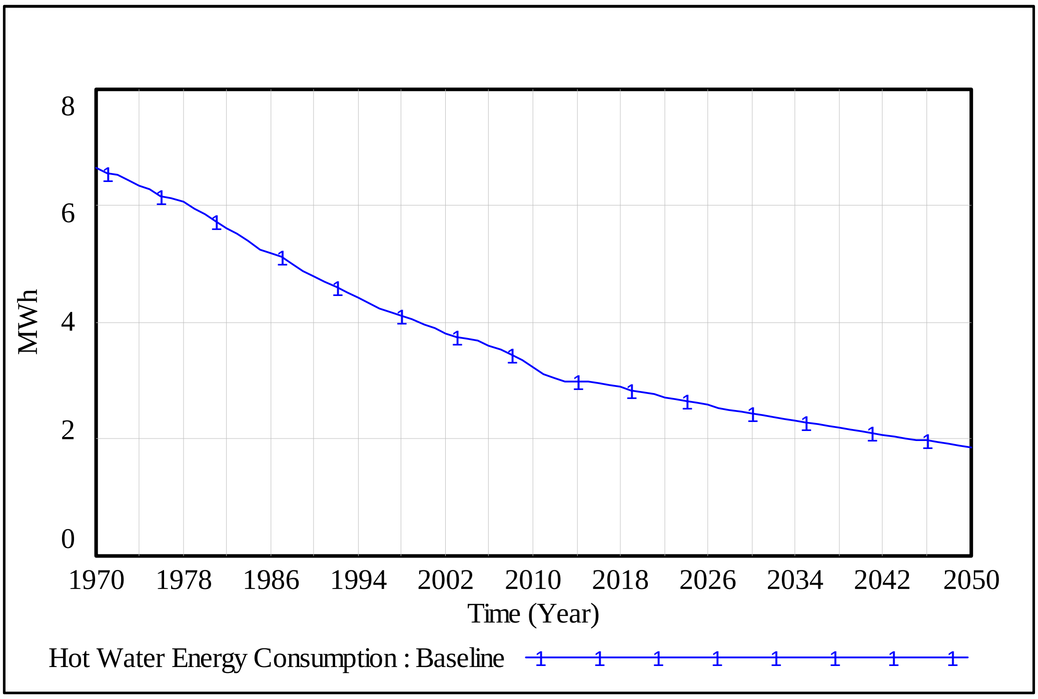


Figure 7.15: Average hot water energy consumption per household

7.7.3 Behaviour Analysis of Cooking Energy Consumption

The insight as revealed by the model output for average cooking energy consumption per household is illustrated in Figure 7.16. Generally, the trend has been on a downward direction since 1970 until 2050 with a steep slope till 1990s and the downward trend seems levelling for a short period since year 2000 apart for a short period of between 2008 and 2016. The general downward trend may be due to changes in lifestyle through saving in household cooking energy as most families eat in eateries, which consequently reduces the rate of cooking at home. However, the trend levelling up is more pronounced around the year 2016 until 2050. This saw the slope of the trend of average household cooking energy to be gentler compared to the preceding years. The reason that could be adduced for this trend could be explained as a result of a decline in the size of households. This is due to the fact that cooking energy per head is claimed to be higher in single – person households [Energy Saving Trust (EST), DECC, & (Department of Environment, Food and Rural Affairs (DEFRA), 2012].

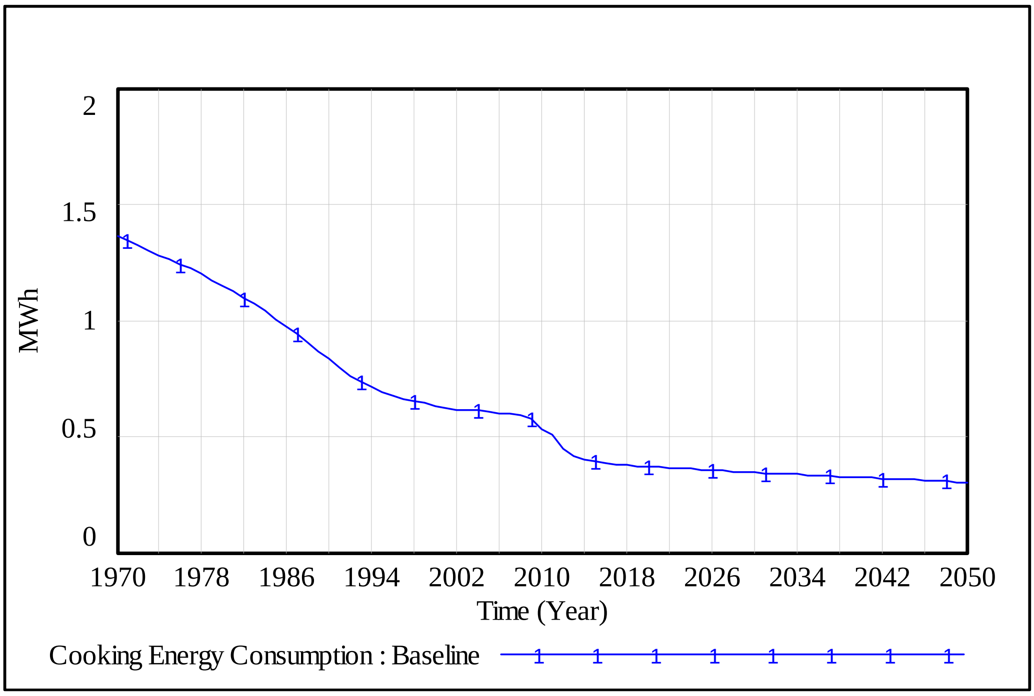


Figure 7.16: Average cooking energy consumption per household

7.7.4 Behaviour analysis of lighting energy consumption

Household lighting energy remains a small fraction of total household energy. The behaviour exhibited by the output of the model is shown in Figure 7.17. The graph shows that the average lighting energy consumption per household remarkably follows an upward trend since 1970 until 2004 when begins to gradually come down. This decline may be as a result of Government's policy of the Carbon Emissions Reduction Target (CERT), which ensures that energy – consuming incandescent bulbs are replaced in homes with energy – efficient ones. However, the simulation result suggests that the rate of decline of household lighting energy consumption would decrease as from 2016 as against the trend witnessed between 2004 and 2016. This may be as a result of likely increase in the lighting points in homes especially in the kitchens and bathrooms, which are even most times of higher specifications. This may therefore likely reduce rate of decline by offsetting the savings that would have recorded should the trend of decline between 2004 and 2016 maintained.

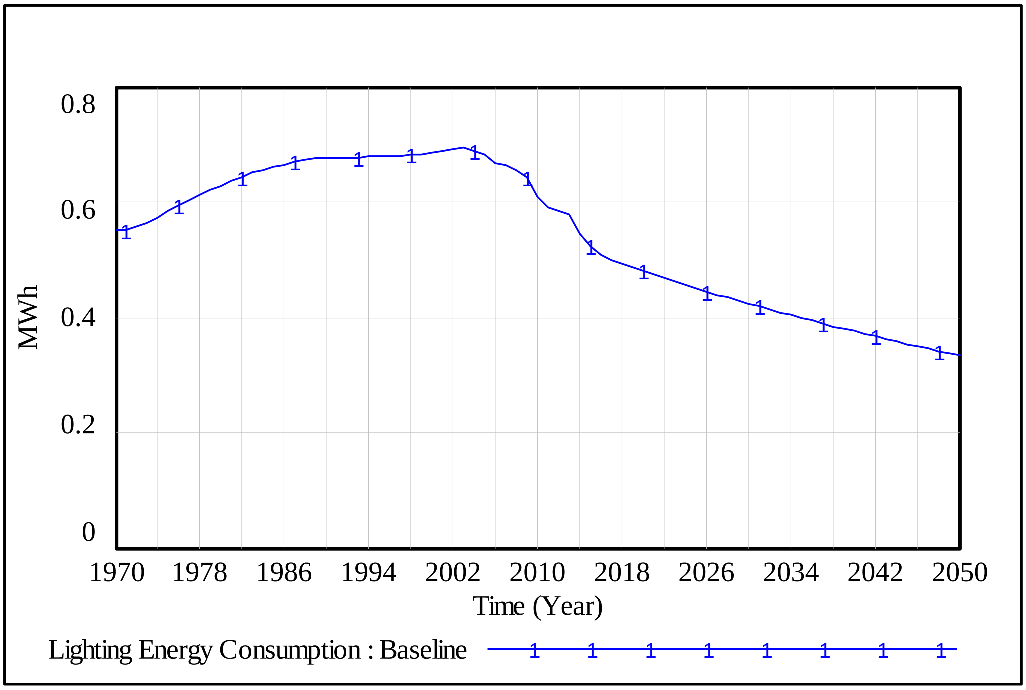


Figure 7.17: Average lighting energy consumption per household

7.7.5 Behaviour Analysis of Household Appliances Energy Consumption

The simulation result of the model as shown in Figure 7.18 suggests that household appliances energy use has been on the increase since 1970. This result is consistent with historical data (Palmer & Cooper, 2012). The reasons for this trend are explained based on three factors that could be responsible based on the author's conjecture. Firstly, the trend may be due to the fact that many homes now acquire electric gadgets more than before, which continue to grow, based on changes in occupants' lifestyle and their access to more disposable income. Secondly, owing these gadgets alone may not result in surge in household appliances energy if they are not put into use. So, the rate at which these gadgets are being put into use has been on the increase. This may probably due to changes in lifestyle as previously argued. Additionally, changing to the use of energy – consuming appliances for some tasks or games that were previously or traditionally completed manually as well as using homes as offices may be responsible for this surge.

Thirdly, the results of the study conducted by EST *et al.* (2012) indicate that the use of cold appliances like freezer and large fridges has been on the increase and they constitute about 50% of the household appliances energy use. Further, there has been growth in the use of microwaves to thaw out frozen food. Combining all these together has seen household appliances energy on the increase. However, there is an event overturn in and around 2016 as dictated by the result of the simulation that household appliances energy will follow a gentle decline till 2050. This output may explain the optimistic view regarding different on-going research efforts directed at improving the energy efficiency of cold appliances. This hopefully would see the deployment of even more energy efficient cold appliances in the coming years as they have a lion share in the household appliances energy consumption.

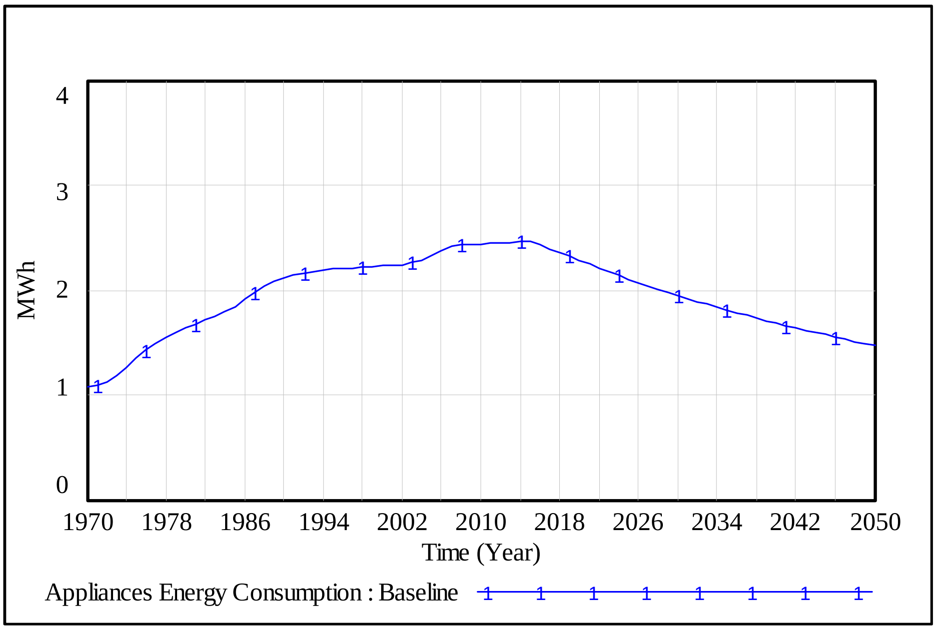


Figure 7.18: Average appliances energy consumption per household

7.7.6 Behaviour Analysis of Average and Total Annual Household Energy Consumption

Figure 7.19 shows the trend exhibited by the average annual household energy consumption. It is necessary to state that the average annual household energy is determined by summing up all the different average household energy consumption based on end-use as discussed in the preceding sub-sections above. The trend for average annual household energy consumption follows the pattern exhibited by average household space heating energy consumption. This trend further explains the fact that household space heat energy has the biggest chunk of UK household energy therefore moderating the behaviour of average household energy. Similarly, total annual household energy consumption, as shown in Figure 7.20, follows the same trend as this was computed for the entire UK housing stock. The output of average annual household energy consumption is multiplied by the number of households which has been growing over the years may be due to conversion of some office buildings to homes. However, the effect of the growth in number of households may have overblown the total annual household energy consumption for the UK housing stock to some extent.

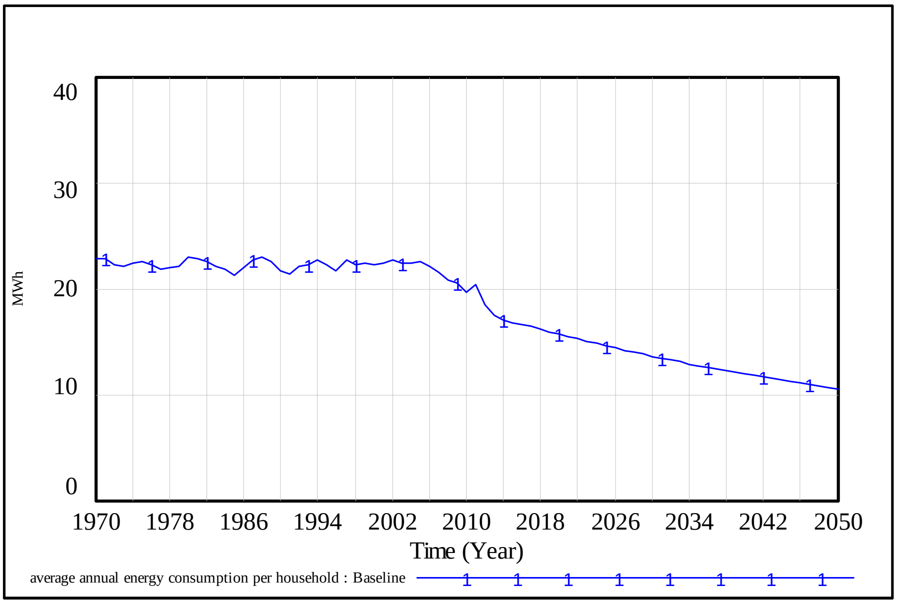


Figure 7.19: Average annual energy consumption per household

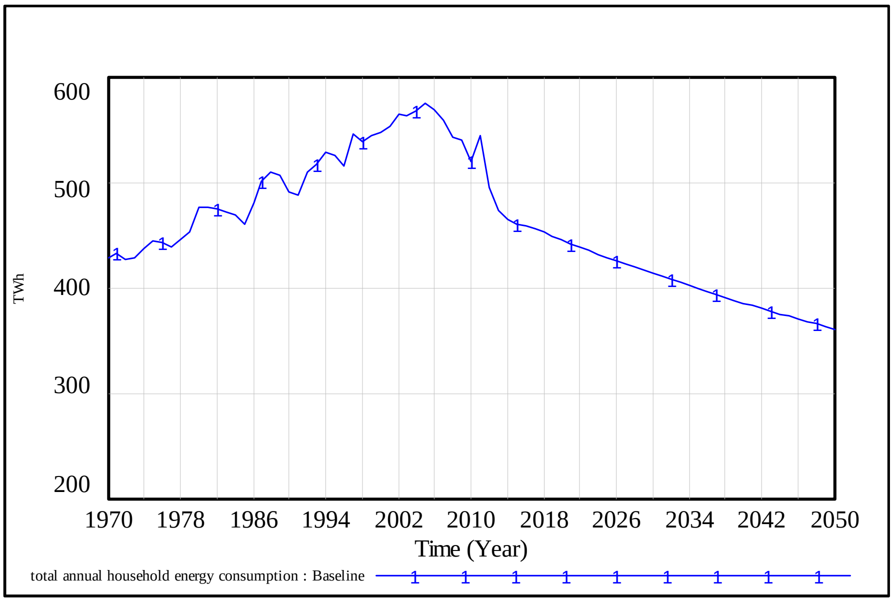


Figure 7.20: Total annual energy consumption for the UK housing stock

A further analysis regarding the household energy consumption based on end uses for the entire UK housing stock is carried out for the 'baseline' scenario. This analysis is conducted for the years 2020 and 2050 relative to the year 1990. This kind of analysis is necessary majorly to determine the extent to which the household energy consumption has been reduced or otherwise under the ‘baseline’ scenario assumptions for the model. Tables 7.2 and 7.3 illustrate the changes in household energy for the year 2020 and 2050 relative to the year 1990 respectively.

The results of this analysis for the year 2020 based on the ‘baseline’ scenario as shown in Table 7.2 suggest that the total household energy consumption for the entire UK housing stock is expected to witness a reduction of about 45.92TWh of energy. This amount translates to about 9% reduction by the year 2020. Further to this, the analysis within the period suggests that space heating is expected to witness a reduction of about 8%, hot water about 26%, cooking about 44% and lighting about 11%. However, appliances energy for the same period is expected to increase by about 35%.

Table 7.2: Change in household energy consumption by end-use based on ‘baseline’ scenario for the year 2020 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2020) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	276.88	-24.04	-7.99
Hot Water	108.20	79.41	-28.79	-26.61
Cooking	18.88	10.52	-8.36	-44.28
Lighting	15.29	13.62	-1.67	-10.92
Appliances	47.93	64.87	+16.94	+35.34
Total	**491.22**	**445.30**	**-45.92**	**-9.35**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

For the year 2050, the analysis of results as shown in Table 7.3 indicates that the total household energy for the UK housing stock is expected to reduce by about 27% relative to 1990 under the ‘baseline’ scenario assumptions. This percentage sees the total household energy less by 130.67TWh when compared to 491.22TWh it was in the base year 1990. Additionally, the results of the model suggest that the energy consumption due to space heating is expected to reduce by 76.37TWh, which translates to about 25% reduction in energy by 2050 relative to 1990 as base case. Also, the energy consumption attributable to hot water is anticipated to reduce as well by 44.47TWh, which amounts to about 41% reduction, again relative to 1990 base case. Correspondingly, the results of the model suggest that the energy consumption for cooking is expected to marginally reduce by about 45% as against the 44% reduction envisaged for the year 2020. As expected, the model results indicate that the energy consumption for lighting is expected to reduce as well for about 25%. Regarding the appliances energy consumption, the model results suggest that this is anticipated to increase by about 5% relative to the base year 1990. However, this witnesses a reduction in consumption when compared to the results of the year 2020.

Table 7.3: Change in household energy consumption by end-use based on ‘baseline’ scenario for the year 2050 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2050) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	224.55	-76.37	-25.38
Hot Water	108.20	63.73	-44.47	-41.10
Cooking	18.88	10.40	-8.48	-44.92
Lighting	15.29	11.44	-3.85	-25.18
Appliances	47.93	50.43	+2.5	+5.21
Total	**491.22**	**360.55**	**-130.67**	**-26.60**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

The changes expected to occur in energy consumption based on end uses are based on the projection of continuation of current trends in fabric insulation, energy efficiency, energy prices, and consumption behaviour. As fabric insulation ('insulation factor') and energy efficiency improve ('effect of energy efficiency standard improvement on dwelling energy efficiency'), reduction in household energy consumption is anticipated. Also, standard consumption behaviour with moderate rise in energy prices ('% increment on energy bills') is expected to lead to a reduction in household energy consumption by the year 2050 as model output suggests. However, it needs to emphasise that the results of the simulation run for the 'baseline' scenario indicate that the total number of UK households as well as average internal temperature increases within this period. They now tend to increase the total household energy consumption. Within this period, the occupants' thermal comfort also increases as can be seen in Figure 7.11, Section 7.5 of this chapter. The implication of these would result in rebound effects as the majority of the savings accruable would have been expended on getting an improved comfort.

7.8 Behaviour Analysis of Household CO_2 Emissions Module

Figure 7.21 (see Table B2 in Appendix B for the values) show the graphs of household carbon emissions by end-use, while Figure 7.22 show that of household carbon emissions in terms of average annual household and total household respectively. These results are profound as the behaviour exhibited by household carbon emissions by end-use (Figure 7.21) as well as the one shown in Figure 7.22 is similar to the ones demonstrated by household energy consumption by end-use (Figures 7.14 – 7.18), and average and total annual household energy consumption (Figures 7.19 – 7.20) respectively. This trend may be due to the fact that carbon emissions are as a result of energy consumption. However, the dominant type of energy consumed by householders would go a long way in moderating household carbon emissions. Assessing the average annual carbon emissions per household and total annual household carbon emissions, it was noted that carbon emissions has been on a downward direction since 1970. That is, average annual carbon emissions per household have fallen remarkably since 1970 and the model projects that the trend will be sustained till 2050 based on the carbon reductions agenda of the government. The output is similar to the trend witness in historical data (Palmer & Cooper, 2012) as the trend (Figure 7.22) follows a 'lumpy' trend with troughs and peaks that corresponds to mild and severe weather conditions.

It is necessary to conduct a further analysis of results in order to reveal additional insights as well as see the extent to which the carbon emissions reductions target are achieved for the 'baseline' scenario. Tables 7.4 and 7.5 illustrate the changes or reductions expected in household carbon emissions for the years 2020 and 2050 relative to the year 1990. The Climate Change Act of 2008 in the UK stipulates carbon emissions reductions target of 34% and 80% relative to 1990 level by the years 2020 and 2050 respectively.

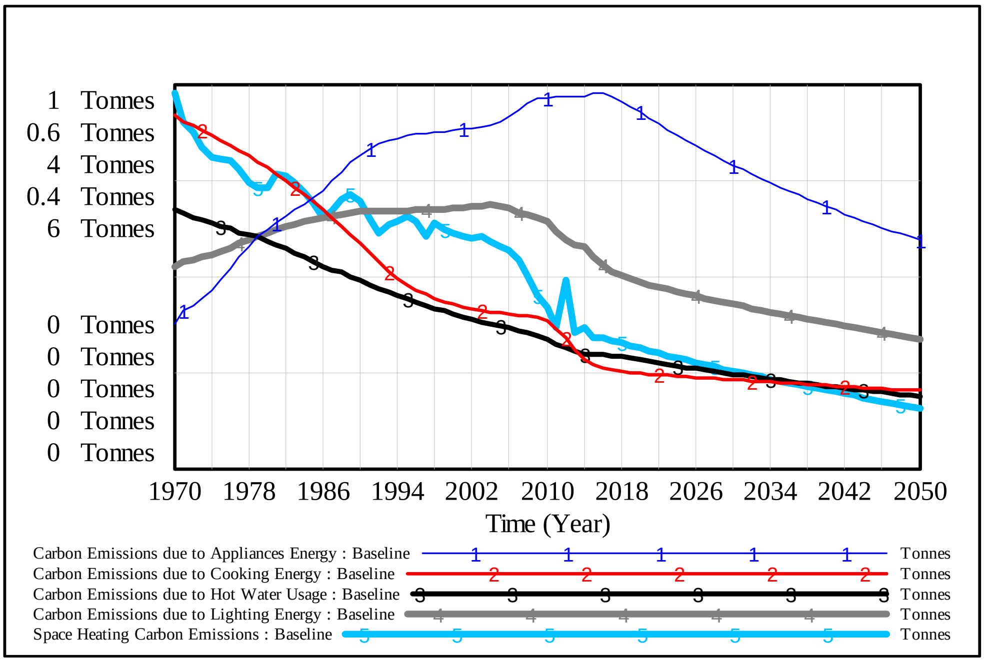


Figure 7.21: The graph of household carbon emissions by end-use under the 'baseline' scenario

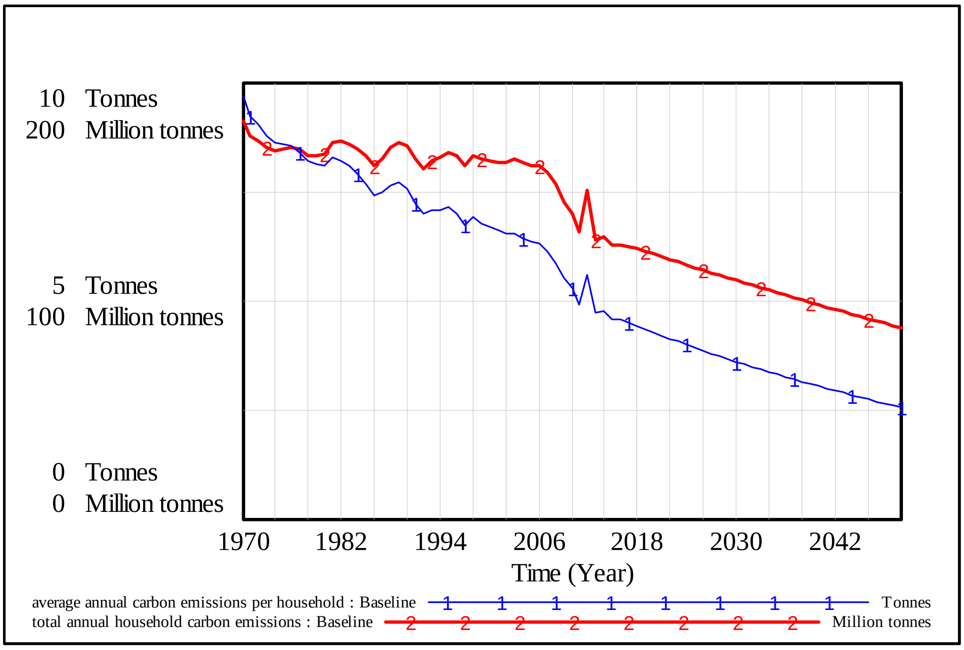


Figure 7.22: The graph of total and average annual household carbon emissions under the 'baseline' scenario

Table 7.4: Change in household carbon emissions by end-use based on 'baseline' scenario for the year 2020 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2020) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	53.19	-41.28	-43.70
Hot Water	44.15	32.09	-12.06	-27.32
Cooking	7.93	4.21	-3.72	-46.91
Lighting	6.04	5.50	-0.54	-8.94
Appliances	18.43	26.29	*+7.86*	*+42.65*
Total	**171.01**	**121.28**	**-49.73**	**-29.08**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

To this end, the model results in Table 7.4 suggest that the carbon emissions ascribable to the UK households are expected to decline by 49.73 million tonnes of CO_2 by the year 2020. This amount represents about 29% reductions in carbon emissions. The implication of this result is that under the 'baseline' scenario, it unlikely to meet the target reductions of 34% as enshrined in the Climate Change Act of 2008. A further analysis based on end uses reveals that the greatest reductions are expected to happen in space heating, which is anticipated to witness 41.28 million tonnes of CO_2 reductions by the year 2020.

Table 7.5: Change in household carbon emissions by end-use based on 'baseline' scenario for the year 2050 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2050) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	32.46	-62.01	-65.64
Hot Water	44.15	25.71	-18.44	-41.77
Cooking	7.93	4.16	-3.77	-47.54
Lighting	6.04	4.61	-1.43	-23.68
Appliances	18.43	20.35	*+1.92*	*+10.42*
Total	**171.01**	**87.28**	**-83.73**	**-48.96**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

The analysis conducted for the year 2050 reveals that the carbon emissions attributable to the UK housing stock are expected to decline by up to 83.73 million tonnes of CO_2. This amount represents about 49% reductions in carbon emissions by the middle of this century. Similarly, the implication of this result under the 'baseline' scenario suggests that it unlikely to meet the target reductions of 80% as enshrined in the Climate Change Act of 2008. An additional analysis based on end uses shows that the chunk of the reductions expected in carbon emissions are to occur in space heating. This is anticipated to witness about 62 million tonnes of CO_2 reductions by the year 2050.

7.9 Comparison of 'Baseline' Scenario Results with Other Model Results

The section discusses results of comparison of the 'baseline' scenario with the results of Johnston's (2003) 'business-as-usual' scenario. The Johnston's (2003) 'business-as-usual' scenario is based on the current trends of energy efficiency improvements as at the time the research was conducted. Most of the assumptions made by Johnston (2003) for the scenario are similar to this model's 'baseline' scenario assumptions. The results of this comparative analysis are summarised in Tables 7.6 and 7.7 for household energy consumption and household carbon emissions respectively. The results shown in Tables 7.6 and 7.7 for the total annual household energy consumption and carbon emissions display the same pattern of trend. There are, however, some differences in the two models. The values of total annual household energy consumption are lower than that of Johnston (2003).

Table 7.6: Change in household carbon emissions by end-use based on 'baseline' scenario for the year 2050 relative to 1990

	Total annual household energy consumption (KWh)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
'Baseline' scenario	491.2	546.8	519.4	445.3	413.1	385.4	360.6
Business-as-usual scenario of Johnston (2003)	-	556.9	555.0	547.8	530.1	511.4	437.9

Table 7.7: Change in household carbon emissions by end-use based on 'baseline' scenario for the year 2050 relative to 1990

	Total annual household carbon emissions (million tonnes of CO_2)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
'Baseline' scenario	171.0	164.2	140.1	121.3	109.2	98.0	87.3
Business-as-usual scenario of Johnston (2003)	-	132.7	132.5	137.1	127.7	118.0	97.5

This may likely due to the fact that the evidence from historical data utilised by this model suggest a drastic reduction in energy consumption. This is because of different schemes of Government regarding energy consumption yielding positive results. These differences are likely due to different assumptions made, input data utilised, and/or the modelling philosophy employed by the two models. Regarding the different assumptions made, the two models clearly show that there are some differences in household carbon emissions (see Table 7.7). This difference may be as a result of the assumption made by this model regarding the energy to carbon conversion factor as enunciated in Section 6.6.6. Also, input data utilised are different. Johnston (2003) used data from a number of sources, basically from Shorrock and Dunster (1997) as published by BRE. This research too utilised data from different sources, basically from Palmer and Cooper (2012) as published by DECC. It should be noted that DECC is the Government body housing energy data in the UK. Data used in this research is more recent than that of Johnston (2003). This may therefore account for the differences. Finally, it may be due to the modelling philosophy used by the two models. Johnston's model was implemented using Excel template based on building physics, which only utilises quantitative data; while the model in this research is implemented using SD, which is based on feedback control. It is worth mentioning that the SD modelling approach utilised in this thesis combined both the quantitative and qualitative data sources together, this is seen as the main strength of this approach.

7.10 Chapter Summary

This chapter has described and discussed the general assumptions made under the 'baseline scenario'. The model behaviour under this scenario suggested the way by which household energy consumption and carbon emissions attributable to the UK housing stock would evolve over the years under the assumptions that the current energy efficiency measures, consumption behaviour and energy prices trends will be sustained. The results of key variables from each of the modules were discussed. In the population/household module, the model behaviour indicated that the total UK population is on the upward trend until 2050. Also, the number of households in the UK was predicted by the model to likely grow on a yearly average of 1.02%, while the average household size tends toward two per household by the year 2050. Under the dwelling internal heat module, the model output suggests that both the dwelling internal heat and dwelling internal temperature will continue to grow. These are due to improvements envisaged in dwellings' thermal performance, thereby increasing dwellings' airtightness and the desire to improve thermal comfort by raising the temperature set-point by householders.

Furthermore, the chapter discussed the insights observed from key variables under the occupants thermal comfort module. These include the behaviour of perceived dwelling temperature that the model output suggests that will grow over the year until 2050. The reason for this trend is as offered under the discussion of dwelling internal heat and dwelling internal temperature. This is seen to result in improved occupants' thermal comfort. Within the climatic-economic-energy efficiency interaction module, the model results suggest that the unfavourable climatic effects will decline as a result of efforts aiming at reducing carbon emissions. However, the model result suggests that the effect of energy efficiency standard improvement on dwelling energy efficiency will tend to improve. The results from the scenario suggest that about 9% and 27% reductions in household energy consumption are visible by the years 2020 and 2050 respectively below the year 1990 levels. These translate to savings of 29% and 49% in carbon emissions by the years 2020 and 2050 respectively. The insights from the model show that the greatest savings in both household energy consumption and carbon emissions are expected from space and water heating.

Chapter 8

MODEL TESTING AND VALIDATION

8.1 Introduction

In SD methodology, model testing and validation are regarded as important stages. This chapter therefore reports the model testing and validation process as completed for the developed model in this thesis. This chapter first discusses the SD validation tests that can be performed. This is followed by some background information on experts and professionals who took part in the validation exercise. Afterward, the chapter discusses the results of the validation tests performed in terms of structure-oriented and behaviour pattern tests.

8.2 Model Validation Tests

As previously given under Section 6.6, the developed model in this thesis is simulated using Vensim DSS for Windows Version 5.11A software. Vensim is one of the SD modelling tools that commonly in use to build, simulate and analyse SD models. Researchers acknowledge Model Testing and Validation (MTaV) as an important aspect of any model-based methodology like SD (Barlas, 1996; Ranganath & Rodrigues, 2008) and as such, a crucial step that is not to be disregarded whatsoever. It is significant in the sense that the validity of results emanating from the model is heavily dependent on the validity of the model itself. MTaV is the process of testing the soundness and correctness of construction of the model while establishing confidence in the usefulness of the model (Coyle, 1997; 1977). Hence, this MTaV exercise proves the credibility of the outputs from the model and ascertains that the results accurately represent reality. Testing the model actually means validating it.

However, some researchers argue that MTaV is a controversial issue (Barlas, 1996) because there is no single approach that would allow the modellers to ascertain that their models have been validated. Further to this controversy, Sterman (2000) contends that complete model validation is practically impossible and as such more emphasis needs to be laid on model testing in order to build confidence that the model is adequate for the intended purpose.

To this extent, there are quite a number of tests to assess the validity of SD models. This is generally divided into structure-oriented and behaviour pattern tests (Forrester & Senge, 1980; Barlas, 1985; 1996; Richardson & Pugh, 1999; Sterman, 2000; Groesser & Schwaninger, 2012). The tests include and not limited to (1) structure-oriented tests – boundary adequacy, structure assessment, dimensional consistency, parameter assessment, extreme conditions, and integration error, (2) behaviour pattern tests – behaviour reproduction, behaviour anomaly, family member, surprise behaviour, sensitivity analysis, and system improvement. The purpose of each of these test and tools/procedures required are illustrated in Table 8.1 as adapted from the work of Sterman (2000). The tests are therefore discussed in Sections 8.4 and 8.5.

8.3 Details of Participants in Model Testing and Validation

This section discusses the details of the experts (both from energy and SD backgrounds) that participated in the model validation process as explained in research methodology chapter. Table 8.2 shows the background information of the fifteen experts that took part in the review of the model and its output (see Appendix D1 for the validation instrument).

Similarly to the background questions asked the interviewees during the model conceptualisation validation as explained in Chapter 6, these same background questions were asked. This is basically to once again establish the reliability of the participants in the model validation.

Table 8.1: SD validation tests

Test	Purpose of Test	Recommended Tools and Procedures
A. Structure Validity		
1. Boundary Adequacy	Are the important concepts for addressing the problem endogenous to the model? Does the behaviour of the model change significantly when boundary assumptions are relaxed? Do policy recommendations change when the boundary is extended?	Use model boundary charts, subsystem diagrams, causal diagrams, stock and flow maps, and direct inspection of model equations. Use interviews, workshops to solicit expert opinion, archival materials, review of literature, direct inspection/participation in system processes, *etc.* Modify model to include plausible additional structure; make constants and exogenous variables endogenous, then repeat sensitivity and policy analysis
2. Structure Assessment	Is the model structure consistent with relevant descriptive knowledge of the system? Is the level of aggregation appropriate? Does the model conform to basic physical laws such as conservation laws? Do the decision rules capture the behaviour of the actors in the system?	Use policy structure diagrams, causal diagrams, stock and flow maps, and direct inspection of model equations. Use interviews, workshops to solicit expert opinion, archival materials, direct inspection or participation in system processes, as in (1) above. Conduct partial model tests of the intended rationality of decision rules. Conduct laboratory experiments to elicit mental models and decision rules of system participants. Develop disaggregate submodels and compare behaviour to aggregate formulations. Disaggregate suspect structures, then repeat sensitivity and policy analysis.
3. Dimensional Consistency	Is each equation dimensionally consistent without the use of parameters having no real world meaning?	Use dimensional analysis software. Inspect model equations for suspect parameters.
4. Parameter Assessment	Are the parameter values consistent with relevant descriptive and numerical knowledge of the system? Do all parameters have real world counterparts?	Use statistical methods to estimate parameters (wide range of methods available). Use partial model tests to calibrate subsystems. Use judgemental methods based on interviews, expert opinion, focus groups, archival materials, direct experience, *etc.* Develop disaggregate submodels to estimate relationships for use in more aggregate models.
5. Extreme Conditions	Does each equation make sense even when its inputs take on extreme values? Does the model respond plausibly when subjected to extreme policies, shocks, and parameters?	Inspect each equation. Test response to extreme values of each input, alone and in combination. Subject model to large shocks and extreme conditions. Implement tests that examine conformance to basic physical laws.
6. Integration Error	Are the results sensitive to the choice of time step or numerical integration method?	Cut the time step in half and test for changes in behaviour. Use different integration methods and test for changes in behaviour.

(Adapted from Sterman, 2000)

Table 8.1: *Continued.*

Test	Purpose of Test	Recommended Tools and Procedures
B. Behaviour Validity		
7. Behaviour Reproduction	Does the model reproduce the behaviour of interest in the system (qualitatively and quantitatively)? Does it endogenously generate the symptoms of difficulty motivating the study? Does the model generate the various modes of behaviour observed in the real system? Do the frequencies and phase relationships among the variables match the data?	Compute statistical measures of correspondence between model and data: descriptive statistics (*e.g.* R^2); time domain methods (*e.g.* autocorrelation functions); frequency domain methods (*e.g.* spectral analysis); many others. Compare model output and data qualitatively, including modes of behaviour, shape of variables, asymmetries, relative amplitudes and phasing, unusual events. Examine response of model to test inputs, shocks, and noise.
8. Behaviour Anomaly	Do anomalous behaviours result when assumptions of the model are changed or deleted?	Zero out key effects (loop knockout analysis). Replace equilibrium assumptions with disequilibrium structures.
9. Family Member	Can the model generate the behaviour observed in other instances of the same system?	Calibrate the model to the widest possible range of related systems.
10. Surprise Behaviour	Does the model generate previously unobserved or unrecognised behaviour? Does the model successfully anticipate the response of the system to novel conditions?	Keep accurate, complete, and dated records of model simulations. Use model to simulate likely future behaviour of system. Resolve all discrepancies between model behaviour and your understanding of the real system. Document participant and client mental models prior to the start of the modelling effort.
11. Sensitivity Analysis	*Numerical sensitivity:* Do the numerical values change significantly…. *Behavioural sensitivity:* Do the modes of behaviour generated by the model change significantly…. *Policy sensitivity:* Do the policy implications change significantly…. ….when assumptions about parameters, boundary, and aggregation are varied over the plausible range of uncertainty?	Perform univariate and multivariate sensitivity analysis. Use analytic methods (linearization, local and global stability analysis, *etc.*). Conduct model boundary and aggregation tests listed in (1) and (2) above. Use optimisation methods to find the best parameters and policies. Use optimisation method to find parameter combinations that generate implausible results or reverse policy outcomes.
12. System Improvement	Did the modelling process help change the system for the better?	Design instruments in advance to assess the impact of the modelling process on mental models, behaviour, and outcomes. Design controlled experiments with treatment and control groups, random assignment, pre-intervention and post-intervention assessment, *etc.*

As shown in Table 8.2, the organisation type, academic qualification, years of experience in household energy related issues, and years of experience in system dynamics modelling of the interviewees are captured. The interview participants are nine from the private sector representing 60% of the interviewees, while the remaining six representing 40% belongs to the public sector. This indicates that the views of both the public and private sectors regarding issues relating to household energy consumption are captured. The academic qualification of the participants reveal that majority (*N=9*) of the interviewees hold a minimum of master’s degree (60% of the interviewees), four of them representing 26.7% hold a bachelor’s degree, while the remaining 13.3% hold a PhD degree. The implication of this is that all the interviewees have the requisite academic qualification qualified them to presumably knowledgeable about the issues being sought by the study.

It is equally important to capture the years of experience of the interviewees in order to ensure that those interviewed have involved and have deep knowledge on issues relating to household energy consumption and/or SD. The interviewees have an average of 17.5 years of experience on issues relating to household energy, which incidentally, the same as for those interviewed during the model conceptualisation stage in Chapter 6. Similarly, the mean years of experience of the three interviewees in SD modelling is 18.4 years as shown in Table 8.2. This implies that the system dynamicists that participated in the validation are with requisite years of experience.

Again as done at the model conceptualisation stage in Chapter 6, the interview of each interviewee started with a brief description of the research by highlighting its aim and objectives. The purpose of the validation task together with the expected outcomes was explained to each of the interviewees mainly to ensure that the exercise is as clear as possible to them. The interviewees were first given the final causal diagrams produced for each of the modules in the model. The SFD developed from the CLDs were shown to them on the laptop together with the assumptions made. Some of the tests performed within the Vensim software were demonstrated to them prior to the model simulation. The model simulation was then performed for the ‘baseline’ scenario and the graphs of the major outputs from the model were viewed by the interviewees. Some other scenarios were performed and the outputs from them were assessed. This face validity then forms the basis for the validity by scoring approach based on some pre-determined criteria as shown in Table 8.3. Further to the face validation, the system dynamicists interviewed subjected the model to another round of scrutiny by performing all the necessary model validation tests. Also, they check some of the equations developed in the model and assess their appropriateness and conformity with the general rules guiding the SD modelling.

Table 8.2: Background information of experts participated in model validation

Category	**Classification**	**Frequency**	**Percentage (%)**
Organisation Type *(N=15)*	Public	6	40
	Private	9	60
	Total	**10**	**100**
Academic Qualification *(N=15)*	Bachelor’s degree	4	26.7
	Master’s degree	9	60
	PhD	2	13.3
	Total	**10**	**100**
Years of Experience in Household Energy Related Issues *(N=12)*	6-10	2	16.7
	11-15	3	25
	16-20	6	50
	21-25	1	8.3
	Mean = 17.5		
Years of Experience in System Dynamics Modelling *(N=3)*	11-15	1	33.3
	16-20	2	66.7
	Mean = 18.4		

N = Number of interviewees

For scoring method, the interviewees were asked to assess the model according to a set of pre-determined criteria based on the SD model reviewed by them. Chew and Sullivan (2000) argues that the objective of any model validation is to ensure that it adequately reflects the model objectives. Further to this, Sargent (2005) and Martis (2006) suggest that the model developed should adequately meet the following criteria: logical structure, clarity, comprehensiveness, practical relevance, applicability, and intelligibility of the model. These criteria were the ones included in the questions asked the interviewees. The scores ascribed to each of the criteria are based on '5' representing 'excellent', '4' – 'above average', '3' – 'average', '2' – 'below average', and '1' – 'poor'. Table 8.7 shows the results for this method of validation.

Table 8.3: Model validation based on scoring method

Criteria	**Score**					**Mean* Score**
	5	**4**	**3**	**2**	**1**	
Logical structure	4	8	3	0	0	**4.07**
Clarity	5	8	2	0	0	**4.20**
Comprehensiveness	3	9	3	0	0	**4.00**
Practical relevance	4	10	1	0	0	**4.20**
Applicability	2	9	4	0	0	**3.87**
Intelligibility	2	7	6	0	0	**3.73**

**Mean Score =(5*n_s + 4*n_4 +3*n_3 + 2*n_2 +1*n_1)/(5+4+3+2+1) where n_s, n_4,…. correspond responses relating to 5, 4, …. respectively.*

The logical structure has a mean score of 4.07 indicating that this score is by far above the average. The logical structure here assesses the consistency of the model with the properties of the real system being mimicked. This results indicate that no logical disjoint with the real system exist. Also, the mean scores for clarity and practical relevance are each 4.02 suggesting that the respondents agree that the model is well clear with practical relevance on issues relating to household energy consumption and carbon emissions. Furthermore, model comprehensiveness has a mean score of 4.00, which shows that the model captures important variables purporting to influence energy and carbon emissions and has the capability of addressing the problem under study. Applicability and intelligibility of the model have a mean score of 3.87 and 3.73 respectively as shown in Table 8.3. These scores are, once again, above the average suggesting the usefulness of the model. They also reinforce the comments of the experts interviewed as given under the Section 8.4.2.

8.4 Structure – Oriented Tests

The main aim of structure-oriented tests is to ascertain that the model outputs capture and consistent with the real system being replicated. The tests ensure that the model is appropriate for the target audience (Ranganath & Rodrigues, 2008). Further to this, the tests focus on the suitability of the level of aggregation and determine whether or not the basic physical laws are strictly adhered to regarding the parameters utilised in the model. In this research, the model is subjected to the following structure-oriented tests in order to have it validated.

8.4.1 Boundary Adequacy Test

As shown in Table 8.1, the boundary adequacy tests assess the appropriateness of the model boundary to capture the problem under investigation. The model boundary charts for this model is shown in Table 6.2 of Chapter 6, which is one of the useful tools to conduct boundary adequacy tests. Apart from the model boundary chart, the model CLDs of different modules were validated qualitatively through a series of interviews held with experts and practitioners in issues relating to household energy as explained in research methodology chapter as well as Section 6.2 of Chapter 6. The feedback from these interviews indicates that the study captures important variables relating to HECCE. However, some of the interviewees are of the opinion that there are more rooms for improvement through making some of the exogenous variables like occupants' behaviour in the model endogenous as well as expanding the boundary of the model by including some of the excluded variables in the upgraded version of the model.

8.4.2 Structure Assessment Test

According to Sterman (2000), the structure assessment tests whether or not the model structure is consistent with relevant descriptive knowledge of the system and conforms to basic physical laws. It also tests whether or not the level of aggregation of the model is appropriate as tested under the model boundary adequacy tests. In this research, the modeller (author) ensures that the structure of the model considers all the real life issues that are consistent with relevant descriptive knowledge in the subject. This is done at both model conceptualisation and complete model validation stages.

At the model validation stage, the results of the interviews conducted indicate that both the energy and SD experts interviewed are satisfied with the structure of the model in terms of its description of the relevant knowledge in the subject. One of the interviewees reports that *"the structure of the model makes it easy to follow and is simple to understand even if you are not familiar with energy issues or system dynamics"*. Another interviewee expresses that *"the structure of the model demonstrates how a large number of variables are interrelated in a logical manner"*. When asked to comment generally on the structure of the model, another interviewee notes that *"this is a very well developed model which appears to represent a very impressive body of work"*.

Additionally, both the modeller and the system dynamicists interviewed qualitatively inspected some of the model equations in order to assess whether or not they are conformable to and consistent with the basic physical laws. The result of this exercise suggests that all the equations inspected are conformable to basic physical laws and do make sense. Also, the reports of the interviews conducted the energy experts suggest that the model includes all the significant variables and the level of aggregation is consistent with the target audience for the model.

8.4.3 Dimensional Consistency Test

The dimensional consistency test assesses the model equations for dimensional consistency and check whether or not all the units and values attributed to the model parameters are consistent with relevant understanding of the system under investigation (Sterman, 2000). In order to ensure that the model is validated accordingly, the dimensional analysis tool within the Vensim software was used to conduct this test. In Vensim, the software automatically checks the dimensions of all the variables and the equations in the model in order to ascertain that they are consequently balanced. For the model in this thesis, the dimensional analysis tool was invoked and all the units of the model variables and equations were verified and balanced accordingly.

8.4.4 Parameter Assessment Test

According to Sterman (2000), the parameter assessment test evaluates the model parameters and check whether or not all their values are consistent with relevant descriptive and numerical noesis of the system. This is consistent with the argument of Ranganath and Rodrigues (2008) that the numerical values of parameters should have real system equivalents. In order to ensure that the parameter assessment of the model variables is adequately evaluated, Sterman (2000) suggests the tools and procedures for achieving this as shown in Table 8.1. Among the ways suggested are the statistical and judgemental methods. The values of majority of parameters in the model are taken from relevant published data sources as discussed in Section 4.4.2. For example, the following parameters (*solar flux*, *solar transmittance factor for glazing*, *frame factor*, *etc.*) under the dwelling internal heat module are extracted from the SAP data (BRE, 2012) (See Section 4.42.

8.4.5 Extreme Conditions Test

The extreme conditions test evaluates how sound and robust the model is based on its response to the variables subjected to extreme values. This test then assesses the model equations and check whether or not they still make any sense when subjected to extreme conditions. In order to test and validate the model against this structure-oriented test, the model was subjugated to extreme values of some parameters. For example, the model was submitted to extreme values of 'insulation factor' and '% increment of energy bills', which are varied for 0% and 100%. The model results indicate that the behaviour of the output still make sense without any plausible or irrational response in terms of the values of outputs as shown in Figures 8.1 to 8.4.

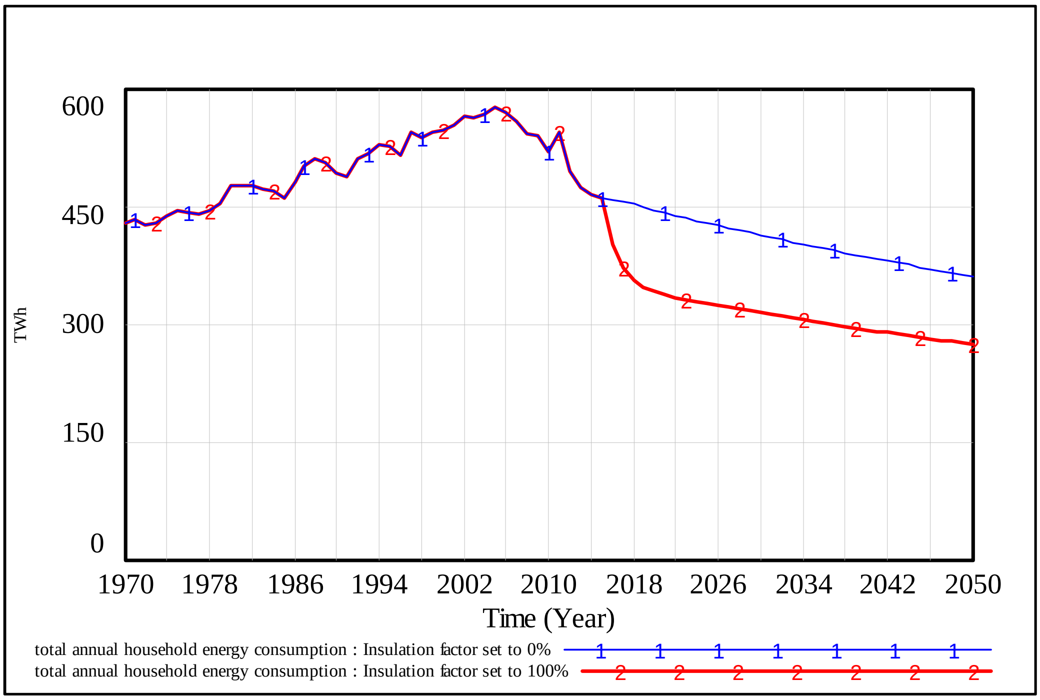


Figure 8.1: Total annual household energy consumption under 'insulation factor' set to 0% and 100%

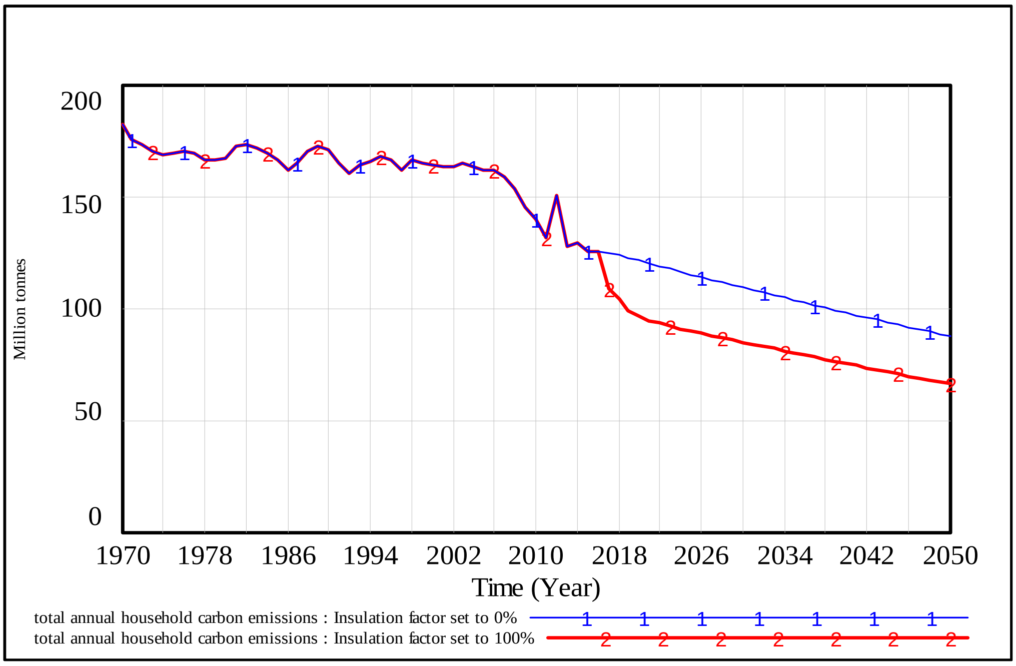


Figure 8.2: Total annual household carbon emissions under ‘insulation factor’ set to 0% and 100%

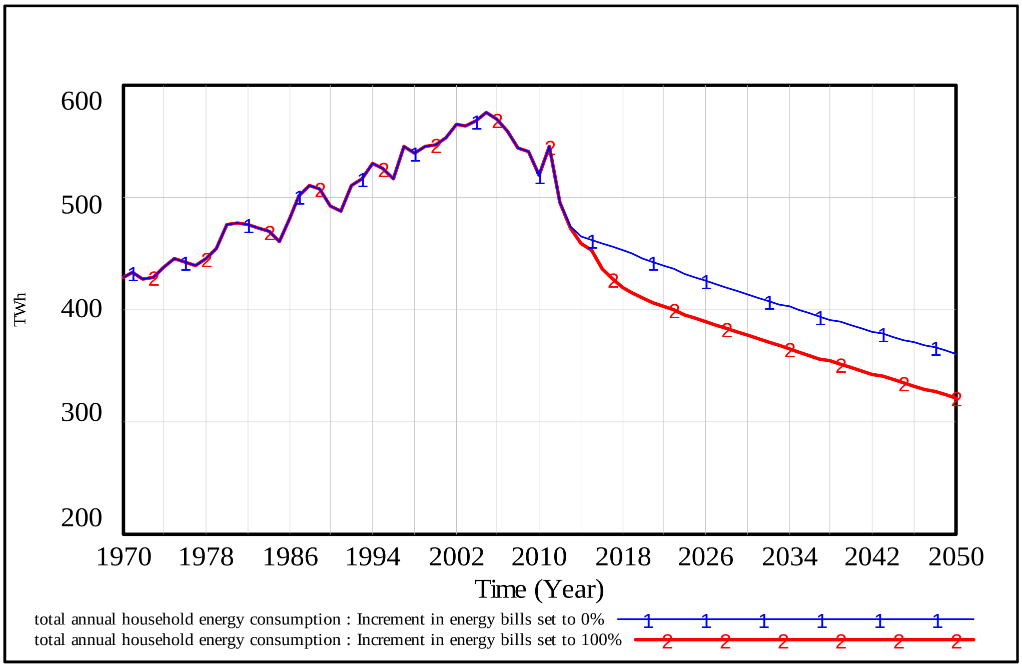


Figure 8.3: Total annual household energy consumption under ‘increment in energy bills’ set to 0% and 100%

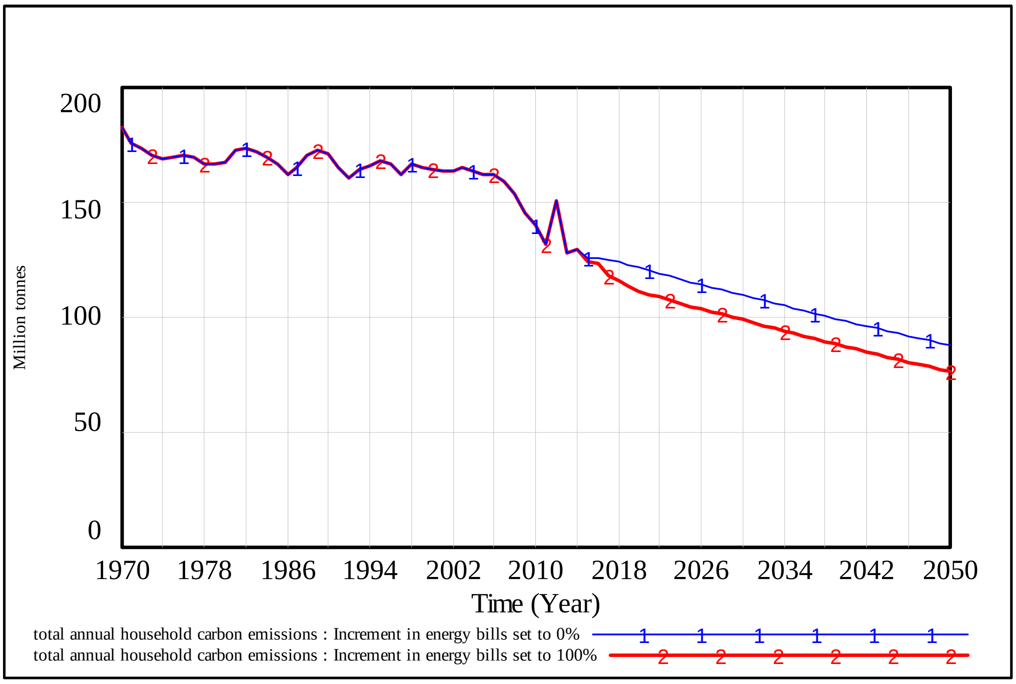


Figure 8.4: Total annual household carbon emissions under ‘increment in energy bills’ set to 0% and 100%

8.4.6 Integration Error Test

In this section, the model’s robustness was further assessed by performing the integration error tests for the model. Sterman (2000) argues that the integration error tests the sensitivity of the model results to the choice of *Time Step* and/or numerical integration methods employed in the simulation. He recommends cutting the *Time Step* used in the simulation into halve in order to check whether or not there are changes in the behaviour of the model outputs. Similarly for the integration method employed, Sterman (2000) submits that changes in model behaviour need to be checked and tested against different integration methods.

In this research, both the changes attributed to the choice of *Time Step* and integration method tests were conducted. Integration error test was conducted by first splitting the *Time Step* of one (*Time Step = 1*) used for the simulation into two (*i.e. Time Step = 0.5*) and then run the simulation again. The final outputs (in terms of household energy consumption and carbon emissions) (see appendix D2) of the models were examined to check whether or not there are changes in their behaviour. In order to test whether or not there are changes, a hypothesis was set up. The null hypothesis (H_0) signifies that there is no statistically significant difference between the means of the model outputs for *Time Step=1* and *Time Step=0.5*, while the alternate hypothesis (H_1) signifies that there is statistically significant difference between the two means. Mathematically the hypothesis was set up as shown in the below equations:

$$H_0\!: \; \mu_{i \; Time\,Step=1} - \mu_{i \; Time\,Step=0.5} = 0 \qquad (Eq.\ 8.1)$$

$$H_1\!: \; \mu_{i \; Time\,Step=1} - \mu_{i \; Time\,Step=0.5} \neq 0 \qquad (Eq.8.2)$$

Where μ_i *indicates the mean of variable of interest in the model*

A paired sample t-test was conducted for ten different variables in the model, which includes energy consumption and carbon emissions for space heating, hot water, cooking, lighting, and appliances for the UK housing stock as shown in Table 8.4. In order to take a decision regarding the hypothesis, the significance value (*p*-value) is compared to the significance level ($\alpha = 0.05$), and based on these two values, the null hypothesis is either rejected or not rejected. If the *p*-value is less than the significance level, the null hypothesis is rejected (*i.e.* p-value $< \alpha$, reject the null); otherwise the null hypothesis is not rejected. In this case, the *t* statistics computed for the ten paired variables of interest as shown in Table 8.4 reveals that the *p*-value for all the ten paired variables is greater than the value of significance level. This means that the *p* values of 0.527, 0.181, 0.251, 0.259, 0.779, 0.495, 0.418, 0.567, and 0.320 are greater than the α-value of 0.05. Therefore, the null hypothesis is accepted and the alternative hypothesis rejected. This by implication means that there is no statistically significant difference in the means of output of variables of interest shown in Table 8.4. That is, the results portend to indicate that there are no changes in behaviour of those selected outputs.

Table 8.4: Paired sample t-test for *Time Step* changes

		Paired Differences			t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean			
Pair 1	SHEC_1 - SHEC_0.5	.00827	.11729	.01303	.635	80	.527
Pair 2	HWEC_1 - HWEC_0.5	.00111	.00742	.00082	1.348	80	.181
Pair 3	CEC_1 - CEC_0.5	-.00049	.00384	.00043	-1.157	80	.251
Pair 4	LEC_1 - LEC_0.5	-.00037	.00293	.00033	-1.136	80	.259
Pair 5	AEC_1 - AEC_0.5	.00049	.00384	.00043	1.157	80	.251
Pair 6	SHCE_1 - SHCE_0.5	.00222	.07101	.00789	0.282	80	.779
Pair 7	HWCE_1 - HWCE_0.5	.00037	.00486	.00054	0.686	80	.495
Pair 8	CCE_1 - CCE_0.5	-.00025	.00273	.00030	-0.815	80	.418
Pair 9	LCE_1 - LCE_0.5	.00012	.00193	.00021	0.575	80	.567
Pair 10	ACE_1 - ACE_0.5	.00037	.00333	.00037	1.000	80	.320

SHEC = space heating energy consumption; HWEC = hot water energy consumption; CEC = cooking energy consumption; LEC = lighting energy consumption; AEC = appliances energy consumption; SHCE = carbon emissions due to space heating energy; HWCE = carbon emissions due to hot water energy; CCE = carbon emissions due to cooking energy; LCE = carbon emissions due to lighting energy; ACE = carbon emissions due to appliances energy; Sig. = significance, Std. = standard; df = degree of freedom.

In addition to cutting the *Time Step* into half with the use of *Euler* numerical integration method, the model is simulated using four different integration methods. These integration methods are (1) fixed second order Runge-Kutta (*fRK2*), (2) auto second order Runge-Kutta (*aRK2*), (3) fixed fourth order Runge-Kutta (*fRK4*), and (4) auto fourth order Runge-Kutta (*aRK4*). As done for the hypothesis testing above under the *Time Step* splitting, hypotheses were again set up as follow:

1. To test whether or not there is statistically significant difference between the results of the simulation performed by *Euler* and *fRK2* numerical

integration methods, the hypothesis in equations 8.3 and 8.4 are formulated.

$$H_0:\ \mu_{i\ Euler} - \mu_{i\ fRK2} = 0 \qquad (Eq.\ 8.3)$$

$$H_1:\ \mu_{i\ Euler} - \mu_{i\ fRK2} \neq 0 \qquad (Eq.\ 8.4)$$

2. To test whether or not there is statistically significant difference between the results of the simulation performed by *Euler* and *aRK2* numerical integration methods, the hypothesis in equations 8.5 and 8.6 are formulated.

$$H_0:\ \mu_{i\ Euler} - \mu_{i\ aRK2} = 0 \qquad (Eq.\ 8.5)$$

$$H_1:\ \mu_{i\ Euler} - \mu_{i\ aRK2} \neq 0 \qquad (Eq.\ 8.6)$$

3. To test whether or not there is statistically significant difference between the results of the simulation performed by *Euler* and *fRK4* numerical integration methods, the hypothesis in equations 8.7 and 8.8 are formulated.

$$H_0:\ \mu_{i\ Euler} - \mu_{i\ fRK4} = 0 \qquad (Eq.\ 8.7)$$

$$H_1:\ \mu_{i\ Euler} - \mu_{i\ fRK4} \neq 0 \qquad (Eq.\ 8.8)$$

4. To test whether or not there is statistically significant difference between the results of the simulation performed by *Euler* and *aRK4* numerical integration methods, the hypothesis in equations 8.9 and 8.10 are formulated.

$$H_0:\ \mu_{i\ Euler} - \mu_{i\ aRK4} = 0 \qquad (Eq.\ 8.9)$$

$$H_1:\ \mu_{i\ Euler} - \mu_{i\ aRK4} \neq 0 \qquad (Eq.\ 8.10)$$

Again, a paired sample t-test was carried out for energy consumption and carbon emissions of space heating, hot water, cooking, lighting, and appliances for the entire UK housing stock as shown in Table 8.5. The same decision rules as for the *Time Step* splitting were used to test if there is any statistically significant difference between the behaviour of simulation outputs performed by *Euler* and four other integration methods. As before, the *t* statistics computed for the ten paired variables of interest as shown in Table 8.4 for each of *fRK2*, *aRK2*, *fRK4*, and *aRK4* show that the *p*-value for all the ten paired variables are greater than the value of significance level for all the four integration methods (Table 8.5). Therefore, the null hypothesis is accepted and the alternative hypothesis rejected for all of them. This by implication means that it is safe to say that there is no statistically and significantly difference in the means of output of variables of interest shown in Table 8.5. That is, there are no significant changes in behaviour of these variables of interest.

8.5 Behaviour Pattern Tests

The main purpose of behaviour pattern tests is to ensure that the model output is consistent with the behaviour patterns of historical time series data of the variables in the real system under investigation (Ranganath & Rodrigues, 2008). A model is therefore considered validated behaviourally if the results of simulation performed give similar behavioural patterns when compared with behaviour patterns observed in the time series data of the real system (Sterman, 2000). The historical time series are shown in the reference modes as discussed in Section 6.4 of Chapter 6.

Table 8.5: Paired sample t-test for integration method changes

	Euler - Fixed RK2			Euler - Auto RK2			Euler - Fixed RK4			Euler - Auto RK4		
	t	df	Sig. (2-tailed)	t	df	Sig. (2-tailed)	t	df	Sig. (2-tailed)	t	df	Sig. (2-tailed)
Household energy consumption												
Space heating	-1.671	80	.099	-1.556	80	.124	-1.707	80	.092	-1.523	80	.132
Hot water	-1.937	80	.056	-.757	80	.451	-1.472	80	.145	-1.625	80	.108
Cooking	-1.811	80	.074	-1.114	80	.269	-1.944	80	.055	-1.114	80	.269
Lighting	-1.401	80	.165	-1.029	80	.307	-1.865	80	.066	-1.029	80	.307
Appliances	1.044	80	.300	1.857	80	.067	1.668	80	.099	1.811	80	.074
Household carbon emissions												
Space heating	-1.839	80	.070	-1.959	80	.054	-1.039	80	.302	-1.961	80	.053
Hot water	-.827	80	.411	-1.862	80	.066	-1.862	80	.066	-1.862	80	.066
Cooking	-1.089	80	.279	-.438	80	.663	1.389	80	.169	-.438	80	.663
Lighting	-.630	80	.530	-1.598	80	.114	-.630	80	.530	-.630	80	.530
Appliances	.883	80	.380	.961	80	.339	.847	80	.399	.961	80	.339

In this research, the behaviour pattern validation is achieved by comparing the pattern of behaviour of the baseline simulation run with the historical time series data (reference modes). The behaviour anomaly, behaviour reproduction and behavioural sensitivity analysis tests are the behaviour pattern validation tests conducted and they are discussed in the following sub-sections.

8.5.1 Behaviour Anomaly Test

The behaviour anomaly test assesses the behaviour shown by the model and check whether its output conflict in any way with the real system behaviour (Ranganath & Rodrigues, 2008). Also according to Sterman (2000), the behaviour anomaly test evaluates how implausible behaviour arises should the assumptions made in the model altered. In order to conduct this test in this research, a loop knockout analysis was carried out on one of the loops in the occupants' thermal comfort module and its effect was assessed on the output of the model (see Figure 8.5 for example). The results of the behaviour anomaly test indicate that no anomaly of any kind exists in the output of the model as no erratic behaviour was noticed when the simulation was performed.

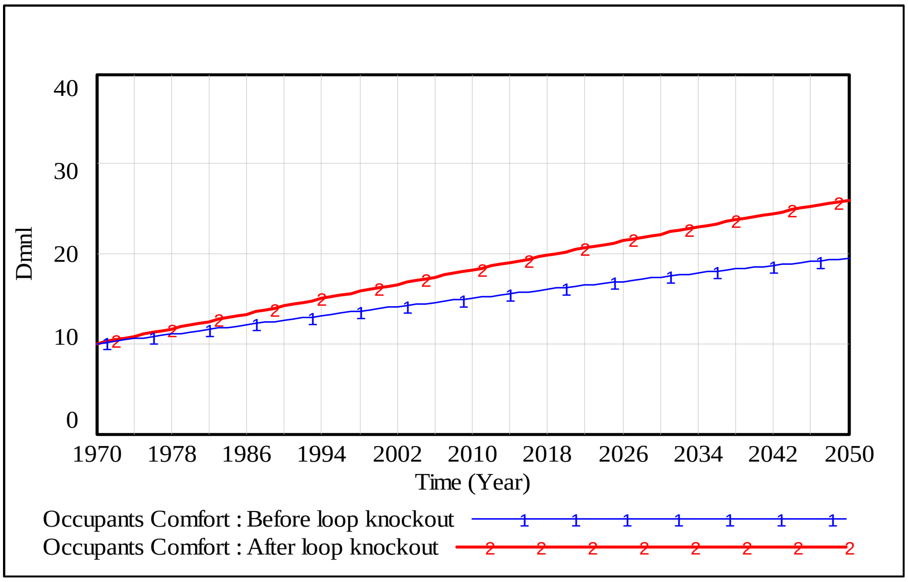


Figure 8.5: Effect of loop knockout on occupants comfort

8.5.2 Behaviour Reproduction Test

To conduct behaviour reproduction test, Sterman (2000) suggests computation of some statistical measures as shown in Table 8.1 to include descriptive statistics (*e.g.* R^2). Similarly, Barlas (1996) recommends trend comparison between the model output and actual (historical) data by formulating a linear, quadratic, or an exponential trend; comparing the periods by performing an autocorrelation function test; and comparing the means by determining percentage error in the means.

The baseline model output of this research were compared to actual (historical) data by carrying out a trend analysis of the model output and historical data based on autoregressive integrated moving averages (ARIMA). Two variables of interest in the model were selected for the purpose of this test. The variables selected are the 'average annual energy consumption per household' and 'average annual CO_2 emissions per household'. The choice of these variables is dictated by the fact that the main output of this research is both household energy consumption and household carbon emissions. However, the historical time series data available on carbon emissions are not disaggregated as done for energy consumption end uses. Therefore, the 'average annual energy consumption per household' and 'average annual CO_2 emissions per household' are chosen as the test variables. The 'goodness of fit' (R squared) results for the two variables of interest are as shown in Table 8.6. The results suggest a good 'goodness of fit' for the two variables explored based on the values of R^2 as *0.991* and *0.999* for average annual CO_2 emissions per household and average annual energy consumption per household respectively.

The results also show the mean absolute percentage error (MAPE) for the two variables as very small (*MAPE=0.900% for average annual CO_2 emissions per household, and MAPE=0.074% for average annual energy consumption per household*) (Table 8.6).

Table 8.6: Validation based on statistical significance of behaviour reproduction

Model	**Model Fit statistics**			**Ljung-Box Q**			**Number of Outliers**
	R-squared	**MAPE**	**MaxAPE**	**Statistics**	**DF**	***P* value**	
Model –Actual (Average Annual Carbon Emissions per Household	.991	.900	3.494	14.366	18	.741	0
Model-Actual (Average Annual Energy Consumption per Household	.999	.074	.482	9.757	18	.940	0

MAPE = mean absolute percentage error; MaxAPE = maximum absolute percentage error; DF = degree of freedom; p value = significance value.

Swanson, Tayman and Bryan (2011) suggest a MAPE of less than 10% as being very good. Based on this suggestion, it is then safe to say that the maximum absolute percentage error (MaxAPE) computed for the two variables as indicated in Table 8.6 is adequate as well (*MaxAPE=3.494% for average annual CO_2 emissions per household, and MaxAPE=0.482% for average annual energy consumption per household*).

Further to these tests, autocorrelation function tests were conducted in order to detect any significant errors in the periods of the time series for the model outputs and actual data by testing a hypothesis. If sample autocorrelation function for simulated model is represented by $r_s(k)$ and the one for the actual (historical) data is $r_a(k)$, then the null hypothesis is formulated thus:

$$H_0: r_s(1) - r_a(1) = 0, r_s(2) - r_a(2) = 0, \ldots\ldots, r_s(M) - r_a(M) = 0 \qquad (Eq.\ 8.11)$$

and the alternative hypothesis is,

$$H_1: r_s(k) - r_a(k) \neq 0 \text{ for at least one } k \qquad (Eq.\ 8.12)$$

Where k is any pair of values

It needs to note that [$r_s(k) - r_a(k)$] = 0 under the H_0 and as such an interval is constructed based on the standard error (SE) of the difference of $r_s(k) - r_a(k)$ under which the H_0 is rejected should the difference [$r_s(k) - r_a(k)$] fall outside the interval:

$$\begin{cases} -SE[rs\ (k) - ra\ (k)], \\ \\ SE[rs\ (k) - ra\ (k)], \end{cases} \qquad (Eq.\ 8.13)$$

In order to take a decision regarding the hypothesis, the same decision rule as formulated under Section 8.4.6 above was used. That is, the significance value (*p* value) is compared to the significance level ($\alpha = 0.05$), and the null hypothesis is either rejected or accepted. That is, if the p value is less than the significance level, the null hypothesis is rejected (if *p* value < *α*, reject the null); otherwise the null hypothesis is accepted.

In this case, the LJung – Box Q statistics computed for the two variables of interest as shown in Table 8.6 reveals that the *p* value for average annual CO_2 emissions per household is greater than the significance level (*p* value of 0.741 > *α-value* of 0.05). Therefore, the null hypothesis is not rejected and it is safe to conclude that there are no significant errors in the periods of the time series for the model outputs and actual data for average annual CO_2 emissions per household. Similarly, the null hypothesis is not rejected for average annual energy consumption per household (*p* value of 0.940 > *α-value* of 0.05), which implies that there are no significant errors in the periods of the time series for the model outputs and actual data for average annual energy consumption per household.

The plots of the residual autocorrelation function (ACF) fall within the upper critical limit (UCL) and lower critical limit (LCL) for the two variables as shown in Figures 8.6 and 8.7 for average annual CO_2 emissions per household and average annual energy consumption per household respectively. The results in these figures imply that the values of $[r_s(k) - r_a(k)]$ for within acceptable limits set. These results further reinforce the outcome of the hypothesis tested.

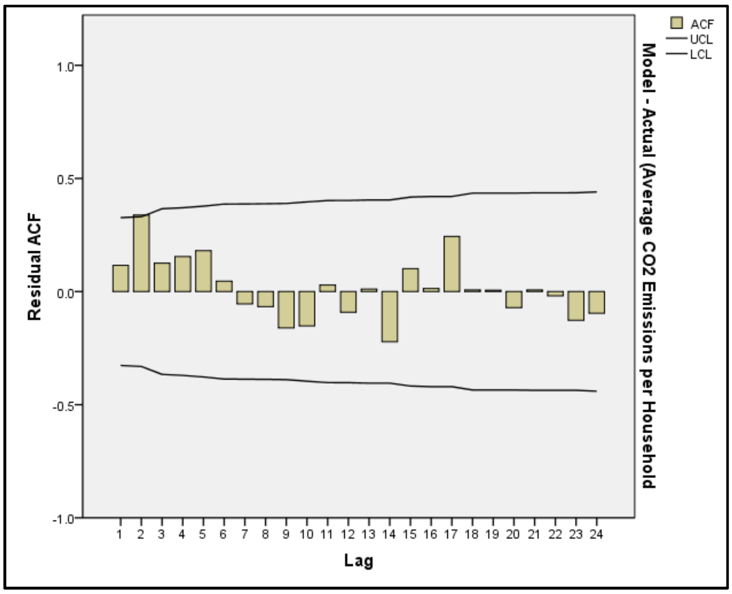


Figure 8.6: Plots of residual autocorrelation function for carbon emissions

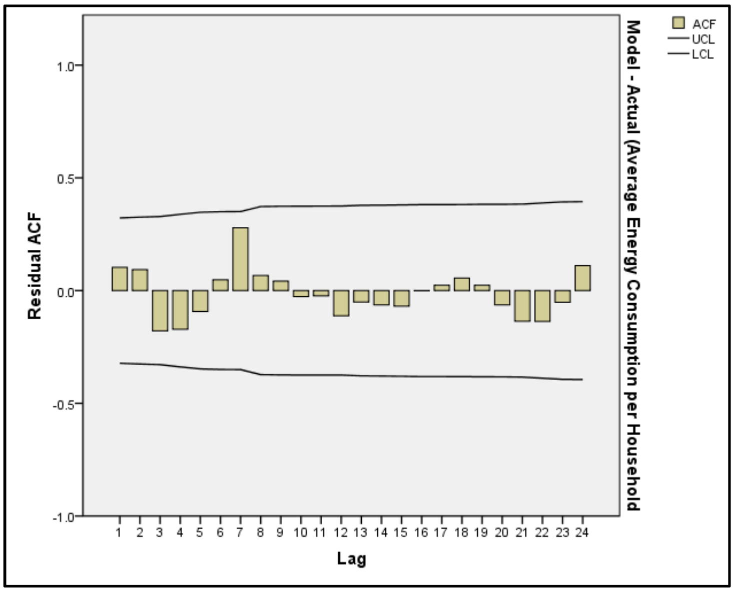


Figure 8.7: Plots of residual autocorrelation function for energy consumption

8.5.3 Behavioural Sensitivity Analysis

As part of model behaviour patterns validation in SD methodology, sensitivity analysis considers the sensitivity of the model to various model structures or different parameter values. Sterman (2000) and Moxnes (2005) argue that the most common type of sensitivity analysis conducted for SD models validation are numerical sensitivity, behavioural sensitivity, and policy sensitivity. The details of these sensitivity analyses are as shown in Table 8.1. In this research, behavioural sensitivity analysis was performed in order to find out whether or not the patterns of behaviour of the model outputs generated are significantly changed when there are changes to some of the parameters in the model.

The research used the approach reported in Rahmandad and Sterman (2012) to carry out the sensitivity analysis for behaviour patterns test. Table 8.7 reports the results of the sensitivity analysis performed for the model. Two parameters adjudged by the modeller (author) to possibly influence the model output in terms of household carbon emissions and energy consumption is further investigated.

These parameters are 'energy to carbon conversion factor' and 'carbon depletion factor'.

Table 8.7: Results of a set of behavioural sensitivity analysis for the model

Mean (SD) with different *i* and *j* based on 1000 iterations		Energy to carbon conversion factor *i*		
		0.4246	0.5246	0.6246
Carbon depletion factor *j*				
1.225	SHCE	73.00 (24.41)**	74.40 (25.38)**	75.47 (26.20)**
	HWCE	38.76 (8.29)**	39.88 (8.65)**	40.37 (8.89)**
	CCE	6.39 (2.28)**	6.69 (2.36)**	6.99 (2.43)**
	LCE	5.78 (0.93)**	5.99 (0.88)*	6.39 (0.85)**
	ACE	21.07 (5.98)**	22.13 (5.79)**	22.96 (5.65)**
1.325	SHCE	67.44 (22.76)*	68.81 (23.68)	69.95 (24.46)*
	HWCE	35.85 (7.75)*	36.88 (8.09)	37.39 (8.42)*
	CCE	5.99 (2.13)*	6.19 (2.20)	6.87 (2.27)*
	LCE	5.13 (0.85)*	5.54 (0.80)	5.94 (0.78)*
	ACE	19.72 (5.48)*	20.47 (5.30)	21.43 (5.17)**
1.425	SHCE	63.05 (21.36)**	63.99 (22.23)**	64.52 (22.98)**
	HWCE	33.27 (7.30)**	34.29 (7.62)**	35.33 (7.94)**
	CCE	5.45 (2.00)**	5.75 (2.07)*	5.96 (2.13)**
	LCE	4.94 (0.78)**	5.15 (0.74)*	5.45 (0.71)*
	ACE	18.70 (5.06)**	19.04 (4.89)*	19.27 (4.77)*

*SHCE = carbon emissions due to space heating energy for UK housing stock; HWCE = carbon emissions due to hot water energy for UK housing stock; CCE = carbon emissions due to cooking energy for UK housing stock; LCE = carbon emissions due to lighting energy for UK housing stock; ACE = carbon emissions due to appliances energy for UK housing stock; **significant at p-value<0.01; *significant at p-value<0.05, SD = standard deviation*

The two of them are changed over three values each. A factorial analysis of method of experimentation was used to formulate the scenarios. The results of this formulation yield a total of nine different scenarios. The nine scenarios are achieved by varying the energy to carbon conversion factor *(i)* and carbon depletion factor *(j)* around their baseline values of 0.5246 and 1.325 respectively as shown in Table 8.7.

In the table, the report of 1000 simulations performed for each of the scenarios in terms of mean values and standard deviation of the model outputs for carbon emissions due to space heating, hot water, cooking, lighting, and appliances are given. This amounts to total simulations of 9000 with each simulation from 1970 to 2050 using a *Time Step* of one year. In order to assess how sensitive the model output to the changes in the two parameters under consideration, a t-test for group means with unequal variances was conducted by comparing the results to the baseline results for the values of *i* and *j*. The results indicate that all the scenarios compared with the baseline are statistically different. Those with *p-value* < 0.05 are shown with a single asterisk, while those that are statistically different at *p-value* < 0.01 are with double asterisks.

8.7 Chapter Summary

This chapter has described and discussed the testing and validation exercises conducted for the model. The chapter discussed the validation done with 15 experts in the field of energy and SD. Further, the chapter described and discussed the tests performed within the SD modelling software – Vensim. These tests are categorised into the structure-oriented and behaviour-pattern tests. For the structure-oriented tests, the following tests were performed: boundary adequacy tests, structure assessment test, dimensional consistency test, parameter assessment test, extreme conditions test, and integration error test. Also, the behaviour pattern tests include behaviour anomaly test, behaviour reproduction test, and behavioural sensitivity analysis. The results of all these tests yielded positive answers confirming that the model satisfies all the rules and regulations of the SD approach and the model output are consistent with the real system.

Chapter 9

POLICY FORMULATION AND ANALYSIS (ILLUSTRATIVE SCENARIOS)

9.1 Introduction

In Chapter seven, the ‘baseline’ scenario that was presented communicates the most probable way in which the household energy consumption and carbon emissions of the UK housing stock will evolve over the years starting from 1970 until 2050. This is based on the assumption that the trends depicted by historical data will continue in that way. Evidently, if there is therefore any policy change in future that is clearly different from the current ones, the profile of household energy consumption and carbon emissions could be altered. This may result in producing a set of entirely different consumption/emissions profile of the UK housing stock. For example, the UK Government may decide to implement a stringent energy efficiency policy if it is apparent that the current energy efficiency is unlikely to yield the required legally binding carbon emissions reduction targets. To this end, this chapter uses the discussions under the ‘baseline’ scenario to develop illustrative scenarios that may evolve as a result of some policy changes. Many scenarios can be assumed and for the purpose of illustration, four hypothetical scenarios are assumed that include ‘efficiency’, ‘behavioural change’, ‘economic’, and ‘integrated’ scenarios. In all of these scenarios, the future of household energy consumption and carbon emissions for the entire UK housing stock is explored. And as such, the household energy consumption carbon emissions reductions attributable to each of the scenarios are given and discussed. The rest of the chapter therefore explains the underlay assumptions for each of the scenarios and discusses the results emanating from them.

9.2. ‘Efficiency’ Scenario

9.2.1 ‘Efficiency’ Scenario Assumptions

This scenario is based on the assumptions made under the baseline scenario, but describes a situation whereby more evidence regarding the negative impact of climate change as a result of greenhouse emissions continues to emerge. This new evidence about the threat of negative effect of climate change is assumed to continue. This will further reinforce the need to meet the legally binding carbon reduction targets as set by the Government, for example reduction targets based on Climate Change Act of 2008 in the UK. Also, the scenario assumes that more evidence will emerge on the possibility of not meeting the legally binding carbon reduction targets as the report of European Union (EU) entitled “EU study predicts clean energy, climate failure by 2050” EU (2013) suggests. Based on this new evidence, it is then portends to trigger a more stringent energy efficiency measures in order to deeply cut carbon emissions.

Energy efficiency measures are then assumed to concentrate on household dwellings and this is technology led. And as such, it is assumed that there will be improvements in the uptake of dwelling insulation measures thereby resulting in each household’s dwelling thermally insulated with increasing energy efficiency rating of dwellings like SAP rating. Further to these assumptions, airtightness of dwellings will increase and it is again assumed that a great deal energy savings will arise from this scenario. However, occupants will offset any savings that would have been made by seeking for more thermal comfort thereby increasing their dwellings internal temperature set-point from 19ºC to 21ºC. At this, ‘standard’ consumption behaviour is still assumed to be maintained by the householders as done under the ‘baseline’ scenario. Fabric insulation depicted as ‘insulation factor’ in the model is therefore assumed to increase by 25% beyond the levels set under the ‘baseline’ scenario.

Additionally, a structural adjustment is made to the model as shown in Figure 9.1. Under the 'baseline' scenario, the 'SAP rating' of the dwellings in the UK are qualitatively modelled within the SD and this was used to directly model the 'effect of energy efficiency standard improvement on dwelling energy efficiency'. However, in this scenario, it is assumed that the 'SAP rating' will gradually increase until 2040 at a gentle slope of 0.75% beyond the level it were in the year 2010. This is assumed not to go beyond 0.95 (in a scale of 0 – 1). To qualitatively achieve this, an intermediary dummy variable was introduced within the model as shown in Figure 9.1. The model equation for it is also shown in Equation 9.1.

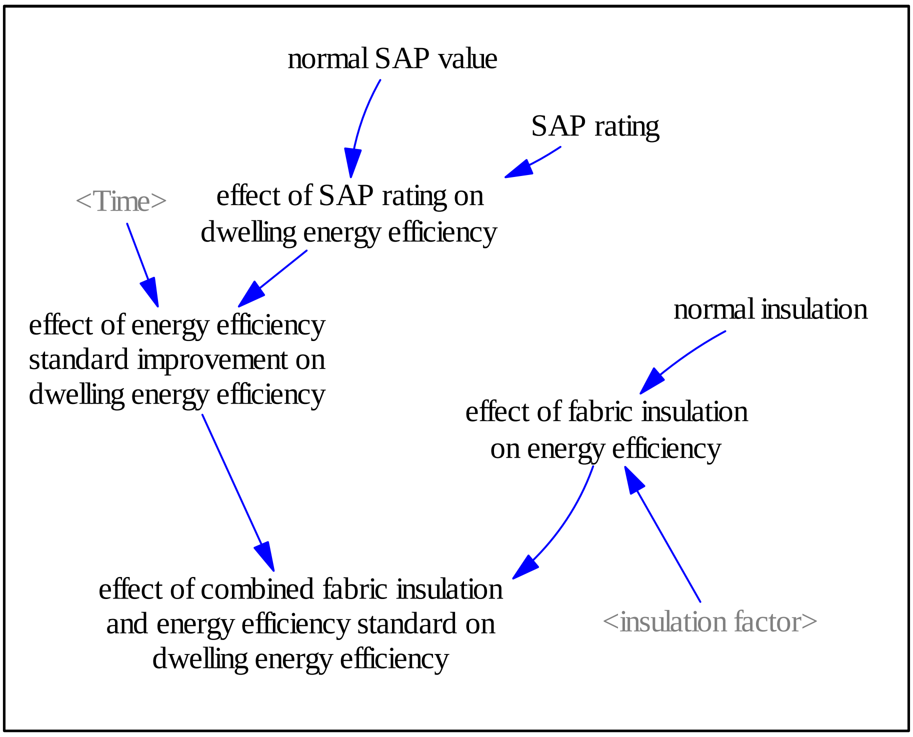


Figure 9.1: Structural adjustment to the climatic-economic-energy efficiency interaction module

effect of energy efficiency standard improvement on dwelling energy efficiency = IF THEN ELSE(Time<=2010, effect of SAP rating on energy efficiency standard improvement, MIN (0.95, effect of SAP rating on energy efficiency standard improvement + RAMP (0.0075, 2010, 2040))) *(Eq. 9.1)*

9.2.2 Analysis of the 'Efficiency' Scenario Results for Household Energy Consumption

Figure 9.2 captures the combined behaviour of energy consumption per household by end-uses as attributable to space heating, hot water, cooking, lighting, and appliances based on efficiency scenario (see appendix C1 for the combined behaviour with the baseline scenario). Also, Figure 9.3 shows a combined graph of total and average annual household energy consumption under the efficiency scenario. Visually, the graphs (Figures 9.2 & 9.3) display a downward trend for all the variables indicated in the graphs thereby showing that there are reductions in household energy consumption across the board. However, the graphs show little information on the extent to which household energy consumption reductions in the years 2020 and 2050 relative to the year 1990. This information is necessary in order to know whether or not the reduction targets based on the Climate Change Act of 2008 are achieved by this scenario. To this end, more analysis of the simulation results is carried out to provide further insights into the reduction targets achieved.

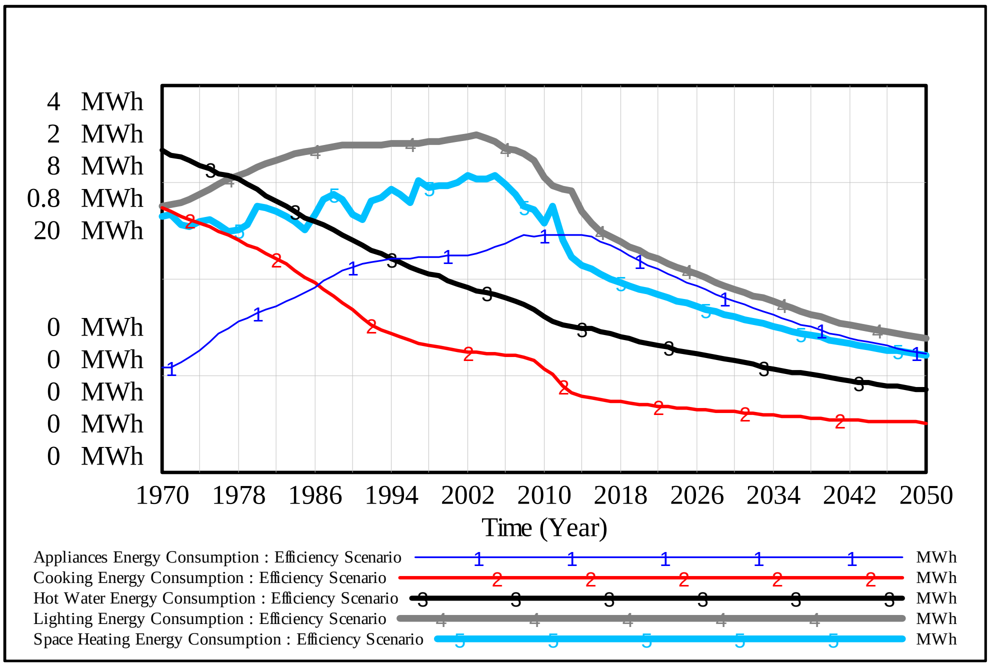


Figure 9.2: Household energy consumption by end-use under the efficiency scenario

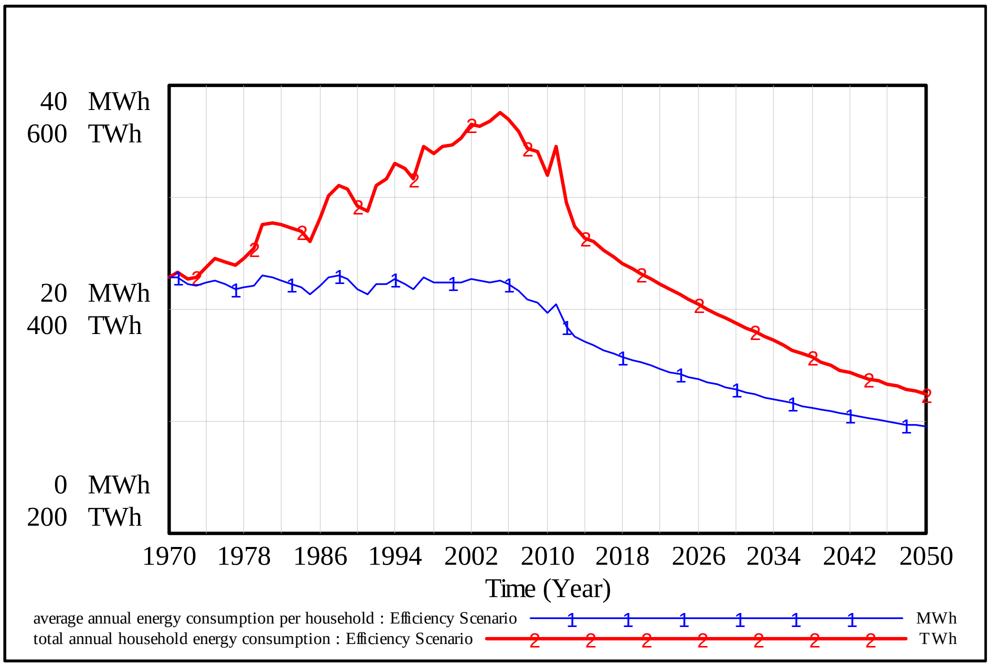


Figure 9.3: Total and average annual household energy consumption under the efficiency scenario

The results of further analysis conducted on the household energy consumption based on end uses for the entire UK housing stock is shown in Tables 9.1 and 9.2 illustrating the changes in household energy for the year 2020 and 2050 relative to the year 1990 respectively.

For the year 2020, the results of analysis of ‘efficiency’ scenario as shown in Table 9.1 suggest that the total household energy consumption for the entire UK housing stock is expected to reduce by about 60.59TWh of energy representing 12.33% reduction relative to the year 1990 levels. Furthermore, the analysis suggests that apart for the household appliances energy that is expected to surge within this period by about 30%, others are expected to decline within this same period. That is, household energy for space heating, hot water, cooking and lighting is expected to dip relative to 1990 levels. This is with a reduction of about 11% for space heating, about 29% for hot water, about 47% for cooking, and about 15% for lighting.

Table 9.1: Change in household energy consumption by end-uses based on 'efficiency' scenario for the year 2020 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2020) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	268.84	-32.08	-10.66
Hot Water	108.20	76.74	-31.46	-29.08
Cooking	18.88	9.97	-8.91	-47.19
Lighting	15.29	12.96	-2.33	-15.24
Appliances	47.93	62.14	+14.21	+29.65
Total	**491.22**	**430.63**	**-60.59**	**-12.33**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

A similar analysis was conducted for the year 2050 as shown in Table 9.2. The results of the analysis indicate a reduction of 34.03% relative to 1990 levels in total household energy consumption for the entire UK housing stock. When this total household energy is disaggregated by end-use, the model results suggest that the household energy consumption attributable to space heating is anticipated to reduce by 94.89TWh, which is about 32% reduction compared to 1990 levels. Further to this, the household energy consumption due to hot water is expected to reduce by about 50.32TWh, which amounts to about 47% reduction, again relative to the base case 1990. Additionally, the model results suggest that cooking energy is expected to decline by about 54% while the lighting energy is as well expected to witness a fall of about 39%. Paradoxically, household energy consumption for appliances declines by about 12% for the year 2050 relative to 1990 levels, which indeed increased by about 30% for the year 2020 as discussed above. Ordinarily, this is expected to surge under the guise of technological improvements in household appliances. This is premised on the possibility of increment in its adoption rate among the householders with increasing number of households.

Table 9.2: Change in household energy consumption by end-uses based on 'efficiency' scenario for the year 2050 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2050) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	206.03	-94.89	-31.53
Hot Water	108.20	57.88	-50.32	-46.51
Cooking	18.88	8.70	-10.18	-53.92
Lighting	15.29	9.41	-5.88	-38.46
Appliances	47.93	42.06	-5.87	-12.25
Total	**491.22**	**324.07**	**-167.15**	**-34.03**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Changes to the parameters and structure of the model as relates to the fabric insulation and energy efficiency improvement for 'efficiency' scenario is expected to reduce household energy consumption. The results in Tables 9.1 and 9.2 suggest that there are reductions in energy consumption apart from that of appliances for the year 2020. These percentage reductions are then compared with the 'baseline' scenario results as shown in Table 9.3. While the results generally show reductions in the total household energy and household energy by end-use, the amount of these reductions to meet the necessary carbon emissions reduction targets for the year 2020 and 2050 is therefore unlikely. This is due to the fact that efforts aiming at only the fabric insulation and energy efficiency improvement in general cannot bring about the required level of savings in energy consumption. In fact, a rebound effect is even likely to set in, such that the savings made may be expended on getting an improved thermal comfort.

Table 9.3: Comparison of ‘efficiency’ scenario with ‘baseline’ scenario results for the percentage reductions in household energy consumption

	‘baseline’ scenario (2020)	**‘efficiency’ scenario (2020)**	**‘baseline’ scenario (2050)**	**‘efficiency’ scenario (2050)**
Space heating	-7.99	-10.66	-25.38	-31.53
Hot Water	-26.61	-29.08	-41.10	-46.51
Cooking	-44.28	-47.19	-44.92	-53.92
Lighting	-10.92	-15.24	-25.18	-38.46
Appliances	+35.34	+29.65	+5.21	-12.25
Total	**-9.35**	**-12.33**	**-26.60**	**-34.03**

9.2.3 Analysis of the ‘Efficiency’ Scenario Results for Household Carbon Emissions

Household carbon emissions by end-uses, and total and average annual household carbon emissions are shown in Figures 9.4 and 9.5 respectively. The behaviour of efficiency scenario simulation results for household carbon emissions based on end-uses (Figure 9.4) (see appendix C2 for the combined behaviour with the baseline scenario) displays a similar behaviour as shown for household energy consumption by end-uses (Figure 9.2). The graph shows a downward trend for carbon emissions for all the end-uses. This, therefore, indicates reductions in carbon emissions profile for space heating, hot water, cooking, lighting, and appliances.

Similarly, the insights from the average and total annual household carbon emissions (Figure 9.5) follow a downward trend as well. These trends correspond to the same trends witnessed in average and total annual household energy consumption as shown in Figure 9.3. The similarity is based on the reason advanced in Section 7.8 of Chapter 7 that there is a strong correlation between energy consumption and carbon emissions. However, the behaviour of space heating carbon emissions plays a central role in explaining the behaviour displayed by both the average annual and total annual carbon emissions for the UK housing stock. This is in consonance to the observation of Palmer and Cooper (2012) as well.

As expected for the average annual carbon emissions per household and total annual household carbon emissions, they are moving on a downward direction since 1970. The two have remarkably fallen since 1970 and the model suggests that the trend is anticipated to be sustained until 2050 based on the carbon reductions agenda of the government. However, Figure 9.5 shows little detail about the amount of reductions achieved under this scenario. Hence, there is the need for a further analysis.

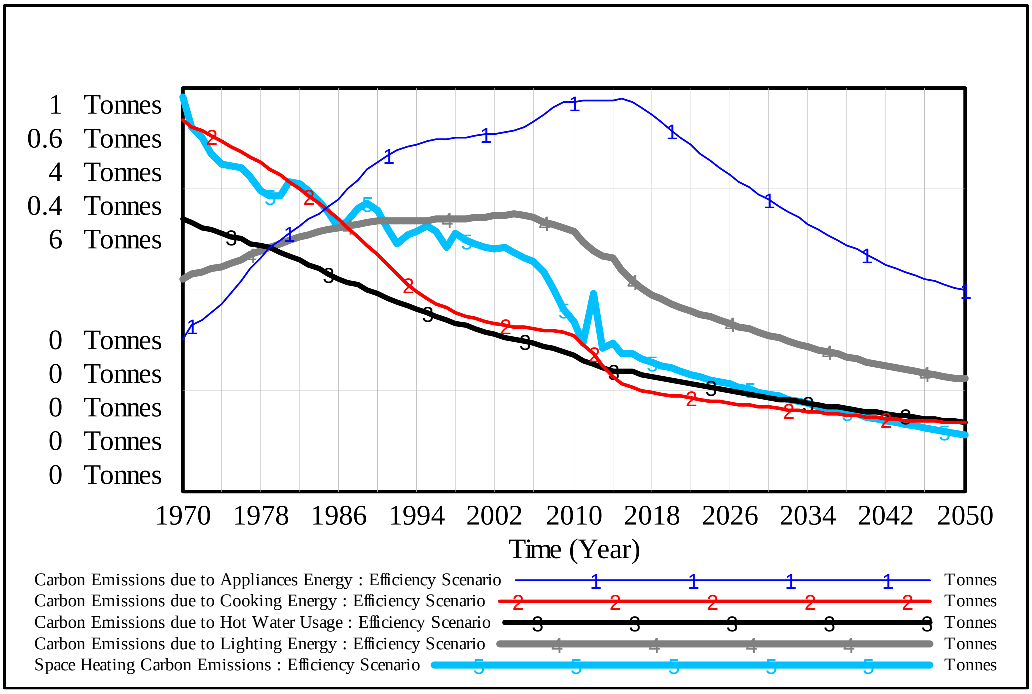


Figure 9.4: Household carbon emissions by end-uses under the ‘efficiency’ scenario

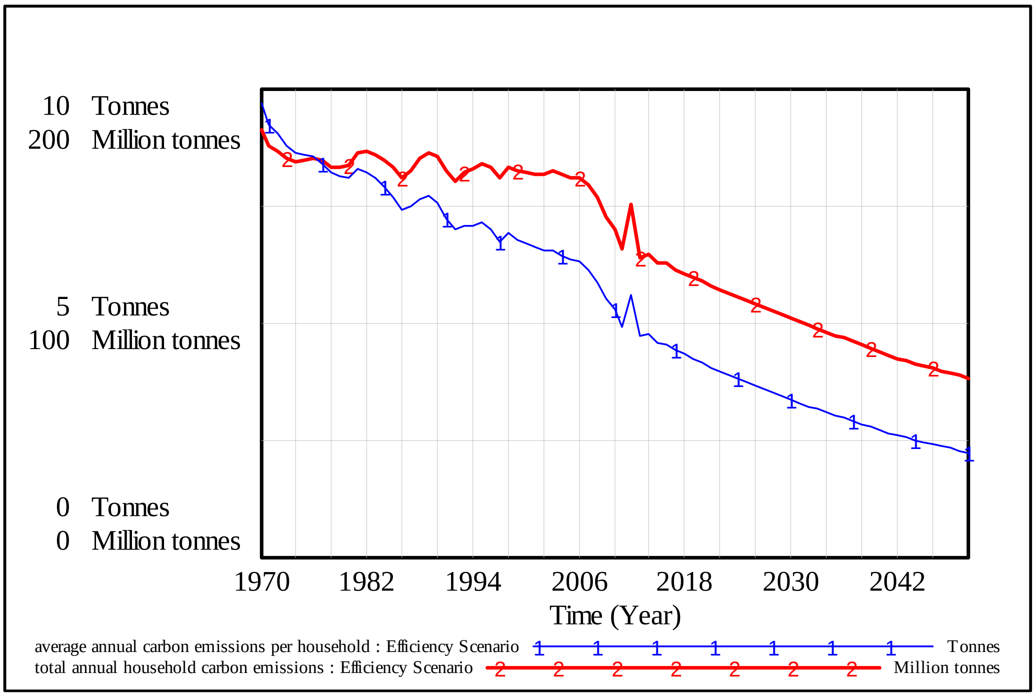


Figure 9.5: Total and average annual household carbon emissions under the ‘efficiency’ scenario

The amount of reductions in carbon emissions anticipated in the years 2020 and 2050 are respectively shown in Tables 9.4 and 9.5. The results suggest that the largest amount of reductions is expected to come from space heating in the amount of 42.79 and 65.71 million tonnes of CO_2 for 2020 and 2050 respectively. The results also indicate that substantial amount of reductions is expected from hot water as well. Both the space and water heating therefore remain the dominant end-uses where much of the reductions to meet the carbon emissions targets are anticipated. Correspondingly, some reductions are also anticipated in cooking and lighting below the 1990 levels for the years 2020 and 2050 as respectively shown in Tables 9.4 and 9.5. However, for appliances, the expectation is a mixed one as the results show that no reductions in carbon emissions below the 1990 levels are anticipated. Although, there are technological improvements in home appliances in terms of energy efficiency, but this advancement could not be immediately translated into much savings. However, by 2050 (Table 9.5), some savings are expected. Generally, it is clear from the results of this scenario that carbon emissions target for 2020 and 2050 will not be met.

Table 9.4: Change in household carbon emissions by end-uses based on 'efficiency' scenario for the year 2020 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2020) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	51.68	-42.79	-45.29
Hot Water	44.15	31.15	-13.00	-29.44
Cooking	7.93	4.03	-3.90	-49.18
Lighting	6.04	5.28	-0.76	-12.58
Appliances	18.43	25.39	+6.96	37.76
Total	**171.01**	**117.53**	**-53.48**	**-31.27**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.5: Change in household carbon emissions by end-uses based on 'efficiency' scenario for the year 2050 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2050) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	28.76	-65.71	-69.56
Hot Water	44.15	23.36	-20.79	-47.09
Cooking	7.93	3.47	-4.46	-56.24
Lighting	6.04	3.79	-2.25	-37.25
Appliances	18.43	17.00	-1.43	-7.76
Total	**171.01**	**76.37**	**-94.64**	**-55.34**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

The results show that savings of about 31% and 55% will be met for 2020 and 2050 as against minimum targets of 34% and 80% respectively. The implication of this is that laying much of the emphasis on energy efficiency improvements alone without corresponding efforts on other aspects of policy target is unlikely to yield the required level of savings.

9.2.4 Comparison of 'Efficiency' Scenario with Johnston's Model Results

The results of the 'efficiency' scenario are compared with the results of Johnston's (2003) 'demand side' scenario. The Johnston's (2003) 'demand side' scenario is based on a strong desire to make a significant stride in energy efficiency improvements. Most of the assumptions made are similar to this model's 'efficiency' scenario assumptions. The results of this comparative analysis are succinctly summarised in Tables 9.6 and 9.7 for household energy consumption and household carbon emissions respectively.

Table 9.6: Comparative analysis of household energy consumption attributable to 'efficiency' scenario and 'demand side' scenario of Johnston (2003)

	Total annual household energy consumption (KWh)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
'Efficiency' scenario	491.2	546.8	519.4	430.6	387.0	348.9	324.1
'Demand side' scenario of Johnston (2003)	-	556.4	517.2	461.0	415.6	371.9	278.9

The results as shown in Tables 9.6 and 9.7 for the total annual household energy consumption and carbon emissions display the same pattern of trend. However, the results clearly indicate that there are some differences in the two models. These differences are likely due to different assumptions made, input data used, and the modelling philosophy employed by the two models as explained in Section 7.9.

Table 9.7: Comparative analysis of household carbon emissions attributable to 'efficiency' and 'demand side' scenarios

	Total annual household carbon emissions (million tonnes of CO_2)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
'Efficiency' scenario	171.0	164.2	140.1	117.53	101.9	87.6	76.37
'Demand side' scenario of Johnston (2003)	-	132.6	119.5	107.0	93.6	81.7	60.7

9.3 'Behavioural Change' Scenario

9.3.1 'Behavioural Change' Scenario Assumptions

This scenario is also based on major assumptions made under the 'baseline' scenario. The effects of occupants' behavioural change on household energy consumption and carbon emissions are the main policy driver that this scenario illustrates. And as such, frugal consumption behaviour is emphasised by this scenario. That is, their daily habitual behaviours tend towards energy saving in their homes. In addition, it is assumed that this will have effect on the dwelling internal temperature set-point as maintained by the occupants. A set-point of dwelling internal temperature is therefore assumed to be 18.5ºC. Also, within this scenario, energy prices are assumed to increase a little bit thereby necessitating the energy bills paid by the householders to slightly increase by 5% beyond the level assumed under the 'baseline' scenario. In terms of energy efficiency, the assumption of this scenario is similar to that of 'baseline' scenario that no much substantive changes are made to the current trends in household energy efficiency apart from the continuation of the existing trends. For this scenario, no attempt is made to change any of the parameters within the population/household module. Therefore no special effects are anticipated from the ‘number of households’ and ‘average household size’ other than their profile as generated internally within the model.

9.3.2 Analysis of the ‘Behavioural Change’ Scenario Results for Household Energy Consumption

The behaviour of household energy consumption based on end-uses is shown in Figure 9.6 (see appendix C3 for the combined behaviour with the baseline scenario). Also, the behaviour of average and total annual household energy consumption are depicted in Figure 9.7. A visual inspection on the two Figures indicates that household energy consumption under the ‘behavioural change’ scenario is identical to the household energy consumption under the ‘efficiency’ scenario illustrated in Figures 9.2 and 9.3 above as the trends tend to decline as they approach 2050. However, they are different in terms of the level of reductions achieved by 2020 and 2050. The reductions in ‘behavioural change’ scenario are more pronounced and as such the insights there portend that they are likely to be more than the reductions achieved under the ‘efficiency’ scenario.

Tables 9.8 and 9.9 show the results of the further analysis carried out. This time around, as done for the ‘baseline’ and ‘efficiency’ scenarios, the household energy consumption for the entire UK housing stock is analysed for the year 2020 and 2050 relative to the year 1990 respectively (Tables 9.8 and 9.9). The consumption profile is unchanged as such when compared to the ‘efficiency’ scenario because the space heating is still the one responsible for the largest chunk with a reduction of about 72.20TWh and 117.01TWh for 2020 and 2050 respectively. This is followed by hot water, which account for reductions of 45.85TWh and 55.94TWh based on expectation for the year 2020 and 2050 respectively. For these two years cooking and lighting energy are also expected to decline as well. Although, the reductions anticipated by the results are minimal.

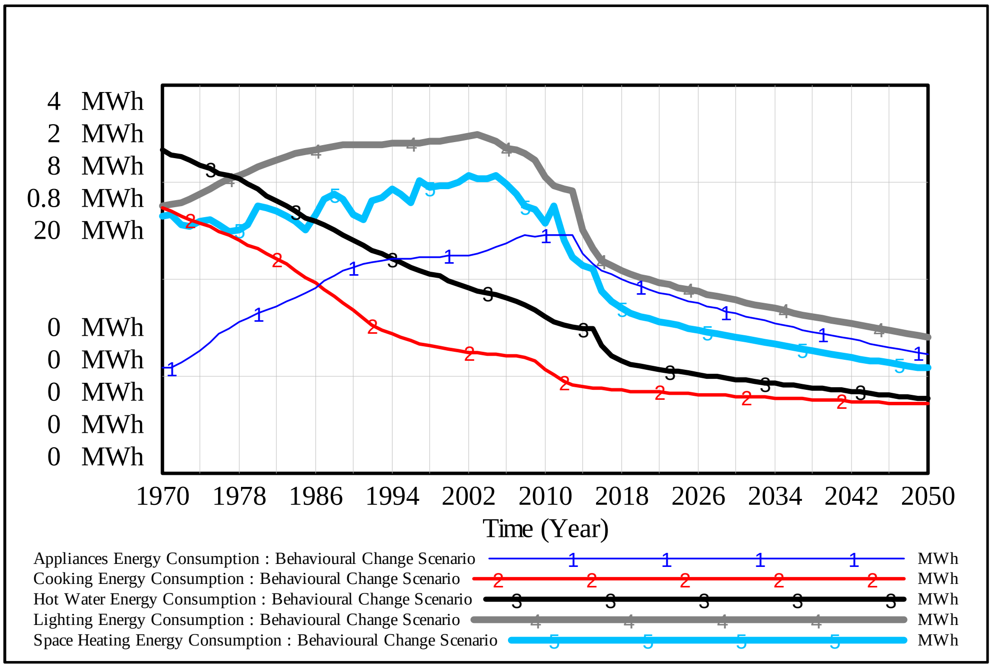


Figure 9.6: Behaviour of household energy consumption based on end-uses under the ‘behavioural change’ scenario

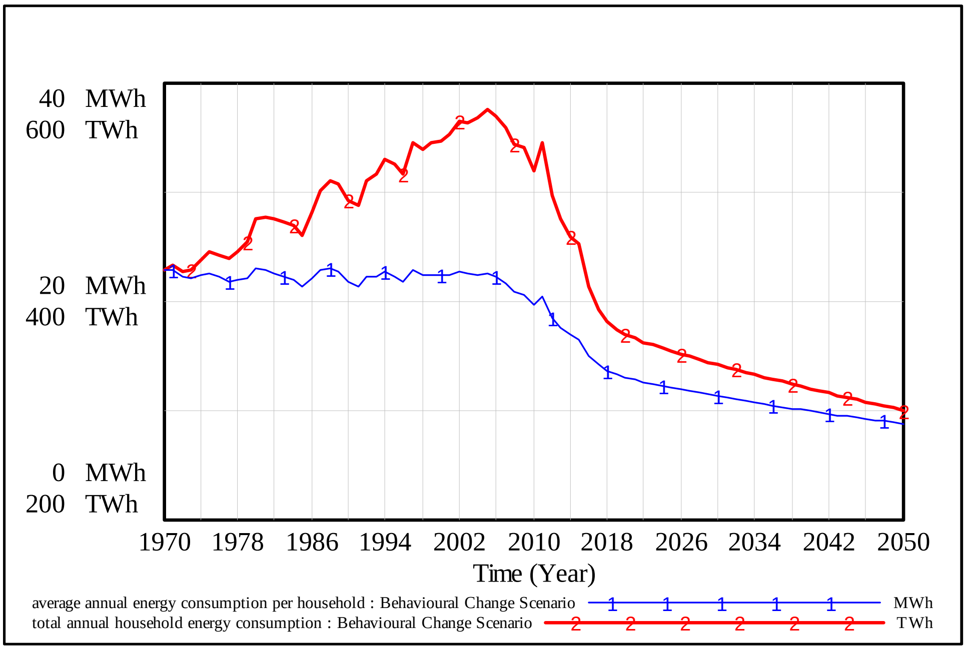


Figure 9.7: Behaviour of average and total annual household energy consumption under the ‘behavioural change’ scenario

However, household energy consumption for appliances grew by 6.64TWh beyond 1990 levels in the year 2020 as experienced in the ‘efficiency’ scenario. This is likely to attribute to the fact that the number of households continues to increase thereby increasing the number of household appliances acquisition during this period. By 2050 however, the scenario results suggest that the appliances energy consumption will marginally reduce below 1990 levels (Table 9.9).

The profound insight from the analysis conducted reveals that the savings in the total household energy consumption under the ’behaviour change’ scenario is generally more than that of ‘efficiency’ and ‘baseline’ scenarios. These results reinforce the comment of Janda (2011) that *‘buildings don’t use energy; people do’*. The result implies that occupants’ behavioural change have the capability of contributing to the household energy consumption reductions and consequently contribute to carbon emissions reduction targets of Government in conjunction with other policy frameworks.

Table 9.8: Change in household energy consumption by end-uses based on ‘behavioural change’ scenario for the year 2020 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2020) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	228.72	-72.20	-23.99
Hot Water	108.20	62.35	-45.85	-42.38
Cooking	18.88	11.88	-7.00	-37.08
Lighting	15.29	11.44	-3.85	-25.18
Appliances	47.93	54.57	6.64	13.85
Total	**491.22**	**368.95**	**-122.27**	**-24.89**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.9: Change in household energy consumption by end-uses based on 'behavioural change' scenario for the year 2050 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2050) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	183.91	-117.01	-38.88
Hot Water	108.20	52.26	-55.94	-51.70
Cooking	18.88	12.06	-6.82	-36.12
Lighting	15.29	9.53	-5.76	-37.67
Appliances	47.93	42.07	-5.86	-12.23
Total	**491.22**	**299.84**	**-191.38**	**-38.96**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

9.3.3 Analysis of the 'Behavioural Change' Scenario Results for Household Carbon Emissions

As before, Figures 9.8 (see appendix C4 for the combined behaviour with the baseline scenario) and 9.9 illustrate the profile of household carbon emissions by end-uses, and total and average annual household carbon emissions respectively. The two Figures display similar consumption behaviour as shown for the household energy consumption above (Figures 9.6 and 9.7). Again, the graphs show a downward trend for carbon emissions for all the end-uses till 2050 under a varying degree of reductions. This, therefore, indicates reduction in carbon emissions profile of UK housing stock is anticipated.

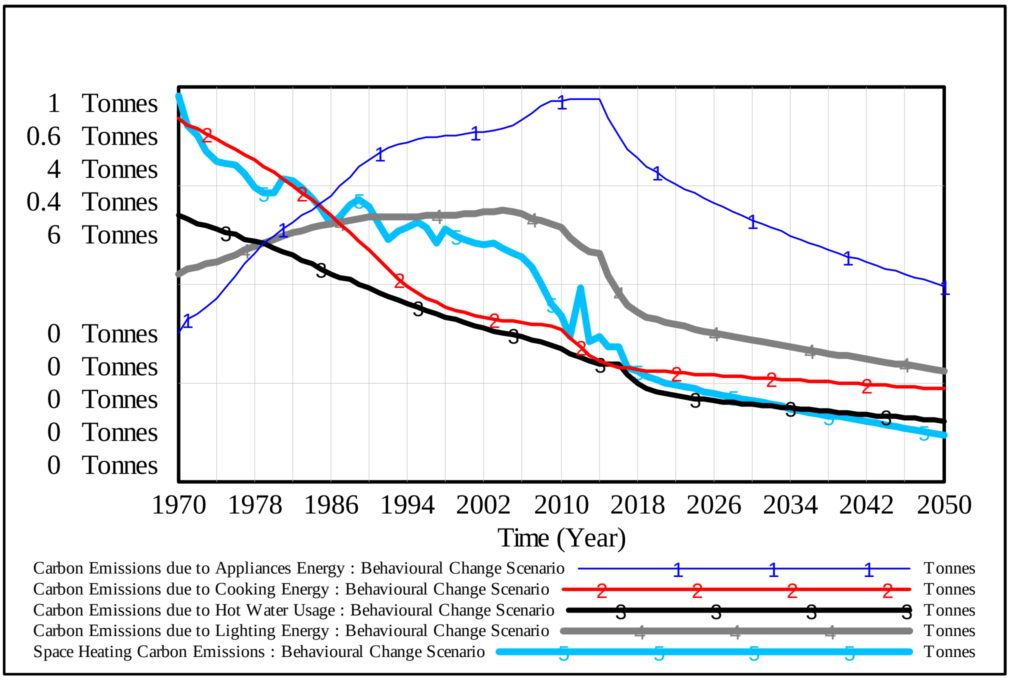


Figure 9.8: Behaviour of household carbon emissions based on end-uses under the 'behavioural change' scenario

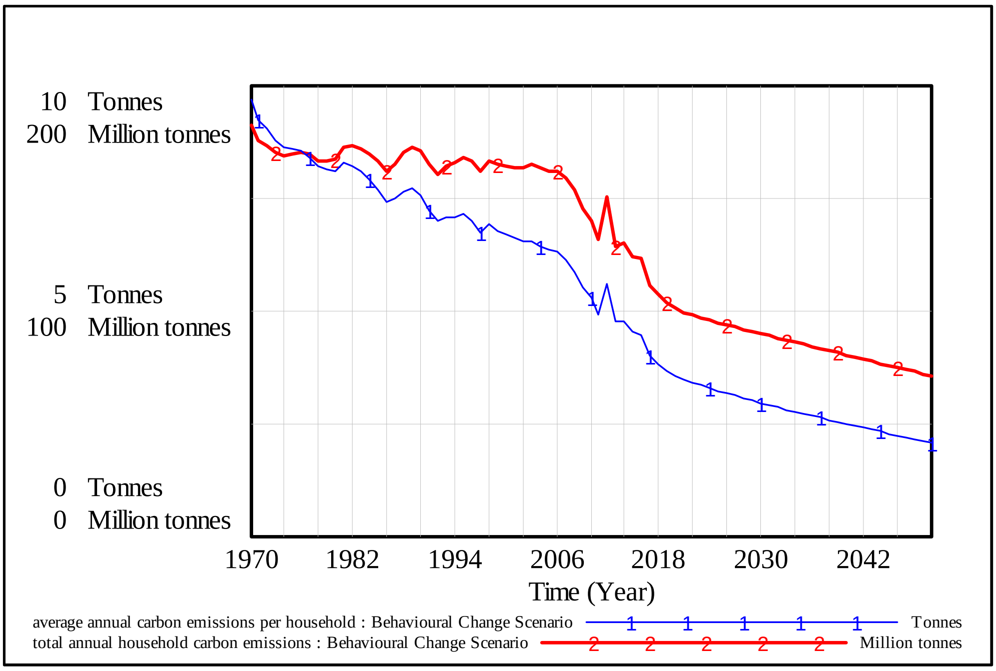


Figure 9.9: Behaviour of average and total annual household carbon emissions under the 'behavioural change' scenario

Tables 9.10 and 9.11 clearly illustrate the amount of reductions in carbon emissions anticipated in the years 2020 and 2050 respectively. Similar results are observed when this scenario is compared to that of ‘efficiency’ scenario. As for ‘efficiency’ scenario, the largest chunk of reductions is expected from space heating (50.71 and 70.12 million tonnes of CO_2 for 2020 and 2050 respectively). This is followed with the carbon emissions attributable to hot water (18.51 and 23.12 million tonnes of CO_2 for 2020 and 2050 respectively). It is therefore clear that both the space and water heating still remain the dominant end-uses where the greatest reductions in carbon emissions targets are expected. Accordingly, some reductions are also anticipated in cooking and lighting below the 1990 levels for the years 2020 and 2050 similar to what the results for ‘efficiency’ scenario suggest. Like ‘efficiency’ scenario, the appliances energy consumption is expected to show no reductions in carbon emissions below the 1990 levels. The implication of this is that Government policy is required to address this trend.

Generally, it is clear from the results of this scenario that carbon emissions target for the year 2020 is likely to be met. The model results show a total of about 41% as against the target of 34% as enshrined in the Climate Change Act of 2008. This result is illuminating in the sense that a vigorous behavioural campaign, as it is in this scenario, in additional to the efficiency measures through building regulations and other Government’s policy frameworks has the capability of meeting the relevant emissions reduction targets. However, by the middle of this century, the results for this scenario indicate it is unlikely to meet the carbon emissions reduction targets of 80%. The results show that only about 58% carbon emissions reductions are likely to be met. As suggested under the ‘efficiency’ scenario, the Government policy should target other policy areas in addition to the ‘behavioural change’ in order to meet the required level of reductions.

It is equally important to state that the results of this scenario are not compared with model results from other studies because of unavailability relevant previous results to compare with.

Table 9.10: Change in household carbon emissions by end-uses based on 'behavioural change' scenario for the year 2020 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2020) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	43.76	-50.71	-53.68
Hot Water	44.15	25.64	-18.51	-41.93
Cooking	7.93	4.75	-3.18	-40.10
Lighting	6.04	4.64	-1.40	-23.18
Appliances	18.43	22.19	3.76	20.40
Total	**171.01**	**100.98**	**-70.03**	**-40.95**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.11: Change in household carbon emissions by end-uses based on 'behavioural change' scenario for the year 2050 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2050) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	24.35	-70.12	-74.22
Hot Water	44.15	21.03	-23.12	-52.37
Cooking	7.93	4.81	-3.12	-39.34
Lighting	6.04	3.84	-2.20	-36.42
Appliances	18.43	16.99	-1.44	-7.81
Total	**171.01**	**71.02**	**-99.99**	**-58.47**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

9.4 ‘Economic’ Scenario

9.4.1 ‘Economic’ Scenario Assumptions

Economic scenario is also based on the ‘baseline’ scenario, but with emphasis on the effects of energy bills on household energy consumption and carbon emissions. The scenario describes a future where the UK Government will formulate a policy freezing the energy prices in order to score some political points. This is assumed to cause a reduction in energy bills payable by the householders. The scenario anticipates the likelihood of this dip in energy bills to free up more disposable income for householders in an attempt to lower the number of those in fuel poverty. With this, the scenario assumes that the householders will seek more thermal comfort as a result of more disposable income, thereby increasing their dwelling internal temperature set-point a little bit, though with ‘standard’ consumption behaviour. It is necessary to state that the scenario has the potential of illustrating the impact of energy prices surge or dip on the household energy consumption and carbon emissions. Therefore, for this scenario, all other variables are kept as they were for the ‘baseline’ scenario apart from the following changes made to some of the parameters within the model. The ‘% increment in energy bills’ is set at -5% and the dwelling internal temperature set-point is set to 20°C.

9.4.2 Analysis of the ‘Economic’ Scenario Results for Household Energy Consumption

The behaviour exhibited by the household energy consumption in terms of end-uses and average and total annual household energy consumption are illustrated in Figures 9.10 (see appendix C5 for the combined behaviour with the baseline scenario) and 9.11 respectively. Similarly to other scenarios run, a visual inspection of the two Figures shows that the trends of household energy consumption under the ‘economic’ scenario are on the downward approach as they tend towards 2050. The slopes are gentler as the graphs tend towards 2050 when compared with both the ‘efficiency’ and ‘behavioural change’ scenarios. The reductions in ‘economic’ scenario seem subtle and the insights there auspicate that they are unlikely to meet the required reductions target. Therefore, a detailed analysis is required to reveal any hidden insights.

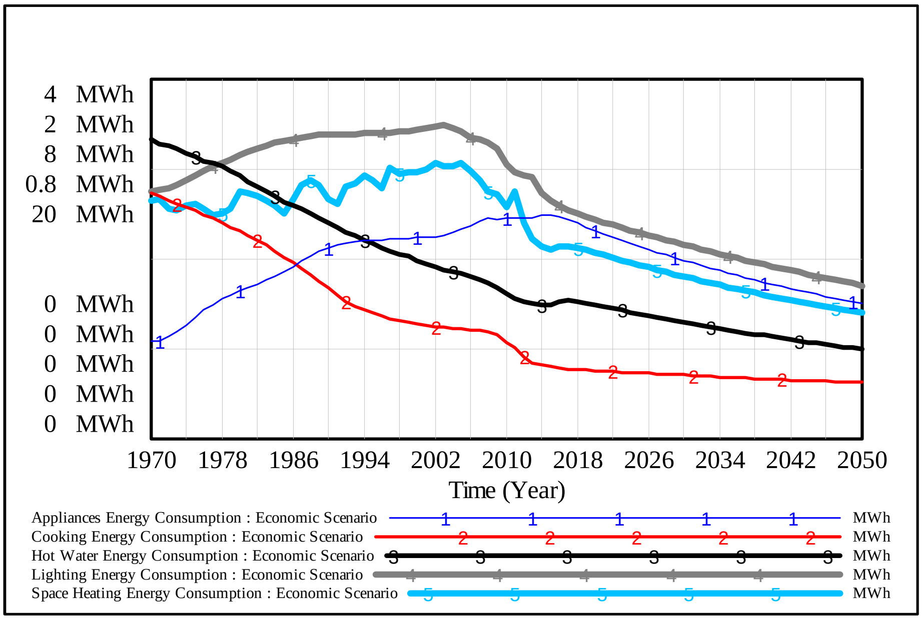


Figure 9.10: Behaviour of household energy consumption based on end-uses under the ‘economic’ scenario

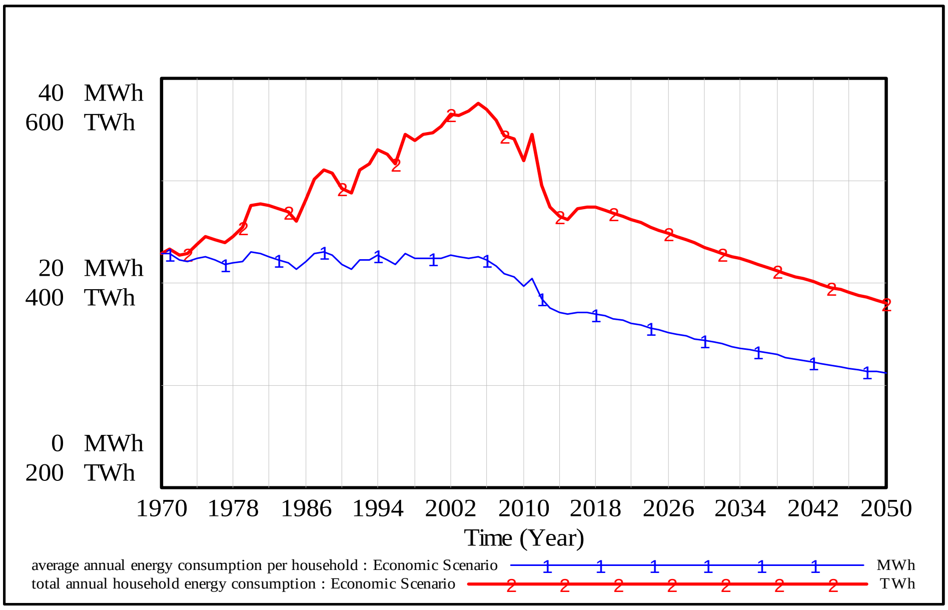


Figure 9.11: Behaviour of average and total annual household energy consumption under the ‘economic’ scenario.

Tables 9.12 and 9.13 show the results of detailed analysis conducted on household energy consumption of UK housing stock for the year 2020 and 2050 respectively as done for other previous scenarios. Interestingly, the results of simulation for the scenario show that only about 10.87% and 22.62% reductions are expected to happen in the year 2020 and 2050 respectively in total household energy consumption for the UK housing stock (Tables 9.12 and 9.13). These results indicate reduced savings when compared to the results of the ‘efficiency’ and ‘behavioural change’ scenarios in Sections 9.2.2 and 9.3.2 above. The results are therefore unsurprising as they are expected because of the assumptions of the scenario relating to energy prices reduction. Reduction in energy bills frees up more disposable income to householders, which they won’t mind spending on an improved thermal comfort at home. This allows occupants to raise their dwellings internal temperature set-point. Also, freezing energy prices by Government threatens energy security and innovative investments in clean energy by energy service providers. All these explain the insights from the results.

Additionally, the consumption profile remains unchanged as such as witnessed in the previous scenarios simulated. This is mainly due to the fact that space heating still account for the largest amount of savings in household energy consumption. The savings here are about 37.47TWh and 62.17TWh for 2020 and 2050 respectively. This is closely followed by hot water with reductions of 24.01TWh and 40.41TWh as expected for the year 2020 and 2050 respectively. Both the cooking and lighting energy are expected to decline as well. As usual, household energy consumption for appliances is expected to grow by about 17.76TWh beyond 1990 levels in the year 2020 (Table 9.12). Again, this increase may be attributed to rise in number of households thereby increasing the number of household appliances acquisition during this period. Also, availability of more disposable income as result of reduction in energy bills may encourage householders to purchase more home appliances, which invariably results in increased energy consumption. By 2050 however, the scenario results suggest that the appliances energy consumption will marginally reduce below 1990 levels

(Table 9.13). Again, there is no suitable past studies to compare the output of this scenario with.

Table 9.12: Change in household energy consumption by end-uses based on 'economic' scenario for the year 2020 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2020) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	263.45	-37.47	-12.45
Hot Water	108.20	84.19	-24.01	-22.19
Cooking	18.88	10.69	-8.19	-43.38
Lighting	15.29	13.82	-1.47	-9.61
Appliances	47.93	65.69	17.76	37.05
Total	**491.22**	**467.84**	**-53.38**	**-10.87**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.13: Change in household energy consumption by end-uses based on 'economic' scenario for the year 2050 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2050) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	238.75	-62.17	-20.66
Hot Water	108.20	67.79	-40.41	-37.35
Cooking	18.88	10.58	-8.30	-43.96
Lighting	15.29	11.66	-3.63	-23.74
Appliances	47.93	51.33	3.40	7.09
Total	**491.22**	**380.11**	**-111.11**	**-22.62**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

9.4.3 Analysis of the 'Economic' Scenario Results for Household Carbon Emissions

The behaviour exhibited by the household carbon emissions by end-uses, and total and average annual household carbon emissions are illustrated in Figures 9.12 (see appendix C6 for the combined behaviour with the baseline scenario) and 9.13 respectively. These results are again profound as they depict similar trends as demonstrated by the ones for household energy consumption shown in Figures 9.10 and 9.11 above. The emissions profile displayed in the two Figures indicate that towards the year 2050, the household carbon emissions is expected to fall. However, the rate of decline of the graphs is gentle making it to be a little bit different from those of 'efficiency' and 'behavioural change' scenarios. Based on the author's conjecture, this gentle slope suggests that it unlikely for this scenario to meet the legally binding carbon emissions reduction targets of Government.

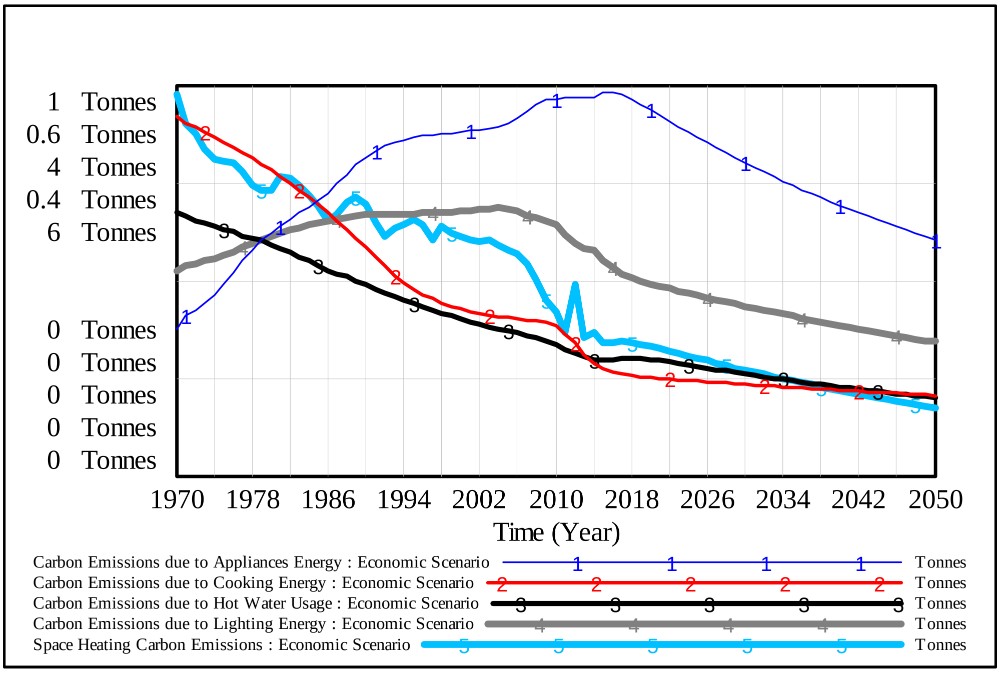


Figure 9.12: Behaviour of household carbon emissions based on end-uses under the 'economic' scenario

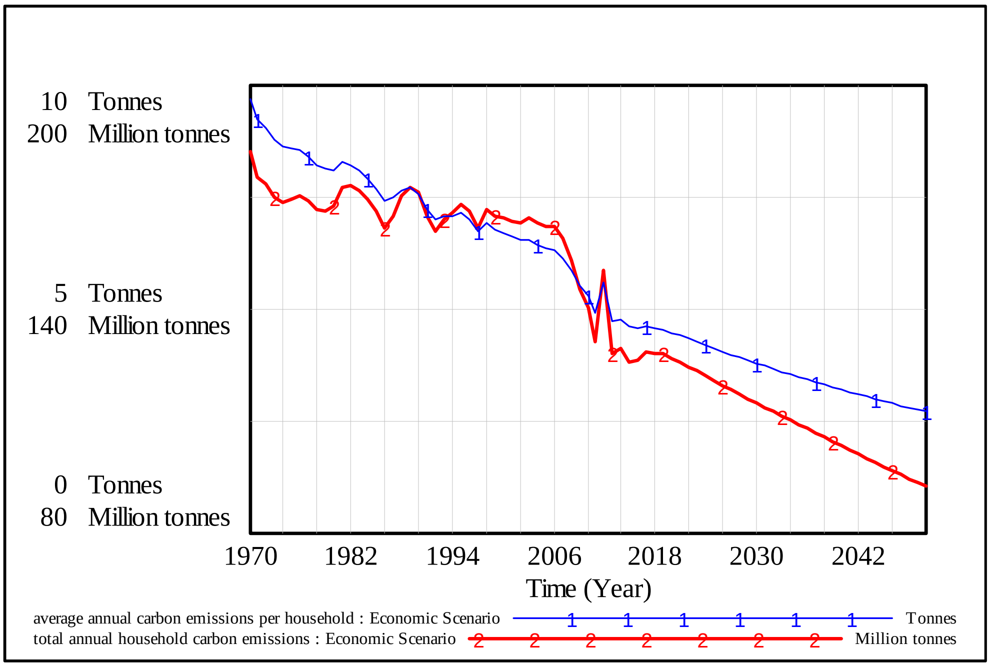


Figure 9.13: Behaviour of average and total annual household carbon emissions under the ‘economic’ scenario

Tables 9.14 and 9.15 show the total amount of carbon emissions reductions envisaged by the scenario in the year 2020 and 2050 respectively. As for other scenarios, the results for this scenario suggest that the largest chunk of reductions is expected to come from space heating in the amount of 38.04 and 59.18 million tonnes of CO_2 for 2020 and 2050 respectively. Also, it is evident from the results of this scenario that substantial amount of reductions is expected from hot water as well in the amount of 10.27 and 16.80 million tonnes of CO_2 for 2020 and 2050 respectively. These results still reinforce the fact that both the space and water heating remain the main end-uses where much of the reductions to meet the carbon emissions targets are anticipated in like manner as other pervious scenarios. In the same way, savings in carbon emissions due to cooking and lighting are expected for the years 2020 and 2050, but the savings are limited when compared to both the space heating and hot water. Conversely, no savings are expected from the carbon emissions due to appliances as the level emissions for this end-use is anticipated not to fall below the 1990 levels for both the year 2020 and 2050 as the results suggest in Tables 9.14 and 9.15 respectively. When the total carbon emissions reductions for the year 2020 and 2050 are examined, it is evident from the Tables 9.14 and 9.15 that the results of this scenario are unlikely to meet the carbon emissions reduction targets as enshrined in the Climate Change Act of 2008. The results show that savings of about 25.86% and 46.04% are anticipated by the year 2020 and 2050 as against the minimum targets of 34% and 80% respectively. The implication of these results is profound that freezing energy prices as Government policy in order to score some political points is at the detriment of meeting the required legally binding carbon emissions reduction targets.

Table 9.14: Change in household carbon emissions by end-use based on 'economic' scenario for the year 2020 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2020) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	56.43	-38.04	-40.27
Hot Water	44.15	33.88	-10.27	-23.26
Cooking	7.93	4.28	-3.65	-46.03
Lighting	6.04	5.58	-0.46	-7.62
Appliances	18.43	26.61	8.18	44.38
Total	**171.01**	**126.78**	**-44.23**	**-25.86**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.15: Change in household carbon emissions by end-use based on 'economic' scenario for the year 2050 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2050) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	35.29	-59.18	-62.64
Hot Water	44.15	27.35	-16.80	-38.05
Cooking	7.93	4.23	-3.70	-46.66
Lighting	6.04	4.69	-1.35	-22.35
Appliances	18.43	20.71	2.28	12.37
Total	**171.01**	**92.27**	**-78.74**	**-46.04**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

9.5 'Integrated' Scenario

9.5.1 'Integrated' Scenario Assumptions

The 'integrated' scenario integrates and harmonises the assumptions made under the 'efficiency', behavioural change, and 'economic' scenarios as they impact on the household energy consumption and carbon emissions of the UK housing stock. The scenario assumes that the energy efficiency improvements as described and emphasised under the 'efficiency' scenario will be maintained. Further, the scenario assumes that householders will display frugal energy consumption behaviour. And as such, they are interested in monitoring their energy usage at home. That is, they exercise some behavioural habit aiming at saving energy consumption at home like turning down heating in vacant rooms, washing at lower temperature, *etc.* With all these, they are however assumed to maintain a dwelling internal temperature set-point of 20ºC. Additionally, within this period, energy prices are expected to be frozen as explained under the ‘economic’ scenario in Section 9.4.1.

9.5.2 Analysis of the ‘Integrated’ Scenario Results for Household Energy Consumption

Figures 9.14 and 9.15 display the behaviours of household energy consumption based on end-uses, and the behaviours of average and total annual household energy consumption per household in the UK housing stock. By conducting a quick visual inspection on Figure 9.14 (see appendix C7 for the combined behaviour with the baseline scenario), the trends that observed are similar to the ones display by the ‘behavioural change’ scenario. This indicates that the household energy consumption under the ‘integrated’ scenario tends to decline as they approach 2050. Similarly, the profile of average and total annual household energy consumption as shown in Figure 9.15 also tends to decline as they move towards 2050.

Energy savings from these graphs when compared to that of ‘behavioural change’ scenario are almost the same thing as little or no differences are noticed by the visual inspection. However, there is a well pronounced difference between the behaviour of this scenario (in terms of household energy) when compared to corresponding Figures under the ‘efficiency’ scenario. The insights from the scenario then show that there is possibility of more savings from this scenario than ‘efficiency’ scenario. But, it is difficult to make this kind of conjecture when compared to the ‘behavioural change’ scenario.

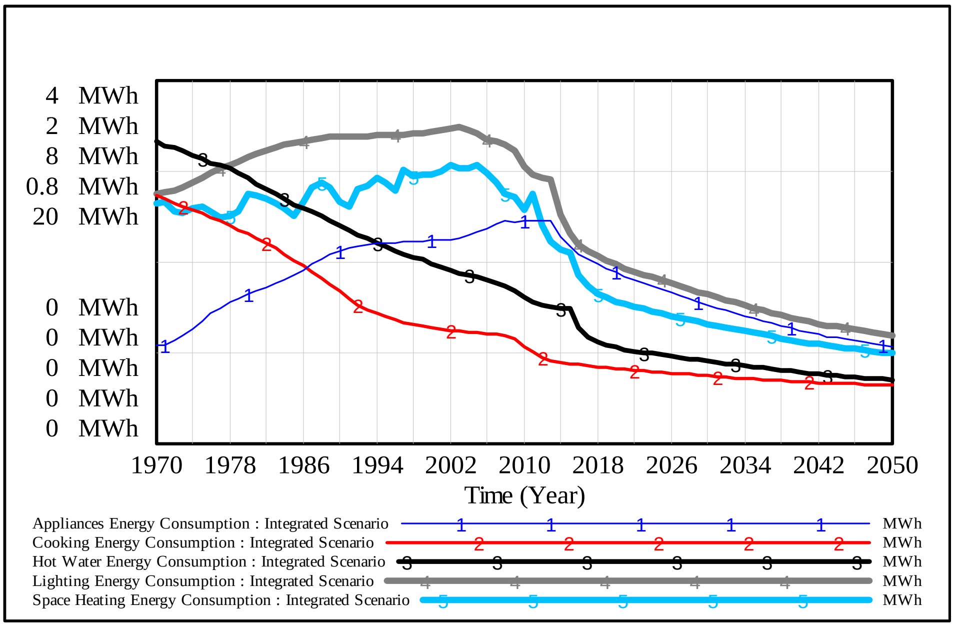


Figure 9.14: Behaviour of household energy consumption based on end-uses under the 'integrated' scenario

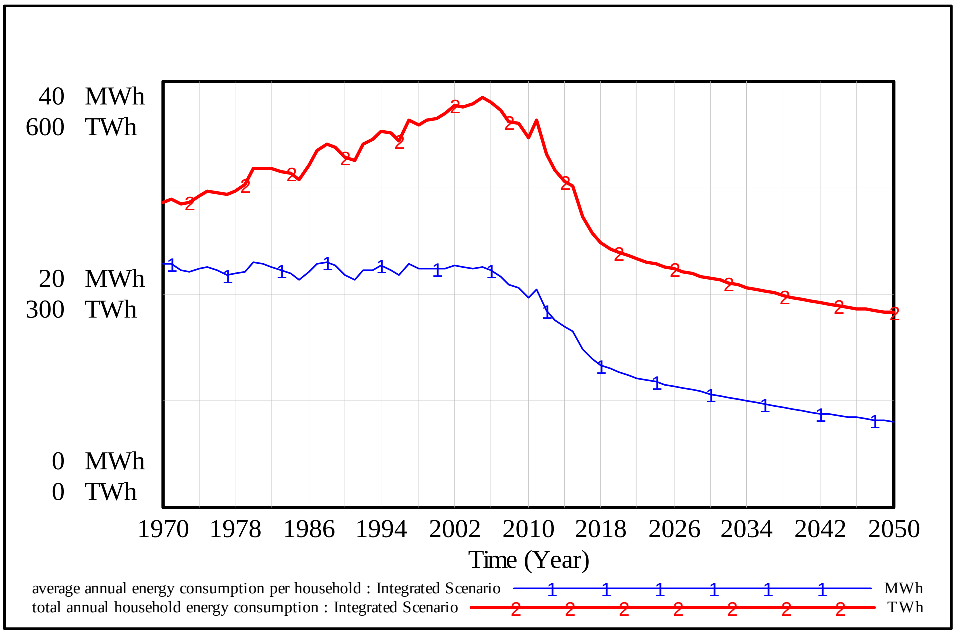


Figure 9.15: Behaviour of average and total annual household energy consumption under the 'integrated' scenario

As done for all the previous scenarios, a further analysis is carried out in order to bring forth all the hidden insights from the scenario that Figures 9.14 and 9.15 cannot explain. The household energy consumption for the UK housing stock is analysed for the year 2020 and 2050 relative to the year 1990 and shown in Tables 9.16 and 9.17 respectively. The profile of the contribution of each household energy end-use to energy savings for this scenario remains unchanged when compared to the previous scenarios because the space heating is still responsible for the lion share of savings of expected in household energy consumption. For example, the results of this scenario suggest that about 79.31TWh and 131.56TWh reductions are anticipated by the year 2020 and 2050 respectively. As expected, this is followed by hot water with savings of 48.38TWh and 60.48TWh for the year 2020 and 2050 respectively (Tables 9.16 and 9.17 respectively). These figures show that they are lower than the savings anticipated under both the ‘efficiency’ and ‘behavioural change’ scenarios.

Correspondingly, cooking and lighting energy are also expected to follow suit as space and water heating. However, the volume of the savings anticipated are small as only 7.22TWh and 4.11TWh are expected to be saved in cooking and lighting energy consumption respectively for the year 2020. The results of household energy consumption for appliances are unsurprising for this scenario when compared to the previous trends. For the year 2020, this no savings is recorded below the levels of the year 1990. Again, the likely reason for this insight is due to the fact that the number of households continues to increase (as the model results suggest) thereby increasing the number of household appliances acquisition and consequently more energy are used. However, the scenario results suggest that the appliances energy consumption will reduce below 1990 levels by 11.41TWh by the year 2050 (Table 9.17).

The analysis of results are illuminating as Table 9.16 shows that a total savings of about 27% below 1990 levels is expected by the year 2020, whereas a total savings of about 44% is anticipated by the 2050. These figures are more than any of the previous scenarios.

Table 9.16: Change in household energy consumption by end-uses based on 'integrated' scenario for the year 2020 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2020) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	221.61	-79.31	-26.36
Hot Water	108.20	59.82	-48.38	-44.71
Cooking	18.88	11.66	-7.22	-38.24
Lighting	15.29	11.18	-4.11	-26.88
Appliances	47.93	53.49	5.56	11.60
Total	**491.22**	**357.76**	**-133.46**	**-27.17**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.17: Change in household energy consumption by end-uses based on 'integrated' scenario for the year 2050 relative to 1990

	Household energy consumption (1990) (TWh)	**Household energy consumption (2050) (TWh)**	***Change in household energy consumption (TWh)**	***Percentage change in household energy consumption (%)**
Space heating	300.92	169.36	-131.56	-43.72
Hot Water	108.20	47.72	-60.48	-55.90
Cooking	18.88	10.93	-7.95	-42.11
Lighting	15.29	8.18	-7.11	-46.50
Appliances	47.93	36.52	-11.41	-23.81
Total	**491.22**	**272.70**	**-218.52**	**-44.49**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

9.5.3 Analysis of the 'Integrated' Scenario Results for Household Carbon Emissions

As shown for all other previous scenarios, Figures 9.16 (see appendix C8 for the combined behaviour with the baseline scenario) and 9.17 illustrate the behaviour exhibited by the household carbon emissions by end-uses, and total and average annual household carbon emissions respectively. Again, both Figures display a downward trend for carbon emissions for all the end-uses, and total and average annual household carbon emissions as they approach 2050 under a varying degree of savings. This downward trends show a relieve sign of likelihood of achieving reductions in carbon emissions profile of UK housing stock. A detail analysis of these savings is carried out below.

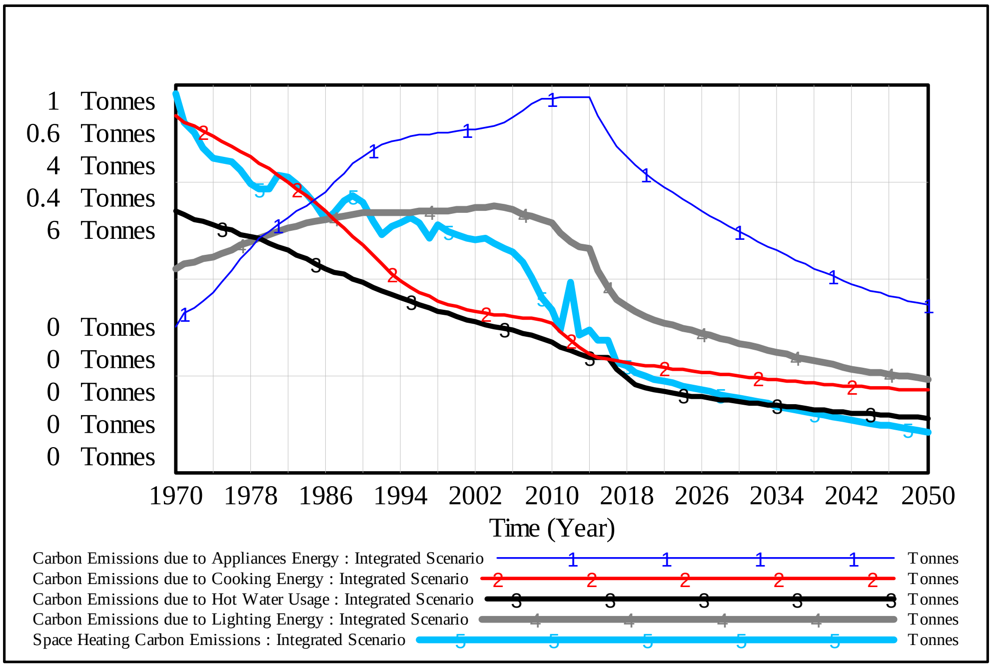


Figure 9.16: Behaviour of household carbon emissions based on end-uses under the 'integrated' scenario

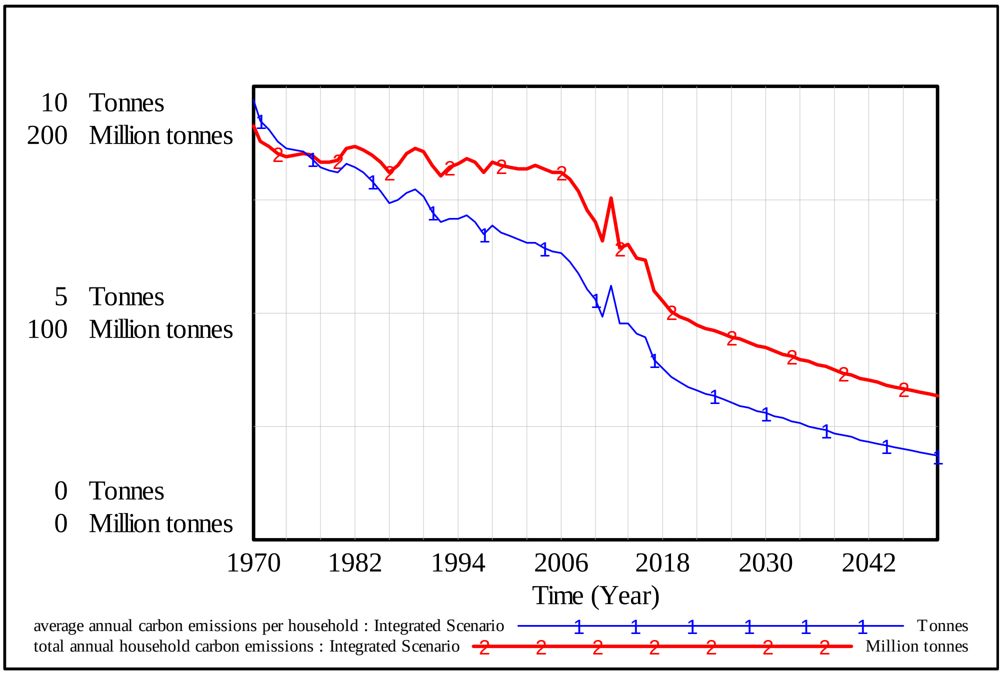


Figure 9.17: Behaviour of average and total annual household carbon emissions under the 'integrated' scenario

It is clear from Tables 9.18 and 9.19 the amount of reductions in household carbon emissions as expected in the years 2020 and 2050 respectively. The results are similar to the ones observed under the previous scenarios as the greatest reductions are expected from space heating (52.05 and 73.04 million tonnes of CO_2 for 2020 and 2050 respectively). Expectedly, how water contribute the second largest reductions in carbon emissions attributable to this end-use (19.41 and 24.97 million tonnes of CO_2 for 2020 and 2050 respectively). It is, again, apparent that both the space and water heating are the dominant end-uses where the largest chunk of reductions in carbon emissions targets is anticipated. As discussed for under the household energy consumption in Section 9.5.2, some reductions are also expected in cooking and lighting below the 1990 levels for the years 2020 and 2050. These reductions are similar to what other previous scenarios suggest.

However, the model results for this scenario are similar to previous scenarios that carbon emissions due to the appliances are unlikely to fall below the 1990 levels. Government policy is therefore required to overturn this trend with a deep cut in carbon emissions attributable to home appliances. However, the model results for this scenario in Table 9.19 suggest that the carbon emissions attributable to appliances is expected to fall below 1990 levels thereby showing a sign of savings.

Generally, it is apparent from the results of this scenario that carbon emissions reduction target for the year 2020 is likely to be met. This is similar to the ‘behavioural change’ scenario. The result in Table 9.18 suggests that a total of about 43% carbon emissions are expected as against the target of 34% that is legally binding. This result therefore shows the efficacy of a vigorous behavioural change campaign, which in additional to the improvements in energy efficiency measures through stringent building regulations and other UK Government’s policy frameworks display the capability of meeting the legally binding emissions reduction targets.

With these giant strides shown by the scenario for the year 2020, yet it unlikely to meet the carbon emissions reduction targets of 80% by the middle of this century. The result indicates that only about 63% carbon emissions reductions are likely to be achieved. As suggested under the ‘efficiency’ and ‘behavioural change’ scenarios, the Government policy needs to allow the market forces to dictate energy prices as this will ensure energy security and levels of commitment from the energy service provider to further invest in clean energy. Although, the effect of growth in the number of households and decline in average household size are not independently explored by this model, the model has the capability of exploring these effects. However, Government policy is required to moderate the growth in the number of households and decline in the average household size as the duo controls the profile of the UK housing stock carbon emissions profile.

Table 9.18: Change in household carbon emissions by end-use based on 'integrated' scenario for the year 2020 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2020) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	42.42	-52.05	-55.10
Hot Water	44.15	24.74	-19.41	-43.96
Cooking	7.93	4.69	-3.24	-40.86
Lighting	6.04	4.57	-1.47	-24.34
Appliances	18.43	21.91	3.48	18.88
Total	**171.01**	**98.33**	**-72.68**	**-42.50**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

Table 9.19: Change in household carbon emissions by end-use based on 'integrated' scenario for the year 2050 relative to 1990

	Household carbon emissions (1990) (million tonnes of CO_2)	**Household carbon emissions (2050) (million tonnes of CO_2)**	***Change in household carbon emissions (million tonnes of CO_2)**	***Percentage change in carbon emissions (%)**
Space heating	94.47	21.43	-73.04	-77.32
Hot Water	44.15	19.18	-24.97	-56.56
Cooking	7.93	4.36	-3.57	-45.02
Lighting	6.04	3.29	-2.75	-45.53
Appliances	18.43	14.75	-3.68	-19.97
Total	**171.01**	**63.01**	**-108.00**	**-63.15**

**Relative to 1990 base as enshrined in Climate Change Act of 2008*

9.5.4 Comparison of 'Integrated' Scenario with Johnston's Model Results

The results of the 'integrated' scenario are compared with the results of Johnston's (2003) 'integrated' scenario. It needs to emphasise that the Johnston's (2003) 'integrated' scenario has a different modelling assumptions compared to the 'integrated' scenario in this thesis. However, this scenario is viewed as the closest to this thesis' 'integrated' scenario. The 'integrated' scenario in Johnston (2003) tries to capture both the supply and demand sides of energy and carbon emission with an assumption of clean energy coming from the supply side. That is, improved energy efficiency in electricity generation is assumed. The results of this comparative analysis are succinctly summarised in Tables 9.20 and 9.21 for household energy consumption and household carbon emissions respectively.

Table 9.20: Comparative analysis of household energy consumption attributable to 'efficiency' and 'demand side' scenarios

	Total annual household energy consumption (KWh)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
'Integrated' scenario	491.2	546.8	519.4	357.8	321.5	291.5	272.7
'Integrated' scenario of Johnston (2003)	-	556.4	517.2	461.0	415.6	371.9	278.9

Table 9.21: Comparative analysis of household carbon emissions attributable to 'efficiency' and 'demand side' scenarios

	Total annual household carbon emissions (million tonnes of CO_2)						
	1990	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
'Integrated' scenario	171.0	164.2	140.1	98.3	84.2	72.3	63.0
'Integrated' scenario of Johnston (2003)	-	132.6	115.4	96.6	83.5	71.6	51.2

The results clearly indicate that there are some differences in the output of the two models. These differences are however likely to due to different assumptions made, different input data, and possibly the modelling philosophy employed by the two models as previously argued in Section 7.9. Again, it is worth highlighting that the model in this thesis captured both the quantitative and qualitative data of which current and previous modelling paradigms lacks. Qualitative data were captured based on knowledge elicitation of those considered as experts in the field of energy. This makes the approach in this thesis to be more robust and inclusive enough.

9.6 Summary of the Results for all the Scenarios

The summary of the results for all the scenarios for household energy and carbon emissions is shown in Tables 9.22 and 9.23 respectively.

Table 9.22: Percentage reductions in household energy consumption for all scenarios

	Baseline scenario (%)	**Efficiency scenario (%)**	**Behavioural change scenario (%)**	**Economic scenario (%)**	**Integrated scenario (%)**
2020					
Space heating	-7.99	-10.66	-23.99	-12.45	-26.36
Hot Water	-26.61	-29.08	-42.38	-22.19	-44.71
Cooking	-44.28	-47.19	-37.08	-43.38	-38.24
Lighting	-10.92	-15.24	-25.18	-9.61	-26.88
Appliances	+35.34	+29.65	13.85	37.05	11.60
Total	***-9.35***	***-12.33***	***-24.89***	***-10.87***	***-27.17***
2050					
Space heating	-25.38	-31.53	-38.88	-20.66	-43.72
Hot Water	-41.10	-46.51	-51.70	-37.35	-55.90
Cooking	-44.92	-53.92	-36.12	-43.96	-42.11
Lighting	-25.18	-38.46	-37.67	-23.74	-46.50
Appliances	+5.21	-12.25	-12.23	7.09	-23.81
Total	***-26.60***	***-34.03***	***-38.96***	***-22.62***	***-44.49***

One of the most significant evidence from all the scenarios is that it is unlikely for any of the scenarios to individually meet the required legally binding reductions of 80% cut in carbon emissions.

Table 9.23: Percentage reductions in household carbon emissions for all scenarios

	Baseline scenario (%)	**Efficiency scenario (%)**	**Behavioural change scenario (%)**	**Economic scenario (%)**	**Integrated scenario (%)**
2020					
Space heating	-43.70	-45.29	-53.68	-40.27	-55.10
Hot Water	-27.32	-29.44	-41.93	-23.26	-43.96
Cooking	-46.91	-49.18	-40.10	-46.03	-40.86
Lighting	-8.94	-12.58	-23.18	-7.62	-24.34
Appliances	+*42.65*	37.76	20.40	44.38	18.88
Total	***-29.08***	***-31.27***	***-40.95***	***-25.86***	***-42.50***
2050					
Space heating	-65.64	-69.56	-74.22	-62.64	-77.32
Hot Water	-41.77	-47.09	-52.37	-38.05	-56.56
Cooking	-47.54	-56.24	-39.34	-46.66	-45.02
Lighting	-23.68	-37.25	-36.42	-22.35	-45.53
Appliances	+*10.42*	-7.76	-7.81	12.37	-19.97
Total	***-48.96***	***-55.34***	***-58.47***	***-46.04***	***-63.15***

9.7 Chapter Summary

This chapter has described and extensively discussed some policy scenarios formulated in order to illustrate the use of the model in this thesis. The illustrative scenarios developed demonstrated the other ways by which household energy consumption and carbon emissions attributable to the UK housing stock would evolve over the years under different assumptions. The ‘efficiency’ scenario generally considers the effects of improvements in energy efficiency measures on household energy consumption and ultimately on household carbon emissions. Also, the ‘behavioural change’ scenario tries to model the effects of occupants’ change of energy consumption behaviour on household energy consumption and carbon emissions profile. Further, the ‘economic’ scenario assumes a case of policy change by Government favouring energy prices reduction, thereby reducing the energy bills payable by the householders and its consequences on household energy consumption and carbon emissions. And lastly, an ‘integrated’ scenario combines the assumptions in the first three scenarios and then analyses its effects on household energy consumption and carbon emissions.

The results from the ‘efficiency’ scenario suggest that about 12% and 34% reductions in household energy consumption are visible by the years 2020 and 2050 respectively below the year 1990 levels. The results further suggest that the household carbon emissions are likely to be reduced by about 31% and 55% in the years 2020 and 2050 respectively below the 1990 levels. Additionally, the results of the ‘behavioural change’ scenario indicate that about 25% and 39% reductions in household energy consumption are possible in the years 2020 and 2050 respectively below the year 1990 levels. The model suggests that these reductions in household energy consumption is likely to translate to about 41% and 58% reductions in household carbon emissions in the years 2020 and 2050 respectively when compared to 1990 as the base case. Furthermore, the results for the ‘economic’ scenario show that about 11% and 23% reductions in household energy consumption in the years 2020 and 2050 respectively are possible when compared to the base year 1990. These translate to savings of 26% and 46% in carbon emissions by the years 2020 and 2050 respectively. And finally, the results from the ‘integrated’ scenario suggest that reductions of about 27% and 44% in household energy consumption are possible for the years 2020 and 2050 respectively. These figures amount to about 43% and 63% savings in household carbon emissions for the years 2020 and 2050 respectively.

One of the most significant evidence from the scenarios is that it is likely to meet the 34% carbon emissions target under the ‘behavioural change’ and ‘integrated’ scenarios under vigorous campaign of energy consumption behavioural change of householders. However, the results for all the scenarios indicate that it is unlikely for any of the scenarios to meet the required legally binding reductions of 80% cut in carbon emissions. Comparison of the model results with other studies clearly indicates there are some differences in the results. These are attributed to different assumptions made, different input data, and possibly the modelling philosophy employed.

Chapter 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Introduction

The aim of this research is to develop a system dynamics based model of the socio-technical systems of energy consumption and carbon emissions of UK housing sector. This Chapter brings together the findings emanating from the research as discussed in Chapters two to nine and the main conclusions are drawn from them to reflect the achievement of research objectives. Prior to highlighting the research originality and contribution to knowledge, the Chapter provides details on the implications of research findings for research, practice, and society. The Chapter also presents the limitations of the research in this thesis and the recommendations for future research directions conclude the Chapter.

10.2 Achievement of Research Objectives and Summary of the Main Conclusions

Objective 1: *To identify the social and technical variables influencing household energy consumption and carbon emissions.*

Chapter two was used to fulfil this objective. Particularly, Section 2.3 of the chapter carries out the review of extant literature on previous empirical studies relating to the STS of household energy consumption and carbon emissions. This is with a view to establishing the theoretical underpinning of frameworks used in conceptualising household energy consumption and carbon emissions. It was shown that the frameworks are principally fall within two major domains: disciplinary and integrated frameworks. Disciplinary framework focuses on how individual disciplines illustrate the approach to solving energy and carbon emissions problems by formulating a framework. For example, engineering approach looks at the technology of energy consumption and carbon emissions.

On the hand, integrated framework uses a holistic approach to combine a number of disciplines together and provide a framework capable of shaping the issue of energy consumption and carbon emissions based on the limitations of disciplinary framework. With these serving as background to achieving this objective, Section 2.3.2 of Chapter two reviews extant literature and established that the social and technical variables influencing household energy consumption and carbon emissions come basically from three interacting systems comprising of the dwellings, occupants, and external environment. The variables identified within the dwellings system are related to dwellings' physical characteristics. Also, variables related to occupants system are in terms of household characteristics, occupants' thermal comfort, and occupants' behaviour. And finally, the variables related to external environment system are in terms of climatic, economic, and cultural influences. The variables used for model conceptualisation in Chapter six are drawn from these frames of variables and mapped into six different modules.

Objective 2: *To review the modelling approaches used in forecasting household energy consumption and carbon emissions.*

Chapter two was used to achieve this objective based on the review of extant literature within the field of study. The review demonstrates that there are quite a number of energy and carbon emissions models that have evolved over the years with the capability of forecasting and estimating energy consumption and carbon emissions, especially in the housing sector of the economy. The findings and conclusions emanating from the literature review suggest the following:

- The models used in forecasting energy and carbon emissions of the housing sector basically follow two major epistemic approaches of top-down and bottom-up methods. The top-down technique relies on the kind of interaction subsisting between the energy sector and the economy in general at aggregated level in order to predict and forecast the behaviour of energy consumption and carbon emissions when some changes are made to the policy parameters within such models. On the other hand, bottom-up techniques mainly focus on only the energy sector utilising a disaggregated approach of either statistical or building physics method that contains a high level of details to model energy consumption and carbon emissions.

- The identified models vary considerably based on the levels of disaggregation, complexity, resolution of output, output aggregation levels, scenario analysis performed, model validation, and their availability to the members of public for scrutiny.

- A careful appraisal of the existing modelling approaches suggests that there are a number of limitations in the existing modelling techniques, which are (1) lack of transparency in the model algorithms, (2) inability to account for the complex, interdependencies, and dynamic nature of the issue of energy consumption and carbon emissions, (3) limited evidence to show for the occupants-dwelling interactions, and (4) lack of enough capacity to accommodate qualitative data input.

- And as such, there is the need to scout for more robust modelling approaches that take into consideration the kind of complexity involved and bedevilling the issue of household energy consumption and carbon emissions due to high inter-dependencies, chaotic, non-linearity, and qualitative nature of some of the variables involved.

Objective 3: *To identify the most suitable modelling approach to conceptualise the complex Socio-Technical Systems (STS) of household energy consumption and carbon emissions.*

Chapter three was used to achieve this objective. The later part of Chapter two serves as the background upon which the discussion in Chapter three was based. This highlights the shortcomings of the current energy and carbon emissions modelling tools for housing sector in use. Chapter three therefore discusses the shortcomings identified in Section 2.6 of Chapter two as the main strengths of the STS. Before the review of extant literature on modelling techniques for STS, Chapter three grounded the STS theoretically and philosophically. The findings from the chapter reveal the following:

- The domain of application of STS is majorly in the areas of human-computer interaction studies, information technology, software engineering, engineering (general), business and management, medicine and the host of others.

- The modelling techniques for the STS include actor network theory, agent-based modelling technique, bayesian belief network, configuration modelling, fuzzy logic, morphological analysis, social network analysis, and system dynamics.

- These techniques are analysed for their capability to capture the problem under investigation within this thesis against a set of criteria that include (1) transparency, (2) multiple interdependencies (3) dynamic situations (4) feedback processes (5) non-linear relationships (6) *hard* and *soft* data (7) uncertainties of the variables involved, (8) chaotic assumptions and (9) the use of the model as learning laboratory. A careful appraisal of all the techniques shows that the system dynamics approach is the most suitable technique in conceptualising the problem under investigation in the context of this thesis based on its ability to meet all the set criteria.

Objective 4: *To develop the dynamic model of the socio-technical systems of household energy consumption and carbon emissions.*

This objective is the main thrust of the research work in this thesis. Chapters five, six, seven and eight were used to fulfil this objective. Chapter five thoughtfully discusses and explains the system dynamics methodology as applied to the developed model within this thesis. The model has been developed and includes modules, which are: population/household, dwelling internal heat, occupants thermal comfort, climatic-economic-energy efficiency interaction, household energy consumption, and household CO_2 emissions. Chapter six therefore discusses the development of the model. The chapter described and discussed the model conceptualisation which is regarded as the system thinking stage of the modelling process in the form of causal diagrams. This then leads to the model formulation stage in the form of stock and flow diagrams and the model algorithms are subjected to both quantitative and qualitative data sources. Chapter seven discusses the model results for the 'baseline' scenario, which serves as the base case for all other scenarios formulated in Chapter nine. The key findings from the 'baseline' simulation conducted on the developed model reveal the following:

- In the population/household module, the model behaviour indicated that the total UK population is on the upward trend until 2050 with an average yearly increase of 0.31%. When comparing this result with historical data available from ONS (2013), it shows an annual growth of 0.28%.

- The number of households in the UK was predicted by the model to likely grow on a yearly average of 1.02%, while the average household size tends toward two per household by the year 2050. When comparing the model results with historical data available from DECC (Palmer & Cooper, 2012), the number of households grows by a yearly average of 0.99% and the mean household size stands at 2.29 as at 2010 as against 2.95 in 1970.

- Under the dwelling internal heat module, the model output suggests that both the dwelling internal heat and dwelling internal temperature will continue to grow. This is mainly because of the improvements envisaged in dwellings' thermal performance due to increasing dwellings' airtightness. Also, because of the desire of householders to improve thermal comfort by raising the temperature set-point.

- The insights observed from the occupants thermal comfort module suggest that the behaviour of perceived dwelling temperature would grow over the year until 2050 with improved occupants' thermal comfort.

- Within the climatic-economic-energy efficiency interaction module, the model findings suggest that the unfavourable climatic effects will decline as a result of efforts aiming at reducing carbon emissions.

- The findings relating to household energy consumption suggest that about 27% savings in household energy consumption are visible by the year 2050 below the year 1990 levels.

- The model result indicates that reductions in household energy consumption translate to the savings of about 49% in carbon emissions by the year 2050 below the base year of 1990.

- The insights from the model show that the greatest savings in both household energy consumption and carbon emissions are expected from space and water heating.

Chapter eight validates the model. The testing and validation of the developed model are done basically to build confidence in the model results.

Objective 5: *To use the developed model to evaluate the effects of energy efficiency, occupants behavioural change, and energy prices on household energy consumption and carbon emissions.*

This objective was achieved in Chapter nine. The chapter describes and extensively discusses some policy scenarios formulated in order to illustrate the use of the model. The illustrative scenarios developed demonstrates the other ways by which household energy consumption and carbon emissions attributable to the UK housing stock would evolve over the years under different assumptions. Four scenarios were illustrated to include ‘efficiency’, ‘behavioural change’, ‘economic’, and ‘integrated’ scenarios.

The ‘efficiency’ scenario generally considers the effects of improvements in energy efficiency measures on household energy consumption and ultimately on household carbon emissions. Additionally, the ‘behavioural change’ scenario tries to model the effects of occupants’ change of energy consumption behaviour on household energy consumption and carbon emissions profile. Furthermore, the ‘economic’ scenario assumes a case of policy change by Government favouring energy prices reduction, thereby reducing the energy bills payable by the householders and its consequences on household energy consumption and carbon emissions. And lastly, an ‘integrated’ scenario combines the assumptions in the first three scenarios and then analyses its effects on household energy consumption and carbon emissions.

The following therefore give the summary of findings and conclusions from the illustrative scenarios:

1. <u>‘Efficiency’ Scenario</u>

- The findings from the ‘efficiency’ scenario suggest that about 12% reductions in household energy consumption are visible by the year 2020 below the base year 1990.

- Also for the year 2050, it is visible to make savings of about 34% in household energy consumption below the base year 1990.

- The results further suggest that the household carbon emissions for this scenario are likely to reduce by about 31% in the year 2020 below the base year 1990.

- Additionally, the results indicate that the household carbon emissions are likely to reduce by about 55% in the year 2050 below the base year 1990.

2. <u>‘Behavioural Change’ Scenario</u>

- For ‘behavioural change’ scenario, the findings show that about 25% savings in household energy consumption are possible in the year 2020 below the 1990 levels.

- Also, the findings for this scenario indicate that about 39% savings in household energy consumption are possible in the year 2050 below the 1990 levels.

- For household carbon emissions under this scenario, it is likely to have about 41% reductions by the year 2020 when compared to 1990 as the base case.

- The model results also suggest that about 58% savings in household carbon emissions by the year 2050 are possible when compared to 1990 as the base case.

3. ‘Economic’ Scenario

- The findings under the ‘economic’ scenario show that about 11% reductions in household energy consumption in the year 2020 are possible when compared to the base year 1990.

- Also for the year 2050, the scenario suggests that about 23% reductions in household energy consumption are possible when compared to the base year 1990.

- For household carbon emissions, the results suggest that there is likely to be savings of about 26% by the year 2020 relative to the base year 1990.

- Additionally, the findings show that the reductions in household energy consumption under this scenario for the year 2050 are likely to translate to savings of about 46% in household carbon emissions for the same year relative to the base year 1990.

4. ‘Integrated’ Scenario

- The results from the ‘integrated’ scenario suggest that reductions of about 27% in household energy consumption are possible by the year 2020 below the base year 1990.

- Also, the findings from this scenario suggest that reductions of about 44% in household energy consumption are possible by the year 2050 below the base year 1990.

- For the household carbon emissions, there is likely to be about 43% savings by the year 2020 below the base year 1990.

- Finally, the reductions witnessed in household energy consumption for the year 2050 are likely to amount to about 63% savings in household carbon emissions for the same year below the base year 1990.

5. General Conclusions from all the Scenarios

- One of the main findings for all the scenarios indicates that it is unlikely for any of the scenarios by its own to meet the required legally binding reductions of 80% cut in carbon emissions by 2050 unless this is vigorously pursued.

- For all the scenarios, the insights from the model show that the greatest reductions in both household energy consumption and carbon emissions are expected from both the space and water heating.

- Comparison of the model results with similar studies like that of Johnston's (2003) clearly indicates there are some differences in the results. These are attributed to difference in assumptions made, input data, and possibly the modelling philosophy employed.

10.3 Implications of Research Findings for Research, Practice, and Society

The developed model as the output of the research in this thesis has a number of implications for research, practice, and/ or society.

Firstly, the study explored the complex intrinsic interrelationships among the STS of dwellings, occupants, and environment, as related to energy consumption and carbon emissions, by capturing their causes and effects. This is with the sole aim of improving the understanding of the complex system of household energy consumption and carbon emissions from systems thinking perspective thereby extending the knowledge base of system dynamics to household energy and carbon emissions. For example, the causal diagrams can lead to theory building by the interested researchers. Additionally, the output of this research has the capability to spur research activities as enunciated under the recommendations for future research directions in Section 10.6.

Secondly, the research in this thesis has implications for practice. The developed model in this research builds on the existing modelling efforts, which are traditionally restricted to building physics and regression-based forecasting, in order to generate new insights into the future using a non-deterministic systems approach. This then adds to the pool of tools available in the field for practitioners. Since the developed model is highly transparent as all the variables and algorithms developed can be scrutinised, it therefore has capacity to immensely benefit from the software developers by prototyping it into other suitable user friendly platforms.

Thirdly, the outcome of this research has implications for society. This is by providing the policy makers with a decision making tool upon which different scenarios regarding HECCE can be tested before implementation.

10.4 Research Originality and Contribution to Knowledge

The originality of this research lies in the application of system dynamics approach to capture and solve the complex problem relating to the future profiles of household energy consumption and carbon emissions by providing a policy advice tool to the policy makers. This is in an attempt to meet the carbon emissions reduction targets as enshrined in the Climate Change Act of 2008. Consequently, the research effort within this thesis has made a number of contributions to knowledge. The unique contribution is the development of a model that incorporates socio-technical issues that can be used for decision making over time. Other contributions are highlighted below:

- The research in this thesis indicates the first system dynamics modelling efforts applied to the entire UK housing sector in order to model the household energy consumption and carbon emissions based on the complex socio-technical interactions of the influencing variables.

- The model, especially the developed conceptual model – system thinking aspect, is capable of improving the theoretical knowledge base regarding the complex intrinsic inter-relationships that exist among the socio-technical influences of household energy consumption and carbon emissions.

- The developed model within this thesis has the capability of being used to simulate and predict the future profiles of UK household energy consumption and carbon emissions over different time horizons.

- The developed model has the capability of producing a clear understanding of household energy consumption and carbon emissions associated with it. This can serve as a decision making policy tool with the capability to direct policy decisions by testing the effect different policy scenarios such as energy efficiency improvements and behavioural change likely to have on household energy consumption and carbon emissions. The insights generated will allow policy makers to make informed decisions regarding any future policy formulations concerning energy and carbon emissions within the UK housing sector.

- The developed model is also capable of modelling and exploring the potential rate at which the carbon emissions reduction targets are being achieved within the UK housing sector.

10.5 Limitations of the Research

Any research effort relating to systems modelling, as the case is in this thesis, is likely to have a number of strengths as well as suffer some drawbacks. The strengths of this research in terms of contribution to knowledge are stated in Section 10.4. The limitations of this research upon which further developments can be made are therefore summarised below:

- The research within this thesis is based purely on modelling of the household energy consumption and carbon emissions (demand side). And as such, the energy generation (energy supply side) attributable to the housing sector has not been considered and modelled by the model developed in this thesis. Therefore, the developed model cannot explicitly explore the technical improvements to the energy supply side in terms of reduced carbon content of supplied energy as envisaged by these technical improvements. This then serves as a limitation to the research.

- The developed model in this thesis is an aggregated model of the entire UK households. And as such, no attempt is made to disaggregate the household energy consumption and carbon emissions based on different dwelling types. Consequently, it is difficult to explore the energy consumption and carbon emissions profiles attributable to the households within these different dwelling types. This is another limitation of this research. However, its inclusion will in no way affect the final results of the developed model.

- There are a number of variables that are not considered in the developed model, since it is necessary to set a boundary for the research. The variables include some that are relating to dwellings physical characteristics and occupants behaviour as stated in Section 6.3 of Chapter six such as dwelling exposure, dwelling orientation, occupants' social class, and the likes. Inclusion of these variables and others, undoubtedly, would improve the accuracy of the developed model and allow further options in the output of the developed model to be explored.

- Another limitation of the research is in the energy to carbon conversion factor used in the developed model. It is believed that different fuels are used for different end uses with different carbon emission factors. For example, householders are likely to use gas, electricity, or oil, *etc.* as fuel in order to achieve space and water heating in their dwellings. The carbon emission contents of each of these fuels differ. This research therefore used the same aggregated energy to carbon emission factors for all the household energy consumption end uses. Changes to these carbon emissions factor will greatly alter the profile of household carbon emissions estimated by the developed model.

- The developed model in this research is limited in its application to other countries because it is specifically developed for the UK housing sector. This is mainly because the model algorithms are based on the UK data. However, other countries can benefit from it by domesticating the model algorithms.

10.6 Recommendations for Future Research Directions

The work within this thesis serves as the foundational system dynamics model upon which further research can be conducted in order to fully explore other options required to reduce the carbon emissions of the UK households. To this extent, the following areas of further research are recommended to vigorously pursue in the coming years:

- A research on the energy supply side of the housing sector based on the system dynamics approach is encouraged. This is considered important because of the need to highlight the effect of clean energy supply, due to technological advancement, on the household energy consumption and carbon emissions. The output of such a research can be linked to the developed model in this research to form an improved socio-technical model of energy and carbon emissions of the UK housing sector.

- The current version of the developed model in this thesis is an aggregated model of the entire UK households. Another line of research can be followed by disaggregating this based on different dwelling types such as detached, semi-detached dwellings and the likes. This is to evaluate the carbon emissions profiles attributable to each of these dwelling types. This line of research is considered important mainly because of the need to expand the capability and scope of the analysis performed by the developed model.

- The research within this thesis can be replicated with an expanded model boundary to accommodate all the variables that are excluded by this current research. This will include incorporation of the carbon emission factors of different fuels used for different end uses of household energy consumption. Also, this further research is considered important in order to improve on the accuracy of the developed model.

- Additionally, it needs to highlight that the developed model within this thesis is specifically developed for the UK. And as such, the research within this thesis can be replicated for other developed countries. This is considered necessary in order for other developed countries to benefit from it by domesticating the model. Domesticating the model will entail using the data collected from the country replicating the model. This will be at the system conceptualisation and formulation stages of model development.

10.7 Chapter Summary

This chapter serves as the reflective summary of the research presented within this thesis as it brings together the findings of the research. The chapter has indeed demonstrated how the aim and objectives of the research have been achieved and gave the main conclusions that follow the findings. The implications of the research for research, practice, and society were highlighted and discussed. Undoubtedly, the research effort within this thesis has made some contributions to knowledge and these were accordingly highlighted by the chapter. The snapshots of the research limitations and recommendations for further research were given as well.

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APPENDIX A

Model Equations

"% increament on energy bills"=

-5

Units: per cent [0,100,25]

appliances energy:=

GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'M2')

Units: MWh

Appliances Energy Consumption= INTEG (

(rate of appliances energy usage-energy to carbon conversion a),

initial appliances usage)

Units: MWh

appliances energy consumption for UK housing stock=

Appliances Energy Consumption*households/10^6

Units: TWh

appliances usage demand=

2

Units: Dmnl

area of opening=

10

Units: m*m

Area of windows and glazed doors

Artificial heat transfer=

("discrepancy in int & setpoint temp"*insulation factor)+"total dwelling heat gains (dhg)"
/Time
Units: Watts/Year

average annual carbon emissions per household=
Carbon Emissions due to Cooking Energy+Carbon Emissions due to Hot Water Usage
+Carbon Emissions due to Lighting Energy+Carbon Emissions due to Appliances Energy
+Space Heating Carbon Emissions
Units: Tonnes

average annual electricity bill:=
GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'P2')
Units: £

average annual energy bills=
IF THEN ELSE(Time<=2010, ((average annual electricity bill+average annual gas bill
)+(5139.16-2.455*Time+164.363*weighted average energy prices+12.612
*effect of dwelling energy efficiency on energy bills))/2, FORECAST(((average annual electricity bill
+average annual gas bill)+(5139.16-2.455*Time+164.363*weighted average energy prices
+12.612
*effect of dwelling energy efficiency on energy bills))/2,39,-45))
Units: £

average annual energy consumption per household=
Cooking Energy Consumption+Hot Water Energy Consumption+Lighting Energy Consumption

+Space Heating Energy Consumption+Appliances Energy Consumption
Units: MWh

average annual gas bill:=

GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'O2')

Units: £

average effect of solar gains=

0.9*area of opening*frame factor*average solar access factor*solar flux*solar transmittance factor for glazing

Units: Watts

average household size=

Population/households

Units: People/Households

average life expectancy=

78.8

Units: Year

average solar access factor=

0.7

Units: Dmnl [0.3,1,0.01]

average total fertility rate=

3

Units: Dmnl

births=

IF THEN ELSE(Time=population equilibrium time,deaths, IF THEN ELSE(Time<=2011

, average total fertility rate*Population

*0.08/reproductive time, FORECAST(average total fertility rate*Population

*0.08/reproductive time,39,100)))

Units: People/Year

carbon depletion=

Carbon Emissions due to Appliances Energy*carbon depletion factor

Units: Tonnes/Year

carbon depletion factor=

1.325

Units: 1/Year [-2,5,0.005]

Carbon Emissions due to Appliances Energy= INTEG (

(energy to carbon conversion -carbon depletion)*0.5246,

initial appliances usage carbon emissions)

Units: Tonnes

carbon emissions due to appliances energy of UK housing stock=

Carbon Emissions due to Appliances Energy*households/10^6

Units: Million tonnes

Carbon Emissions due to Cooking Energy= INTEG (

(energy to carbon conversion - carbon depletion)*0.5246,

initial cooking carbon emissions)

Units: Tonnes

carbon emissions due to cooking energy of UK housing stock=

Carbon Emissions due to Cooking Energy*households/10^6

Units: Million tonnes

carbon emissions due to hot water energy of UK housing stock=
Carbon Emissions due to Hot Water Usage*households/10^6
Units: Million tonnes

Carbon Emissions due to Hot Water Usage= INTEG (
(energy to carbon conversion hw-hw carbon depletion)*0.5246,
initial hot water usage carbon emissions)
Units: Tonnes

Carbon Emissions due to Lighting Energy= INTEG (
(energy to carbon conversion l-l carbon depletion)*0.5246,
initial lighting usage carbon emissions)
Units: Tonnes

carbon emissions due to lighting energy of UK housing stock=
Carbon Emissions due to Lighting Energy*households/10^6
Units: Million tonnes

carbon emissions due to space heating energy of UK housing stock=
Space Heating Carbon Emissions*households/10^6
Units: Million tonnes

cooking energy:=
GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'K2')
Units: MWh

Cooking Energy Consumption= INTEG (
(cooking energy rate-energy to carbon conversion),
initial cooking energy)
Units: MWh

cooking energy consumption for UK housing stock=

Cooking Energy Consumption*households/10^6

Units: TWh

cooking energy rate=cooking energy*effect of energy efficiency standard on cooking energy/

effect of energy bills on energy consumption/0.88

-0.35*FORECAST(cooking energy/1.88, 40, e)) ,

Units: MWh/Year

deaths=

Population*mortality

Units: People/Year

demand for cooking energy=

2

Units: Dmnl

dhg due to appliances less cooking=

((207.8*(total floor area*average household size)*EXP(0.4714))*(1+0.157*COS

(2*pi*(Time-1.178)))*1000/60)/5000

Units: Watts

dhg due to artificial lighting=

(59.73*(total floor area*average household size)^0.4714)*0.96^2*(1+0.5*COS

(2*pi*(Time-0.2)))*0.85*1000/(24*30*12)

Units: Watts

dhg due to cooking=

35+(7*average household size)
Units: Watts

dhg due to no of people=
60*average household size
Units: Watts

dhg due to water heating=
80.5*average household size
Units: Watts

"discrepancy in int & ext temp"=
external air temp-dwelling int temp
Units: Deg Cent

"discrepancy in int & setpoint temp"=
IF THEN ELSE("% increament on energy bills"=0, setpoint temp-dwelling int temp
, IF THEN ELSE("% increament on energy bills"=25, setpoint temp-0.5-dwelling int temp
, IF THEN ELSE("% increament on energy bills"=50, setpoint temp-1-dwelling int temp
, IF THEN ELSE("% increament on energy bills"=75, setpoint temp-1.5-dwelling int temp
, setpoint temp-2-dwelling int temp))))
Units: Deg Cent

dwelling int temp=
Dwelling Internal Heat/(65*temperature conversion factor)
Units: Deg Cent

Dwelling Internal Heat= INTEG (

(Artificial heat transfer+Natural heat transfer),

130000)

Units: Watts

dwelling internal temp=

dwelling int temp*1.7

Units: Deg Cent

effect of combined fabric insulation and energy efficiency standard on dwelling energy efficiency

=

IF THEN ELSE(Time<2011, 1+(effect of energy efficiency standard improvement on dwelling energy efficiency

+effect of fabric insulation on energy efficiency

), 1+(effect of energy efficiency standard improvement on dwelling energy efficiency

+effect of fabric insulation on energy efficiency

)+RAMP(0.01,2010,2050))

Units: Dmnl

effect of dwelling energy efficiency on energy bills=

1/effect of combined fabric insulation and energy efficiency standard on dwelling energy efficiency

Units: Dmnl

effect of energy bills on energy consumption=

1-(1/((1+(1/average annual energy bills)*100)+effect of dwelling energy efficiency on energy bills

)-0.9)*(1-(1/(1+"% increament on energy bills"

/normal energy bills)))/effect of unfavourable climatic effects on international energy prices

Units: Dmnl

effect of energy efficiency on hot water energy=

1/effect of combined fabric insulation and energy efficiency standard on dwelling energy efficiency

Units: Dmnl

effect of energy efficiency on space heating=

1/effect of combined fabric insulation and energy efficiency standard on dwelling energy efficiency

Units: Dmnl

effect of energy efficiency standard improvement on dwelling energy efficiency

= WITH LOOKUP (

SAP rating/normal SAP value,

([(0,0)-

(1,1)],(0.18,0),(0.23,0.048),(0.303,0.084),(0.365,0.154),(0.402,0.222

),(0.434,0.312),(0.455,0.407),(0.481,0.544),(0.507645,0.657895),(1,1)))

Units: Dmnl

effect of energy efficiency standard on cooking energy=

IF THEN ELSE(Time<2011, 1/(1+(effect of energy efficiency standard improvement on dwelling energy efficiency

)), 1/(1+(effect of energy efficiency standard improvement on dwelling energy efficiency

)+RAMP(0.01,2010,2050)))

Units: Dmnl

effect of energy efficiency standard on lighting and appliances energy=

IF THEN ELSE(Time<2011, 1/(1+(effect of energy efficiency standard improvement on dwelling energy efficiency

)), 1/(1+(

effect of energy efficiency standard improvement on dwelling energy efficiency
)+RAMP(0.01,2010,2050)))
Units: Dmnl

effect of fabric insulation on energy efficiency= WITH LOOKUP (
insulation factor/normal insulation,
([(0,0)-
(1,1)],(0,0),(0.1,0.058),(0.2,0.162),(0.3,0.248),(0.4,0.305),(0.5
,0.364),(0.6,0.391),(0.7,0.491),(0.75,0.524)))
Units: Dmnl

effect of unfavourable climatic effects on international energy prices=
2*unfavourable climatic effects
Units: Dmnl

energy to carbon conversion for space heating=
Space Heating Energy Consumption*energy to carbon conversion factor
Units: Tonnes/Year

energy to carbon conversion aappliances=
Appliances Energy Consumption*energy to carbon conversion factor
Units: Tonnes/Year

energy to carbon conversion ck=
Cooking Energy Consumption*energy to carbon conversion factor
Units: Tonnes/Year

energy to carbon conversion factor=
0.5246
Units: Dmnl [-1,1,0.01]

energy to carbon conversion hw=
Hot Water Energy Consumption*energy to carbon conversion factor
Units: Tonnes/Year

energy to carbon conversion l=
Lighting Energy Consumption*energy to carbon conversion factor
Units: Tonnes/Year

external air temp:=
GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'B2')
Units: Deg Cent

frame factor=
0.7
Units: Dmnl [0.7,0.8,0.01]
frame factor for windows and doors (fraction of opening that is glazed) (0.7-0.8)

great discomfort=
LOOKUP EXTRAPOLATE(great discomfort lookup , dwelling int temp)
Units: Dmnl

great discomfort lookup(
[(30,33)-(40,43)],(31.1927,33.0877),(32.8746,33.7895),(34.4342,34.886),(35.9939,36.2018),(37.5229,37.4298),(38.7156,38.5702),(39.9388,39.7544))
Units: Dmnl

growth in occupants activity level=
1.25
Units: Dmnl [0,3,0.1]

heat losses=
-40*average household size
Units: Watts

Hot Water Energy Consumption= INTEG (
(rate of hot water energy usage-energy to carbon conversion hw),
initial hot water usage)
Units: MWh

hot water energy consumption for UK housing stock=
Hot Water Energy Consumption*households/10^6
Units: TWh

hot water usage demand=
Occupants Comfort
Units: Dmnl

hot water usage energy:=
GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'J2')
Units: MWh/Year

households=
-3.436e+008+182058*Time+0.067*Population
Units: Households

humidex value=
IF THEN ELSE(dwelling int temp<25
:OR:
relative humidity<50,
MAX(dwelling int temp*2.35,dwelling internal temp),
no discomfort from heat stress

)
Units: Dmnl

hw carbon depletion=
Carbon Emissions due to Hot Water Usage*carbon depletion factor
Units: Tonnes/Year

initial appliances usage=
1.07
Units: MWh

initial appliances usage carbon emissions=
0.375
Units: Tonnes

initial cooking carbon emissions=
0.55
Units: Tonnes

initial cooking energy=
1.36
Units: MWh

initial hot water usage=
6.64
Units: MWh

initial hot water usage carbon emissions=
2.7
Units: Tonnes

initial lighting usage=

0.55

Units: MWh

initial lighting usage carbon emissions=

0.21

Units: Tonnes

initial occupants comfort=

10

Units: com

initial occupants metabolic buildup=

0.9

Units: met

initial population=

5.5632e+007

Units: People

initial space heating carbon emissions=

5.85

Units: Tonnes

initial space heating energy=

13.18

Units: MWh

insulation factor=

0

Units: Watts/Year/Deg Cent [0,100,25]

l carbon depletion=

Carbon Emissions due to Lighting Energy*carbon depletion factor
Units: Tonnes/Year

lighting energy:=
GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'L2')
Units: MWh/Year

Lighting Energy Consumption= INTEG (
(rate of lighting energy usage-energy to carbon conversion l),
initial lighting usage)
Units: MWh

lighting energy consumption for UK housing stock=
Lighting Energy Consumption*households/10^6
Units: TWh

lighting energy demand=
2
Units: Dmnl

mortality=
mortality lookup(average life expectancy/one year)
Units: 1/Year

mortality lookup(
[(20,0)-
(80,0.006)],(20,0.00567),(30,0.00366),(40,0.00243),(50,0.00155),(60
,0.00082),(70,0.00023),(80,0.0001))
Units: 1/Year

Natural heat transfer=
“discrepancy in int & ext temp”*(100-insulation factor)

```
Units: Watts/Year

no discomfort=
        LOOKUP EXTRAPOLATE(no discomfort lookup, dwelling int temp )
Units: Dmnl

no discomfort from heat stress=
        IF THEN ELSE( dwelling int temp<30
:AND:
        relative humidity>25,
no discomfort,
        some discomfort heat stress)
Units: Dmnl

no discomfort lookup(
        [(20,26)-
(25,30)],(0.202446,31.6009),(0.234251,29.2807),(0.292966,26.7588)
,(0.346789,25.2456),(0.449541,23.2281),(0.540061,22.1184),(0.657492,21.0088
),(0.784709,20.5044),(0.899694,20.4035),(0.992661,20.3026),(20.0153,26.0526
),(21.1009,26.3333),(22.0489,26.5439),(22.844,26.7368),(23.578,27.0351),(24.18
96
,27.3333),(25,27.8246))
Units: Dmnl

normal energy bills=
        100
Units: Dmnl

normal insulation=
        100
Units: Dmnl
```

normal SAP value=

100

Units: Dmnl

Occupants activity level=

(Occupants Metabolic Buildup*growth in occupants activity level)

Units: act

occupants behaviour=

2

Units: Dmnl [1,3,1]

Occupants Comfort= INTEG (

Perceived dwelling temp*"discrepancy in int & setpoint temp",

initial occupants comfort)

Units: Dmnl

Occupants Metabolic Buildup= INTEG (

((Perceived dwelling temp/30)/Occupants activity level)*0.05,

initial occupants metabolic buildup)

Units: Dmnl

one year=

1

Units: Year

Perceived dwelling temp=

IF THEN ELSE(humidex value<=(Occupants Comfort+Occupants Metabolic Buildup

)*probability of putting on clothing*probability of window opening

, (Occupants Comfort+Occupants Metabolic Buildup)*probability of putting on clothing

```
*probability of window opening , FORECAST
    (humidex value,200,-100))
Units: Deg Cent

pi=
    3.142
Units: Dmnl

Population= INTEG (
    births-deaths,
        initial population)
Units: People

population equilibrium time=
    2500
Units: Year

probability of putting on clothing=
    IF THEN ELSE(Occupants Metabolic Buildup>0
:AND:
some discomfort heat stress
>0,
            LOOKUP EXTRAPOLATE (putting on clothing lookup,
Occupants Comfort/10), 0)
Units: Dmnl

probability of window opening=
    IF THEN ELSE(Occupants Metabolic Buildup>0
:AND:
some discomfort heat stress
>0,
            LOOKUP EXTRAPOLATE (window opening lookup,
```

Occupants Comfort/100), 0)
Units: Dmnl

putting on clothing lookup(
[(0,0.6)-
(1,1)],(0,1),(0.058104,0.898246),(0.165138,0.814035),(0.284404,0.742105
),(0.425076,0.7),(0.593272,0.670175),(0.761468,0.650877),(0.990826,0.635088
))
Units: Dmnl

rate of appliances energy usage=
appliances energy*effect of energy efficiency standard on lighting and appliances energy
/effect of energy bills on energy consumption
/0.88-0.25*
FORECAST(appliances energy/0.88, 39, 507)

Units: MWh/Year

rate of hot water energy usage=
(hot water usage energy
*effect of energy efficiency on hot water energy/effect of energy bills on energy consumption
/0.88-0.25*FORECAST (hot water usage energy
/1.88, 39, 175))*(0.6*setpoint temp)/dwelling internal temp
)

Units: MWh

rate of lighting energy usage=
lighting energy*effect of energy efficiency standard on lighting and appliances energy

```
/effect of energy bills on energy consumption
        /0.88-0.25*
        FORECAST (lighting energy/0.88, 39, 600)) ,

Units: MWh/Year


rate of space heating=
                        (space heating energy
*effect of energy efficiency on space heating
        /effect of energy bills on energy consumption
        *1.14-0.15*FORECAST (space heating energy
        *0.53,                39, 450))*(0.6*setpoint temp)/dwelling internal temp
) ,
Units: MWh/Year


relative humidity:=
        GET XLS DATA( 'Datasets.xlsx' , 'Datasets' , 'A' , 'D2' )
Units: per cent [0,100,1]


reproductive time=
        90
Units: Year


SAP rating:=
        GET XLS DATA ( 'Datasets.xlsx' , 'Datasets' , 'A' , 'N2' )
Units: Dmnl [0,100,1]


setpoint temp=
        20
Units: Deg Cent [10,30,0.5]


sh carbon depletion=
```

Space Heating Carbon Emissions*carbon depletion factor
Units: Tonnes/Year

solar flux=
150
Units: Dmnl [0,500,1]
solar flux on the applicable surface (solar irradiance)

solar transmittance factor for glazing=
0.76
Units: Dmnl [0.5,0.9,0.01]

some discomfort=
LOOKUP EXTRAPOLATE(some discomfort lookup, dwelling int temp)
Units: Dmnl

some discomfort heat stress=
IF THEN ELSE(dwelling int temp<36
:OR:
relative humidity>50,
some discomfort,
great discomfort)
Units: Dmnl

some discomfort lookup(
[(25,27)-
(30,33)],(25.2905,27.0263),(26.422,27.4211),(27.4159,27.8684),(28.4557
,28.4737),(29.2355,29.0789),(29.9847,29.8947))
Units: Dmnl

Space Heating Carbon Emissions= INTEG (
(energy to carbon conversion-sh carbon depletion)*0.5246,

```
                initial space heating carbon emissions)
Units: Tonnes

space heating demand=
        Occupants Comfort/ one com
Units: Dmnl

space heating energy:=
        GET XLS DATA ( 'Datasets.xlsx' , 'Datasets' , 'A' , 'I2' )
Units: **undefined**

Space Heating Energy Consumption= INTEG (
        (rate of space heating-energy to carbon conversion),
                initial space heating energy)
Units: MWh

space heating energy consumption for UK housing stock=
        Space Heating Energy Consumption*households/10^6
Units: TWh

temperature conversion factor=
        225
Units: Watts/Deg Cent [0,1000,1]

total annual household carbon emissions=
        average annual carbon emissions per household*households/10^6
Units: Million tonnes

total annual household energy consumption=
        average annual energy consumption per household*households/10^6
Units: TWh
```

"total dwelling heat gains (dhg)"=

(dhg due to appliances less cooking+dhg due to artificial lighting+dhg due to cooking
+dhg due to no of people+dhg due to water heating+average effect of solar gains
+heat losses)

Units: Watts

total floor area=

85

Units: **undefined**

unfavourable climatic effects=

SMOOTH((1-(1/average annual carbon emissions per household)), 5)

Units: Dmnl

weighted average energy prices:=

GET XLS DATA ('Datasets.xlsx' , 'Datasets' , 'A' , 'Q2')

Units: **undefined**

window opening lookup(

[(0,0)-
(1,1)],(0,0),(0.0795107,0.258772),(0.198777,0.495614),(0.40367,0.75
),(0.617737,0.890351),(0.801223,0.960526),(1,1))

Units: **undefined**

APPENDIX B
Baseline Scenario

Table B.1: Baseline Household Energy Consumption (TWh)

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
1970	247.54	124.71	25.54	10.33	20.10
1971	251.94	124.45	25.51	10.46	20.62
1972	244.24	124.89	25.37	10.66	21.61
1973	244.59	124.38	25.19	10.93	22.97
1974	252.12	123.99	25.06	11.22	24.67
1975	257.69	123.57	24.94	11.52	26.59
1976	254.39	122.74	24.79	11.83	28.40
1977	248.98	122.95	24.58	12.15	29.99
1978	253.92	122.98	24.36	12.46	31.37
1979	262.15	121.78	24.10	12.72	32.66
1980	284.08	120.88	23.84	13.02	33.84
1981	284.70	119.29	23.51	13.32	34.97
1982	283.88	118.27	23.15	13.58	36.13
1983	280.52	117.06	22.77	13.85	37.32
1984	277.80	115.53	22.31	14.08	38.58
1985	269.80	113.66	21.78	14.29	39.98
1986	290.58	112.90	21.31	14.54	41.72
1987	309.69	112.73	20.74	14.76	43.46
1988	318.24	110.91	20.13	14.96	45.20
1989	315.37	109.53	19.51	15.15	46.66
1990	300.92	108.20	18.88	15.29	47.93
1991	297.64	106.92	18.12	15.40	48.89
1992	321.25	105.65	17.51	15.55	49.70
1993	328.89	104.29	17.03	15.68	50.50
1994	341.94	103.20	16.67	15.85	51.28
1995	338.86	101.95	16.36	16.00	51.96
1996	330.04	100.77	16.10	16.13	52.46
1997	360.09	99.78	15.90	16.30	53.00
1998	353.88	98.85	15.75	16.50	53.56
1999	359.33	98.25	15.62	16.65	54.18
2000	362.70	97.02	15.52	16.84	54.77
2001	368.84	96.26	15.42	17.04	55.29
2002	380.81	94.99	15.34	17.25	55.84
2003	379.56	94.23	15.43	17.45	56.74
2004	382.72	93.86	15.48	17.44	57.87
2005	389.48	93.54	15.52	17.37	59.32
2006	383.08	92.46	15.48	17.17	60.82
2007	372.20	91.32	15.46	17.18	62.55
2008	356.90	89.82	15.38	17.11	63.65
2009	356.29	87.65	15.08	16.91	63.90

Table B.1: *Continued.*

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
2010	339.89	84.85	14.02	16.10	64.57
2011	367.04	82.69	13.48	15.77	65.14
2012	320.58	81.25	11.95	15.67	65.65
2013	299.39	80.86	11.22	15.68	66.15
2014	290.28	80.97	10.86	14.81	67.28
2015	286.96	81.33	10.69	14.35	67.45
2016	285.51	81.40	10.61	14.09	67.17
2017	283.53	81.08	10.56	13.92	66.68
2018	281.35	80.58	10.54	13.80	66.10
2019	279.11	80.01	10.53	13.71	65.49
2020	276.88	79.41	10.52	13.62	64.87
2021	274.69	78.81	10.52	13.54	64.25
2022	272.54	78.21	10.51	13.46	63.64
2023	270.44	77.62	10.51	13.39	63.05
2024	268.39	77.04	10.50	13.31	62.46
2025	266.38	76.46	10.50	13.24	61.89
2026	264.41	75.90	10.50	13.16	61.33
2027	262.47	75.34	10.49	13.09	60.78
2028	260.57	74.78	10.49	13.01	60.24
2029	258.70	74.24	10.49	12.94	59.71
2030	256.86	73.70	10.48	12.86	59.19
2031	255.05	73.16	10.48	12.79	58.69
2032	253.26	72.63	10.47	12.72	58.19
2033	251.50	72.10	10.47	12.64	57.70
2034	249.76	71.58	10.47	12.57	57.21
2035	248.04	71.06	10.46	12.50	56.74
2036	246.34	70.55	10.46	12.43	56.28
2037	244.66	70.04	10.46	12.35	55.82
2038	243.01	69.53	10.45	12.28	55.37
2039	241.37	69.03	10.45	12.21	54.92
2040	239.75	68.53	10.44	12.14	54.49
2041	238.15	68.03	10.44	12.07	54.05
2042	236.57	67.54	10.44	12.00	53.63
2043	235.01	67.05	10.43	11.93	53.21
2044	233.46	66.56	10.43	11.86	52.80
2045	231.93	66.08	10.42	11.79	52.39
2046	230.42	65.60	10.42	11.72	51.99
2047	228.93	65.13	10.42	11.65	51.59
2048	227.45	64.66	10.41	11.58	51.20
2049	225.99	64.19	10.41	11.51	50.81
2050	224.55	63.73	10.40	11.44	50.43

Table B.2: Baseline Household Carbon Emissions (Million Tonnes of CO2)

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
1970	109.87	3.94	10.33	3.94	7.04
1971	102.66	4.09	10.28	4.09	7.76
1972	100.65	4.17	10.26	4.17	8.12
1973	96.85	4.25	10.21	4.25	8.51
1974	94.72	4.35	10.14	4.35	9.00
1975	95.09	4.46	10.09	4.46	9.63
1976	95.65	4.57	10.04	4.57	10.35
1977	93.79	4.70	9.98	4.70	11.08
1978	90.59	4.82	9.90	4.82	11.74
1979	89.81	4.95	9.81	4.95	12.33
1980	90.69	5.06	9.71	5.06	12.87
1981	95.85	5.17	9.61	5.17	13.36
1982	96.40	5.29	9.49	5.29	13.82
1983	95.10	5.40	9.35	5.40	14.29
1984	92.52	5.51	9.20	5.51	14.76
1985	89.69	5.61	9.02	5.61	15.25
1986	85.30	5.69	8.82	5.69	15.79
1987	88.41	5.79	8.63	5.79	16.44
1988	93.33	5.88	8.41	5.88	17.12
1989	95.86	5.96	8.17	5.96	17.81
1990	94.47	6.04	7.93	6.04	18.43
1991	88.63	6.10	7.68	6.10	18.97
1992	84.51	6.15	7.39	6.15	19.40
1993	88.36	6.20	7.13	6.20	19.76
1994	90.21	6.26	6.92	6.26	20.09
1995	92.92	6.32	6.75	6.32	20.40
1996	91.40	6.38	6.61	6.38	20.69
1997	86.97	6.44	6.50	6.44	20.91
1998	92.41	6.50	6.41	6.50	21.13
1999	90.80	6.57	6.34	6.57	21.35
2000	90.24	6.64	6.28	6.64	21.59
2001	89.41	6.71	6.23	6.71	21.82
2002	89.24	6.79	6.19	6.79	22.04
2003	90.87	6.87	6.16	6.87	22.26
2004	89.36	6.95	6.17	6.95	22.57
2005	88.10	6.97	6.19	6.97	22.98
2006	87.88	6.96	6.20	6.96	23.51
2007	84.32	6.90	6.20	6.90	24.08
2008	78.48	6.88	6.19	6.88	24.74
2009	70.68	6.86	6.17	6.86	25.25

Table B.2: *Continued.*

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
2010	66.34	6.79	6.07	6.79	25.47
2011	58.66	6.55	5.75	6.55	25.72
2012	78.69	6.38	5.50	6.38	25.95
2013	57.58	6.30	5.00	6.30	26.17
2014	59.64	6.28	4.65	6.28	26.37
2015	55.94	6.03	4.44	6.03	26.75
2016	56.10	5.83	4.33	5.83	26.91
2017	55.26	5.69	4.27	5.69	26.88
2018	54.66	5.61	4.24	5.61	26.73
2019	53.90	5.55	4.22	5.55	26.53
2020	53.19	5.50	4.21	5.50	26.29
2021	52.45	5.46	4.21	5.46	26.05
2022	51.73	5.43	4.21	5.43	25.80
2023	51.01	5.40	4.20	5.40	25.55
2024	50.30	5.37	4.20	5.37	25.31
2025	49.59	5.33	4.20	5.33	25.07
2026	48.89	5.30	4.20	5.30	24.84
2027	48.19	5.27	4.20	5.27	24.61
2028	47.49	5.24	4.19	5.24	24.39
2029	46.80	5.21	4.19	5.21	24.17
2030	46.11	5.18	4.19	5.18	23.96
2031	45.42	5.15	4.19	5.15	23.75
2032	44.74	5.12	4.19	5.12	23.54
2033	44.05	5.09	4.19	5.09	23.34
2034	43.37	5.06	4.18	5.06	23.14
2035	42.68	5.04	4.18	5.04	22.94
2036	42.00	5.01	4.18	5.01	22.75
2037	41.32	4.98	4.18	4.98	22.56
2038	40.64	4.95	4.18	4.95	22.38
2039	39.96	4.92	4.18	4.92	22.20
2040	39.28	4.89	4.17	4.89	22.02
2041	38.59	4.86	4.17	4.86	21.84
2042	37.91	4.83	4.17	4.83	21.67
2043	37.23	4.80	4.17	4.80	21.49
2044	36.55	4.78	4.17	4.78	21.32
2045	35.87	4.75	4.17	4.75	21.16
2046	35.19	4.72	4.16	4.72	20.99
2047	34.51	4.69	4.16	4.69	20.83
2048	33.82	4.66	4.16	4.66	20.67
2049	33.14	4.63	4.16	4.63	20.51
2050	32.46	4.61	4.16	4.61	20.35

APPENDIX C

Illustrative Scenarios

C1: Household Energy Consumption by End-Use for the 'Baseline' and 'Efficiency' Scenarios

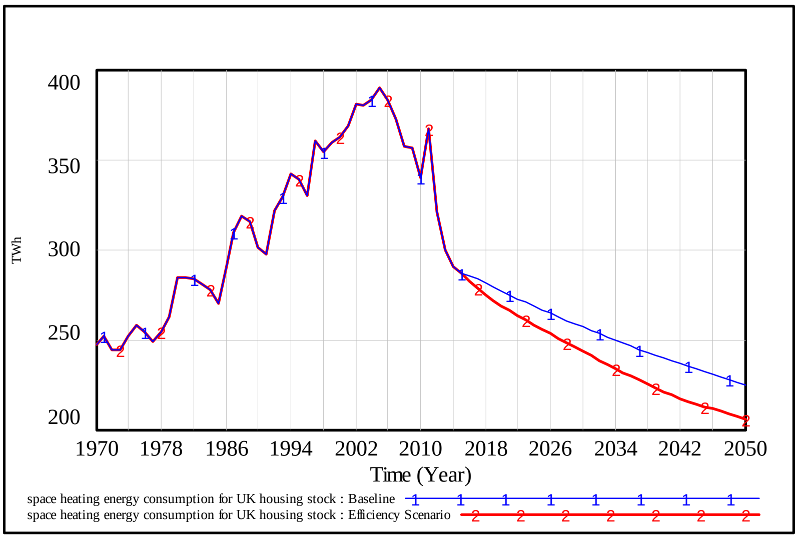

Figure C.1: Space heating energy consumption for the 'baseline' and 'efficiency' scenarios

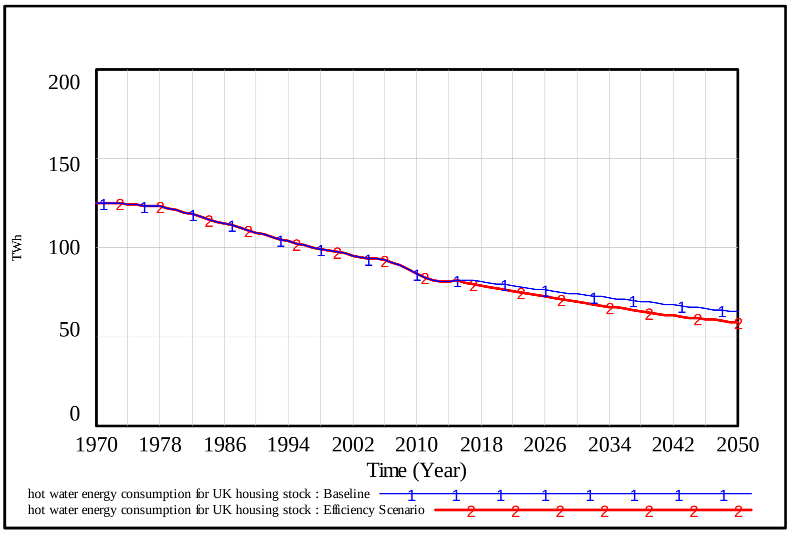

Figure C.2: Hot water energy consumption for the 'baseline' and 'efficiency' scenarios

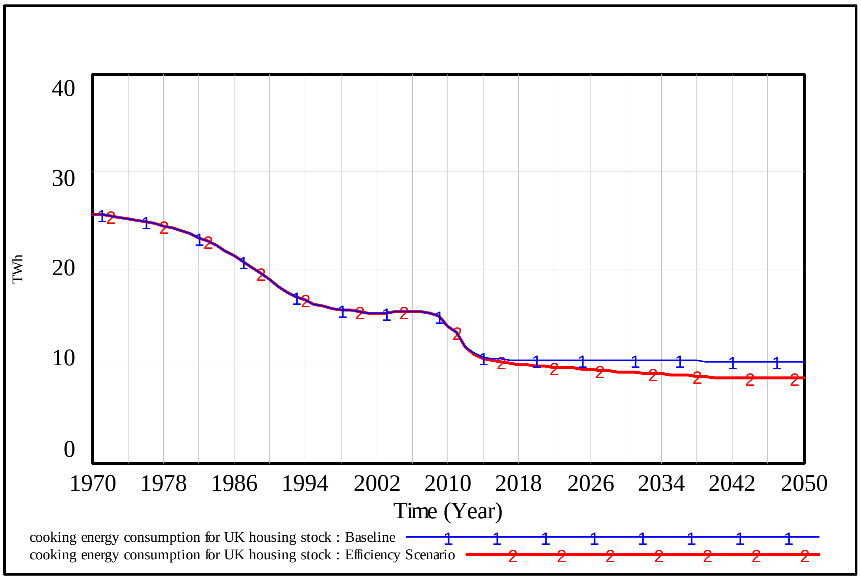

Figure C.3: Cooking energy consumption for the ‘baseline’ and ‘efficiency’ scenarios

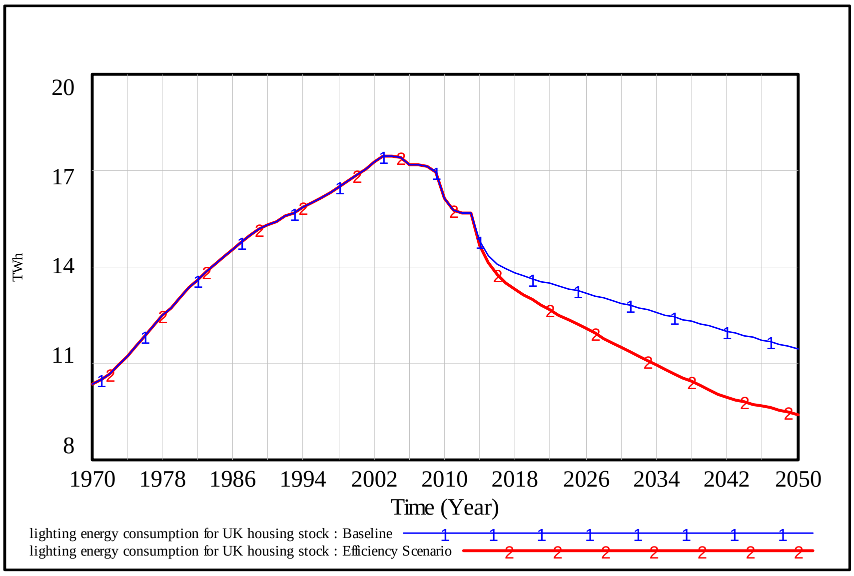

Figure C.4: Lighting energy consumption for the ‘baseline’ and ‘efficiency’ scenarios

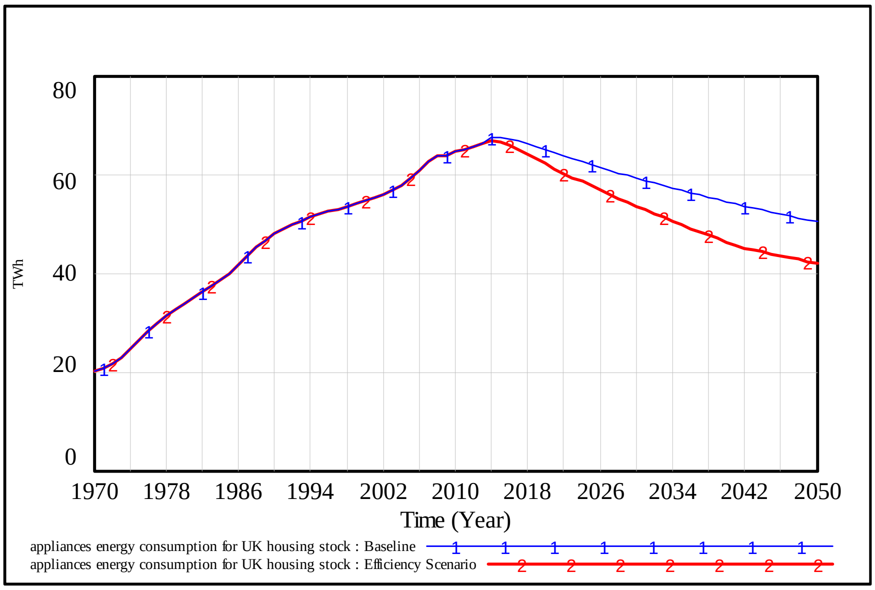

Figure C.5: Appliances energy consumption for the ‘baseline’ and ‘efficiency’ scenarios

C2: Household Carbon Emissions by End-Use for the 'Baseline' and 'Efficiency' Scenarios

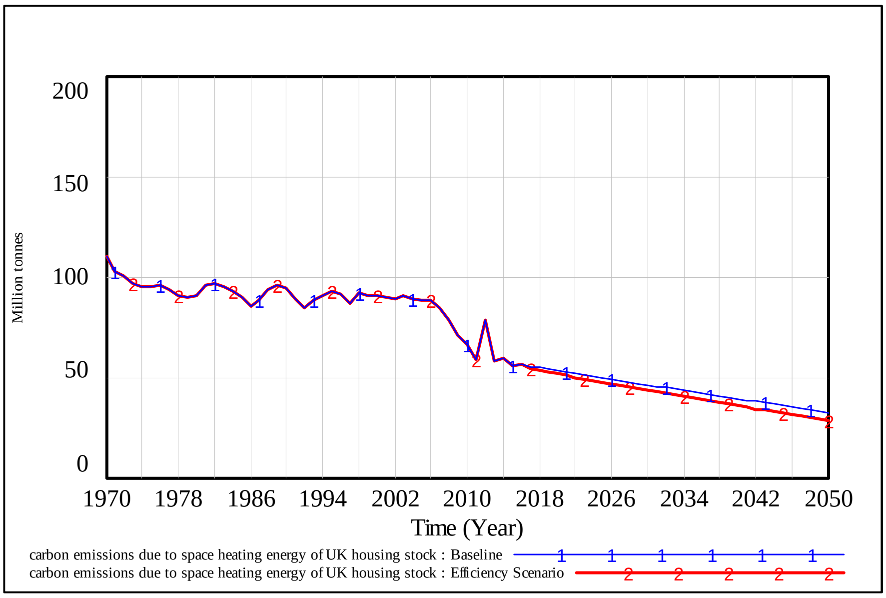

Figure C.6: Carbon emissions due to space heating for the 'baseline' and 'efficiency' scenarios

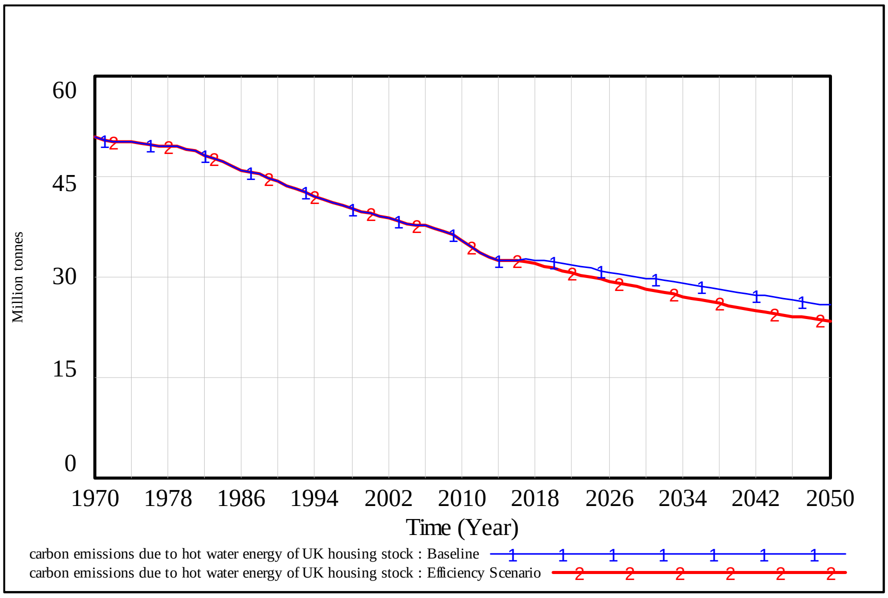

Figure C.7: Carbon emissions due to hot water for the 'baseline' and 'efficiency' scenarios

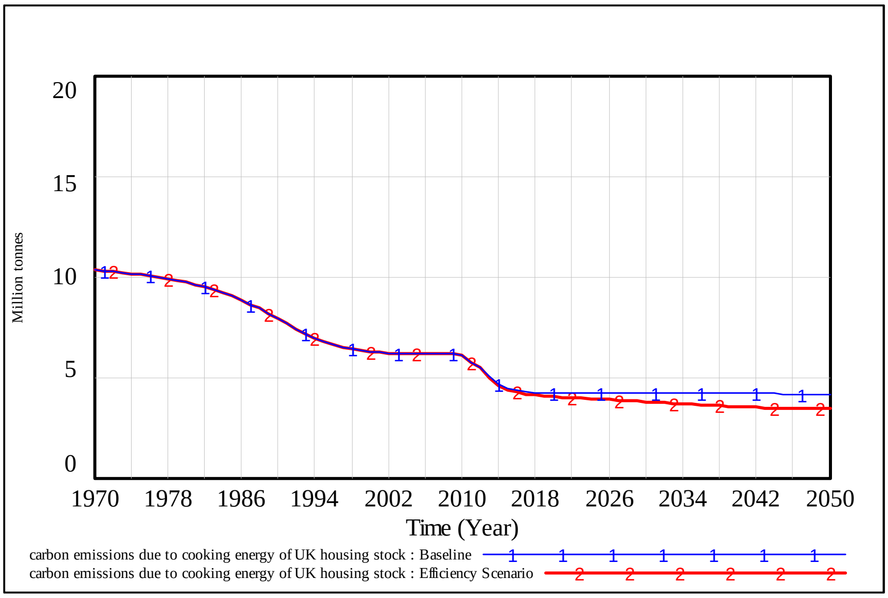

Figure C.8: Carbon emissions due to cooking for the 'baseline' and 'efficiency' scenarios

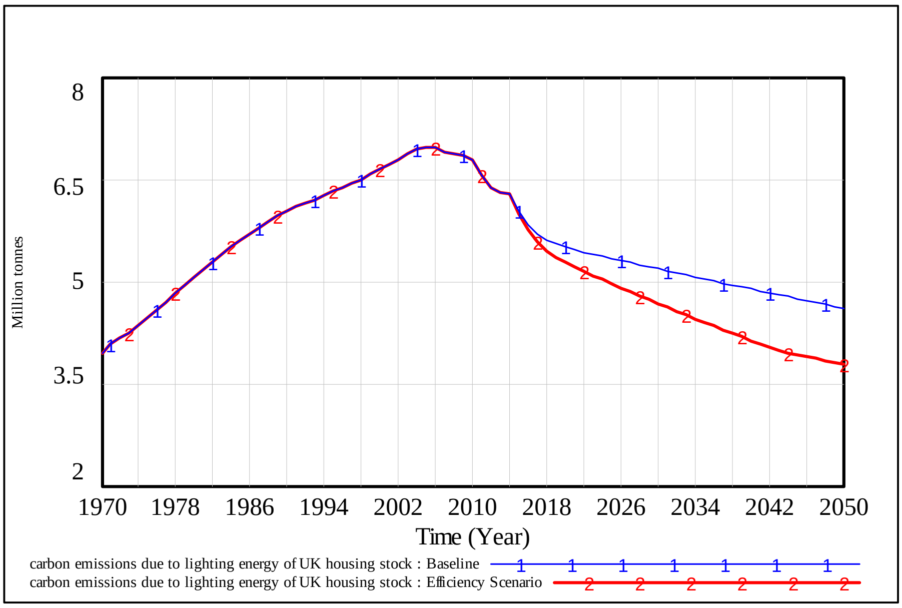

Figure C.9: Carbon emissions due to lighting for the 'baseline' and 'efficiency' scenarios

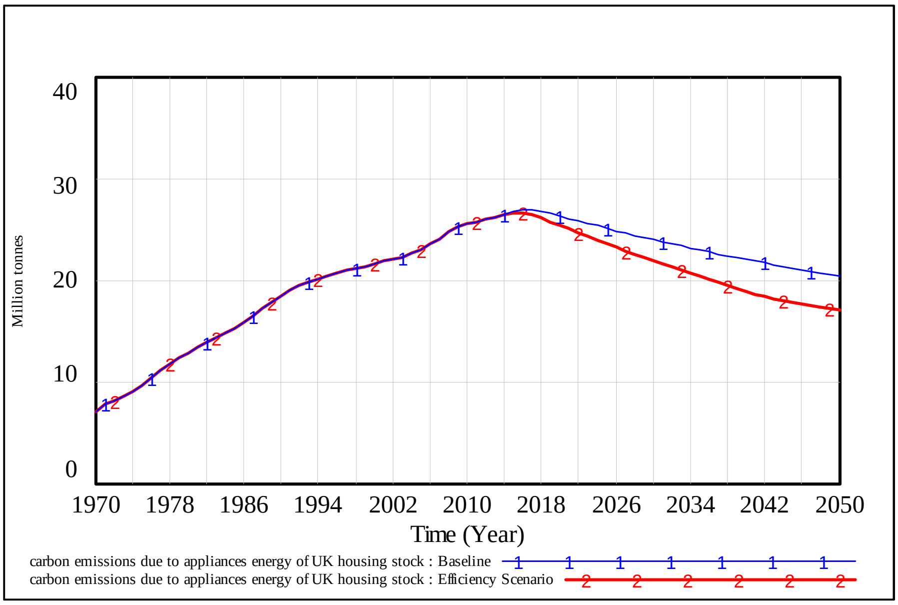

Figure C.10: Carbon emissions due to appliances for the 'baseline' and 'efficiency' scenarios

C3: Household Energy Consumption by End-Use for the ‘Baseline’ and ‘Behavioural Change’ Scenarios

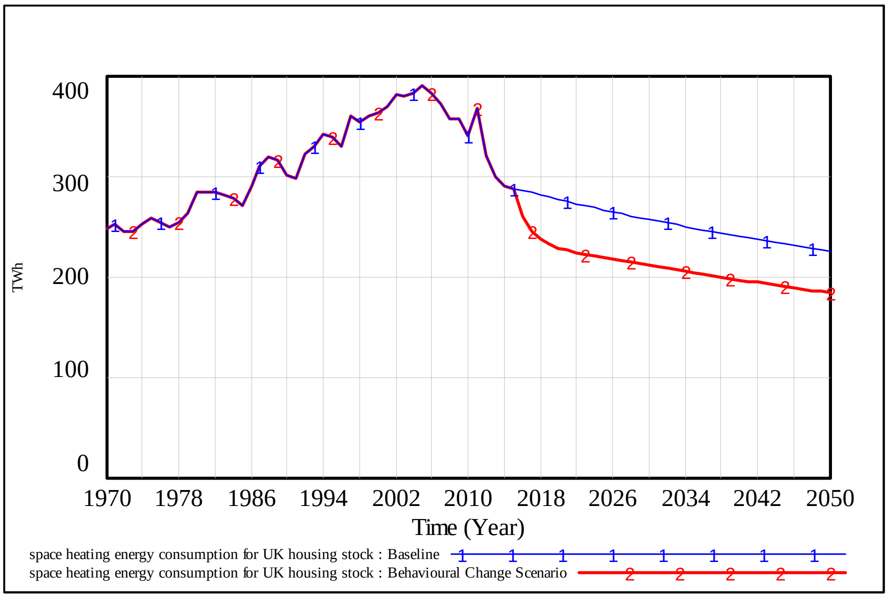

Figure C.11: Space heating energy consumption for the ‘baseline’ and ‘behavioural change’ scenarios

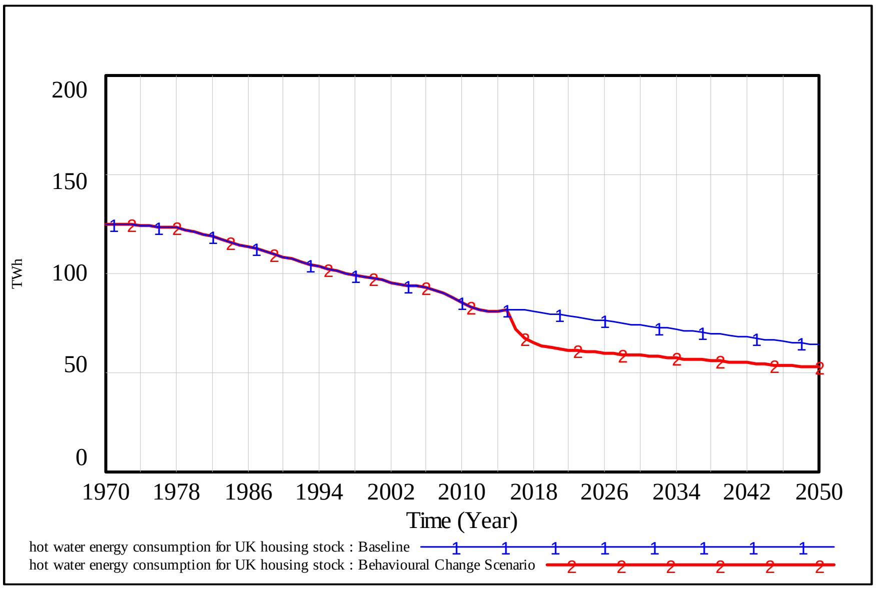

Figure C.12: Hot water energy consumption for the ‘baseline’ and ‘behavioural change’ scenarios

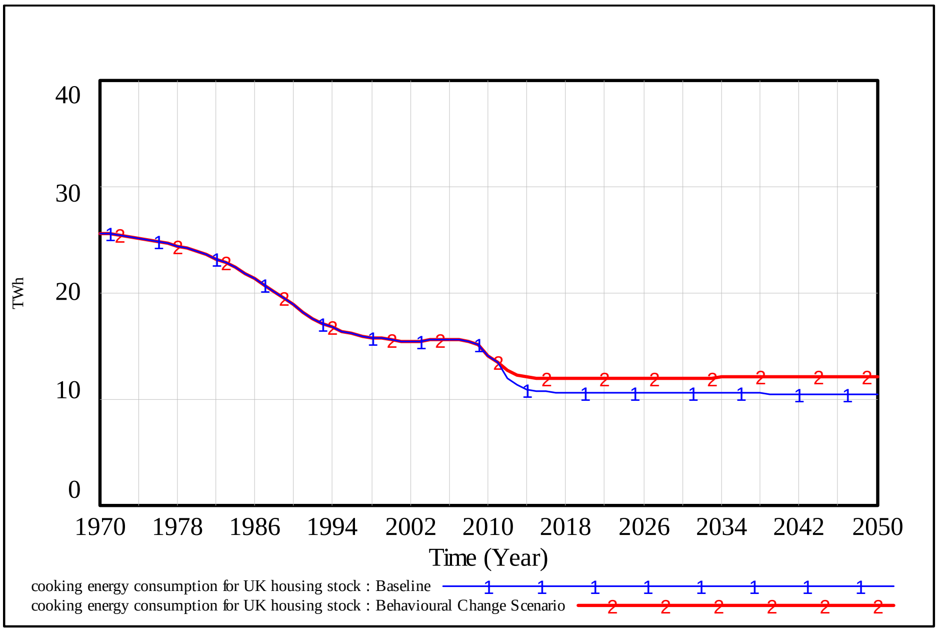

Figure C.13: Cooking energy consumption for the 'baseline' and 'behavioural change' scenarios

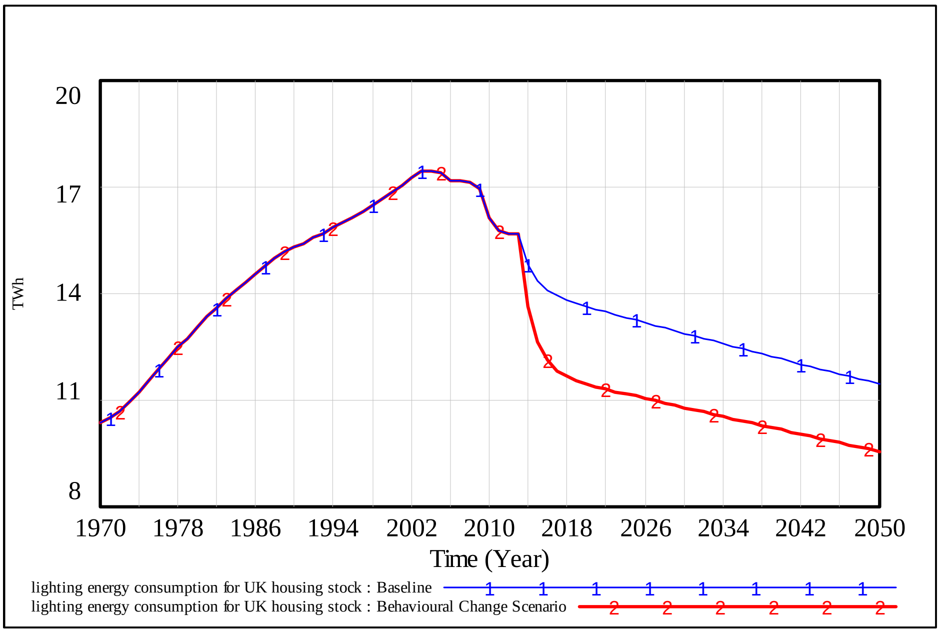

Figure C.14: Lighting energy consumption for the 'baseline' and 'behavioural change' scenarios

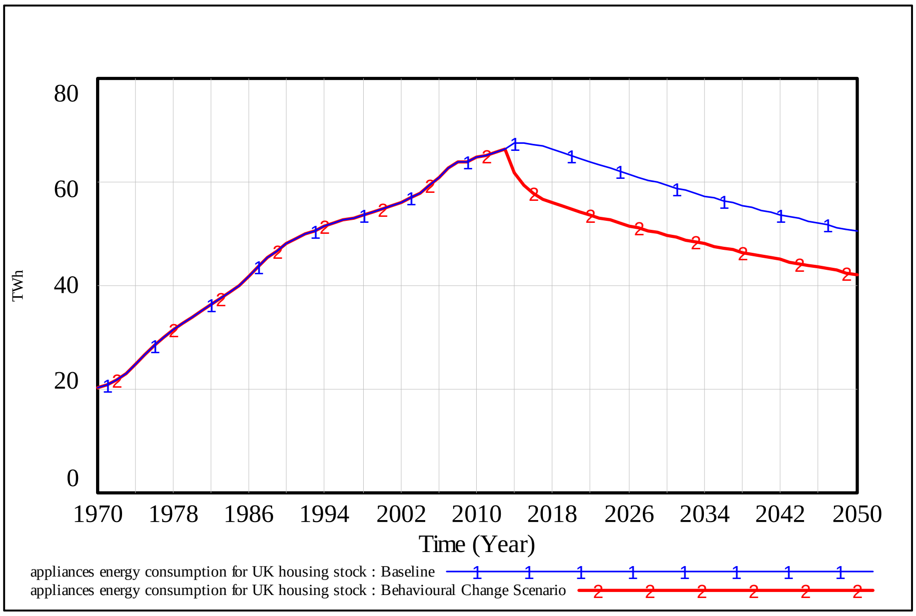

Figure C.15: Appliances energy consumption for the 'baseline' and 'behavioural change' scenarios

C4: Household Carbon Emissions by End-Use for the 'Baseline' and 'Behavioural Change' Scenarios

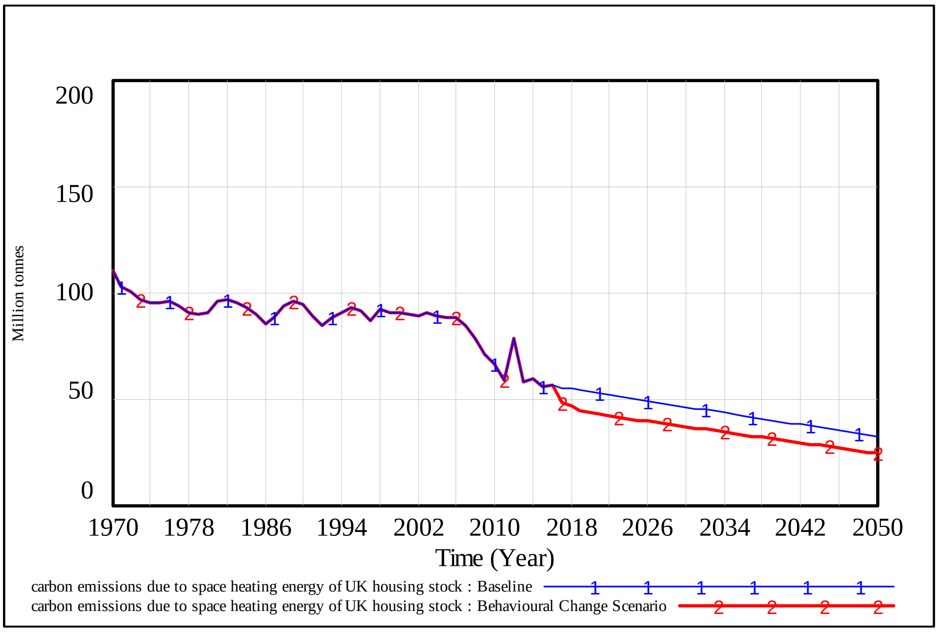

Figure C.16: Carbon emissions due to space heating for the 'baseline' and 'behavioural change' scenarios

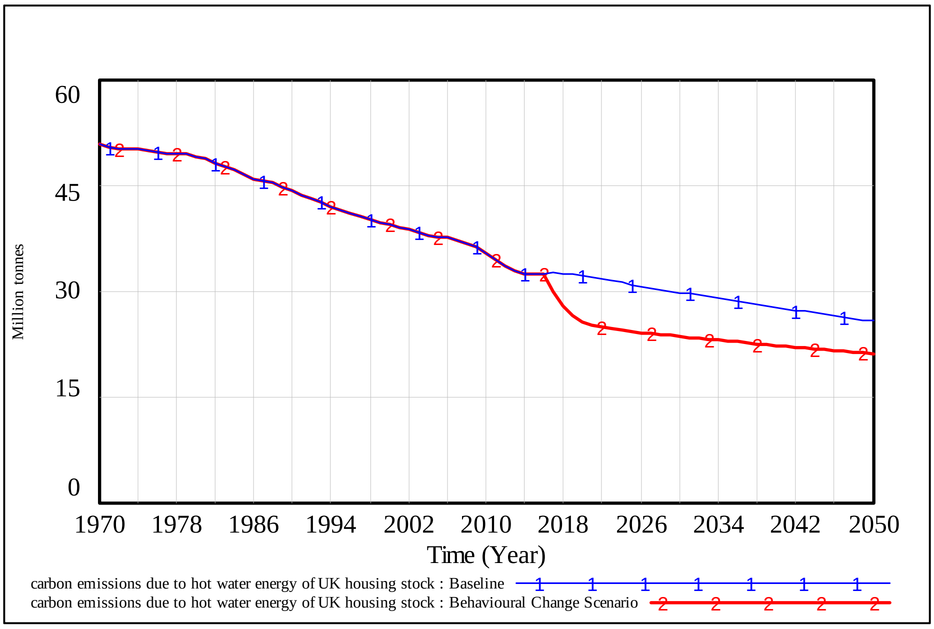

Figure C.17: Carbon emissions due to hot water for the 'baseline' and 'behavioural change' scenarios

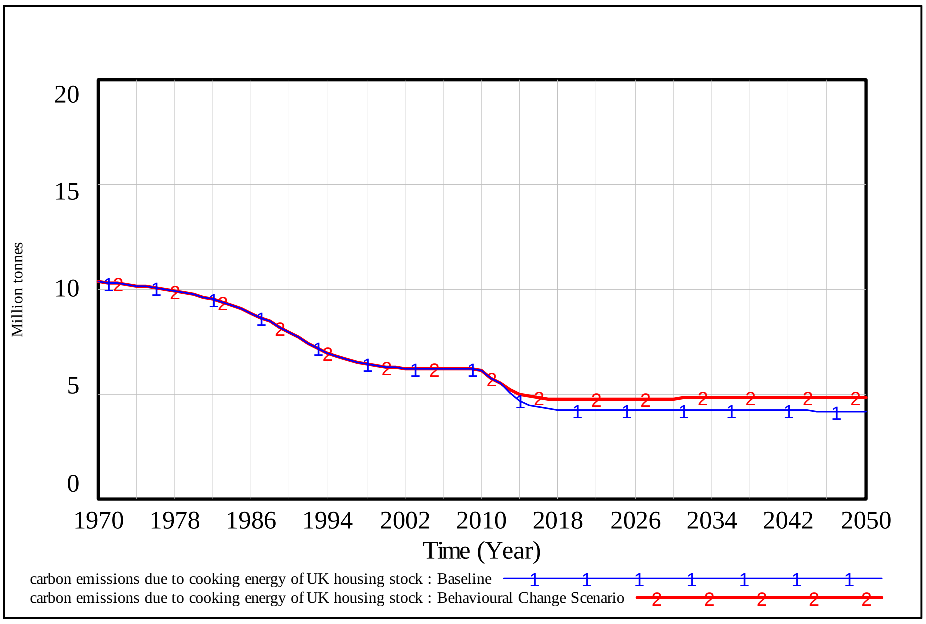

Figure C.18: Carbon emissions due to cooking for the ‘baseline’ and ‘behavioural change’ scenarios

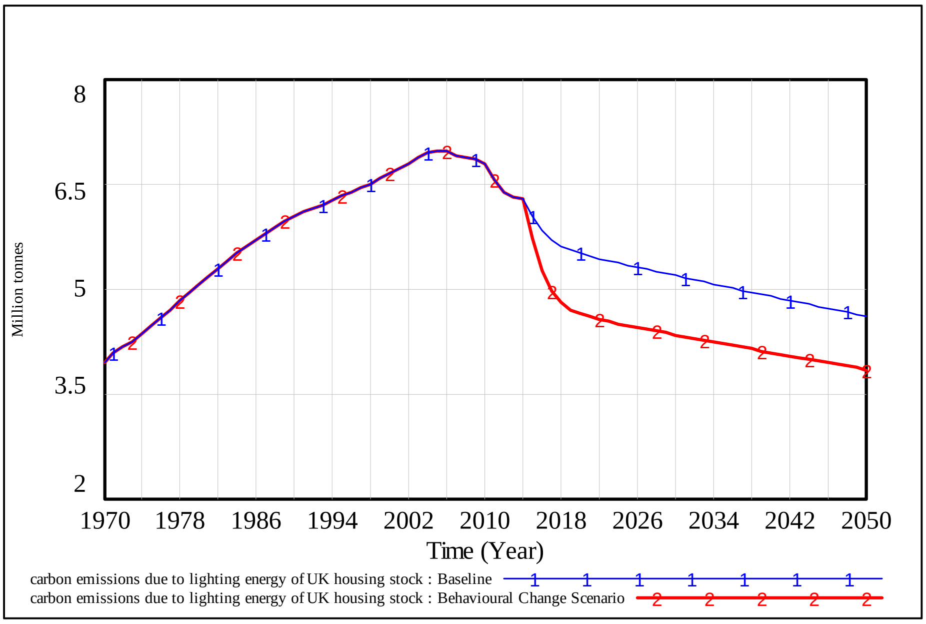

Figure C.19: Carbon emissions due to lighting for the ‘baseline’ and ‘behavioural change’ scenarios

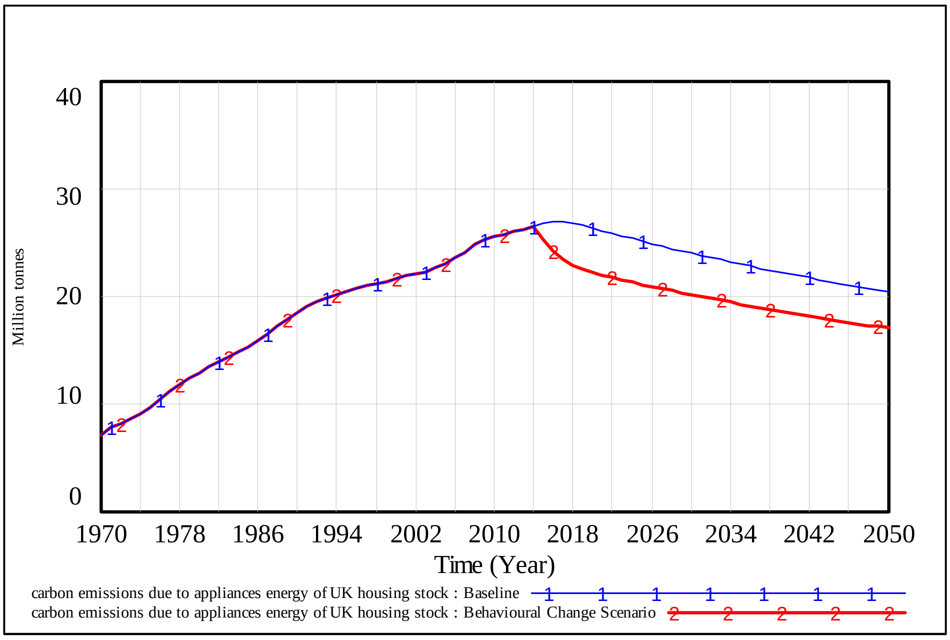

Figure C.20: Carbon emissions due to appliances for the ‘baseline’ and ‘behavioural change’ scenarios

C5: Household Energy Consumption by End-Use for the ‘Baseline’ and ‘Economic’ Scenarios

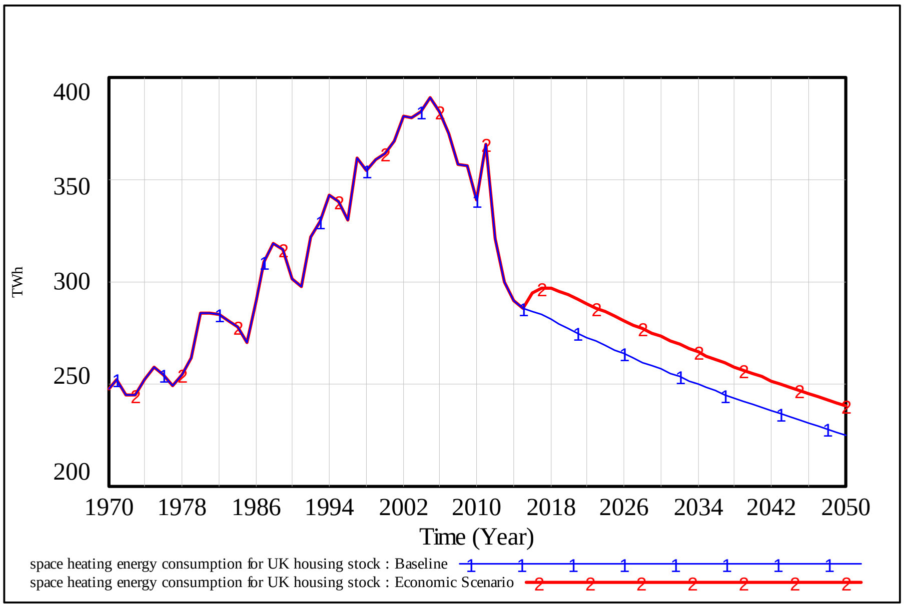

Figure C.21: Space heating energy consumption for the ‘baseline’ and ‘economic’ scenarios

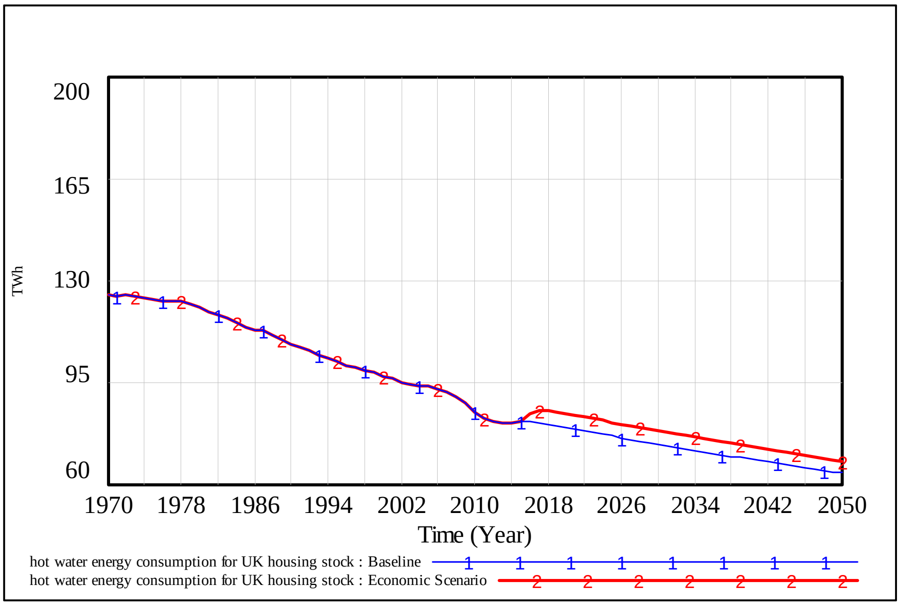

Figure C.22: Hot water energy consumption for the ‘baseline’ and ‘economic’ scenarios

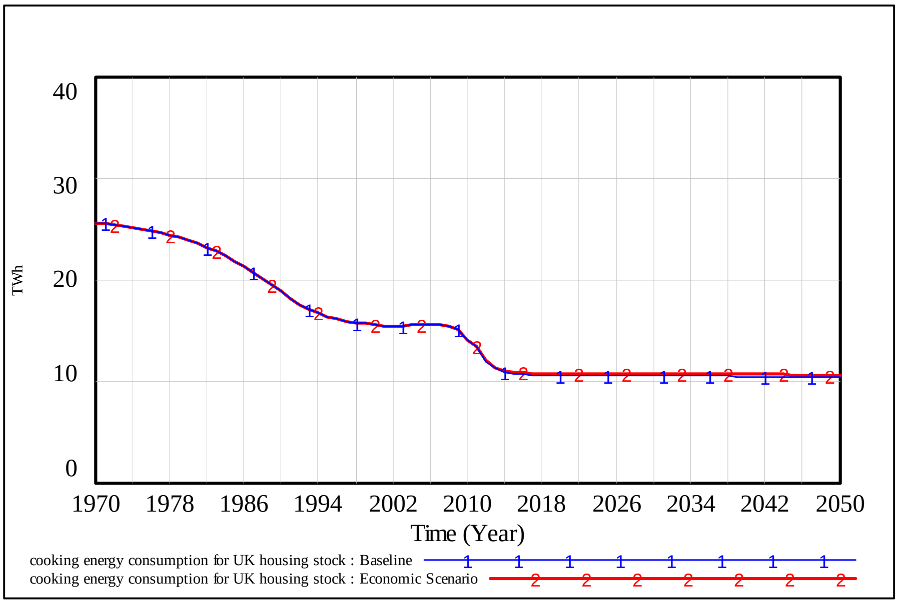

Figure C.23: Cooking energy consumption for the ‘baseline’ and ‘economic’ scenarios

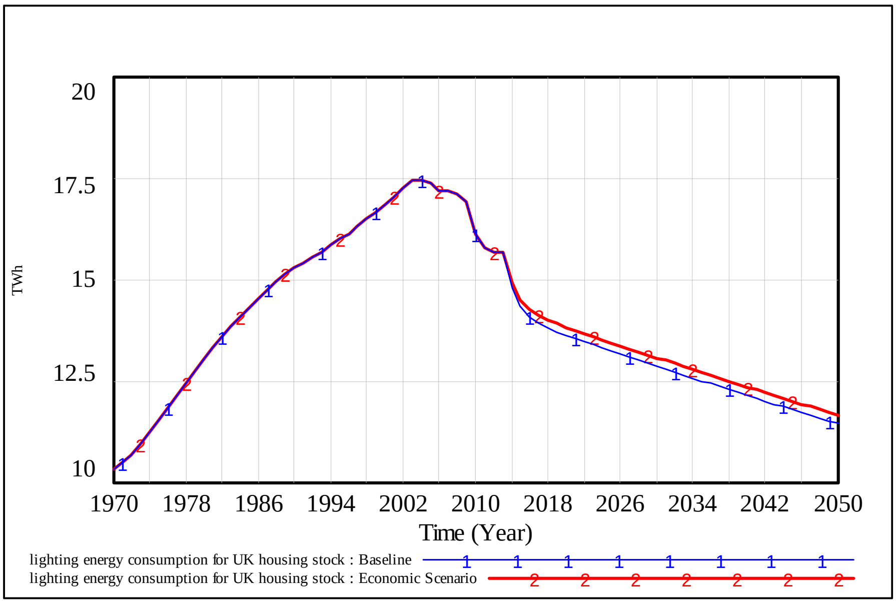

Figure C.24: Lighting energy consumption for the ‘baseline’ and ‘economic’ scenarios

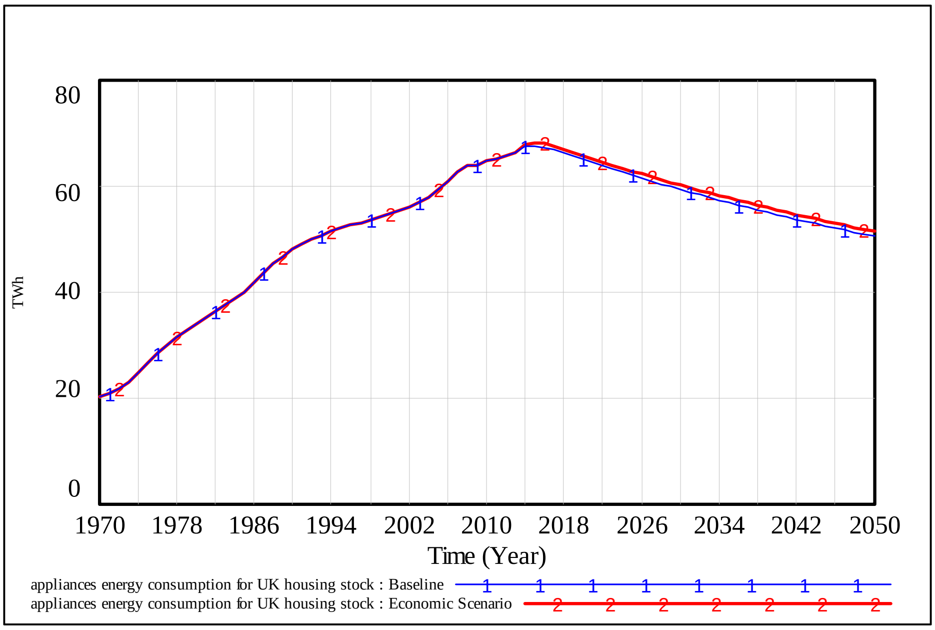

Figure C.25: Appliances energy consumption for the 'baseline' and 'economic' scenarios

C6: Household Carbon Emissions by End-Use for the 'Baseline' and 'Economic' Scenarios

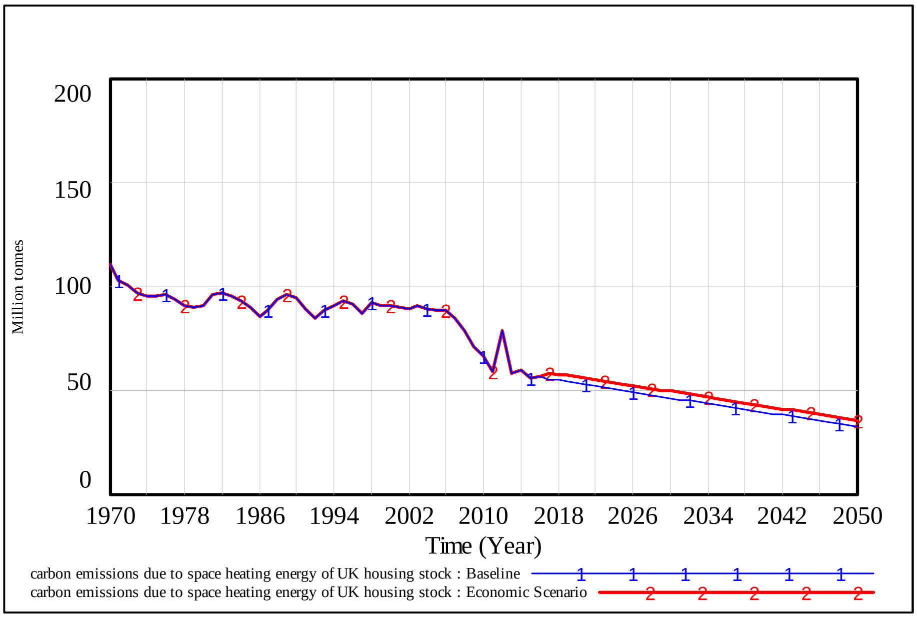

Figure C.26: Carbon emissions due to space heating for the 'baseline' and 'economic' scenarios

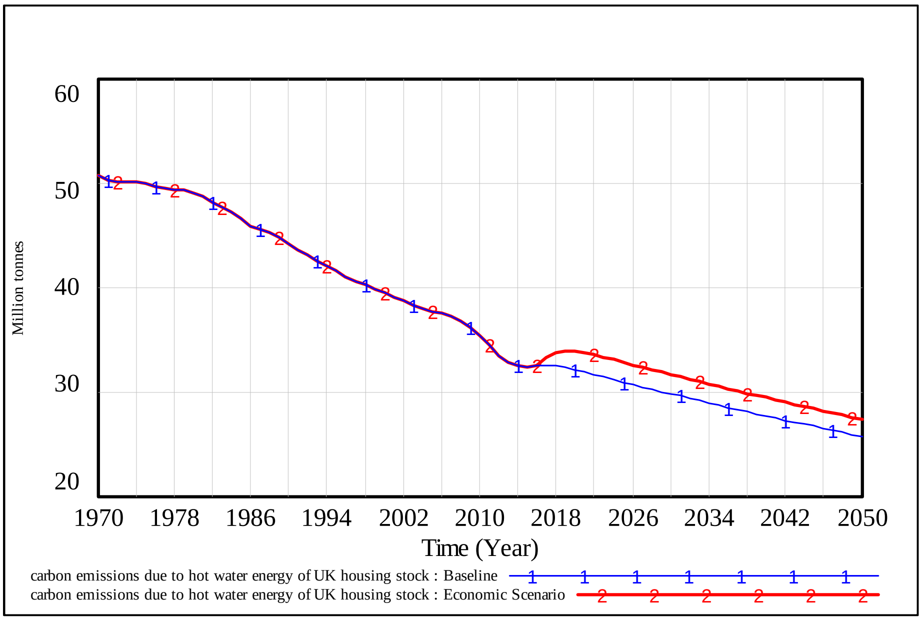

Figure C.27: Carbon emissions due to hot water for the 'baseline' and 'economic' scenarios

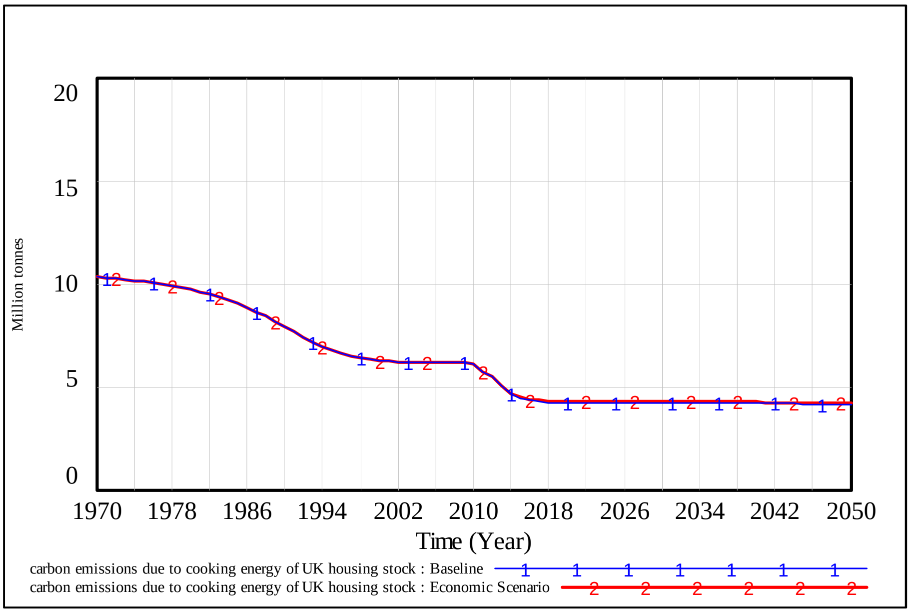

Figure C.28: Carbon emissions due to cooking for the ‘baseline’ and ‘economic’ scenarios

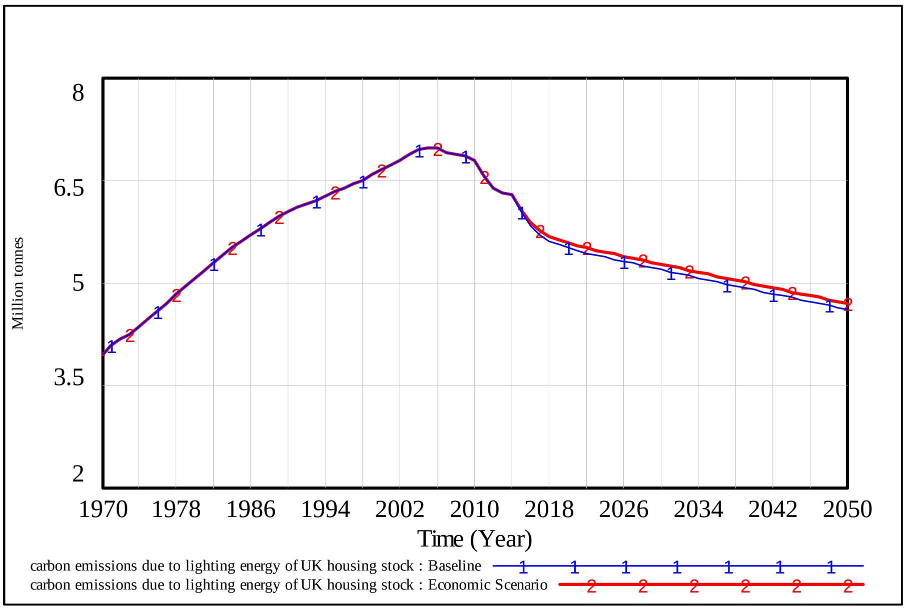

Figure C.29: Carbon emissions due to lighting for the ‘baseline’ and ‘economic’ scenarios

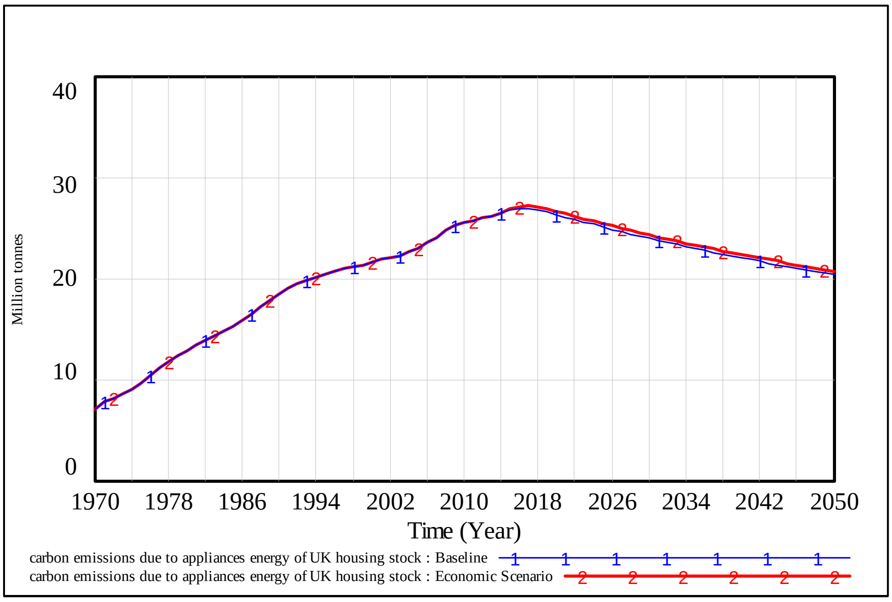

Figure C.30: Carbon emissions due to appliances for the ‘baseline’ and ‘economic’ scenarios

C7: Household Energy Consumption by End-Use for the 'Baseline' and 'Integrated' Scenarios

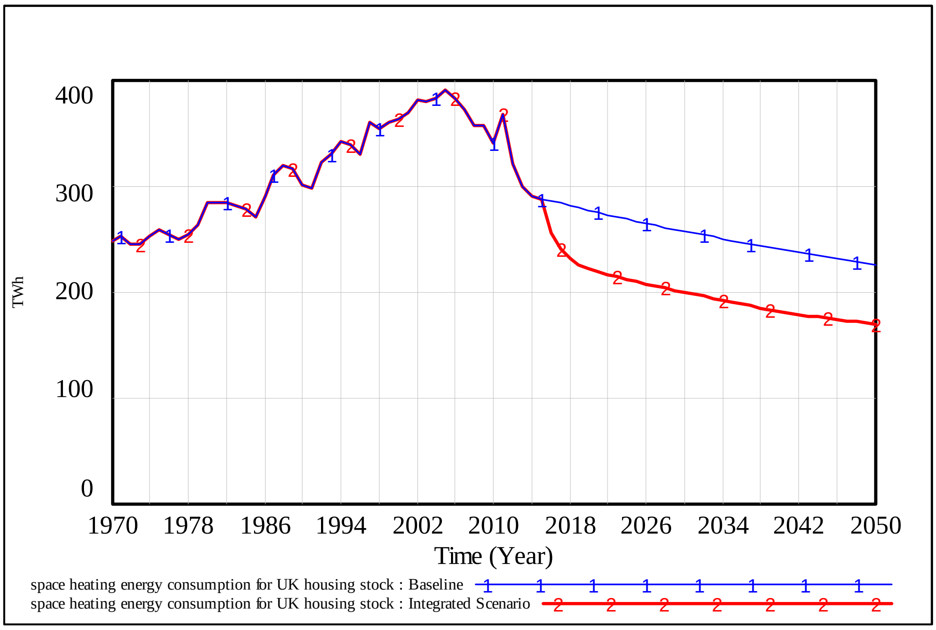

Figure C.31: Space heating energy consumption for the 'baseline' and 'integrated' scenarios

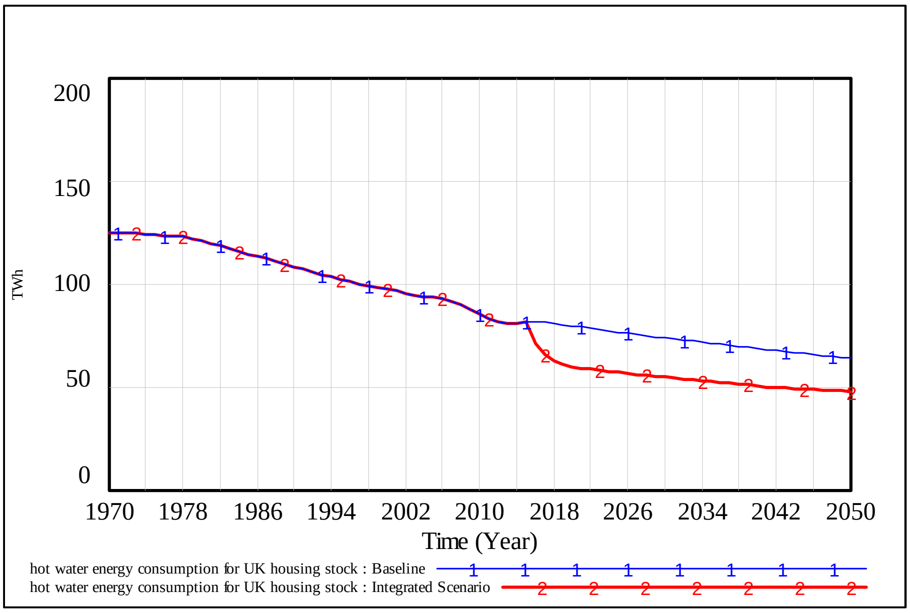

Figure C.32: Hot water energy consumption for the 'baseline' and 'integrated' scenarios

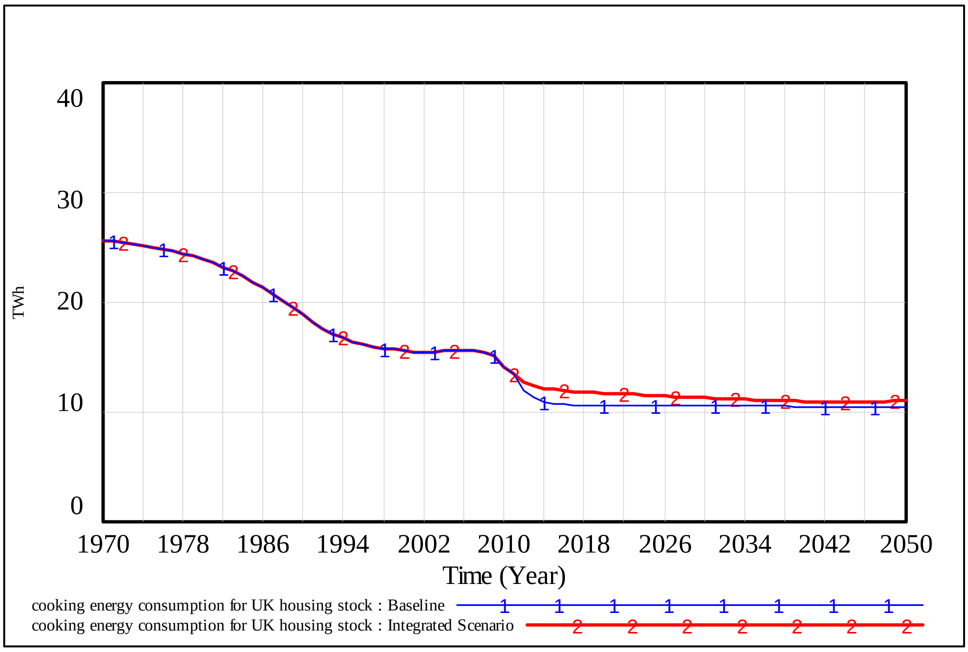

Figure C.33: Cooking energy consumption for the ‘baseline’ and ‘integrated’ scenarios

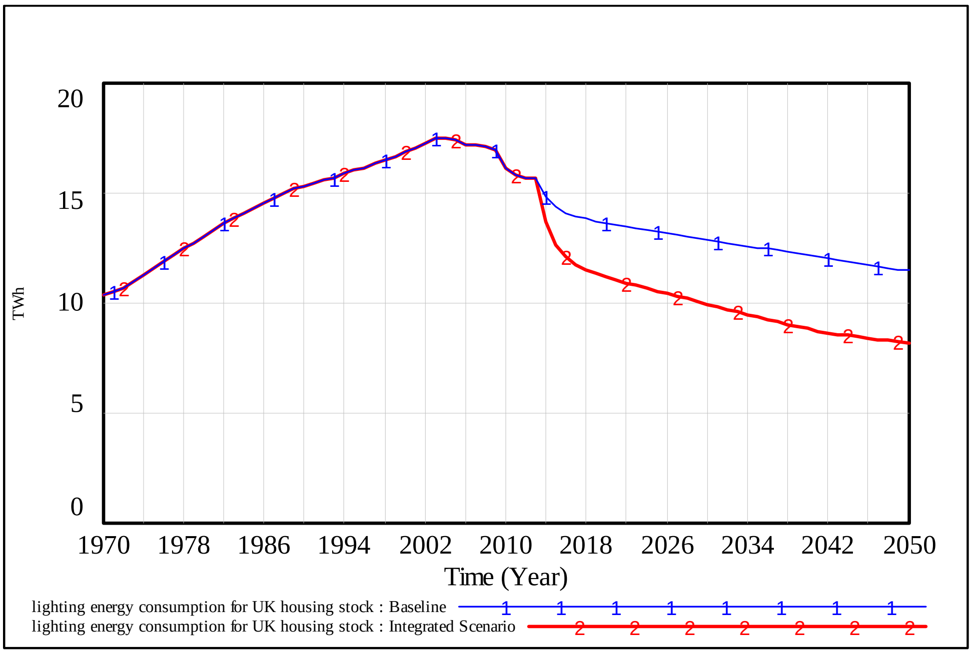

Figure C.34: Lighting energy consumption for the ‘baseline’ and ‘integrated’ scenarios

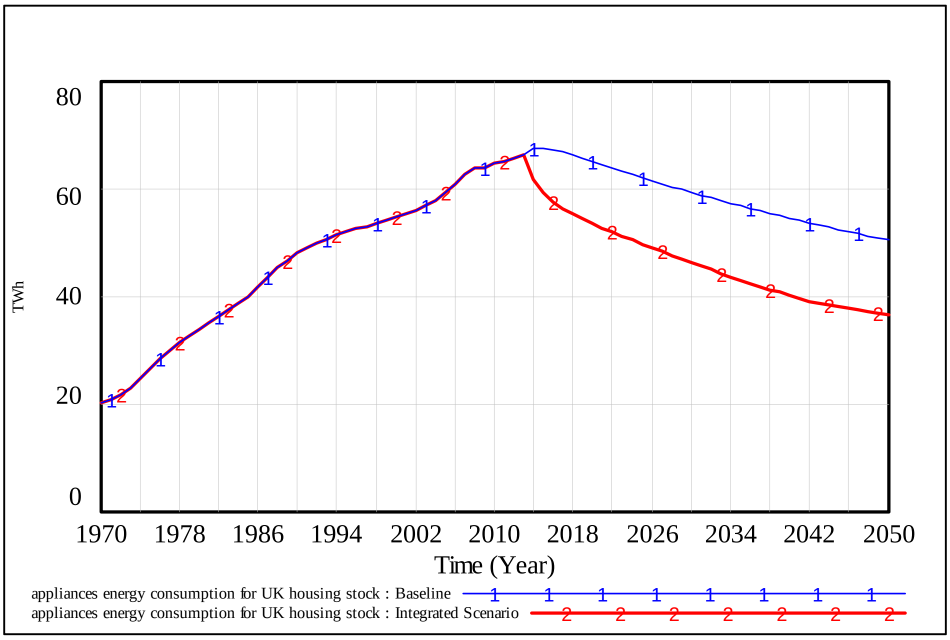

Figure C.35: Appliances energy consumption for the 'baseline' and 'integrated' scenarios

C8: Household Carbon Emissions by End-Use for the 'Baseline' and 'Integrated' Scenarios

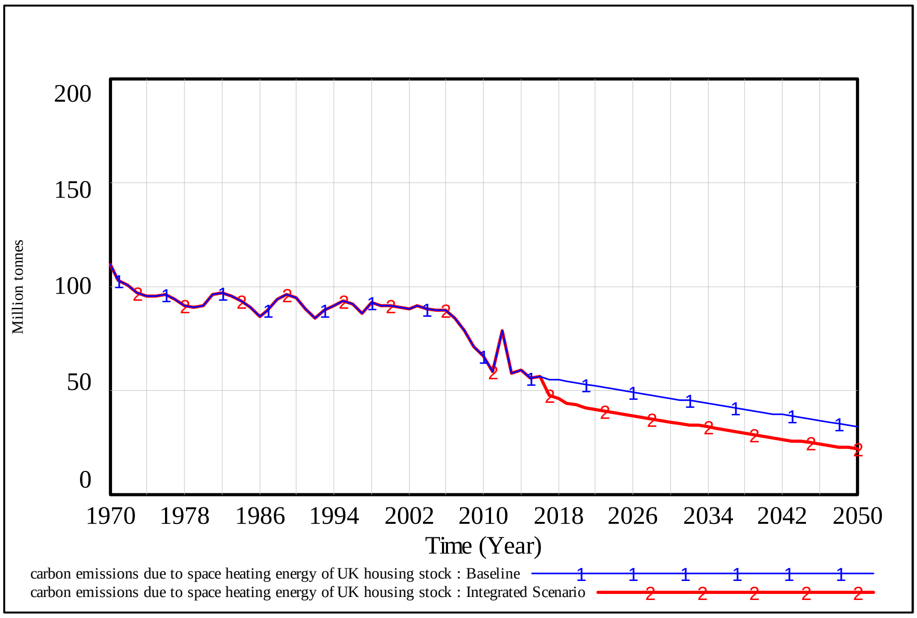

Figure C.36: Carbon emissions due to space heating for the 'baseline' and 'integrated' scenarios

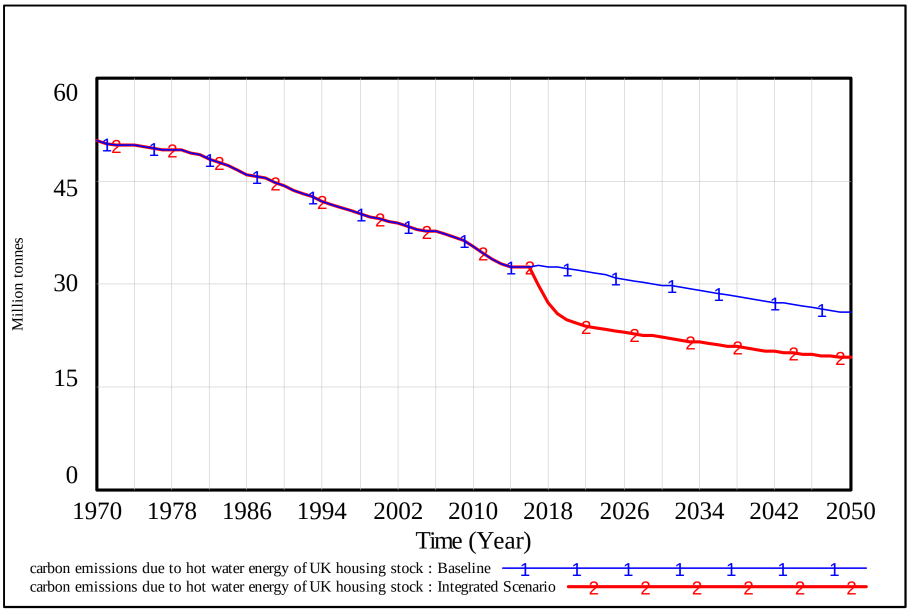

Figure C.37: Carbon emissions due to hot water for the 'baseline' and 'integrated' scenarios

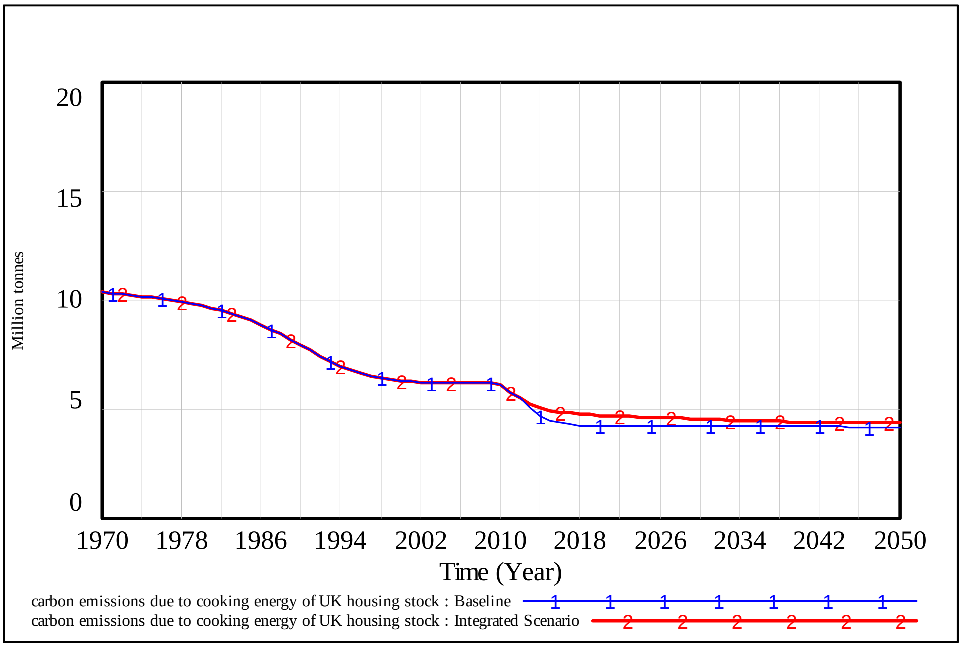

Figure C.38: Carbon emissions due to cooking for the ‘baseline’ and ‘integrated’ scenarios

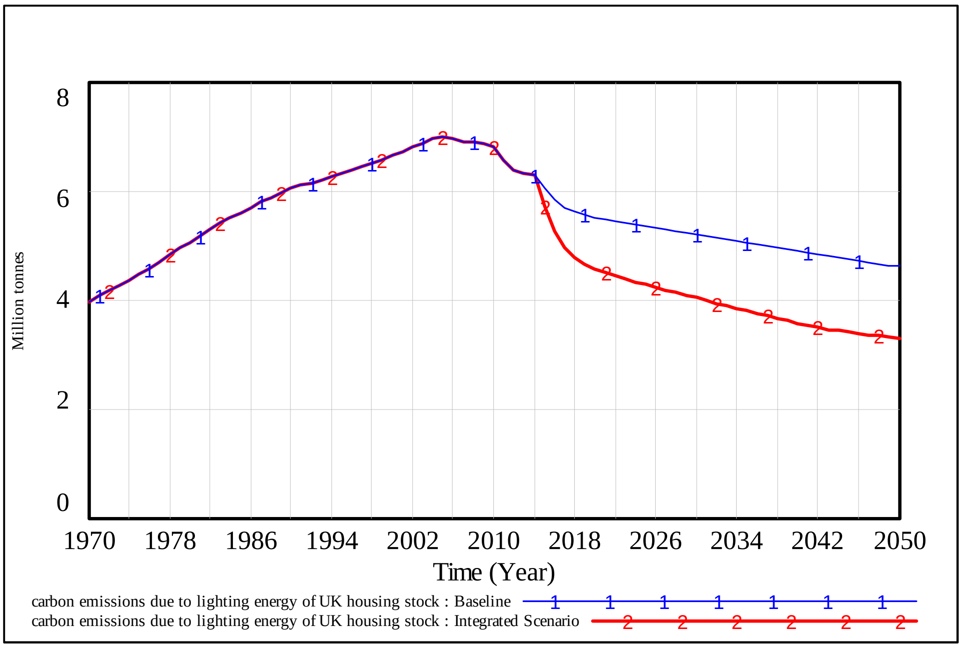

Figure C.39: Carbon emissions due to lighting for the ‘baseline’ and ‘integrated’ scenarios

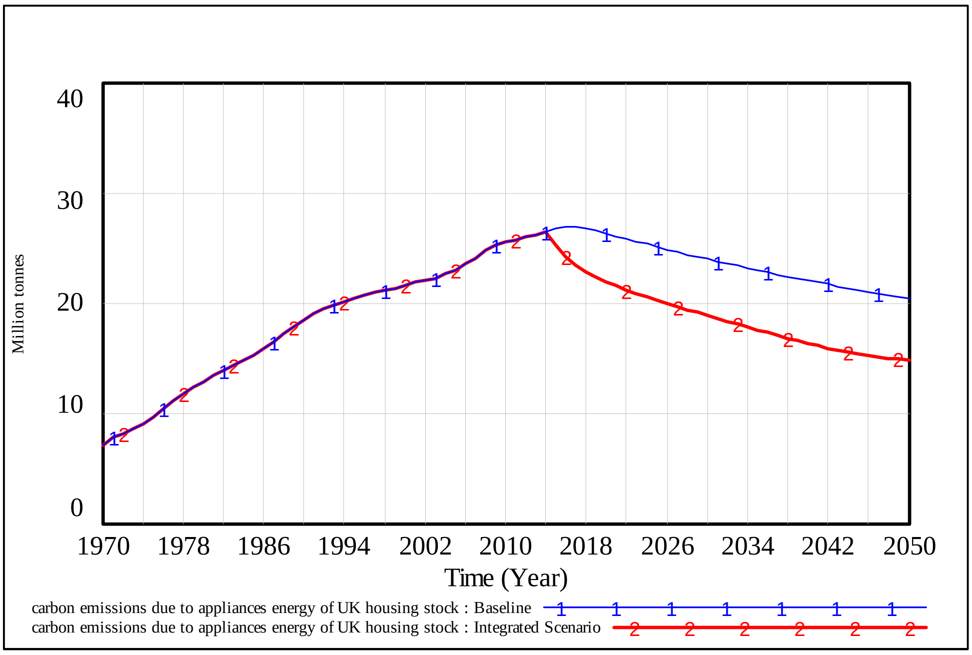

Figure C.40: Carbon emissions due to appliances for the ‘baseline’ and ‘integrated’ scenarios

APPENDIX D

Validation

D1: Instrument for Model Validation

Dynamic Modelling of the Socio-Technical Systems of Household Energy and CO_2 Emissions in the UK

Dear Sir/Madam

The above research is using system dynamics approach to model the social-technical variables influencing household energy consumption and CO_2 emissions (HECCE) in the UK. The study intends to contribute to the body of knowledge by improving the understanding of the complex nature of HECCE by providing a tool capable of studying the behaviour of policies regarding energy and carbon emissions issues in the UK.

As part of the system dynamics processes, model testing and validation by experts in the subject is of paramount importance. Therefore, we seek your assistance in sparing us approximately one hour of your time to assess the model as guided by this protocol.

Please be assured that any information given will be treated in the strictest confidence and used for research purposes only.

Thanks in anticipation.

Yours Sincerely,

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A. Background Information

1. Name of organisation (optional)…………………………………………..

2. Organisation type
   - i. Public
   - ii. Private

3. Academic
   - i. Diploma
   - ii. Bachelor’s degree
   - iii. Master’s degree
   - iv. PhD
   - v. Others (specify)……………………………………………………

4. Experience in household energy related issues
   - i. Yes
   - ii. No

5. Years of experience in household energy related issues
   - i. 1 – 5
   - ii. 6 – 10
   - iii. 11 – 15
   - iv. 16 – 20
   - v. 21 – 25
   - vi. Others……………….

6. Experience in system dynamics modelling
   - i. Yes
   - ii. No

7. Years of experience in system dynamics modelling
   - i. 1 – 5
   - ii. 6 – 10
   - iii. 11 – 15
   - iv. 16 – 20
   - v. 21 – 25
   - vi. Others……………….

B. Model Validation

8. Based on the system dynamics model reviewed, please assess the model according to the following criteria (with 5 – Excellent, 4 – Above average, 3 – Average, 2 – Below average, 1 – Poor)

Criteria	Rating				
	5	4	3	2	1
Logical structure					
Clarity					
Comprehensiveness					
Practical relevance					
Applicability					
Intelligibility					

9. Kindly comment on the model's point of strength

10. Kindly comment on the model’s point of weakness

11. Please give your general comment regarding the model

*****Thank you*****

D2: Time Step Changes for Euler Integration Method

Table D.1: Energy Consumption per Household - Time Step = 1

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
1970	13.18	6.64	1.36	0.55	1.07
1971	13.28	6.56	1.34	0.55	1.09
1972	12.74	6.52	1.32	0.56	1.13
1973	12.64	6.43	1.30	0.56	1.19
1974	12.90	6.34	1.28	0.57	1.26
1975	13.05	6.26	1.26	0.58	1.35
1976	12.76	6.16	1.24	0.59	1.42
1977	12.37	6.11	1.22	0.60	1.49
1978	12.50	6.05	1.20	0.61	1.54
1979	12.78	5.94	1.18	0.62	1.59
1980	13.72	5.84	1.15	0.63	1.63
1981	13.63	5.71	1.13	0.64	1.67
1982	13.47	5.61	1.10	0.64	1.71
1983	13.19	5.50	1.07	0.65	1.75
1984	12.94	5.38	1.04	0.66	1.80
1985	12.46	5.25	1.01	0.66	1.85
1986	13.30	5.17	0.98	0.67	1.91
1987	14.05	5.11	0.94	0.67	1.97
1988	14.31	4.99	0.91	0.67	2.03
1989	14.06	4.88	0.87	0.68	2.08
1990	13.30	4.78	0.83	0.68	2.12
1991	13.05	4.69	0.79	0.67	2.14
1992	13.97	4.59	0.76	0.68	2.16
1993	14.18	4.50	0.73	0.68	2.18
1994	14.62	4.41	0.71	0.68	2.19
1995	14.37	4.32	0.69	0.68	2.20
1996	13.88	4.24	0.68	0.68	2.21
1997	15.03	4.16	0.66	0.68	2.21
1998	14.65	4.09	0.65	0.68	2.22
1999	14.76	4.04	0.64	0.68	2.23
2000	14.78	3.95	0.63	0.69	2.23
2001	14.91	3.89	0.62	0.69	2.24
2002	15.28	3.81	0.62	0.69	2.24
2003	15.11	3.75	0.61	0.69	2.26
2004	15.12	3.71	0.61	0.69	2.29
2005	15.27	3.67	0.61	0.68	2.33
2006	14.91	3.60	0.60	0.67	2.37
2007	14.38	3.53	0.60	0.66	2.42
2008	13.69	3.44	0.59	0.66	2.44
2009	13.56	3.34	0.57	0.64	2.43

Table D.1: *Continued.*

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
2010	12.84	3.21	0.53	0.61	2.44
2011	13.77	3.10	0.51	0.59	2.44
2012	11.94	3.03	0.45	0.58	2.45
2013	11.07	2.99	0.41	0.58	2.45
2014	10.66	2.97	0.40	0.54	2.47
2015	10.46	2.96	0.39	0.52	2.46
2016	10.33	2.95	0.38	0.51	2.43
2017	10.19	2.91	0.38	0.50	2.40
2018	10.04	2.88	0.38	0.49	2.36
2019	9.89	2.84	0.37	0.49	2.32
2020	9.75	2.80	0.37	0.48	2.28
2021	9.60	2.76	0.37	0.47	2.25
2022	9.46	2.72	0.37	0.47	2.21
2023	9.33	2.68	0.36	0.46	2.17
2024	9.19	2.64	0.36	0.46	2.14
2025	9.07	2.60	0.36	0.45	2.11
2026	8.94	2.57	0.35	0.44	2.07
2027	8.82	2.53	0.35	0.44	2.04
2028	8.69	2.50	0.35	0.43	2.01
2029	8.58	2.46	0.35	0.43	1.98
2030	8.46	2.43	0.35	0.42	1.95
2031	8.35	2.39	0.34	0.42	1.92
2032	8.23	2.36	0.34	0.41	1.89
2033	8.13	2.33	0.34	0.41	1.86
2034	8.02	2.30	0.34	0.40	1.84
2035	7.91	2.27	0.33	0.40	1.81
2036	7.81	2.24	0.33	0.39	1.78
2037	7.71	2.21	0.33	0.39	1.76
2038	7.61	2.18	0.33	0.38	1.73
2039	7.51	2.15	0.33	0.38	1.71
2040	7.42	2.12	0.32	0.38	1.69
2041	7.32	2.09	0.32	0.37	1.66
2042	7.23	2.06	0.32	0.37	1.64
2043	7.14	2.04	0.32	0.36	1.62
2044	7.05	2.01	0.31	0.36	1.59
2045	6.96	1.98	0.31	0.35	1.57
2046	6.88	1.96	0.31	0.35	1.55
2047	6.79	1.93	0.31	0.35	1.53
2048	6.71	1.91	0.31	0.34	1.51
2049	6.63	1.88	0.31	0.34	1.49
2050	6.55	1.86	0.30	0.33	1.47

Table D.2: Carbon Emissions per Household - Time Step = 1

Time (Year)	Space Heating	Hot Water	Cooking Energy	Lighting Energy	Appliances
1970	5.85	2.70	0.55	0.21	0.38
1971	5.41	2.65	0.54	0.22	0.41
1972	5.25	2.61	0.54	0.22	0.42
1973	5.00	2.59	0.53	0.22	0.44
1974	4.85	2.56	0.52	0.22	0.46
1975	4.82	2.53	0.51	0.23	0.49
1976	4.80	2.49	0.50	0.23	0.52
1977	4.66	2.45	0.50	0.23	0.55
1978	4.46	2.43	0.49	0.24	0.58
1979	4.38	2.41	0.48	0.24	0.60
1980	4.38	2.37	0.47	0.24	0.62
1981	4.59	2.33	0.46	0.25	0.64
1982	4.57	2.28	0.45	0.25	0.66
1983	4.47	2.24	0.44	0.25	0.67
1984	4.31	2.20	0.43	0.26	0.69
1985	4.14	2.15	0.42	0.26	0.70
1986	3.90	2.10	0.40	0.26	0.72
1987	4.01	2.06	0.39	0.26	0.75
1988	4.20	2.04	0.38	0.26	0.77
1989	4.27	1.99	0.36	0.27	0.79
1990	4.18	1.95	0.35	0.27	0.81
1991	3.89	1.91	0.34	0.27	0.83
1992	3.67	1.87	0.32	0.27	0.84
1993	3.81	1.84	0.31	0.27	0.85
1994	3.86	1.80	0.30	0.27	0.86
1995	3.94	1.76	0.29	0.27	0.87
1996	3.85	1.73	0.28	0.27	0.87
1997	3.63	1.69	0.27	0.27	0.87
1998	3.83	1.66	0.27	0.27	0.87
1999	3.73	1.63	0.26	0.27	0.88
2000	3.68	1.61	0.26	0.27	0.88
2001	3.62	1.58	0.25	0.27	0.88
2002	3.58	1.55	0.25	0.27	0.88
2003	3.62	1.52	0.25	0.27	0.89
2004	3.53	1.50	0.24	0.27	0.89
2005	3.45	1.48	0.24	0.27	0.90
2006	3.42	1.46	0.24	0.27	0.91
2007	3.26	1.44	0.24	0.27	0.93
2008	3.01	1.41	0.24	0.26	0.95
2009	2.69	1.38	0.23	0.26	0.96

Table D.2: *Continued.*

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
2010	2.51	1.34	0.23	0.26	0.96
2011	2.20	1.29	0.22	0.25	0.96
2012	2.93	1.25	0.20	0.24	0.97
2013	2.13	1.21	0.18	0.23	0.97
2014	2.19	1.19	0.17	0.23	0.97
2015	2.04	1.18	0.16	0.22	0.98
2016	2.03	1.18	0.16	0.21	0.97
2017	1.99	1.17	0.15	0.20	0.97
2018	1.95	1.16	0.15	0.20	0.95
2019	1.91	1.14	0.15	0.20	0.94
2020	1.87	1.13	0.15	0.19	0.93
2021	1.83	1.11	0.15	0.19	0.91
2022	1.80	1.10	0.15	0.19	0.90
2023	1.76	1.08	0.14	0.19	0.88
2024	1.72	1.07	0.14	0.18	0.87
2025	1.69	1.05	0.14	0.18	0.85
2026	1.65	1.04	0.14	0.18	0.84
2027	1.62	1.02	0.14	0.18	0.83
2028	1.58	1.01	0.14	0.17	0.81
2029	1.55	0.99	0.14	0.17	0.80
2030	1.52	0.98	0.14	0.17	0.79
2031	1.49	0.97	0.14	0.17	0.78
2032	1.45	0.95	0.14	0.17	0.77
2033	1.42	0.94	0.14	0.16	0.75
2034	1.39	0.93	0.13	0.16	0.74
2035	1.36	0.92	0.13	0.16	0.73
2036	1.33	0.90	0.13	0.16	0.72
2037	1.30	0.89	0.13	0.16	0.71
2038	1.27	0.88	0.13	0.15	0.70
2039	1.24	0.87	0.13	0.15	0.69
2040	1.22	0.86	0.13	0.15	0.68
2041	1.19	0.84	0.13	0.15	0.67
2042	1.16	0.83	0.13	0.15	0.66
2043	1.13	0.82	0.13	0.15	0.65
2044	1.10	0.81	0.13	0.14	0.64
2045	1.08	0.80	0.13	0.14	0.64
2046	1.05	0.79	0.12	0.14	0.63
2047	1.02	0.78	0.12	0.14	0.62
2048	1.00	0.77	0.12	0.14	0.61
2049	0.97	0.76	0.12	0.14	0.60
2050	0.95	0.75	0.12	0.13	0.59

Table D.3: Energy Consumption per Household - Time Step = 0.5

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
1970	13.18	6.64	1.36	0.55	1.07
1971	13.12	6.57	1.34	0.55	1.09
1972	12.76	6.51	1.32	0.56	1.14
1973	12.74	6.42	1.30	0.57	1.19
1974	12.93	6.34	1.28	0.57	1.27
1975	12.96	6.25	1.26	0.58	1.35
1976	12.69	6.17	1.24	0.59	1.42
1977	12.46	6.11	1.22	0.60	1.49
1978	12.59	6.04	1.20	0.61	1.54
1979	13.00	5.94	1.17	0.62	1.59
1980	13.58	5.83	1.15	0.63	1.63
1981	13.53	5.71	1.12	0.64	1.67
1982	13.38	5.61	1.10	0.64	1.71
1983	13.15	5.50	1.07	0.65	1.75
1984	12.86	5.38	1.04	0.66	1.80
1985	12.75	5.26	1.01	0.66	1.85
1986	13.43	5.18	0.97	0.67	1.91
1987	14.00	5.10	0.94	0.67	1.97
1988	14.16	4.99	0.90	0.67	2.03
1989	13.85	4.88	0.87	0.67	2.08
1990	13.32	4.79	0.83	0.68	2.11
1991	13.35	4.69	0.80	0.68	2.14
1992	13.95	4.59	0.76	0.68	2.16
1993	14.23	4.50	0.74	0.68	2.18
1994	14.48	4.41	0.71	0.68	2.19
1995	14.23	4.33	0.70	0.68	2.20
1996	14.22	4.24	0.68	0.68	2.21
1997	14.83	4.17	0.67	0.68	2.21
1998	14.66	4.10	0.65	0.68	2.22
1999	14.74	4.03	0.64	0.68	2.23
2000	14.80	3.96	0.63	0.69	2.23
2001	14.98	3.89	0.62	0.69	2.24
2002	15.18	3.81	0.62	0.69	2.24
2003	15.10	3.76	0.62	0.69	2.26
2004	15.15	3.71	0.61	0.69	2.29
2005	15.16	3.66	0.61	0.68	2.33
2006	14.81	3.60	0.60	0.67	2.37
2007	14.28	3.52	0.60	0.66	2.41
2008	13.78	3.44	0.59	0.65	2.43
2009	13.46	3.33	0.57	0.64	2.43

Table D.3: *Continued.*

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
2010	13.20	3.21	0.53	0.61	2.44
2011	13.27	3.11	0.51	0.59	2.44
2012	11.91	3.04	0.45	0.59	2.44
2013	11.17	3.00	0.42	0.58	2.45
2014	10.76	2.98	0.41	0.55	2.46
2015	10.54	2.97	0.39	0.53	2.45
2016	10.34	2.94	0.39	0.51	2.42
2017	10.16	2.90	0.38	0.50	2.39
2018	10.00	2.86	0.38	0.49	2.36
2019	9.85	2.82	0.37	0.49	2.32
2020	9.70	2.78	0.37	0.48	2.28
2021	9.56	2.75	0.37	0.47	2.25
2022	9.43	2.71	0.37	0.47	2.21
2023	9.30	2.67	0.36	0.46	2.17
2024	9.17	2.63	0.36	0.46	2.14
2025	9.04	2.60	0.36	0.45	2.11
2026	8.92	2.56	0.35	0.44	2.07
2027	8.80	2.53	0.35	0.44	2.04
2028	8.68	2.49	0.35	0.43	2.01
2029	8.56	2.46	0.35	0.43	1.98
2030	8.45	2.43	0.35	0.42	1.95
2031	8.33	2.39	0.34	0.42	1.92
2032	8.22	2.36	0.34	0.41	1.89
2033	8.12	2.33	0.34	0.41	1.86
2034	8.01	2.30	0.34	0.40	1.84
2035	7.91	2.27	0.33	0.40	1.81
2036	7.80	2.24	0.33	0.39	1.79
2037	7.70	2.21	0.33	0.39	1.76
2038	7.61	2.18	0.33	0.38	1.73
2039	7.51	2.15	0.33	0.38	1.71
2040	7.41	2.12	0.32	0.38	1.69
2041	7.32	2.09	0.32	0.37	1.66
2042	7.23	2.06	0.32	0.37	1.64
2043	7.14	2.04	0.32	0.36	1.62
2044	7.05	2.01	0.31	0.36	1.60
2045	6.96	1.98	0.31	0.35	1.57
2046	6.88	1.96	0.31	0.35	1.55
2047	6.79	1.93	0.31	0.35	1.53
2048	6.71	1.91	0.31	0.34	1.51
2049	6.63	1.88	0.31	0.34	1.49
2050	6.55	1.86	0.30	0.33	1.47

Table D.4: Carbon Emissions per Household - Time Step = 0.5

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
1970	5.85	2.70	0.55	0.21	0.38
1971	5.48	2.65	0.54	0.21	0.40
1972	5.23	2.62	0.53	0.22	0.42
1973	5.02	2.59	0.53	0.22	0.44
1974	4.90	2.56	0.52	0.22	0.46
1975	4.85	2.53	0.51	0.23	0.49
1976	4.77	2.49	0.50	0.23	0.52
1977	4.62	2.46	0.50	0.23	0.55
1978	4.49	2.43	0.49	0.24	0.58
1979	4.43	2.40	0.48	0.24	0.60
1980	4.49	2.37	0.47	0.24	0.62
1981	4.55	2.32	0.46	0.25	0.64
1982	4.52	2.28	0.45	0.25	0.65
1983	4.42	2.24	0.44	0.25	0.67
1984	4.28	2.20	0.43	0.26	0.69
1985	4.10	2.15	0.42	0.26	0.71
1986	4.03	2.10	0.40	0.26	0.73
1987	4.11	2.07	0.39	0.26	0.75
1988	4.20	2.03	0.38	0.26	0.77
1989	4.20	1.99	0.36	0.27	0.79
1990	4.06	1.95	0.35	0.27	0.81
1991	3.86	1.91	0.34	0.27	0.83
1992	3.81	1.87	0.32	0.27	0.84
1993	3.84	1.84	0.31	0.27	0.85
1994	3.89	1.80	0.30	0.27	0.86
1995	3.88	1.76	0.29	0.27	0.86
1996	3.76	1.73	0.28	0.27	0.87
1997	3.76	1.70	0.27	0.27	0.87
1998	3.77	1.66	0.27	0.27	0.87
1999	3.72	1.64	0.26	0.27	0.88
2000	3.67	1.61	0.26	0.27	0.88
2001	3.62	1.58	0.25	0.27	0.88
2002	3.61	1.55	0.25	0.27	0.88
2003	3.58	1.52	0.25	0.27	0.89
2004	3.52	1.50	0.24	0.27	0.89
2005	3.47	1.48	0.24	0.27	0.90
2006	3.37	1.46	0.24	0.27	0.92
2007	3.20	1.43	0.24	0.27	0.93
2008	2.95	1.41	0.24	0.26	0.95
2009	2.71	1.37	0.23	0.26	0.96

Table D.4: *Continued.*

Time (Year)	Space Heating	Hot Water	Cooking	Lighting	Appliances
2010	2.47	1.33	0.23	0.25	0.96
2011	2.36	1.29	0.21	0.25	0.96
2012	2.49	1.25	0.20	0.24	0.97
2013	2.30	1.22	0.19	0.23	0.97
2014	2.17	1.20	0.17	0.23	0.97
2015	2.09	1.19	0.17	0.22	0.97
2016	2.04	1.18	0.16	0.21	0.97
2017	1.99	1.17	0.16	0.21	0.96
2018	1.94	1.15	0.15	0.20	0.95
2019	1.90	1.14	0.15	0.20	0.94
2020	1.86	1.12	0.15	0.19	0.92
2021	1.83	1.11	0.15	0.19	0.91
2022	1.79	1.09	0.15	0.19	0.90
2023	1.75	1.08	0.15	0.19	0.88
2024	1.72	1.06	0.14	0.18	0.87
2025	1.68	1.05	0.14	0.18	0.85
2026	1.65	1.03	0.14	0.18	0.84
2027	1.61	1.02	0.14	0.18	0.83
2028	1.58	1.01	0.14	0.17	0.81
2029	1.55	0.99	0.14	0.17	0.80
2030	1.52	0.98	0.14	0.17	0.79
2031	1.48	0.97	0.14	0.17	0.78
2032	1.45	0.95	0.14	0.17	0.77
2033	1.42	0.94	0.14	0.16	0.75
2034	1.39	0.93	0.13	0.16	0.74
2035	1.36	0.92	0.13	0.16	0.73
2036	1.33	0.90	0.13	0.16	0.72
2037	1.30	0.89	0.13	0.16	0.71
2038	1.27	0.88	0.13	0.15	0.70
2039	1.24	0.87	0.13	0.15	0.69
2040	1.21	0.86	0.13	0.15	0.68
2041	1.19	0.84	0.13	0.15	0.67
2042	1.16	0.83	0.13	0.15	0.66
2043	1.13	0.82	0.13	0.15	0.65
2044	1.10	0.81	0.13	0.14	0.64
2045	1.08	0.80	0.13	0.14	0.64
2046	1.05	0.79	0.12	0.14	0.63
2047	1.02	0.78	0.12	0.14	0.62
2048	1.00	0.77	0.12	0.14	0.61
2049	0.97	0.76	0.12	0.14	0.60
2050	0.95	0.75	0.12	0.13	0.59