University of Bath

PHD

Securing a Pathway which leads to an 80% Reduction in Greenhouse Gas Emissions

Effects of Climate Change on Levels of Space Heating and Space Cooling, and Analysis of the Energy Saving Potential of the Adaptive Approach to Thermal Comfort in the Built Environment

Mcgilligan, Charles

Award date:
2013

Awarding institution:
University of Bath

Link to publication

Securing a Pathway which leads to an 80% Reduction in Greenhouse Gas Emissions

Effects of Climate Change on Levels of Space Heating and Space Cooling, and Analysis of the Energy Saving Potential of the Adaptive Approach to Thermal Comfort in the Built Environment

Charles McGilligan

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department of Architecture and Civil Engineering

February 2013

Contents

List of Figures

List of Tables

Acknowledgements

This work could not have been achieved without the help of a number of people to whom I am greatly indebted. Thanks are due first to the late Harry Bruhns for his invaluable assistance, most specifically in directing me to the National Grid and CaRB data. I also thank Steve Raper for his patience and help with some of the statistics in Chapter 2, especially that related to the segmented regression analysis. My fellow COPSE researchers are also thanked for their valuable contributions over the course of the last four years, especially Richard Watkins for the future weather years data. I am also very grateful to the Building Services Research and Information Association for making available to me air-conditioning data free of charge. I owe a huge debt of thanks to my supervisors, Sukumar Natarajan and Marialena Nikolopoulou, both of whom have offered expert guidance in good humour, and both of whom have been so selfless with their time despite their very heavy workloads. Their words of encouragement, sharp eye and expert knowledge have been invaluable.

Finally, I thank my family and my parents in particular. Without their support, patience and love none of this would have been possible. Through thick and thin, from beginning to end, they have always been there. So much has been done, and so much has been given, that it would take another thesis to list the many wonderful ways, both practical and emotional, that I have been helped. I can never begin to repay all you have done for me. Thanks, Mum and Dad.

Abstract

Climate change brings with it a set of challenges if our buildings are to remain thermally comfortable whilst energy consumption is kept to a minimum and greenhouse gas emissions are reduced. As a means of addressing these issues, three models have been constructed using future climate data as forecast by the UK Climate Projections (UKCP09), and they have been used to inform the Department of Energy and Climate Change (DECC) 2050 Calculator. Observing there to be a correlation between regionalised National Grid non-daily metered gas demand and daily air temperature, the first model uses these data and UKCP09 data to estimate future energy savings deriving from a reduced requirement for space heating across the built environment. Using UKCP09 data, the second model estimates the increase in the uptake of residential air-conditioning if the UK were to follow the same experience as Canada, regression data showing a correlation between penetration levels of air-conditioning in the residential sector and air temperature in North America. Resultant levels of space cooling energy consumption are calculated using two different bottom-up approaches, the first of which uses the dwelling as the base unit, and the second of which uses the air-conditioner. Deriving from conventional degree-day theory and substantiated through a series of building simulations, the third model uses a novel metric, the *Adaptive Comfort Degree-Day*, to estimate the energy savings potential of employing adaptive comfort standards for future climates using UKCP09 data. Finally, it is found that pathways prescribed as achieving an 80% reduction in emissions levels by 2050 remain successful when the DECC 2050 Calculator is updated with correctly-weighted air temperatures. However, the demand for space heating is under-estimated by up to 99 TWh when the Calculator is amended so as to take account of data from the preceding space heating model.

Abbreviations and Acronyms

AATC - Adaptive Approach to Thermal Comfort

ACDD - Adaptive Comfort Degree-Day

ASHRAE - American Society of Heating, Refrigeration, and Air-Conditioning Engineers

ASHP - Air-source heat pump

BADC - British Atmospheric Data Centre

BRE - Building Research Establishment

BREDEM - Building Research Establishment Domestic Energy Model

BREHOMES - Building Research Establishment Housing Model for Energy Studies

BSI - British Standards Institution

BSRIA - Building Services Research and Information Association

BTU - British Thermal Unit

CA - Census Agglomeration

CaRB - Carbon Reduction in Buildings

CCS - Carbon Capture and Storage

CDD - Cooling Degree-Day

CEC - California Energy Commission

CEN - Comité Européen de Normalisation

CET - Central England Temperature

CEUD - Comprehensive Energy Database

CEUD - Survey of Household Spending

CHM - Cambridge Housing Model

CHP - Combined Heat and Power

CIBSE - Chartered Insitution of Building Services Engineers

CMA - Census Metropolitan Area

CO_2e - Carbon Dioxide Equivalent

CoP - Coefficient of Performance

COPSE - Coincident Probabilistic Climate Change Weather Data for a Sustainable Built Environment

CWV - Composite Weather Variable

DCLG - Department for Communities and Local Government

DD - Degree-Day

DECarb - Domestic Energy and Carbon (Model)

DECC - Department of Energy and Climate Change

DEFRA - Department for Environment, Food and Rural Affairs

DGTREN - Directorate-General for Transport and Energy

DM - Daily Metered

drm - Daily Running Mean

DSM - Dynamic Simulation Modelling

DUKES - Digest of United Kingdom Energy Statistics

EER - Energy Efficiency Ratio

EIA - US Energy Information Administration

GDP - Gross Domestic Product

GHG - Greenhouse Gas

GSBN - Government Standard Briefing Note

GSHP - Ground-source heat pump

GW - Gigawatt

GWh - Gigawatt Hour

GWP - Global Warming Potential

HDD - Heating Degree-Day

HLC - Heat Loss Coefficient

HVAC - Heating Ventilation and Air-Conditioning

IPCC - Intergovernmental Panel on Climate Change

IVR - Inter-Variable Relationship

IWEC - International Weather for Energy Calculations

J - Joule

k_{lt} - Long-term response factor

k_{st} - Short-term response factor

kWh - Kilowatt Hour

LDZ - Local Distribution Zone

LZC - Low and Zero Carbon

mscm - Million Standard Cubic Metre

MTP - Market Transformation Programme

NCDC - National Climatic Data Center

NCDIA - National Climate Data and Information Archive

NDBS - Nondomestic Building Stock

NDEEM - Nondomestic Energy and Emissions Model

NDM - Non-Daily Metered

NDNI - Non-Domestic & Non-Industry

NDSM - Non-Domestic Stock Model

NG - National Grid

NRCan - Department of Natural Resources (Canada)

NTN - National Transmission Network

NTS - National Transmission System

NTS - National Transmission System

$\%^{le}$ - Percentile

PC - Population Centre

PJ - Petajoule (10^{15} Joules, or 278 GWh)

PMV - Predicted Mean Vote

PPD - Predicted Percentage Dissatisfied

RASS - Residential Appliance Saturation Study

RECS - Residential Energy Consumption Survey

RH - Relative Humidity

SAP - Standard Assessment Procedure

SC - Space Cooling

SCECMORS - Space Cooling Energy Consumption Model for the Residential Sector

SEER - Seasonal Energy Efficiency Ratio

SH - Space Heating

SHECMOBS - Space Heating Energy Consumption Model for the Building Stock

SHEU - Survey of Household Energy Use

SHU - Sheffield Hallam University

SNET - Seasonal Normal Effective Temperature

SRES - Special Report on Emissions Scenarios

t_{drm} - Daily running mean outdoor air temperature

t_{mm} - Mean monthly outdoor air temperature

ttoe - Thousand Tonne of Oil Equivalent

TWh - Terawatt hour

UKCIP02 - UK Climate Impacts Programme 2002

UKCP09 - UK Climate Projections 2009

VBA - Visual Basic for Applications

VOA - Valuation Office Agency

Glossary

With regard to energy use, a number of terms are understood differently by different people. This Glossary sets out what is meant by those terms which are used in this thesis which are most commonly confused.

1. *Energy Demand and Energy Consumption*

Energy Demand

Quantity of energy required.

Energy Consumption

Quantity of energy used by a consumer.

There can be some confusion regarding the interpretation of the term "energy demand", since "quantity of energy required" may be interpreted in different ways by the consumers, suppliers/generators and modellers. Consider the following example. The owner of a building is unsure whether to install a heating system which uses fuel source A which is 80% efficient, or a heating system which uses the more expensive fuel source B, but which is 90% efficient. A modeller is employed to run a heat balance model for the building owner in order to help him/her make the correct decision. In order to maintain thermal comfort, it is found that 100 units of space heating energy are required annually. Thus the heating requirements of the building can be met through the use of 111 (i.e. 100/0.9) units of fuel A or 120 (i.e. 100/0.8) units of fuel B.

   i.   The energy demand is 111 units from the perspective of fuel supplier A.
   ii.   The energy demand is 121 units from the perspective of fuel supplier B.
   iii. The energy demand is 100 units from the perspective of the modeller.
   iv.   The energy consumption is 111 units from all perspectives if fuel A is used.
   v.   The energy consumption is 121 units from all perspectives if fuel B is used.

The context in which the terms are used always makes clear which particular interpretation is being used in this thesis.

2. *Energy Efficiency Ratio, Energy Efficiency Ratio and Coefficient of Performance*

There is a degree of confusion in some of the literature with regard to the use of certain air-conditioning terms, e.g. see footnote. The correct general definitions of energy efficiency ratio, seasonal energy efficiency ratio and coefficient of performance as used in Europe are given below.

Energy efficiency ratio (EER) is the ratio of the declared capacity for cooling and the rated power of the unit when providing cooling at standard rating conditions. The EER has no units.

Seasonal energy efficiency ratio (SEER) is the overall cooling energy efficiency ratio of a unit over the whole cooling season. The SEER has no units.

*Coefficient of Performance (CoP) is the ra*tio of the declared capacity for heating and the rated power of the unit when providing heating at standard rating conditions. The CoP has no units.

Source: (European Commission, 2011)

The literature commonly reports the EER as being approximately 0.85 the value of the SEER although the relationship is not fixed, being dependent upon cycling losses.

3. Short- and long-term response

Short-term response

Increase in electricity consumption from a fixed number of air-conditioners resulting from (i) more intensive use (i.e. switching to a higher power setting), plus (ii) increased number of hours of operation, in response to hotter temperatures.

Short-term response factor (k_{st})

Factor by which space cooling energy consumption increases as a result of the short-term response.

Long-term response

Increase in electricity consumption resulting from increase in the number of air-conditioners (i.e. increased penetration), in response to hotter temperatures.

Long-term response factor (k_{lt})

Factor by which space cooling energy consumption increases as a result of long-term response.

	Present climate	Future hot climate
Number of air-conditioning units	a	a + b
Energy Consumption	A	A' + B
Number of CDDs	x	y

where   A' = k.a
B = k.b

Short-term response: A' − A

Short-term response factor: A' ÷ A (= y ÷ x)

Long-term response: (A' + B) - A

Long-term response factor: (a + b) ÷ a

The long-term response also calculates as (A. k_{st}.k_{lt}) − A.

Preface

This thesis presents research carried in threemain areas, each presented in a chapter of its own (Chapter 2 to Chapter 4). Although each chapter represents a discrete area of research in its own right, they also build towards Chapter 5, the main focus of this study, where pathways which lead to a reduction in emissions of 80% are re-examined in the light of the information gathered in the previous chapters. A précis of each of these four chapters is given below, highlighting the key contributions that each make to their relevant fields of study and thereby extend our knowledge.

Chapter 2: Space Heating Model

Space heating accounts for 30% of energy consumption in the built environment of the UK, and stands second only to transport. In view of the fact that space heating is so much affected by climate and that our climate is forecast to change significantly over the coming years of the 21st century, it is important to understand how the demand for space heating is likely to change. In a future where electricity is likely to be the primary form of energy and which will require a vast reorganisation of the generational and supply networks, this knowledge is of vital importance to policymakers who must ensure that there is enough supply to meet demand, and also to researchers, manufacturers and distributors who must ensure that the technology and systems are in place to cope with the demand.

The residential sector accounts for the majority of our heating, and a number of models exist which can quantify levels of space heating in this sector. However, almost a third of space heating is used in the non-domestic sector.   Although a limited number of non-domestic models have been built, none of them can be used as forecasting tools to examine how levels of demand/consumption will change as the climate changes. This arises as a consequence of the fact that the non-domestic stock is more complex and diverse than the domestic stock.

A different approach to the problem is followed in this thesis. Rather than model each sector in isolation, the residential and non-domestic sectors are modelled en masse. Such an approach is made possible because of the existence of regional daily gas demand data supplied by National Grid, it being possible to correlate these data with regional daily temperature data supplied by the British Atmospheric Data Centre. With gas being used for over 70% of space heating across the residential and non-domestic stock, a clear correlation is seen between non-daily metered gas consumption and air temperature. This forms the basis of a regressional model to forecast future levels of space heating energy consumption, the future daily temperature data deriving from regional weather data deriving from the UKCP09 Weather Generator. Given the acronym SHECMOBS (Space Heating Energy Consumption Model for the Building Stock), it forecasts significant reductions in space heating energy consumption, an 11-12% reduction being forecast for the average climate in the 2030s, and one of 16-22% by the 2050s, depending upon whether global greenhouse gas emission fall in the low, medium or high category. The value of SHECMOBS is twofold. For the layman who only has little information about climate change and has difficulty in appreciating what a rise in temperature of $x\ ^{0}$C means, it immediately makes apparent, in terms which are understandable to him, how large and close a phenomenon it is. Secondly, and most importantly from an academic

point of view, the information that it imparts can be used to inform policymakers as mentioned above since the percentage change in consumption as reported by SHECMOBS is also indicative of the percentage change in demand, such information being used to re-calibrate the DECC 2050 Calculator described in Chapter 5.

This work has been published in *Deriving and using future weather data for building design from UK climate change projections – an overview of the COPSE Project* ((Levermore, et al., 2012), and preparations are in process for further publication of the work in an academic journal, where data is drawn for the DECC 2050 Calculator.

Chapter 3: Space Cooling Model

Just as the demand for space heating is likely to fall, the demand for space cooling is set to increase as air temperatures increase, and in similar fashion to the space heating scenario outlined previously, policymakers, researchers, manufacturers and distributors must ensure that systems are in place so that supply can meet demand.

One of the ways in which cooling demand is met is through mechanical systems, primarily air-conditioners. The penetration rate of air-conditioning in the commercial market is already estimated at 42%. The potential within the market is therefore limited: f the non-domestic stock of 1.7M were to increase at the same rate as that of the residential stock (54%) and saturation reached 100% by 2050, the market would increase by only a factor of 3.6. In view of the very low levels of penetration in the residential sector however, the market could explode over the course of the next 40 years as has happened in the United States and more recently in China where the number of air-conditioning units rose from a value of 0.3 units per 100 households in 1990 to 112 by 2010.

Data from North America has shown a link between air temperature and penetration levels of air-conditioning. Significantly, the current summer climate observed in Canada is similar to that forecast for the UK in the 2050s. What is more, levels of air-conditioning in Canada are considerably higher than they are in the UK. As such, these data can give us an indication of what penetration levels could reach in this country in forty years if we were to follow the Canadian experience of air-conditioning.

However, very little research has been carried out on air-conditioning in the UK, and none have brought together the key elements of penetration of climate. Since these two elements can have such a large effect on levels of space cooling energy consumption, the importance of incorporating both of these elements in a single unified model is clear. For the first time, these elements have been brought together in a space cooling model to forecast energy consumption in dwellings in the future. Given the acronym SCECMORS (Space Cooling Energy Consumption Model for the Residential Sector), the front end consists of a regression model which translates cooling degree-days into levels of penetration, whilst the back end converts penetration levels into energy consumption values. Moreover, the back end uses two different approaches, one which uses the dwelling as the base unit and the other which uses the air-conditioner as the base unit, allowing their output to be cross-checked and therefore adding a degree of robustness to the modelling process.

Under a medium emissions scenario, penetration levels could reach approximately 50% by the 2050s, with the first approach forecasting levels of energy consumption which are 26% higher than the second approach. But the data reveal that even at such high levels of penetration the resultant effect upon stock energy consumption is very small, equivalent to approximately only 1% of the total currently consumed by space heating.

In addition to giving an indication of penetration levels and energy consumption in a 2050s climate under a medium emissions scenario, like SHECMOBS, its greatest value lies in its application to additional future climates and different pathways as modelled in the DECC 2050 Calculator in Chapter 5.

Further informed by data from the DECC Calculator, preparations are being made for publication of the work in an academic journal.

Chapter 4: Adaptive Comfort Degree-Day Model

Whilst the Canadian experience of uptake of air-conditioning projects one vision of the future, embracement of the lately fashionable adaptive approach to thermal comfort (AATC) offers an alternative vision. In this approach, space conditioning (most often cooling, but applicable heating as well) is achieved by natural means through the provision of adaptive opportunity. It is specifically expressed as (i) the provision of easily accessed openable windows, (ii) absence of dress code which forbids dressing for the weather, and(iii)elimination of air-conditioning so that the human body's thermoregulatory system is tuned to the natural environment rather than the narrow temperature limits of the artificial environment provided by air-conditioning. Such is its potential for saving energy, allowing one to remain comfortable at indoor temperatures which those habituated to air-conditioning would find uncomfortably hot, adaptive standards have been set by national standards offices, these adaptive standards setting out the temperature limits for maintaining a comfortable environment. In the UK we have choice of two adaptive standards, the (i) American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) adaptive standard and the (ii) Comité Européen de Normalisation (CEN)/ British Standards Institution (BSI) adaptive standard. The problem for the designer or energy manager who wishes to avail of the AATC is that the two adaptive standards, even though both predicating to provide an environment which is thermally comfortable, set different temperature limits. The problem relates to the issue of compliance, where the approximately 1^0C higher temperature limit of the European adaptive standard makes compliance easier and therefore makes it available to a greater number of buildings which would otherwise have to use mechanical cooling systems to maintain comfort.

In order to compare each adaptive standard's potential for saving energy (equal in amount to the amount of energy which would otherwise be used by a mechanical system maintaining a temperature at a lower temperature limit, a novel metric the ACDD has been created. A theoretical concept deriving from conventional degree-day theory, modelling studies reveal that the ACDD accurately reflects not only potential energy savings but actual energy savings too.

The results show that the energy savings of the additional buildings allowed to avail of the AATC through compliance with the European adaptive standard are significant: buildings using the

European adaptive standard may achieve levels of energy savings in the 2020s which a merely ASHRAE-compliant building could not achieve until the 2080s or later, irrespective of the emissions scenario chosen.

The research has two important aspects to it. Firstly the modelling studies reveal that ACCD metric, developed as a means of quantifying the potential energy savings (in relative terms) of an adaptive standard, is successful in doing this, thus allowing one to be compared against the other for future climates.   In addition, however, the modelling studies reveal that the ACDD can be used to quantify actual energy savings (in relative terms) resulting from implementation of the AATC, and does so without recourse to any specific knowledge of a building's dimensions or thermal characteristics. It thus provides a shorthand way of quickly and simply calculating energy savings (in relative terms) without having to use complex dynamic simulation modelling software.

In that the AATC represents a realistic zero energy method of providing a thermally comfortable environment, it therefore also corroborates two of the modelled pathways described in chapter 5, which do not use mechanical systems for space cooling in the residential sector.

This work has been published in the following peer-reviewed publications: *Energy and Buildings* ((McGilligan, et al., 2011a), the *Proceedings of the 5th International Conference on Solar Radiation and Daylighting 2011* (McGilligan, et al., 2011b) and (McGilligan, et al., 2011c).

Chapter 5: The Building Stock in 2050: Pathways to Securing a Reduction in Emissions of 80%

In recognition of the fact that greenhouse gas emissions must be reduced if we are to avoid serious negative and costly effects of climate change in the latter part of the century, the Climate Change Act 2008 sets down in law that emissions of these gases must be reduced by 80% with reference to a baseline level set in 1990. Such a target can only be met following concerted cross-sector effort, since neither the sectors of the built environment nor any individual sector can achieve this alone.

As a means of exploring the alternative pathways which can be followed in the attainment of this target, the government Department of Energy and Climate Change (DECC) has produced an internally consistent, multi-layered tool, the DECC 2050 Calculator, in which changes in one sector result in changes in measured changes in other sectors if there be a link between them. Contained within the Calculator itself a number of pathways which lead towards the 80% reduction target are prescribed.   When space heating energy consumption in the residential sector is cross-checked against (i) government data for its base year of 2007 and (ii) SHECMOBS data for the reduction in space heating energy consumption for the period 2007-2050 using correctly-weighted air temperature data, the DECC 2050 Calculator is seen to under-estimate the former and over-estimate the latter by a considerable margin. Since space heating (i) is currently responsible for over 15% of emissions (ii), comprises such a large part of the energy budget of the UK, and (iii) will still be responsible for a large part of the nation's consumption in 2050, this could result in levels of energy consumption and levels of emissions in 2050 which are higher than those currently forecast.

The DECC 2050 Calculator is re-run for four key pathways, which cover a broad spectrum of possible pathways, using correctly-weighted temperature data, and featuring amendments which bring its output into alignment with government statistics and SHECMOBS forecasts. Alternative future

climates for 2050 are also investigated, since none of the default pathways consider a future climate other than one based on temperature projections at the 50% probability level under a medium emissions scenario using UKCP09 data.

Levels of space cooling in the residential sector are seen to be very small in comparison to levels of heating. If uptake followed a pattern similar to that seen in Canada, penetration could reach 50-70%, but levels of consumption in this sector would still be dwarfed by levels of co nsumption in the commercial sector.

When the residential sector aspect of the Calculator is re-calibrated so as to align with government space heating statistics and SHECMOBS data, forecast levels of space heating which are approximately twice as high as those estimated by a basic version of the Calculator across all future climates. The difference in energy consumption levels between the two models reaches as high as 99TWh. Extremities of climate for 2050 are not seen to have a very large effect upon space heating energy consumption however, there being only an average difference of 3% between the 30th percentile medium emissions scenario and the 90th percentile high emissions scenario.

Despite the amendments made to the DECC 2050 Calculator, the cross-sector minimum reduction in emissions in the least effective pathway still amounts to 79.7%, the continued success of the pathways mostly deriving from the high level of electrified heating in alliance with its low emissions intensity.

The information revealed by this research is significant because it suggests that whilst the proposed measures defined by the pathway may be sufficient to secure the emissions target reduction of 80%, the generational capacity is insufficient to meet the full demand for space heating during the heating season, requiring that additional generational capacity sufficient to provide up to 99TWh of electricity be provided.

Findings from this chapter will inform the forthcoming publications on space heating and space cooling mentioned above. A separate paper will also be written about this work.

1 Introduction

The climate system is warming, as shown by global observations of changes in air temperature, ocean temperature, sea levels, and snow and ice melt. Such is the wealth of evidence indicating this to be the case that the Intergovernmental Panel on Climate Change (IPCC) is "unequivocal" on this matter in its Fourth Assessment Report. Furthermore, the IPCC states that there is at least a 90% probability that the increase in global temperature observed in the latter part of the mid-twentieth century is due to an increase in anthropogenic greenhouse gas (GHG) emissions, the global increases in carbon dioxide being primarily due to fossil fuel use and land use change, and the increases in methane and nitrous oxide being primarily due to agriculture. (There has been a significant rise in the global atmospheric concentrations of these GHGs since the dawn of the industrial age 250 years ago, with present day levels far exceeding levels determined from ice core samples covering a period of many thousands of years). Moreover, temperatures continue to rise. Perhaps most alarming of all, the last time that the polar regions were significantly warmer than they are today for an extended length of time, sea levels rose by 4-6m due to the reduction in ice (IPCC, 2007).

As clear as it may be that human activity has been a major influence upon climate change, and for all the certitude that we are in the midst of a period of warming, the duration of the period of warming and extent to which temperatures will rise are less certain, with increases of between 1.2 0C and 6.4 0C being forecast before the turn of the century. For the most part, this uncertainty does not derive from an inadequacy in climate science to locate, describe and measure those factors which affect the climate. Indeed, our climate models satisfactorily describe the climate to a large degree, such models contributing to the evidence that the observed recent increases in global air temperature are principally anthropogenic in nature (Figure 1).
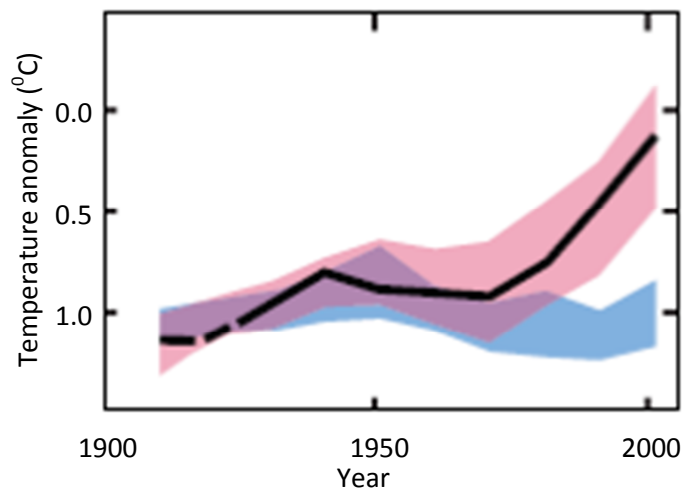
observations: decadal averages for period 1906 to 2005, plotted against the centre of the decade and relative to the corresponding average for 1901–1950. Dashed line - spatial coverage less than 50%.

models using only natural forcings: 5–95% range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes

models using both natural and anthropogenic forcings: 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

Figure 1 Comparison of observed global land change in surface temperature with results simulated by climate models using natural and anthropogenic forcings (IPCC, 2007)

The uncertainty with regard to the future lies rather more in the fact that it remains unclear how society, in all its vast, and inter-connected complexity, will develop over the coming decades; a product of complex dynamic systems, influenced by such factors as changes in demographics, socio-economic development and technological advances, the pathway adopted by society at large, unknown as yet, is of pivotal importance in determining emissions levels and attendant subsequent effect upon global air temperatures. In the absence of a legally-binding agreement forcing emissions limits upon nations, the UK, as with every other nation, must depend on projections, scenarios which set out plausible storylines which describe how the future might unfold and which further detail the emissions pathways associated with each[1].

The UK Climate Projections 2009 (UKCP09) set out just such plausible visions of the future. Deriving from the Met Office Hadley Centre climate model HadCM3[2], and further including the results of other IPCC climate models, UKCP09 provides probabilistic projections for 25km grid squares of the

---

[1] The United Nations Statistics Division reports emissions data for 173 states. The UK is responsible for only 2% of GHG emissions. The United States is responsible for most emissions (21%), with China responsible for 12% (United Nations Statistics Division, 2010). The statistics refer to data gathered in individual years anytime between 1990 and 2008. With the data from China deriving from 1994 (c.f. 2008 for the UK and the US), it is likely that China is now responsible for more than 12% of emissions in view of the rapid development that has taken place there over recent years.

[2] One of the major models used in the IPCC Third and Fourth Assessment Reports (UK Meteorological Office, 2010).

UK (i) for air temperature and a number of atmospheric variables, (ii) for decadal future time periods from the 2020s to the 2080s, (iii) under three future emissions scenarios (UKCP09, 2012e; UKCP09, 2012f). Reflecting scientists' best understanding of how the climate system operates and using a peer reviewed methodology at the very vanguard of the subject field which calls upon the best available evidence, the UKCP09 represents the culmination of seven years of work by (i) the Met Office Hadley Centre, (ii) the UK Climate Impacts Programme (UKCIP) and (iii) a body of over thirty contributing organisations including the Climatic Research Unit, widely recognised as one of the world's leading institutions concerned with the study of natural and anthropogenic climate change (Climatic Research Unit, 2010) (UKCP09, 2012b; UKCP09, 2010).

With the level of emissions being the critical factor which differentiates the air temperature change associated with one particular projection from that of another, the scenarios used for UKCP09 come from the set of over 40 developed by the IPCC which are detailed in their Special Report on Emissions Scenarios (SRES) (IPCC, 2000), and which were used in its Fourth Assessment Report. Whilst the scenarios used by UKCP09 do not comprise the full set of SRES emissions scenarios, the disparate scenarios selected - High (SRES A1FI), Medium (SRES A1B) and Low (SRES B1) - allow one to examine the effect of climate change over a wide span of the spectrum of possibilities (UKCP09, 2012c).

As useful as the actual climate projections themselves are in allowing one to attach a probability to the occurrence of any given future climate for a given emissions scenario, assessment of some of the more important aspects of climate change require data at a higher geographical and temporal resolution, viz. regionalised daily data (knowledge of the weather). UKCP09 has constructed a weather generator to provide these data. Observing there to be a statistical relationships between the weather-defining parameters of rainfall, vapour pressure, sunshine hours, mean daily temperature and diurnal temperature range from past weather records (1961-1995), the UKCP09 Weather Generator functions by applying these inter-variable relationships (IVRs) to a stochastic rainfall model to which the UKCP09 climate forecasts have been fitted so as to produce statistically-equivalent, plausible time series of weather (UKCP09, 2012d). Whilst it is extremely unlikely that the particular outcome deriving from any single run of the UKCP09 Weather Generator will occur (i.e. it cannot forecast the actual weather), the monthly/seasonal/annual results obtained through averaging of multiple runs of the Weather Generator do concur with actual UKCP09 climate projections themselves at the 0.5 probability level[3] . Indeed, confirmation of the performance of the Weather Generator to accurately reproduce climate data is seen in a series of UKCP09 plots where the Weather Generator is used to produce backcasts for Ringway for the baseline period 1961-1990[4] (UKCP09, 2009), an example of the high degree of correspondence between observed data and simulated data being shown in Figure 2[5,6].

---

[3] i.e. the central estimate, where temperatures are as likely to be above the forecast value as below the forecast value.

[4] Ringway is a weather station close to Manchester; the Weather Generator was largely calibrated against weather data collected over the period 1961-1990.

[5] Further validation plots for more locations have subsequently been performed and show a similarly high degree of correspondence (UKCP09, 2011a).

[6] Additionally, it should be noted that weather files created by the Weather Generator have been shown to produce comparable internal environments to the CIBSE future weather years created from UKCIP02 data

Minimum temperature

Maximum temperature

Half months
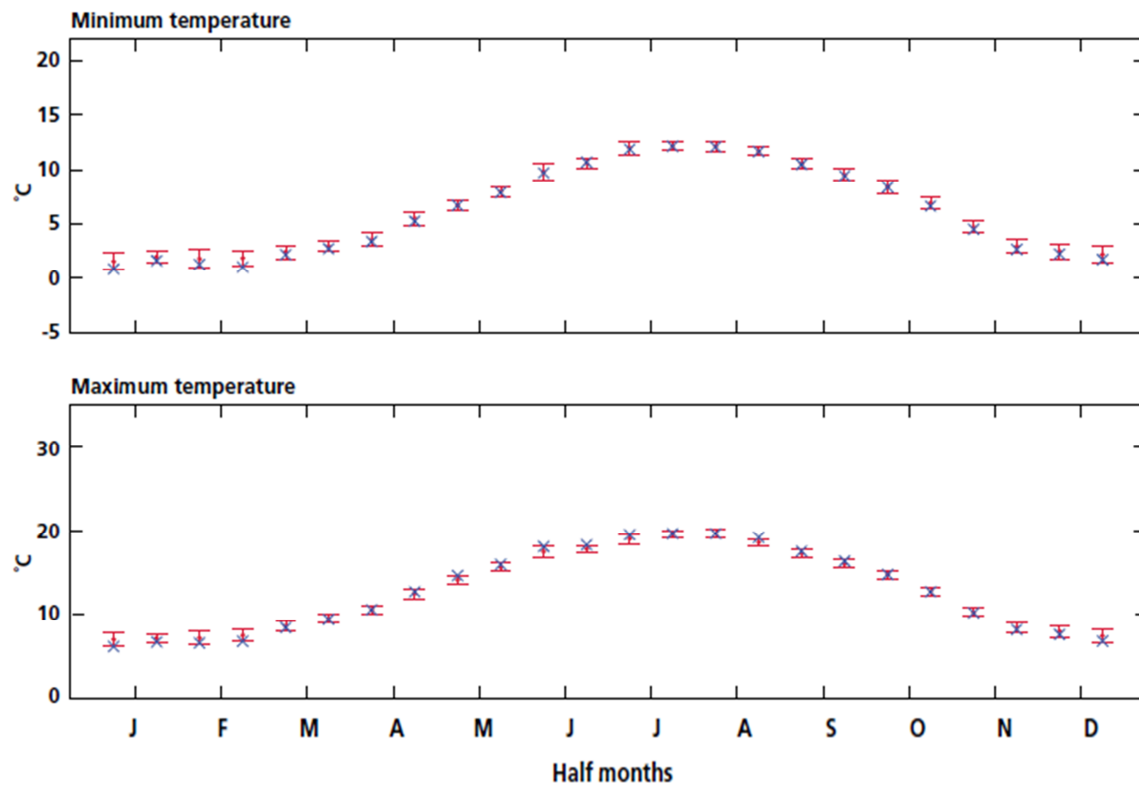
blue crosses - observations
red dots - simulated data (mean of 100 Weather Generator runs)
red bars - simulated data marking the ±2 standard deviation limits which mark out the interval between which 95% of the simulated data fall (from 100 Weather Generator runs)

Figure 2 Validation plot for Ringway observed data based on a 1961–1990 period (UKCP09, 2009)

Of those previously-mentioned aspects of climate change which can only be examined using daily data, four in particular relate to changes in energy consumption in the built environment:

- decrease in demand for space heating
- increase in demand for space cooling
- comparison of adaptive comfort standards
- assessment of the performance of the Department of Climate and Energy Change (DECC) 2050 Calculator

Demand for Space Heating

In view of the fact that the demand for space heating is highest during the summer when air temperatures, on average, are their highest, and that it is at its lowest in winter when air temperatures, on average, are at their lowest (see Figure 3 later), it seems reasonable to investigate whether there is a correlation between air temperature and space heating. If such a correlation exists, one could then apply it to a future climate, where higher average air temperatures are forecast, in order to quantify the demand for space hearting. But since air temperatures are not set

---

(which used the *morphing* procedure), and thus should not be considered inferior in any respect (Eames, et al., 2011).

to rise uniformly over the course of the year, and since they forecast rises vary from location to location (UKCP09, 2012G), the task would have to be performed at a regional level before being built up to the national scale. This is examined further in Chapter 2, in which is described a model which uses daily temperature data disaggregated by location to quantify the reduction in space heating energy.

Demand for Space Cooling

Similarly, the effect of climate change is likely to increase the demand for space cooling. But with the demand likely to be greatest and most frequent in the warmer and more densely populated southern parts of the country, where the set-points of mechanical cooling systems are breached by greater margins and on a more regular occurrence than in other parts of the country, daily regionalised daily temperature data are required in order to fully evaluate the increase in demand for mechanical space cooling. The increase in space cooling energy consumption in the residential stock is estimated by a model described in Chapter 3.

Adaptive Comfort Standards

In recognition of the fact that hotter summers will lead to a greater consumption of energy in the cooling season if that demand for space cooling is met through mechanical systems as mentioned above, attention has lately returned to the Adaptive Approach to Thermal Comfort (AATC) adaptive standards as an alternative means of achieving a thermally comfortable environment in buildings at little or no expense in terms of energy. Yet the two adaptive standards from which energy managers and designers can choose set different temperature limits to describe the zone of thermal comfort, which can lead to very different levels of energy savings. In order to compare the energy savings of buildings which are compliant with the more rigorous ASHRAE adaptive standard with those from buildings which are compliant with the less demanding European adaptive standard, one must use daily temperature since the temperature limits of the European adaptive standard are set with reference to a daily running mean temperature. Chapter 4 compares the energy saving potential of the two adaptive standards, and further explores the issues which may give rise to the difference between them.

DECC 2050 Calculator

In response to the growing realisation that GHG emissions must be curbed if society is not to suffer the more extreme, deleterious consequences of a warming climate, the Climate Change Act was passed in 2008 (Climate Change Act, 2008). The key component of the Act is that overall[7] GHG emissions must be reduced by at least 80% with reference to 1990 baseline levels, such a large reduction in emissions requiring that action is taken since it is extremely unlikely that the target will be attained if a policy of business-as-usual scenario is adopted. Introduced by the Government in

---

[7] i.e. emissions levels may exceed the stated 80% target if the additional emissions are part of a trading scheme; proactive sequestration measures count as negative emissions.

2010, the cross-sector DECC 2050 Calculator provides a mechanism for testing the effectiveness of actions designed to reduce emissions; with regard to the built environment and climate change, this refers to measures designed to reduce space heating and space cooling emissions. Refitting the DECC 2050 Calculator with new input deriving from daily regionalised temperature data allows one to test how well it performs this task, to examine whether it fulfils the function assigned it of ensuring the Government's short- and medium-term planning is consistent with the attainment of the 80% target (DECC, 2012f). Chapter 5 assesses this aspect of the performance of the DECC 2050 Calculator, and examines whether it is fit for purpose.

2 Space Heating Model

The UK Climate Projections (UKCP09) forecast that the coming decades will see a significant rise in temperature over all parts of the country (UKCP09, 2012f). There is also likely to be a concomitant decrease in the demand for space heating in the built environment during the heating season. The level of associated energy savings is necessarily dependent upon the magnitude of the temperature increase and the length by which the heating season is shortened. Given the fact that space heating currently accounts for approximately 43% of energy consumption across the domestic, service and industry sectors in the UK[8] (DECC, 2012h), the savings could be considerable.

This chapter describes a model tasked with quantifying the impact that climate change will have upon space heating consumption in the built environment, across both the domestic stock and the non-domestic (i.e. service plus industry) stock of Great Britain. It explores the varying modelling techniques which can be used to quantify space heating energy savings, culminating in a description of a bespoke space heating model adapted for use with UKCP09 data, and reporting the energy savings forecast by the model

Section 2.1 introduces the possible modelling approaches, Section 2.2 describes the bottom-up approach for a non-domestic model and Section 2.3 describes the top-down approach for a non-domestic model. Section 2.4 moves on to give an overview of the cross-sector top-down National Grid Daily Demand Model. Following this review of the different modelling formats, Section 2.5 describes theSpace Heating Energy Consumption Model for the Building Stock (SHECMOBS), and Section 2.6 reports the results.

2.1 Modelling approaches

Two types of model present themselves as candidates for a stock model: (i) bottom-up model, and (ii) top-down model.

Since the domestic and non-domestic stocks differ in terms of building size, construction and activity, the bottom-up approach necessitates that each are modelled separately. Following extensive characterisation of the residential stock, there exist a number of domestic stock models, notably the Building Research Establishment Housing Model for Energy Studies (BREHOMES) (Shorrock & Dunster, 1997) and the Domestic Energy and Carbon (DECarb) Model (Natarajan & Levermore, 2007), the latter of which used data from the UK Climate Impacts Programme 2002 (UKCIP02), the immediate predecessor of UKCP09, to predict future levels of energy consumption.

Whether the domestic bottom-up model can be used as part of a larger model which models the whole of the built environment, therefore, relies upon whether or not the non-domestic stock can be successfully modelled, either using a bottom-up approach or a top-down approach.

---

[8] These three sectors account for approximately 59% UK energy consumption, with the transport sector accounting for 41%.

Non-Domestic Bottom-Up Model

The bottom-up model reconstitutes the non-domestic stock from the array of its disaggregated constituent elements. At its most basic, the modelling process broadly comprises five steps:

   i.   non-domestic stock is broken down into units of repeatable type,
   ii.   energy consumption of each unit type is calculated,
   iii. energy consumption occurring at unit level is multiplied by the number of units of that type which exist within the stock in order to calculate stock energy consumption,
   iv.   establishment of correlation between stock energy consumption and climate (air temperature), and
   v.   application of correlation to future climates in order to forecast future non-domestic stock energy consumption levels.

Non-Domestic Top-Down Model

The top-down model examines energy consumption data across the non-domestic stock, such data being reported at different levels of specificity (e.g. energy consumption reported by sector or by region), and attempts to identify the dataset which best correlates with reported climate data (air temperature). The correlation deriving from the best-fitting dataset is then applied to future climates in order to forecast future non-domestic stock energy consumption levels.

2.2 Non-Domestic Sector Bottom-up Model

Before the influence of future climates upon energy consumption within the stock can be examined, the bottom-up model demands that the stock must first be characterised. Once characterised, one can then attempt to quantify the influence of climate. The equation describing the bottom-up model as used in BREHOMES and DECarb can be simplified as, where the unitary energy consumption ($e_{i,j}$) is the parameter affected by outdoor air temperature :

Equation 1

$$E = \sum_{i=1}^{N} \sum_{j=1}^{M} e_{i,j} \times n_{i,j}$$

where,

E = energy consumption of stock

i = unit type

j = activity

$e_{i,j}$ = energy consumption of unit of type i and activity j

36

$n_{i,j}$ = number of units of type i and activity j

N = number of different unit types

M = number of different activities

Evaluation of the equation is a relatively straightforward task in relation to the domestic stock. In this case the unit type *i* is a discrete and identifiable dwelling, where the number of different types of dwelling in the stock (N) is simply obtained from surveys such as the regularly updated English Housing Survey (DCLG, 2011); such surveys are realisable because of the great uniformity which exists in the domestic sector, physical inspection of 6,200 properties and interview with 13,300 householders being sufficiently large to capture the 15 basic types[9] which comprise the nation's dwelling stock. Since a dwelling is only associated with one activity (*j*) (i.e. habitation), evaluation of the parameters M and $n_{i,j}$ is also easily accomplished. The final step in the characterisation process, the evaluation of the energy consumption parameter ($e_{i,j}$), is simply achieved by running building simulation programmes for each dwelling type, all of which types have been characterised and of which there are a limited number as previously stated.

The task facing the non-domestic modeller wishing to use the bottom-up approach is, however, of an order of magnitude greater. Regarding building type, not only is there much greater variety in building type and size, but there is also a greater variety in activity too. Nonetheless, two non-domestic models, (i) the Carbon Reduction in Buildings (CaRB) Nondomestic Stock Energy Model (Bruhns, et al., 2006; Bruhns, 2008) and (ii) the Building Research Establishment (BRE) Nondomestic Energy and Emissions Model (NDEEM) (Pout, 2000; Pout, et al., 2002) have attempted to quantify energy consumption within the non-domestic sector[10]. Both models use data from the Nondomestic

---

[9] Detached, semi-detached and terraced dwellings, plus 12 types of flat depending upon number of exposed walls and floor level. It should be noted that further sub-division by wall type, roof type, level of insulation etc. is required to fully characterise the housing stock: DECarb, for example, recognises 8,064 unique combinations (by age) to encapsulate the full breadth of the dwelling stock, whilst BREHOMES, though less comprehensive, still recognises more than 1000 different dwelling categories.

[10] The literature also reports upon another model, described as the UK Non-Domestic Carbon Model (UKNDCM) (Layberry & Hinnells, 2007) or the UK Non-Domestic Carbon Scenario Model (UKNDCSM) (Hinnells, et al., 2008). The model is described as undergoing development, but a search through the literature has revealed no further updates. The model sets out a framework for calculating energy consumption and carbon emissions for different future scenarios, but does not explicitly take account of the facts that the demand for space heating will diminish and the demand for space cooling will increase in a future warmer climate. It resembles the CaRB model and NDEEM, using (in this early stage of the model) the same aged energy consumption data and floorspace data (although further floorspace data is also stated as coming from the Department for Communities and Local Government (1973-2004). Specific energy consumption (energy consumption/m^2) is calculated for each of eight different end-uses (of which space heating and space cooling are two) for a number of different 'building classes'. Furthermore, the model can take account of incidental gains from non-space heating end-uses which contribute to the space heating load, by taking into consideration the proportion of time that the non-heating end-use (e.g. lighting) and space heating are in coincident operation. (Incidental gains which add to the cooling load are calculated in an analogous manner.) The authors state, however, that there is significant potential for error in this aspect of the model since there is little information available. When its output is compared with Government data for 2004, it is seen that the model under-estimates energy consumption in 2004 in the public administration, commerce and miscellaneous sectors by 23%, 6% and 50% respectively. The large disparity between the overall predicted consumption and actual consumption is ascribed to different conditions with respect to climate, energy price

Building Stock (NDBS) Project[11], a research programme funded by the Global Atmosphere Division of the former Department of the Environment, the aim of which was to map the entire non-domestic building stock of England and Wales (Bruhns, et al., 2000b).

With a view to establishing whether or not Equation 1 can be solved for the non-domestic stock, the NDBS data are examined, each of the equation parameters being visited in turn. Section 2.2.1 examines building types (i), Section 2.2.2 examines activities (j), Section 2.2.3 examines the stock size, i.e. numbering parameters (n and M), Section 2.2.4 examines energy consumption (e), and Section 2.2.5 concludes by appraising the CaRB model/NDEEM bottom-up approach.

2.2.1 Non-Domestic Building Type (i)

In order to construct a database of building unit types which is sufficient to map the great variety which exists within the stock, each unit must first be described. Since each unit is described by a number of key elements, these elements, however, must first be identified and described.

The key elements defining non-domestic building type have been explored in great detail by the NDBS Project:

(i)   built form (shape),
(ii)   openings in the fabric of a building (principally glazing (level and type), but additionally including doors),
(iii)   wall type,
(iv)   roof type, and
(v)   building services (e.g. air-conditioning type, heating system type).

The project has yielded an enormous quantity of data, and extensive classification systems have been developed to describe sub-types occurring within each type of element; 17 sub-types of building form by shape (Steadman, et al., 2000a), 66 sub-types of opening (Gakovic, 2000), four basic sub-types of wall construction (Steadman, et al., 2000b), 13 sub-types of roof (Steadman, et al., 2000b), and 37 sub-types of heating , ventilating and air-conditioning (HVAC) systems (Rickaby & Gorgolewski, 2000) have been classified.

A key difficulty lies in the fact whilst energy consumption needs to be measured at the level of the individual building in order to quantify the influence of climate (air temperature), energy consumption may be reported at premises level or sub-premises level: the problem arises because the building may not exactly correspond with the premises for the non-domestic stock. One only has to think of the typical hospital or university, where a single premises may consist of a plethora of different buildings of different sizes and types, in which very different activities may be performed. Moreover, whereas there are huge swathes of uniformity within the domestic stock, each dwelling typically containing only one of each type of element, a single non-domestic building may contain

---

and use of equipment, the UKNDCM energy data having been collected over the period 1990-2002 in contrast to the DUKES data which were collected in 2004.

[11] The data of the NDBS Project were gathered from survey of buildings at 3,350 addresses in Manchester, Swindon, Tamworth and Bury St. Edmunds. External surveys required some 8 person-years to collect and collate the data, and as of 2000, the internal surveys had occupied a team of two to four people for 6 years (Bruhns, et al., 2000b).

several types of any given element. In addition, whilst the vast majority of dwellings fall within a size of limited range, non-domestic buildings range in size from a kiosk in a concourse to the train station in which the kiosk stands. The sheer diversity of the non-domestic stock cannot be under-estimated; and it is this immense diversity which has prevented both the CaRB model and NDEEM from taking full advantage of these painstakingly gathered data, since the various elements have not been mapped with reference to individual building types, as is demanded by building simulation programmes such as EnergyPlus and Tas; and, although stated as being a goal for the CaRB stock energy model (Bruhns, et al., 2006), it would seem, however, that the project concluded in 2010 without having achieved this ambition. In essence, the surveys have yielded insufficient data to solve the term n_i simply because there are so many different non-domestic buildings, the consequence of which is that a bottom-up model of the type used to quantify energy consumption in the domestic stock cannot also be used for the non-domestic stock.

2.2.2 Activity (j)

Although a lack of data prevents Equation 1 being solved in the conventional manner where a unit i is described as a discrete and identifiable building, there are sufficient data to solve the equation if a unit i is re-interpreted as *unit area*. In this construal, the term $e_{i,j}$ evaluates as the specific energy consumption (i.e. energy consumption/m^2) of a particular activity, and the term $n_{i,j}$ evaluates as the total floorspace occupied by that activity in the stock. Indeed, both CaRB and NDEEM recourse to this method in the absence of an alternative. The simplified form of Equation 1 can be written as:

Equation 2

$$E = \sum_{j=1}^{M} n_j \times e$$

where,

n_j = floorspace occupied by activity j

e_j = specific energy consumption activity j

2.2.3 Stock Size

The need to group the thousands of different activities into groups of a manageable size (M) requires judgement, and this has inevitably led to differences between the CaRB model and NDEEM. The CaRB model recognises 65 (70) primary activity types[12] and NDEEM recognises 75 (80) primary types[13] but they both report, however, at the more manageable bulk class level of 11, each class consisting of a number of similar activity types (Table 1). As seen in the table though, the 11 classes of the CaRB model do not cross-correspond with the 11 classes of NDEEM, since different activity groupings were used in the assemblage of the classes of each model.

---

[12] The number of primary types is reported as 65 in (Bruhns, 2008) and as 70 in (Bruhns, et al., 2006).
[13] 80 primary activity types and ten bulk activity classes are reported in the later description of NDEEM (Pout, et al., 2002), the Unclassified class being omitted.

Table 1 Sectoral groupings used to characterise non-domestic stock activities

CaRB Nondomestic Stock Energy Model	NDEEM
Offices	Commercial offices
Retail	Retail
Hotels, catering	Hotels and catering
Leisure	Sports and entertainment
Manufacture	Unclassified
Storage	Warehouses
Transport	Communication and transport
Education	Education
Health	Health
Community	Government
Other	Other

The databanks which the NDBS Project used to quantify floorspace within the stock (n_j) were primarily obtained from the Valuation Office Agency (VOA) of the Inland Revenue, which lists the floorspace data for about 80% of the 1.7 million non-domestic properties in England and Wales[14]. The floorspace for the remaining 0.3 million properties were sourced from multifarious sources, some of the floorspace data having to be approximated using inference processes where data were limited (Bruhns, 2000; Bruhns, et al., 2000a; Bruhns, 2008).

However, the pairing of an activity with a floorspace value was not always straightforward, since premises very often do not present in discrete and tidy forms; for example, there are many instances of shops or factories which contain additional office space, whilst many different activities may be carried out in a single set of premises such as a university.

2.2.4 Energy Consumption

In the absence of a full characterisation of the non-domestic building stock, which precludes the generation of energy consumption data using building simulation software, the CaRB model and NDEEM use energy consumption data gathered in the field from energy survey of sample buildings. Such a method is reliant upon the assumption that, for a given activity, the specific energy consumption values obtained in the sampled buildings are representative of the specific energy consumption of all the buildings within that activity. A laborious procedure, the exercise involves not only physical inspection of buildings, but inspection of the energy-consuming equipment within it and interviews with staff to obtain details of occupancy (numbers and times of use). From these

---

[14] The VOA possesses data for a total of 1.7 million non-domestic premises in England and Wales on which rates are paid (i.e. excludes churches and other places of worship, agricultural buildings and Crown properties (defence establishments, prisons, law courts, central government buildings and "Crown hospitals")) (Bruhns, 2000).

data, consumption estimates can be made and reconciled with actual consumption as recorded from meter readings and energy supply company invoices etc. (Mortimer, et al., 2000a).

Regarding the CaRB model, the energy data comes entirely from energy survey of 740 premises (0.04% of the stock) in the decade beginning 1992 by the Resources Research Unit of Sheffield Hallam University (SHU) (Mortimer, et al., 2000b)[15]; stated as being the most comprehensive non-domestic energy study to date in the UK (Bruhns, et al., 2006), a review of the subsequent literature has yielded no new data as comprehensive as these. NDEEM uses the same data but makes use of additional energy data supplied by local authorities and chains of retail outlets, hotels and other commercial premises (Pout, et al., 2002). In addition, the NDEEM crude results are further normalised to national energy consumption levels (Pout, 2000).

Total energy consumption for a primary activity type in both the CaRB model and NDEEM is calculated as the product of the total floorspace and the corresponding specific energy (kWh/m^2) use for that activity type[16].

2.2.5   Non-Domestic Sector Bottom-Up Appraisal

Considering the fact that there are 1.7 million non-domestic premises in England and Wales, the task of fully characterising the buildings of the non-domestic stock by type is a daunting one if the enormous diversity which resides within the non-domestic stock is to be fully captured. Such is the cost in terms of personnel, time and money in carrying out a comprehensive survey of the non-domestic stock that it is perhaps not surprising that the SHU data and the VOA analysis data have not, thus far, apparently been superseded[17]. Nevertheless, despite the great wealth of information obtained from the NDBS Project data, areas of concern remain.

2.2.5.1 *Representativeness of the Energy Consumption Data*

Most of the activity types show a very large spread in the values of specific energy consumption, where the values at the upper end are an order of magnitude higher than those at the lower end. Taking the activity of *Restaurants and cafés* as an example, specific energy consumption is seen to extend from 1.25 GJ/m^2/year at one extreme to over 5.5 GJ/m^2/year at the other extreme (Mortimer, et al., 2000b). In such a situation where the ranges of reported specific energy

---

[15] The reference actually cited in (Bruhns, et al., 2006) and (Bruhns, 2008) is (Mortimer, et al., 2000a) This is believed to be due to an error in the compilation of the papers; the 2000a paper describes the method by which energy surveys were carried out, whilst the 2000b paper is the one which actually reports the consumption figures.

[16] The exact level of disaggregation used in the calculation of energy consumption in NDEEM is unclear. It is stated that energy consumption in the service sector (other non-domestic sectors are not mentioned) is modelled "with the following levels of disaggregation: [i] seventy-five activities (grouped into eleven activity classes); [ii] nineteen detailed end-uses (nine main end-use categories); [iii] four fuel types (electricity, gas oil, and solid fuels); [iv] and seven size bands." It is not clear whether energy consumptions of groupings [ii] to [iv] are used to construct the energy consumption of an activity class (in the service sector), or whether energy consumptions of groupings [ii] to [iv] are derived from the energy consumption of an activity class.

[17] Following the implementation of the Energy Performance of Buildings Directive in 2008 requiring (i) the display of Display Energy Certificates in public buildings (Article 3), and (ii) the production of Energy Performance Certificates for other non-domestic buildings when constructed let or sold (Article 7) (European Commission, 2002), it is anticipated that new data will start to become available.

consumption values are so large, it is clear that the representativeness of the buildings upon which energy surveys are performed is of paramount importance. Yet, it is not clear that this is the case, a mere 286 retail premises, 186 offices, 50 schools and 20-30 for each of the other sectoral groupings listed in Table 1 being used to model the whole of the non-domestic stock.

2.2.5.2 *Aggregation of Activity Groupings*

In view of the relatively small number of buildings surveyed in the SHU energy survey, it is perhaps a little surprising that the CaRB model apparently so well replicates official energy consumption statistics as reported in DUKES[18]: when the primary activity types of the model are re-grouped into four divisions so as to correspond with the four bulk divisions which constitute the DUKES' non-domestic sectors (viz. public, commerce, miscellaneous and industry), the CaRB model estimates of the public sector and commerce sector for England and Wales are reported as being only 15% lower than actual values for the UK as reported by DUKES for 2004[19] (see Figure 53, Appendix 1). There is, however, a large discrepancy between the DUKES data and the CaRB model data for the industry sector. As pointed out though, one would expect to find a considerable difference between the two since the DUKES industry sectoral data further include energy consumption related to industrial process, which is excluded from the CaRB model (Bruhns, 2008). When this is taken into account, the CaRB model suggests that approximately 49% (or 34%, see Appendix 1) of industrial consumption is building-related. However, this is in disagreement with NDEEM which reports the building-related proportion of the industry sector as amounting to only 18% (Pout, et al., 2002), and in further disagreement with Government statistics (9-11%)[20]. These discrepancies between the models (even though the CaRB model and NDEEM share the same base data, and even though NDEEM data have been normalised against Government DUKES data) brings into question the exactitude of the aggregation process underlying each model. What is more, the fact that the total energy consumption of the four bulk activity divisions in the CaRB model (Figure 53, Appendix 1) is significantly different from the total energy consumption of the 11 primary activity classes (Figure 55, Appendix 1) also asks further questions of the disaggregation process, since there is a difference of 28% between the two, whilst there ought to be none.

2.2.5.3 Age of the Energy Consumption Data

Perhaps the least favourable aspect of these data, however, relate to the age of the SHU energy consumption data, being up to 20 years old in the most extreme case. In view of advances and changes in technology, and changes in working practices, specific energy consumption levels in 2012 are undoubtedly quite different to 1992 - 2000 levels. Whilst Pout has attempted to update the energy data by extrapolation based on product sales and changes in energy consumption, by her

---

[18] NDEEM data cannot be compared with DUKES data since it has been normalised as previously stated.

[19] The 15% discrepancy can, at least in part, be explained by the fact that the CaRB model uses data for England and Wales alone whilst DUKES uses data for the whole of the UK. (DUKES data comprise data from energy supply companies.)

[20] Building-related energy consumption in the industry sector may change from year to year, but it is likely to be of the same order in 2000 (to compare with the CaRB model data) and 2004 (to compare with the NDEEM data). Analysis of Government statistics reveals building-related energy consumption in the industry sector to be estimated at 10.8% (1990), 10.5% (2000), 10.5% (2006), 10.4% (2007), 9.6% (2008) and 9.4% (2009) (DECC, 2011d).

own admission, she states that it is unknown how well the extrapolation procedure reflects fast changing trends in energy demand (Pout, 2007). Are there currently sufficient resources available to develop a precise new non-domestic bottom-up model? It is hard to disagree with Pout (2000) who states:

> *If the housing stock can be effectively represented by 1000 dwelling types, then to represent the entire nondomestic building stock to the same accuracy might require 1 000 000 building types … the availability of consistent, coherent data largely precludes this approach.*

Summarily, the lack of a full characterisation of the non-domestic stock and the aged energy consumption data upon which it must rely preclude the development of a bottom-up non-domestic stock model.

2.3 Non-Domestic Sector Top-down Model

The starting point of any top-down model attempting to quantify the impact of climate change upon space heating energy consumption in the non-domestic stock is to establish if there is a correlation between past weather and past consumption; the equation describing the relationship between past weather and past consumption can then be applied to future weather data in order to calculate future consumption. If a correlation exists, then it is most likely to be found at its strongest in the pairing of weather data with gas consumption data from the service sector in view of the facts that:

i. the service sector accounts for most space heating occurring in the non-domestic stock: 76% occurs in the service sector, with only 24% occurring in the industry sector (DECC, 2011d), and,

ii. gas is the predominant fuel type used for space heating in the service sector: 67% of space heating uses gas, with electricity, the second most important fuel type, only accounting for 19% (DECC, 2011d).

The relationship between gas consumption in the non-domestic stock and the weather is examined in the following sections: Section 2.3.1 considers which gas consumption data are available for the analysis, Section 2.3.2 discusses the choice of weather data, and Section 2.3.3 presents the results and discusses how they may possibly be improved. Section 2.3.4 concludes in an appraisal of the non-domestic sector top-down approach.

2.3.1 Gas Consumption in the Service Sector

In honing in on the service sector as the prime candidate for unearthing a relationship between climate and space heating energy consumption in the non-domestic stock of Great Britain, the analysis is limited to the extent to which national gas consumption has been disaggregated. There are two datasets from which to choose: (i) end-use energy consumption statistics which are

reported annually, and (ii) whole sector consumption statistics which are reported quarterly (and annually)[21]. Given that the end-use statistics are not recorded data, but rather estimates following secondary analysis, one is left to choose the quarterly whole sector statistics. In view of the fact that space heating accounts for 75% of gas consumption in the sector, with the largely non-weather related end-uses of water heating and cooking accounting for the majority of the rest of the consumption (23%) (DECC, 2011d), the inclusion of these latter data in the gas consumption is not, however, considered to be unduly deleterious: since their contribution to total gas consumption in the sector over the course of a year is likely to remain relatively constant, it is considered that they should little disturb the correlation between weather and gas consumption.

2.3.2   Weather Data

The choice of weather data best used as the independent variable in a correlation with gas consumption data is discussed in this section.

2.3.2.1 Degree-days

The relationship between daily mean outdoor air temperature and space heating consumption is a long recognised phenomenon, regression analysis revealing an inverse linear correlation of given slope between the two for a large spread of temperatures. In this linear portion of the graph, each ^{0}C reduction in temperature causes an increase in consumption of y_1. As outdoor air temperatures increase, the linearity of the curve diminishes, however, as heating systems are no longer called upon to maintain indoor thermal comfort. If a linear regression analysis is extended to include these datum points occurring at high temperatures when heating systems are not in operation, the effect is to (i) reduce the coefficient of determination (R^2 value), and (ii) reduce the slope of the linear regression trend line, each ^{0}C reduction in temperature resulting in a fallacious increase in consumption of y_2, where y_2 is less than y_1.

The heating degree-day (HDD) has been conceived as an alternative metric to simple air temperature as a means of circumventing such problems, since it ignores all those days when the temperature is above the threshold temperature (*base temperature*), the temperature above which space heating is not used. Moreover, recognising that the amount of space heating over a period of time is not only dependent upon the magnitude by which the base temperature is exceeded but also on the length of time that the base temperature is exceeded, the HDD also embraces this temporal aspect of weather-related energy consumption. Essentially, the HDD can be thought of as a measure of the length and severity of cold weather over a fixed period of time, cold weather being judged to occur when the outdoor air temperature drops below the base temperature (typically 15.5 ^{0}C) which requires that heating systems are switched on in order to maintain indoor thermal comfort.

There are a number of different ways of calculating degree-days. The simplest method, the mean daily temperature method used by the American Society of Heating, Refrigeration, and Air-

---

[21] National gas consumption statistics derive from data supplied by National Grid and energy suppliers (DECC, 2012d; DECC, 2012e).

Conditioning Engineers (ASHRAE), is the method used in this analysis and is shown in (Equation 3) (CIBSE, 2006)[22].

Equation 3

$$HDD = \sum_{i=1}^{n}(t_b - t_m)$$

where,

HDD = number of heating degree-days over a given period of time (K.day)

t_m = daily mean outdoor temperature (^{0}C)

t_b = base temperature (^{0}C)

n = number of days on which t_m is below t_b over the given period of time

where,

$(t_m - t_b)$ assumes a value of 0 if $t_b < t_m$

2.3.2.2 *Central England Temperature*

As the gas consumption data in Section 2.3.1 are national data, the temperature against which they are correlated must be suitably representative of the country as a whole. The Central England Temperature (CET), a *virtual temperature* representative of a roughly triangular area of the United Kingdom approximately enclosed by the populous conurbations of Bristol, Lancashire and London (and further including that of the West Midlands) (Parker, et al., 1992), is chosen as best characterising the air temperature that most closely corresponds to national gas consumption in the service sector. A composite temperature taken from different weather stations within the area, a large proportion of central England experiences temperatures close to the CET.

2.3.3 Correlation between Space Heating and Weather

Initial analysis suggests a very good correlation between quarterly national gas consumption in the service sector[23] and Central England Temperature[24] degree-days (calculated with reference to a base temperature of 15.5 ^{0}C) (Figure 3 and Figure 4).

---

[22] A cooling degree-day (CDD) is the cooling analogue of the HDD, being measured with reference to exceedance of a given base temperature.

[23] The service sector is designated as *Other final users* in (DECC, 2012g), other final users consisting of the public administration, commerce, agriculture and miscellaneous sub-sectors. Analysis of the 2010 data reveals
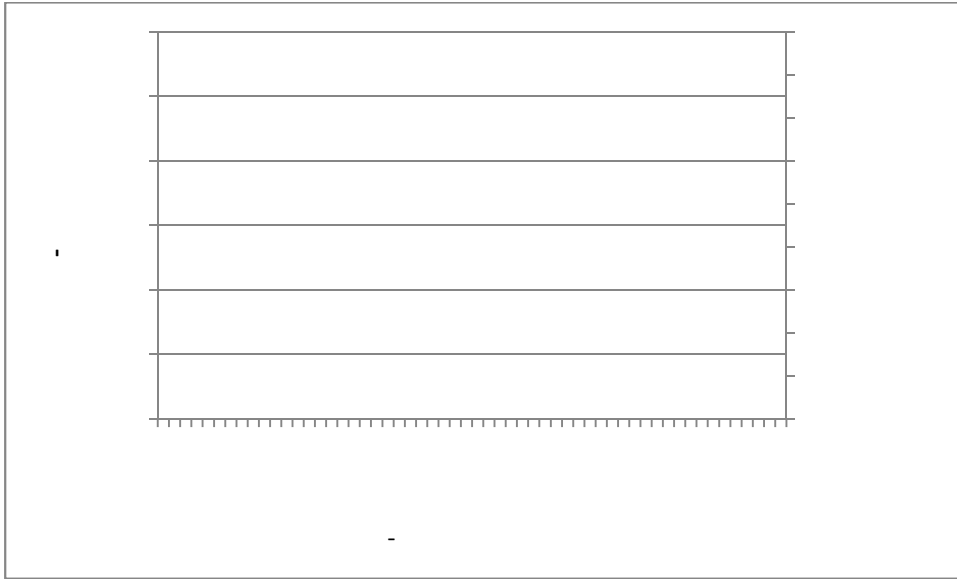
Figure 3 Longitudinal relationship between Central England Temperature HDDs (base temperature 15.5 ^{0}C) and national gas consumption in the service sector over quarterly periods (1998-2011)
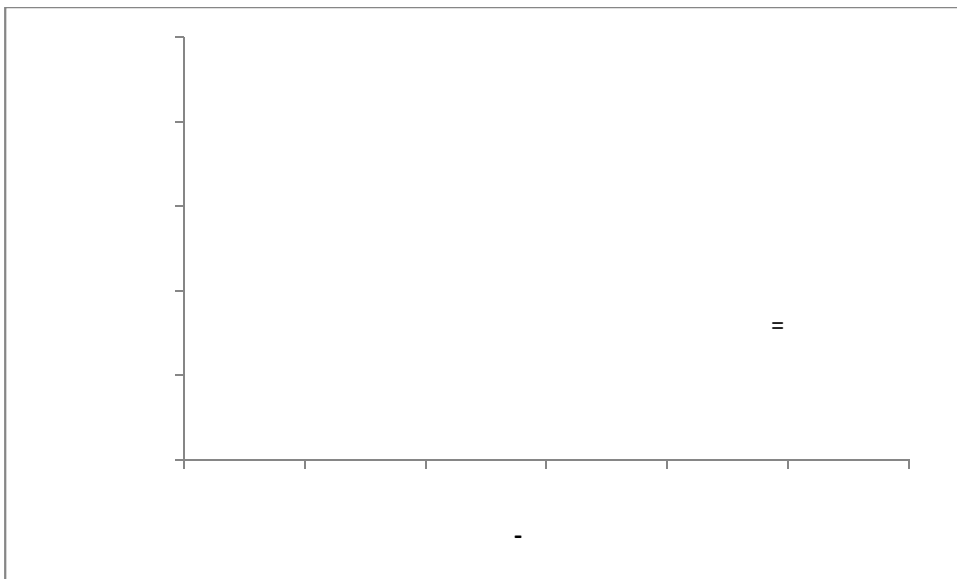
Figure 4 Correlation between national gas consumption in the service sector and Central England Temperature HDDs (base temperature 15.5 ^{0}C) over quarterly periods (1998-2011)

However, it should be noted that with most heating occurring during the winter months and with virtually none at all taking place during the summer months, inclusion of summertime data could serve to introduce spuriously high correlation. Whilst restricting the analysis to an analysis of winter gas demand in response to winter CET degree-days should reveal whether or not this be the case,

that the agriculture sub-sector accounts for2% of consumption and the miscellaneous sector accounts for 19% of consumption. The activities carried out in the miscellaneous sub-sector are many and varied (Standard Industrial Classification (SIC) 2007 codes: 90-99), but are of the type generally perceived to be a service, e.g. activities of sports clubs, library and archive activities, repair of consumer electronics (ONS, 2012).
[24] Source: (UK Meteorological Office, 2012a).

such analysis is hampered by the fact that the quarterly period most commonly used to describe winter (December, January and February) does not coincide with any of the calendar quarter periods used to report gas consumption. That said, it is not considered that using calendar first quarters (January, February and March) for both CET degree-days and gas consumption as an alternative will much interfere with the posited correlation, since there is only 0.3 ^{0}C difference in mean temperature between this quarterly period and the December-February quarter period (UK Meteorological Office, 2012b). So whilst the ideal correlation to investigate would be between (i) *December-February HDDs* and *December-February gas consumption*, the correlation between (ii) *January-March HDDs* and *January-March gas consumption* is examined as an alternative.

Indeed, there is seen to be no correlation when calendar first quarter CET degree-days are plotted against calendar first quarter national gas (Figure 5 and Figure 6).
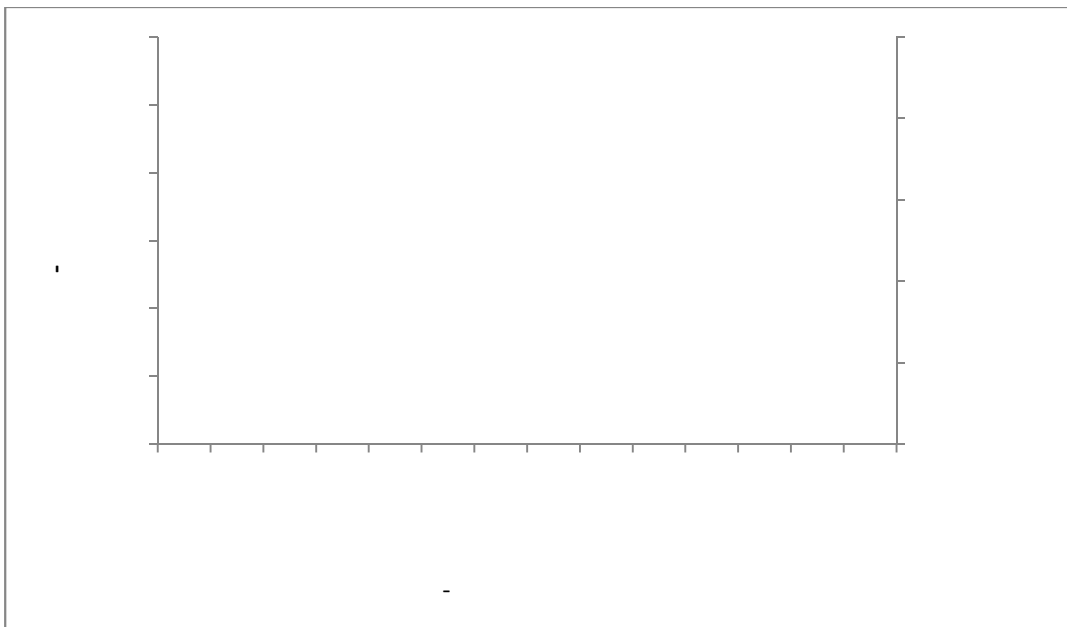
Figure 5 Longitudinal relationship between Central England Temperature HDDs (base temperature 15.5 ^{0}C) and national gas consumption in the service sector for calendar first quarter periods (1998-2011)
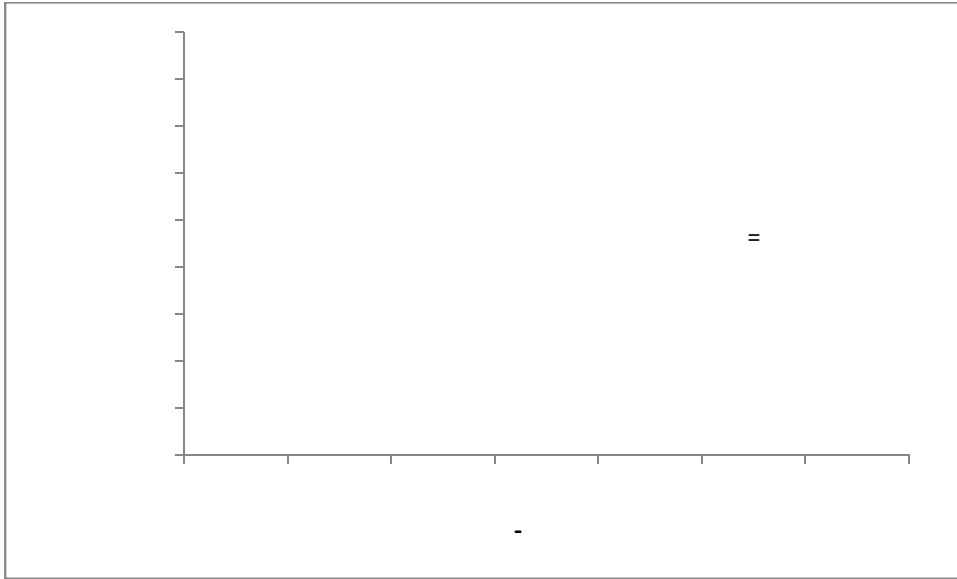
It is clear that further factors are causing scatter in the data. Possible causes of the noise which is obscuring the suspected underlying correlation between consumption and temperature are next examined, with a view to eliminating them.

2.3.3.1 Central England Temperature Representativeness

As the CET is no more than a virtual concept, an amalgam of temperatures from different weather stations, it is possible that it might not be truly representative of a national temperature. The CET, just a single number, fails to say anything about regional variation where, for example, an increase in temperature in the north of the CET region, which is balanced by a decrease in temperature of equal value in the south of the region, would merely be reported as no change in temperature by the CET. This is of especial significance because the CET is not population-weighted and so is not biased towards areas with the highest population centres, and in which gas consumption is greatest.

Examination of HDD profiles from a geographically wide spread of regional weather stations suggests, however, that changes in the CET HDDs are in kilter with HDD changes throughout the country as a whole, the synchronicity of their movement remaining out of step with changes in national gas consumption (Figure 7).
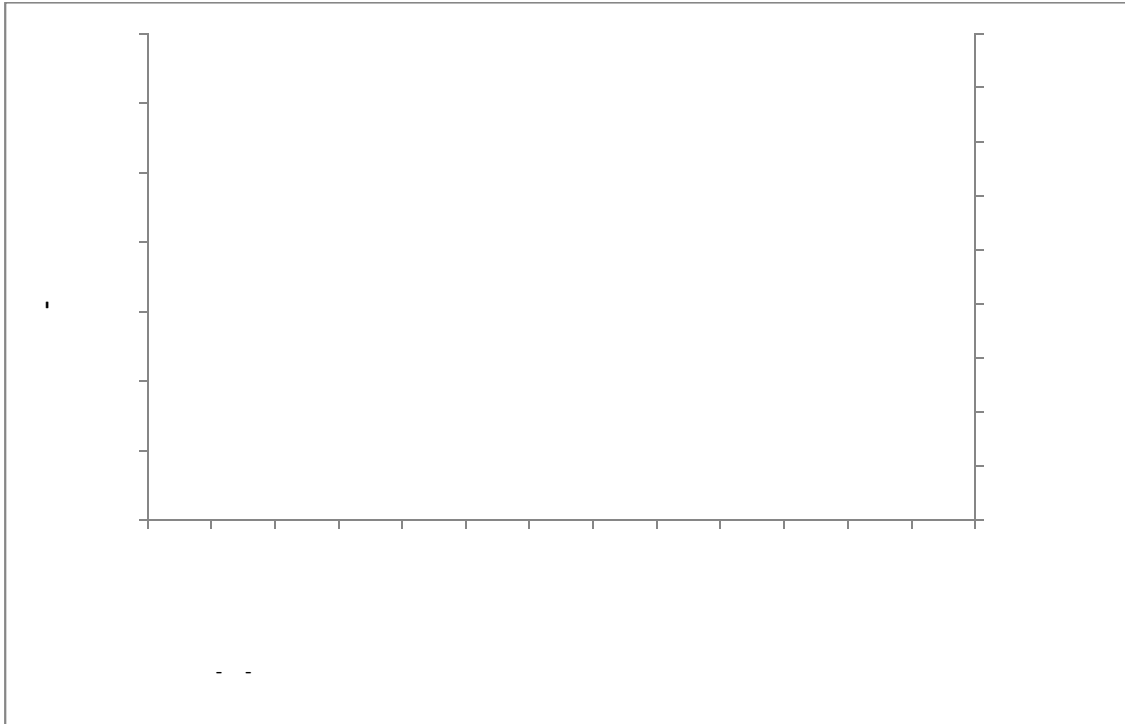
2.3.3.2 Change in Degree-Day Base Temperature

Degree-days are customarily calculated with reference to a base temperature of 15.5 ^{0}C in the United Kingdom, the temperature being based on data from dwellings in the United States in the 1920s, and transposed to a British context in 1934 by Dufton (CIBSE, 2006). In view of the changes experienced over the passage of years in (i) building thermal performance, (ii) incidental gains and (iii) levels of expectation (in consequence of comfort taking), the choice of 15.5 ^{0}C may no longer be appropriate.

As shown in Figure 8 and Figure 9, however, the coefficient of determination is unaffected when the base temperature is either lowered to 14. 5 ^{0}C or raised to 16.5 ^{0}C, there still being an absence of correlation.

---

[25] The regional HDD data derive from hourly observations taken at Meteorological Office weather stations (ECI, 2010). This is in contrast to the CET HDD data which are calculated according to the method described by Equation 3, and derive from daily mean CET data (UK Meteorological Office, 2012a). Despite their different methods of calculation, their movements over the course of time remain highly synchronous.

49
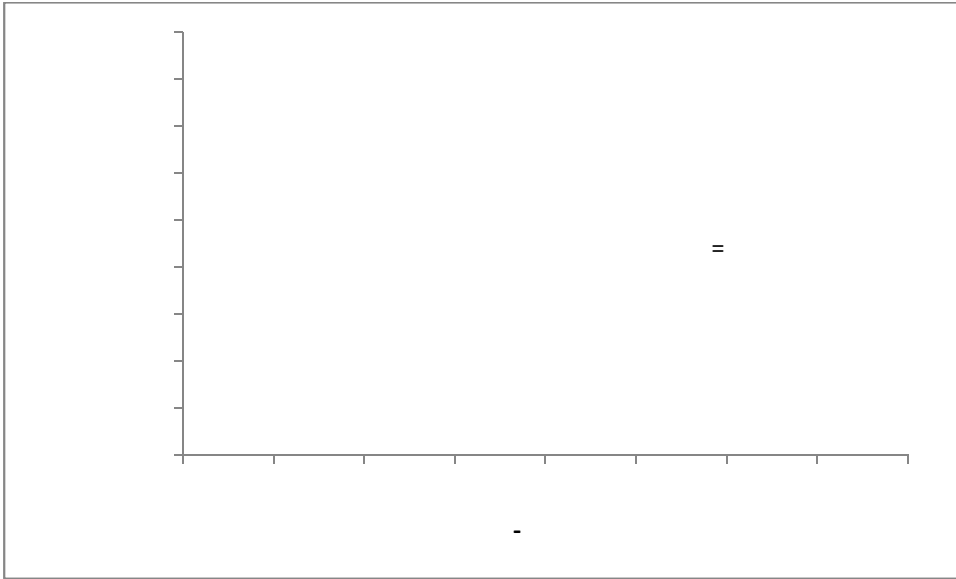
Figure 8 Correlation between national gas consumption in the service sector and Central England Temperature HDDs (base temperature 14.5 ^{o}C) for calendar first quarter periods (1998-2011)
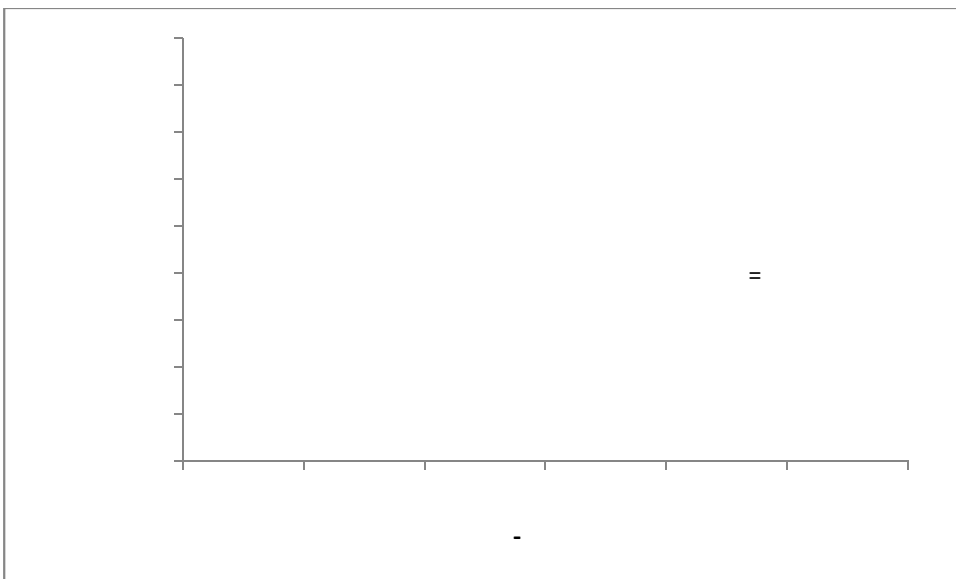
Figure 9 Correlation between national gas consumption in the service sector and Central England Temperature HDDs (base temperature 16.5 ^{o}C) for calendar first quarter periods (1998-2011)

Additionally, it is seen that changing the base temperatures to even more extreme values still does not increase the level of correlation, remaining unchanged at 0.03 for base temperatures of 13.5 ^{o}C, 17.5 ^{o}C, 18.5 ^{o}C and 19.5 ^{o}C and diminishing even further for base temperatures of 12.5 ^{o}C and 11.5 ^{o}C.

2.3.3.3 Base Period of Measurement

The charts above examine data collected over a period of up to 14 years (1998-2011). Changes in the total floorspace, building thermal performance, incidental gains and levels of expectation occurring over this relatively long length of time could manifest itself in the observed scatter. However, repeating the regression analyses for five-year periods of time fails to produce a high degree of correlation in any of the plots (Table 2).

Table 2 Coefficients of determination in the plot of national gas consumption in the service sector against Central England Temperature HDDs (base temperature 15.5 ^{0}C) for calendar first quarter periods over five-year periods of time (1998-2011)

Period of time	R^2 value	Period of time	R^2 value
1998-2002	0.10	2003-2007	0.00
1999-2003	0.32	2004-2008	0.12
2000-2004	0.02	2005-2009	0.05
2001-2005	0.00	2006-2010	0.03
2002-2006	0.12	2007-2011	0.19

2.3.3.4 Disaggregation of Gas Consumption Data

Data for the Government gas statistics are collected (i) annually and quarterly from the country's 20 main gas suppliers[26] (AG1 and QG1 surveys) and (ii) annually from approximately a further 60 smaller suppliers (AG2 survey) (DECC, 2012d)[27]. With a 100% response rate from the main suppliers who are responsible for approximately 95% of gas sales (AG1 and QG1 surveys), and a 25% response rate from the smaller suppliers who are responsible for approximately 5% of sales (AG2 survey), the collected data are not so much a representative sample of gas sales as much as a statement of actual sales. Any errors that there might be within the gas data, therefore, would appear to reside in the disaggregation process which allots gas consumption sub-totals to different sectors, rather than the total gas consumption itself; and indeed the evidence suggests that there may be some error attached to this process. When the relationship between (i) gas consumption in the domestic sector and HDDs is compared to the relationship between (ii) gas consumption in the non-domestic sector and HDDs for quarterly periods, the correlation is seen to be significantly higher in the former case (there being no correlation in the non-domestic sector), even though one might expect to find similar levels of correlation since the proportion of gas used for space heating is similar in both cases[28] (Figure 9, Figure 10 and Figure 11).

---

[26] The main suppliers are required to use the Standard Industrial Classification in their annual data submissions.

[27] The data are further supplemented by data collected monthly or quarterly from the Major Power Producers (MPPs) survey, the Iron and Steel Statistics Bureau (ISSB) survey and an autogenerators survey.

[28] Space heating accounts for76% of gas consumption in the domestic sector and 75% of gas consumption in the service sector (DECC, 2011d).
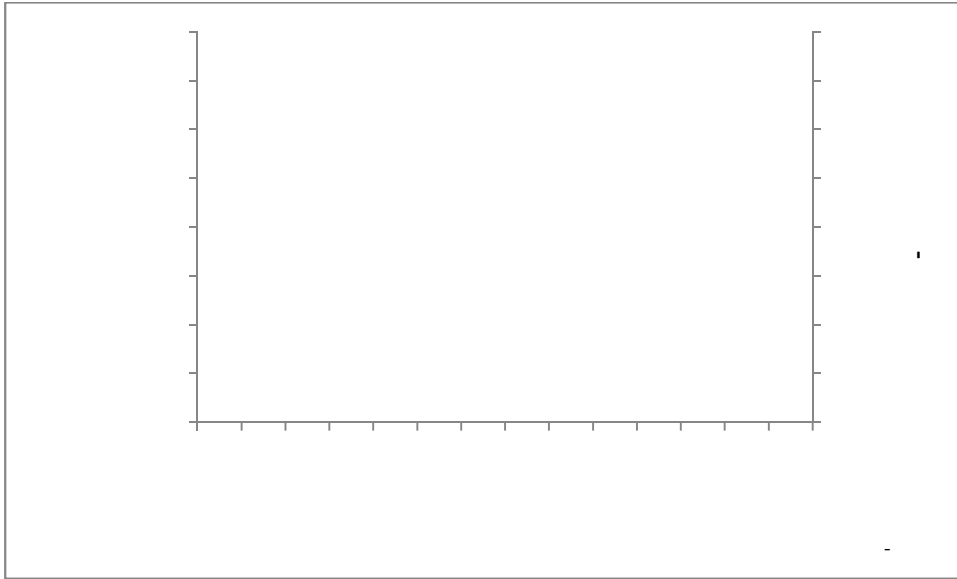
Figure 10 Comparison of national gas consumption in the domestic and service sectors with Central England Temperature HDDs for calendar first quarter periods (1998-2011)
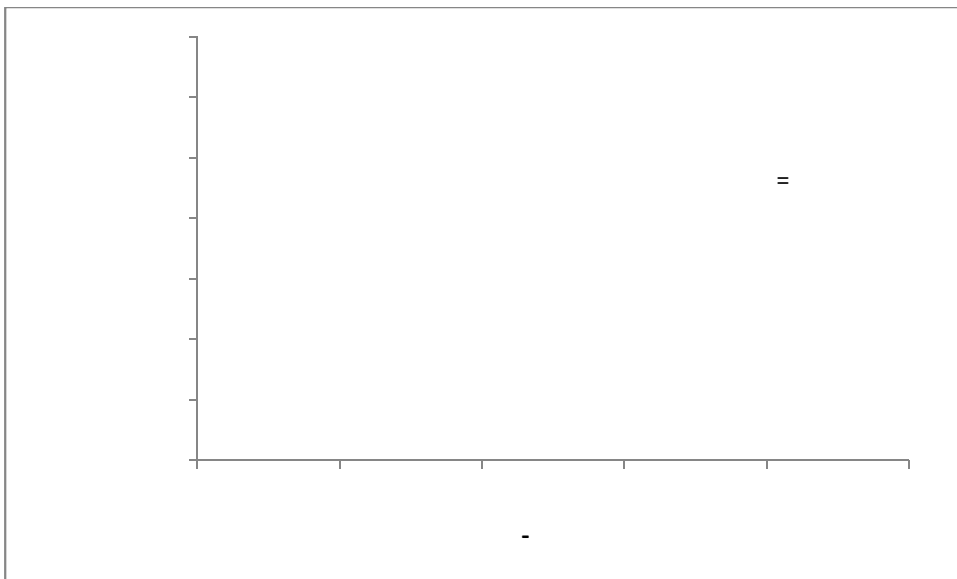
Figure 11 Scatter graph showing correlation between national gas consumption in the domestic sector and Central England Temperature HDDs for calendar first quarter periods (1998-2011)

It is a possibility that part of industry sector gas consumption has incorrectly been apportioned to the service sector, gas consumption in the industry sector (in which large volumes are used in process operations[29]) being less intimately related to climate and more likely to be influenced by economic conditions. However, one cannot exclude the possibility that the rather poor correlation in the service sector arises from a disconnect with the actual weather, resulting perhaps from poor heating controls where heating is supplied although unnecessary (or vice versa). Alternatively

[29] In 2009 (the last year for which data are available) at least 76% of gas consumption in the industry sector was for process operations, with only 11% being used for space heating (DECC, 2011d).

profligacy/lack of awareness in the mindset of users who may not have to pay the heating the bills could be a factor, there being no/little incentive to turn down/switch off heating when opening a window achieves the same result.

2.3.4 Non-Domestic Sector Top-Down Model Appraisal

The evidences suggests that the poor correlation between national gas consumption in the non-domestic sector and degree-days does not derive principally from a deficiency in the quality of the degree-day data, but rather more from problems in the aggregated gas consumption data. Whilst it would seem that problems exist within the sectoral disaggregation process of the non-domestic stock, the still relatively low coefficient of determination for the domestic correlation (0.42) suggests that problems remain elsewhere. It appears that the DECC gas consumption data, published quarterly on a national scale, are simply too coarse, remaining too aggregated at the temporal and/or geographical level to reveal the full complexity of its relationship with climate. This disqualifies the top-down approach as a means of quantifying space heating energy consumption in the non-domestic stock.

In consideration of the fact that a lack of data prevents the development of bespoke non-nondomestic sector model (to be used in conjunction with a domestic sector model such as BREHOMES or DECarb), the cross-sector top-down approach remains the sole method by which space heating energy consumption in the built environment can be quantified. National Grid uses a top-down cross-sector model to forecast daily gas demand. Given the fact that 72% of space heating within the built environment uses gas as its fuel source (DECC, 2012h), it is likely to well represent national patterns of space heating energy in consumption in response to changing weather. This model is examined in the following section in order to establish which elements, if any, can be used in the development of SHECMOBS, a bespoke model described in this thesis to quantify energy consumption across the domestic and non-domestic building stock

2.4 National Grid Daily Demand Model

The gas delivery system in the United Kingdom is a complicated network of producers, transporters, shippers and suppliers. A key player in the market is National Grid, the company which, amongst managing other aspects of the delivery system, owns and operates the National Transmission System (NTS). The NTS is the 7600 km high pressure pipeline which transports gas from eight terminals to over 175 off-take points. From these off-take points the NTS supplies gas directly to (i) Ireland and continental Europe through interconnector pipelines, (ii) a number of large industrial consumers and power stations, and (iii) 13 Local Distribution Zones (LDZs) that contain pipes operating at lower pressure which eventually supply consumers (National Grid, 2012c). Even though the market also contains a number of operators who deliver their gas independently of the NTS, the vast majority of gas is transported through it: total UK consumption figures as reported in DUKES use

national output data from the NTS, with no other source data being cited (DECC, 2011e). In turn, the vast majority of gas used for space heating is conducted through the pipelines of the LDZs.

In its document, *Gas Demand Forecasting Methodology* (National Grid, 2012a), National Grid provides an overview of the process by which it calculates daily gas demand using a cross-sector top-down model. In this model (effectively 13 sub-models – one for each LDZ), it is seen that daily gas demand is proportional to the *Composite Weather Variable (CWV)*, a unified metric amalgamating the five principal determinants of weather which have an influence upon daily gas demand into a single entity. There is seen to be a very close relationship between daily gas demand and the CWV, a near perfect linear correlation[30] being observed, for example, when the seasonal normal LDZ gas demand is plotted against the seasonal normal CWV for the 365 days of the 2009-2010 gas year (Figure 12) (National Grid, 2011).
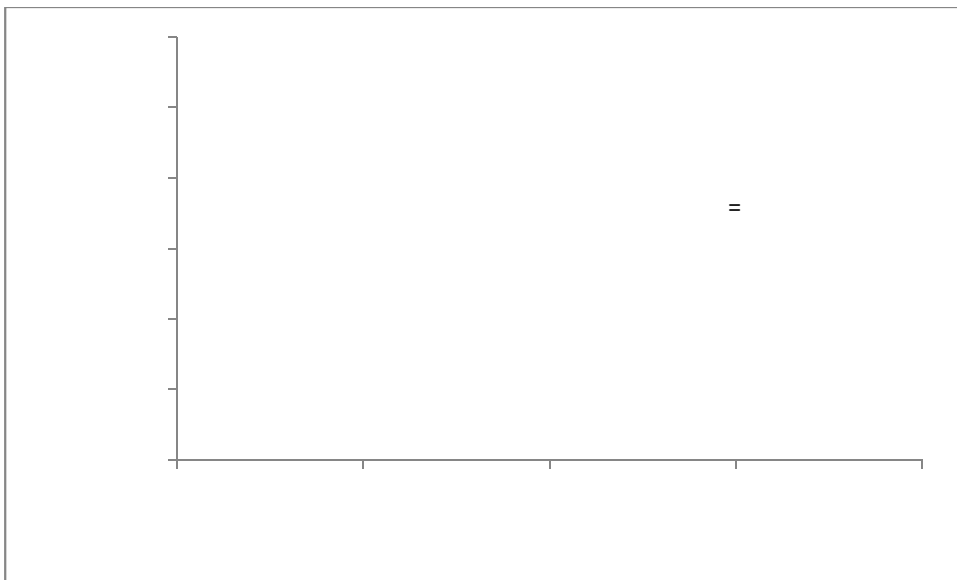
Figure 12 Relationship between the seasonal normal LDZ Daily gas demand and seasonal normal Composite Weather Variable (1 October 2009-31 September2010)

Having established the relationship between the CWV and gas demand, the demand for gas on any particular day in the future can be calculated if the value of the forecast CWV for that day is known.

The five components of the CWV are:

  i.   effective temperature (0.5 x today's temperature + 0.5 x yesterday's effective temperature),
 ii.   pseudo seasonal normal effective temperature,
iii.   wind chill,
 iv.   cold weather upturn, and
  v.   summer cut-off.

---

[30] The plot will necessarily always be imperfect since (i) patterns of demand on weekdays (Monday-Thursday) are different to those at the weekend (Friday-Sunday) and on holidays, and (ii) patterns of demand in autumn are different to those in spring, i.e. consumption resulting from a CWV of a given value will typically be higher for a weekday than for a weekend day/holiday, and higher for an autumn day than a spring day (see Section 2.4.2).

These five elements are examined in turn to establish whether or not the National Grid Daily Demand Model can be used as a basis for formulating SHECMOBS in Section 2.4.1 to Section 2.4.5, with Section 2.4.6 offering a final appraisal.

2.4.1 Effective Temperature

It is found that gas consumption more closely correlates with effective temperature than actual temperature. The effective temperature is a composite temperature which takes account of the fact that thermal comfort is affected by recent thermal experience. National Grid follows the guidance given in British Gas[31] document, TD76 Code of Practice[32] (British Gas, 1987), which states that the daily effective temperature on day n (et_n) should be defined as a function of the average temperature on that particular day (t_n) and preceding[33] days, the preferred definition being:

Equation 4

$$et_n = 0.5t_n + 0.5et_{n-1}$$

As such, the methodology takes account of the lag effect of weather on gas demand, akin to the perception of comfort in the Adaptive Approach to Thermal Comfort as applied in the European Adaptive Comfort standard BS EN 15251:2007 where the perception of comfort is related to a running mean temperature (Nicol & Humphreys, 2010) (see Section 4.2.2).

Since the UKCP09 Weather Generator produces daily weather data, input of daily effective temperature series for SHECMOBS can be achieved without undue difficulty.

2.4.2 Pseudo Seasonal Normal Effective Temperature

The daily seasonal normal effective temperature (SNET) is the averaged, smoothed daily effective temperature over a number of years. When daily gas demand is plotted against daily SNET, the correlation is less good than might have been anticipated. Whilst one might expect a given SNET to result in a given amount of gas being consumed, it is observed that this is not the case: the amount of gas consumed on a day in autumn is likely to be more than that on a day in spring, even though the daily SNET is the same. One cause of the discrepancy relates to the fact that human sensitivity to air temperature is affected not only by recent thermal experience (see Section 2.4.1 above), but is also affected by experience over a longer length of time. In simple terms, having acclimatised to the cold of winter, a temperature of $X\,^\circ$C in spring is perceived as being warmer than the same temperature of $X\,^\circ$C in autumn (when still acclimatised to summer warmth), with the result that

---

[31] British Gas plc. became the monopoly gas supplier in the United Kingdom in 1986 when the nationalised industry was privatised. The company held the monopoly until 1996 when gas supply markets were opened to competition.

[32] All British Gas regions were expected to follow the principles of TD76. The CWV variable is descended from this TD76 methodology. The 0.5 effective temperature parameter value has not changed, remaining a part of the current parameter fitting process. The value of 0.5 suggests that it has always been an arbitrarily selected value rather than the result of in depth analysis (personal communication, Simon Geen (National Grid, contact for *Gas Demand Forecasting Methodology*), 19 March 2009a).

[33] The document accidentally uses the word *proceeding* in the text. The context and insertion of the half-life equation (given above) into the text suggest that this was a typographical error.

heating systems are run for longer/more often in relative terms in autumn. So the same SNET can result in different gas demand datum points in a plot of gas demand against SNET. Counteracting this, a *carry-over* effect in buildings is also likely to be another factor, where buildings with a high thermal mass, which have absorbed and retained some of the heat from summer, have a lower demand for mechanical heating in autumn than in spring, even though the outdoor temperature is the same. In addition, differences in solar gains at different times of the year may be another factor: it is easy to see, for example, how a temperature of 13 °C on a cloudy day in May when the sun is high would result in a different demand for heating compared to a sunny day in October for a south-facing building with a high level of glazing where the sun is low in the sky, even if the outdoor temperature were the same.

The pseudo SNET is the adjusted SNET, where account is taken of this seasonal variation in gas demand. Whilst it is important for the gas industry to take account of this seasonal variation (since it has to anticipate demand for every day of the year in order to ensure that supply meets demand), it is unnecessary to do so for SHECMOBS since it only examines annual average consumption; as long as there is a discernible trend line between daily gas demand and daily effective temperature as shown in Figure 12, scatter either side of the line is unimportant[34].

2.4.3 Wind Chill

Interest in the effect of wind on gas demand became widespread following the exceptionally high demands experienced on a few very windy days in February 1979 (British Gas, 1987). Although the TD76 Code of Practice required that tests for the significance of the chill factor associated with wind be carried out, the guidance stated that, if not statistically significant over several years' past data, the impact made by wind should be ignored.

Whilst inclusion of wind data may possibly serve to reduce the scatter in a plot of daily seasonal normal demand against daily seasonal normal CWV for a particular LDZ, as for the pseudo SNET adjustment mentioned above in Section 2.4.2, it is of little importance as far as SHECMOBS is concerned, as long as there is a discernible trend line between daily gas demand and daily effective temperature as shown in Figure 12[35].

---

[34] Similarly, whilst a daily demand model must take specific account of different patterns of consumption on weekdays, weekend days and holidays, it is unnecessary to do so in a consumption examining annual consumption.

[35] Probabilistic projections of changes in wind were not initially included in UKCP09 because there was too much uncertainty attached to them. Although probabilistic projections for wind speed have since been produced, they are produced in isolation and cannot be used in the Weather Generator projections (UKCP09, 2012a). In consequence, even if the inclusion of wind data did improve the correlation between weather and consumption, they could not be used as an input into the space heating model for future climates, since SHECMOBS relies upon the Weather Generator for its function.

2.4.4 Cold Weather Upturn

The observed linear correlation between effective air temperature and gas demand in the daily model may fail during extreme periods of cold weather[36]. In these instances, the demand of gas appears to be disproportionately large in relation to the temperature and may result from a number of different causes. Whilst the (i) *cancellation of conservation* effect or (ii) *night-override* effect (where central heating is left to run overnight) are cited as possible sources for the observed anomalous demand (British Gas, 1987), (iii) inaccuracy in the measurement of air temperature, where a weather station is sited on a building roof[37], is also suggested as a source of higher than anticipated demand (National Grid, 2012a). Difficulties arise from the fact that whilst the observed increase in uptake in the first two instances is real, it is not in the latter.

It is important that all parts of the regression graph are accurately described, but most especially those parts of the graph when temperatures are lowest and consumption is concomitantly higher. Where there is a cold weather upturn, one cannot simply plot a single linear regression trend line as representing average present day consumption and use the equation of the regression trend line to forecast future consumption, since the incidence of cold weather is likely to diminish in the future (see Appendix 2).

Whether or not a cold weather upturn factor has to be included or not in SHECMOBS is easily established by examining the gas demand/effective temperature regression data for each of the 13 LDZs, a cold weather upturn revealing itself as a deviation in the slope of the trend line. These data are examined in Section 2.5.

2.4.5 Summer Cut-Off

Similarly, it is observed that on exceedance of a certain threshold, increasing air temperatures are seen to no longer effect a change in gas consumption. National Grid implements a warm weather cut-off at the point where there is no further weather sensitivity, since inclusion of these warm weather regression datum points results in an incorrect forecast of demand (see Appendix 2). As such, the application of a warm weather cut-off is tantamount to using degree-days to estimate gas demand (as has previously been described in Section 2.3.2.1), the cut-off temperature being the same as the degree-day base temperature[38].

---

[36] National Grid reports that although a cold weather upturn variable is always included in the daily model, the value of the cold weather upturn is, however, returned as zero for several LDZs (personal communication, Simon Geen (National Grid, contact for *Gas Demand Forecasting Methodology* DECC), 20 October 2010).

[37] When the temperature is very cold, the air temperature recorded at the weather station may not be representative of the air temperatures across the LDZ in general because of the existence of a microclimate atop the roof of the building due to rising heat. It is seen that at least two LDZs use weather data from a building rooftop.

[38] Note that examination of field data gathered for this analysis reveals that there is not a single threshold value above which there is no further weather sensitivity; rather there is a reduced level of weather sensitivity at high temperatures (see Section 2.5). This is not surprising in view of the great variety of buildings (and consequent great variety of base temperatures) which comprise the building stock. In such a case, an additional regression trend line is required to forecast future consumption at higher air temperatures (see Appendix 2, *Reduced Weather Sensitivity in Warm Weather*).

Allowance for reduced consumption in summer for SHECMOBS can be achieved without undue difficulty.

2.4.6 National Grid Daily Demand Model Appraisal

The calculation of the CWV involves the use of parameters which calculates a weighted average of the effective temperature and the pseudo seasonal normal effective temperature. This parameter is different for each LDZ and changes every time the parameters are recalculated every five years, the parameter optimisation process consisting of a number of iterative steps. Unfortunately, National Grid does release these parameters into the public domain (personal communication, Simon Geen (National Grid, contact for *Gas Demand Forecasting Methodology*), 19 March 2009b).

Although one cannot calculate CWVs for use in the future cannot be calculated, one can nevertheless examine whether there is a clear and useable correlation between daily gas demand and weather similar to that in Figure 12, even be it that there expected that there will be a degree of scatter. When daily Non-Daily Metered[39] gas demand for the Southern LDZ (National Grid, 2012c) is plotted against HDDs for Bournemouth[40] (base temperature 15.5 ^{0}C) (ECI, 2010), a clearly discernible trend (and concomitantly high R^2 value) is observed (Figure 13).

Figure with y-axis "Gas demand (mscm)" and x-axis "Degree-days (K.day)", showing trendline equation:
$$y = 1.2145x + 3.6144$$
$$R^2 = 0.89$$
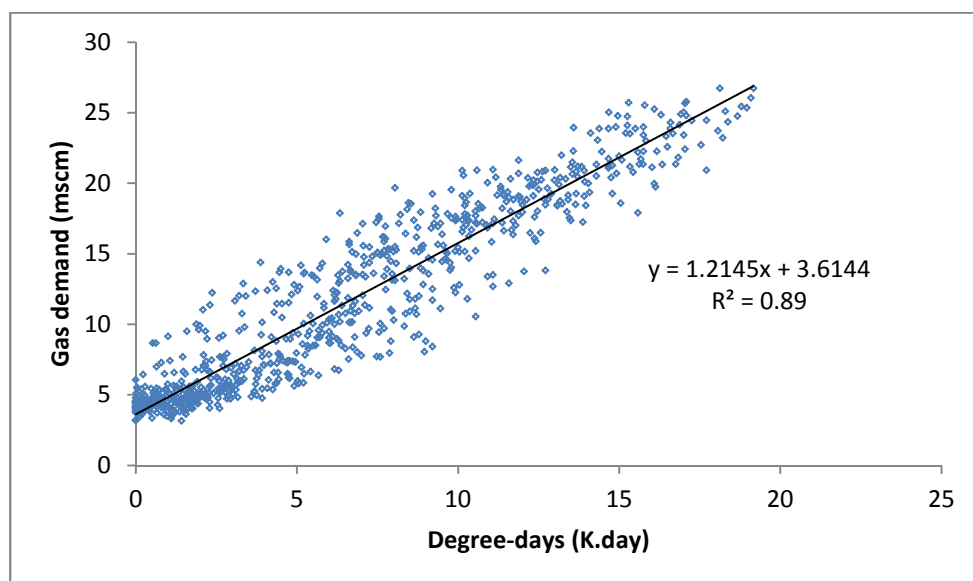
Figure 13 Relationship between daily NDM gas demand in Southern LDZ and heating degree-days for Bournemouth (base temperature 15.5 ^{0}C) (8 November 2008 – 6 January 2011)

More importantly, however, when the plot is repeated only for winter days (December – January), the correlation remains high with a clearly observable trend (Figure 14), which is in stark contrast to the DECC data in Figure 6 where the correlation collapsed for calendar first quarter periods.

---

[39] See Section 2.5.1.
[40] Bournemouth is a city in the Southern LDZ.
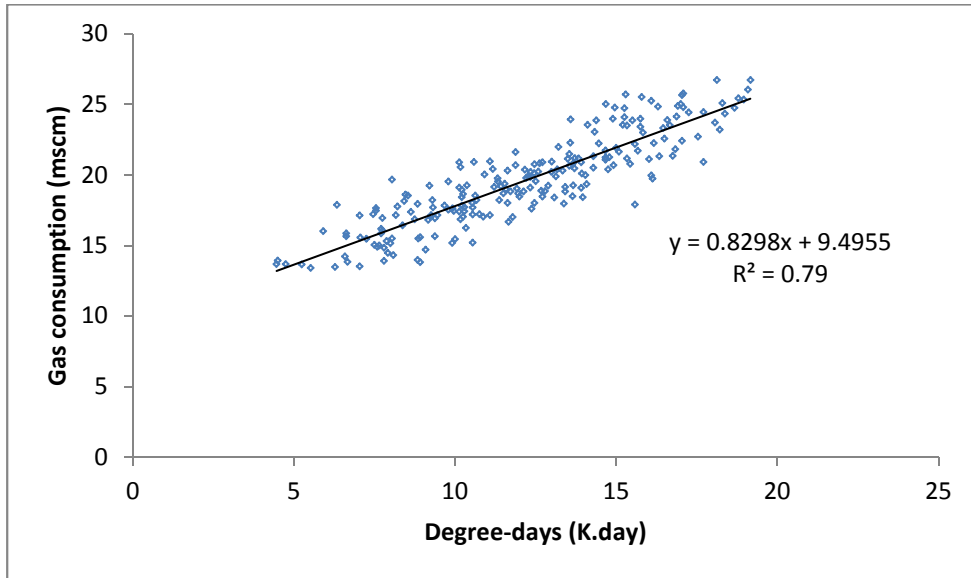
Figure 14 Relationship between daily NDM gas demand in Southern LDZ and heating degree-days for Bournemouth for winter days (base temperature 15.5 ^{0}C) (1 December 2008 – 6 January 2011)

A further point of interest to note is the high concentration of datum points at the extreme-most left of the plot in Figure 13. These data indicate that a choice of 15.5 ^{0}C for the base temperature is of the correct order, but that there are many days when the real base temperature exceeds 15.5 ^{0}C, and it is seen that the equation which describes the annual data in Figure 13 is different to that of the winter data in Figure 14 (in which these datum points of low HDD value are absent). Table 3 compares daily gas demand as calculated by the annual equation and the winter equation for different HDD values.

Table 3 Table Comparison of daily gas demand as calculated by annual equation and winter equation for Southern LDZ for different HDD values

HDDs (K.day)	Daily gas demand (mscm)		Difference (%)
	Annual Equation	Winter Equation	
5	9.7	13.6	-40.9
10	15.8	17.8	-12.9
15	21.8	21.9	-0.5
20	27.9	26.1	6.5

The table shows that that there can be a significant difference between the calculated demand values, and it is clear that a base temperature should not be chosen arbitrarily.

Summarily, the National Grid Daily Demand Models is deemed to provide a suitable framework upon which to build SHECMOBS, but it is also considered that degree-days should not be used as the best metric of weather if the exact base temperature is unknown.

2.5 Space Heating Energy Consumption Model for the Building Stock Model

This section describes the construction of the Space Heating Energy Consumption Model for the Building Stock (SHECMOBS) used for forecasting space heating consumption in future climates. It takes the form of the National Grid Daily Demand Model where disaggregated gas demand data from observations are paired with weather data, and the revealed relationship is applied to future weather data. It comprises four steps:

 i. selection of data (gas demand and weather),
 ii. establishment of correlation between gas demand and weather data,
 iii. establishment of best fit regression trend lines resulting in the formulation of 13 algorithms which are sufficient to characterise national consumption, and
 iv. application of algorithms to future climates projected by the UKCP09 Weather Generator.

These four steps are described in Section 2.5.1 to 2.5.4. The results are presented in Section 2.5.5 and discussed in Section 2.5.6.

2.5.1 Selection of Data

The gas demand data are sourced from National Grid (National Grid, 2012c), and the weather data are sourced from the British Atmospheric Data Centre (BADC) (UK Meteorological Office, 2011).

2.5.1.1 Gas Data

National Grid releases two daily demand datasets for each of the 13 LDZs – the Non-Daily Metered (NDM) dataset and the Daily Metered (DM) dataset. The NDM data account for most of the weather sensitive load and are so called because the gas meters are not read on a daily basis. The DM data typically relate to the gas load for higher demand customers such as large industrial premises, and being less related to the weather, tend to be less variable than the NDM data; the meters are read on a daily basis (National Grid, 2012a). Approximately 80% of the gas transported by National Grid is for the NDM market. Daily demand data are published for each of the datasets for each LDZ.

As the great majority of space heating energy consumption occurs within the NDM dataset and since the DM dataset show only a low degree of correlation with weather (see Appendix 3), the NDM dataset is accordingly chosen as the base data input for SHECMOBS. Unfortunately, since data are not provided for Northern Ireland, SHECMOBS therefore relates to Great Britain rather than the United Kingdom[41].

---

[41] i.e. UK comprises Northern Ireland and Great Britain.

2.5.1.2 *Present Day Weather Data*

Temperature data recorded at weather stations, even though close to one another, can be significantly different. Weather stations across London, for example, have recorded the Urban Heat Island Effect to extend up to 7 ^{0}C (Watkins, et al., 2002), whilst weather stations for Montreal report annual cooling degree-day totals ranging from 158 to 354 (see footnote 118). Since the 13 LDZs are regions which often contain both densely urban and rural areas, with two regions extending to over 200 miles in length, it is clear that a weather station cannot be chosen at random to supply representative weather data for a given LDZ. Therefore, two Met Office weather stations are chosen for each LDZ, the dataset from the weather station which correlates best with the annual gas consumption of the particular LDZ in question eventually being chosen as the representative weather data for input into SHECMOBS. Figure 15 shows the LDZ regions into which the country is divided (National Grid, 2007), and the location of the 26 Met Office weather stations (two per LDZ). Table 4 shows the names and identifying codes of the LDZs and the names of the weather stations, the northern-most station in each pair of stations being labelled as Weather Station 1.

Figure 15 Thirteen LDZs of Great Britain showing the locations of the 26 Met Office weather stations

Table 4 Thirteen LDZs and corresponding Met Office weather stations

LDZ	LDZ Code	Met Office Weather Station 1	Met Office Weather Station 2
Scotland	SC	Glasgow	Edinburgh
Northern	NO	Boulmer	Albemarle
North West	NW	Crosby	Woodford
North East	NE	Dishforth	Linton-on-Ouse
West Midlands	WM	Coleshill	Shobdon
East Midlands	EM	Waddington	Coningsby
Wales North	WN	Valley	Lake Vyrnwy
Wales South	WS	Sennybridge	St. Athan
South West	SW	Filton	Plymouth
South	SO	Middle Wallop	Solent
Eastern	EA	Weybourne	Marham
North Thames	NT	Northolt	Heathrow
South East	SE	Manston	Herstmonceux

2.5.1.3   Age of Correlation Data

In establishing a correlation between past gas demand and past weather data, one has to decide how far in time to go back to collect the data.

National Grid uses data collected from up to the last three years in determining the relationship between gas demand and weather in a LDZ. A regression model is constructed for each of the three years, with actual weather sensitivity of gas demand being calculated from either a single year of data or a combination of all three years. Three years is considered an appropriate time period: using a lesser length of time risks lacing the model with a fallacious weather sensitivity in the case where atypical conditions have caused unusual patterns of gas demand, whereas using a greater length of time increases the risk of the model becoming outdated. The decision to use three years of data (2008-2010) for SHECMOBS is made on the same grounds. In view of the unusually very cold weather experience in January 2010 and December 2010, it is deemed best to consider the 36 months en masse rather than use data for 2010 alone.

2.5.2   Form of Correlation

In establishing a correlation between past gas demand and past weather data, one also has to decide how best to correlate the data in recognition of the fact a linear correlation using HDDs calculated with reference to a base temperature of 15.5 ^{0}C may result in an erroneous estimation of weather sensitivity (Section 2.4.6). The first step in the process involves elucidating the general relationship, establishing the form of the curve in the plot of daily NDM gas demand against daily

effective temperature, for each LDZ. Figure 23 shows a typical regression, where North West LDZ gas demand is plotted against Woodford effective temperature.
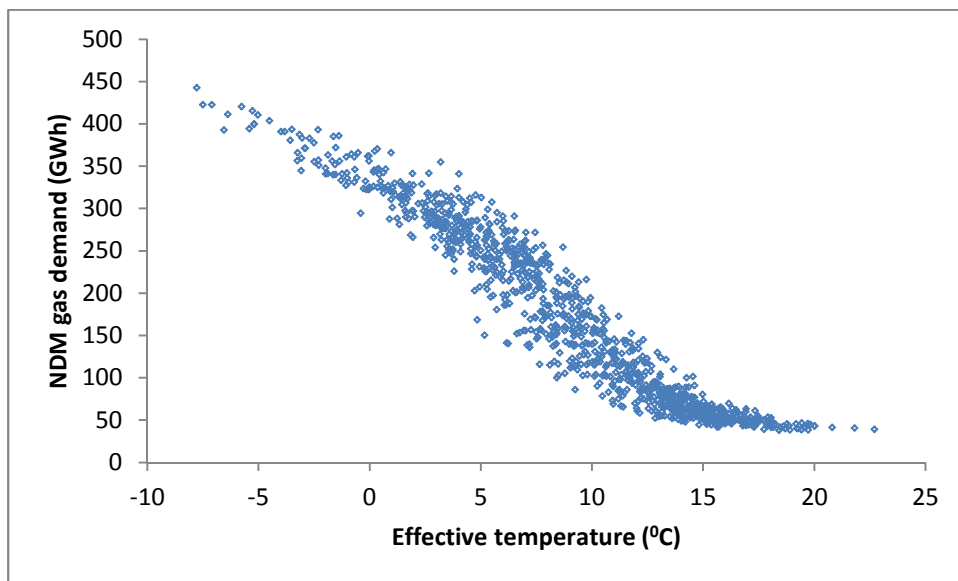
Figure 16 Regression plot of North West LDZ NDM daily gas demand against Woodford effective temperature (2008-2010)

The plots typically resemble a sigmoidal curve. Reading the chart from right to left, weather sensitivity increases as the temperature drops and remains stable in the mid-temperature range; in most plots there is a decrease in sensitivity for low temperatures as in Figure 16 (i.e. cold weather downturn); in a minority of cases the weather sensitivity at low temperatures remains at the same level as for temperatures in the mid-range (e.g. South LDZ/Middle Wallop regression), but in no cases is a cold weather upturn observed. Although most plots show a downturn at low temperatures, and although there is a clear insensitivity to temperature change at high temperatures, identifying the threshold temperatures at which sensitivity changes is less clear.

Logistic transformation suggests itself as the ideal means of surmounting this difficulty since it can be used to transform a sigmoidal curve into a linear curve without requiring the input of these threshold temperatures.

2.5.2.1 Logistic Transformation

The sigmoid curve can be defined by the equation:

Equation 5

$$y = \frac{e^{(a+bx)}}{1 + e^{(a+bx)}}$$

The linear curve created by logistic transformation is defined by the equation:

Equation 6

$$\text{logit}(y) = a + bx$$

where,

$$\text{logit}(y) = ln\left(\frac{y}{1-y}\right)$$

y = space heating occurring on day *i* expressed as a fraction of that which occurs on the day of maximum space heating [42]

x = effective temperature on day i

a, b = constants

Note that the sigmoid-like curve as shown in Figure 16 cannot be transformed in this raw state; the data must first be processed into a useable form: (i) the minimum asymptote must assume a value of 0, so the curve needs to be shifted downwards, and (ii) the level of maximum demand (the maximum asymptote) needs to be ascertained, since *y* cannot be calculated without knowledge of it.

Minimum Asymptote

In the North West LDZ/Woodford example shown in Figure 16 above, subtraction of 38.4 GWh from each NDM gas demand value produces the necessary downward shift[43]. In effect, the non-weather sensitive component of daily gas demand is removed from the data. Downward shifts for the curves of the remaining LDZ/weather station regression plots are achieved in exactly the same way, by subtracting the consumption level which occurred on the day of lowest demand in the particular LDZ in question from all the consumption values for each day within that LDZ.

Maximum Asymptote

It can also be seen in Figure 16 that maximal demand was never achieved in the 36-month period covered by the analysis (i.e. a maximum asymptote was never achieved). Its value, along with the values of the constants *a* and *b*, is calculated using Microsoft Excel Solver.

An initial approximate sigmoid trend line of the form described by Equation 5 is mapped on to the regression data, where the values of the maximum demand and the two additional, constants *a* and *b*, are guessed. Since the values of these three constants are guessed, the trend line is ill-fitting and a low R2 value is returned. Microsoft Excel Solver is set so as to optimise the R^2 value by varying the values of the three constants (maximum demand, *a* and *b*), with the constraints that (i) $0 < R^2 > 1$ and (ii) maximum demand > highest recorded demand in 36-month observation period. The

---

[42] y = 1 when demand is at its maximum (equivalent to the maximum asymptote in a sigmoidal curve); y = 0 when demand is at its minimum (equivalent to the minimum asymptote in a sigmoidal curve).
[43] 38.4 GWh was the demand on the day on which NDM gas demand was lowest in the North West LDZ (26 June 2010).

weather-sensitive regression data for the North West LDZ/Woodford example are re-plotted with the Solver-derived trend line; Figure 17 shows the linear relationship between the logit of gas demand and effective temperature, and Figure 18 transposes the Solver-derived trend line over the original sigmoid-like data.
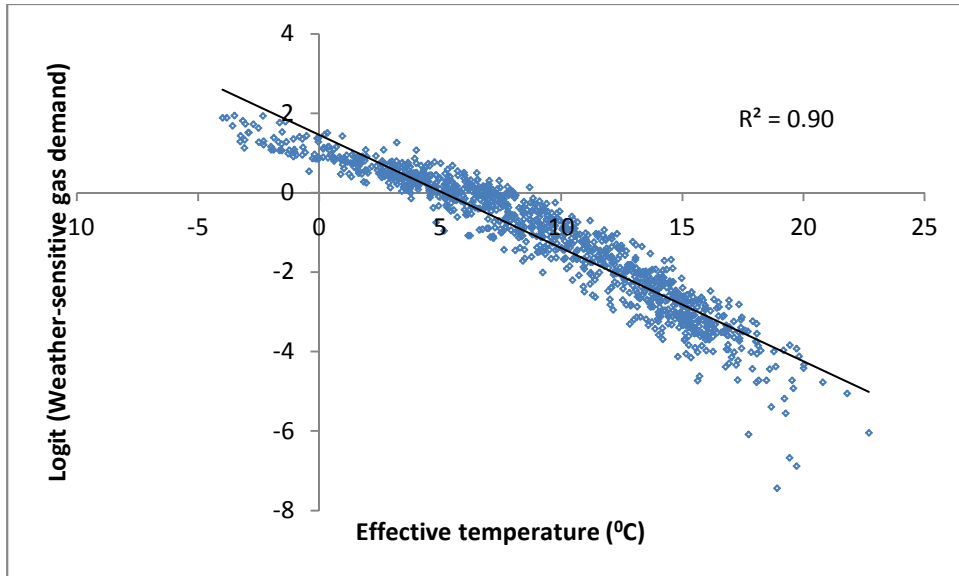
Figure 17 Relationship between logit of North West LDZ daily weather-sensitive NDM gas demand and Woodford effective temperature (2008-2010)
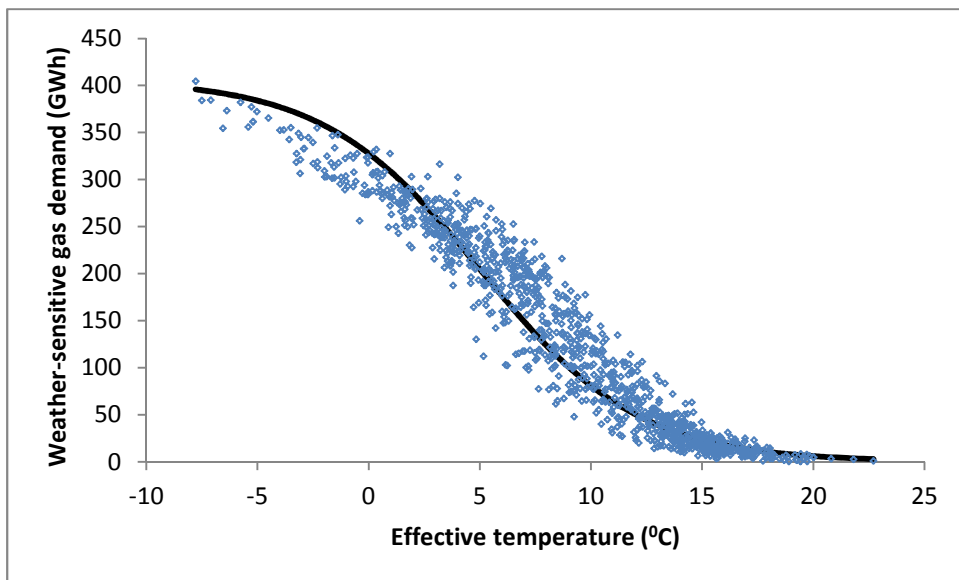
Figure 18 Regression plot of North West LDZ daily weather-sensitive NDM gas demand against Woodford effective temperature showing sigmoidal regression trend line (2008-2010)

The Solver-optimised sigmoid regression trend line is seen to map the regression data in Figure 18 closely, and a high value for the coefficient of determination is returned. But a closer examination of the regression analysis reveals that however well the majority of data are mapped by the trend line,

65

the low temperature and mid-range temperature data are poorly mapped. This arises as a consequence of the fact that there are so many datum points at high temperatures: the highest value for R^2 is achieved by ensuring that the residuals are kept to a minimum in this high temperature region of the plot, the corollary of which is that the lower temperature regions of the plot suffer. If the distribution of temperatures in the future were the same as those of today, the discrepancy would not matter since over-estimates in one part of the year would be exactly cancelled out by under-estimates in other parts of the year (see Appendix 2). But as future climates are likely to be warmer than the present climate, the distribution of temperatures is also likely to be different with fewer datum points in the low temperature region: in consequence the under-estimation of demand for temperatures in the mid-range is not equalled in value by the over-estimation of demand for low temperatures for future climates.

As demand is so high for low and mid-range temperature[44], it is of crucial importance that a regression trend line accurately maps the data in these regions. An alternative statistical solution to this problem is to regress the data piecewise as in the statistical technique known as segmented regression (personal communication, Steve Raper (Statistics Advisory Service University of Bath), 16 May 2011).This is described in the following section.

2.5.2.2 Segmented Regression

In segmented regression, the data are divided into sections and separate regression trend lines are fitted for each segment of the regression. Looking at Figure 16, the data naturally appear to fall into three segments (high, mid-range and low temperature data), and can therefore be fitted with three linear regression trend lines. The difficulty with this method lies in the establishment of the breakpoints which demarcate one segment from another, and indeed, deciding if there is a breakpoint at all; in the case of the South West LDZ/Plymouth for example, whilst there appears to be a breakpoint somewhere in the range 13-14.5 $^{\circ}$C, it is not so clear whether another one also exists which demarcates a cold weather downturn from normal weather sensitivity in the mid-range (Figure 19).

---

[44] In the North West LDZ, 36% of annual consumption occurs when the temperature is below 5 $^{\circ}$C, and a further 50% occurs for temperatures in the range 5-10 $^{\circ}$C (2008-2010).
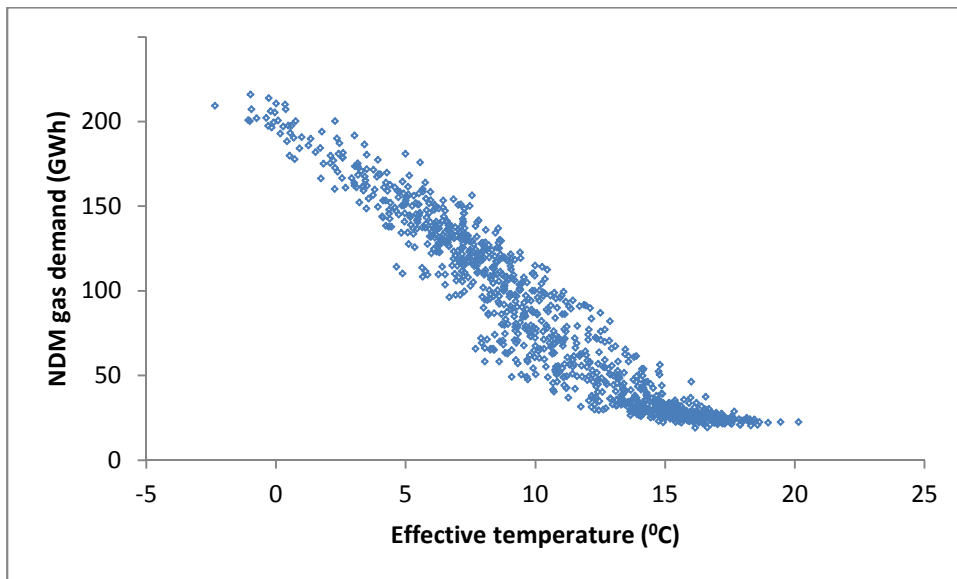
Figure 19 Regression plot of South West LDZ daily weather-sensitive NDM gas demand against Plymouth effective temperature showing sigmoidal regression trend line (2008-2010)

Simply assigning approximate values to the breakpoints as a solution, the underlying premise being that the positive errors in the slope of one or more regression trend lines is cancelled out by the negative errors in the slope of another/other regression trend lines, is not unsatisfactory. When the regression trend lines are fitted to the regression in entirety in such a case, one is likely to find that the individual regression trend lines do not unite to form a single continuous trend line of varying slope, but rather that the line is discontinuous where a step change in demand occurs at each of the break points. Whilst this would not matter if the distribution of future temperatures were the same as the present day, it is likely to make a difference because the future distribution of temperatures, as previously mentioned, is likely to be different: simply, over-estimation of demand in one of the artificially constructed regression trend lines is unlikely to be exactly nullified by under-estimation in the other artificially constructed regression trend line(s)[45] (see Appendix 4).

R is a language and software environment for statistical computing and graphics (R Development Core Team, 2013). It supports a number of different packages, one of which is the Segmented package. This package analyses regression data and finds the best fit breakpoints, allowing the fitting of segmented linear regression trend lines which are continuous with one another. The Segmented package of R is consequently used to analyse the regression data from all 26 regression LDZ gas demand/weather station effective temperature plots.

---

[45] Even though this this no more than a restatement of the assertion that one should not fit a linear regression trend line to data which are not linearly distributed, or that one should not fit an exponential regression trend line to data which are not exponentially distributed, it can be conceptually difficult to understand why the segmented regression lines should align with one another at the breakpoints. Appendix 4 gives an example of how erroneous break points can lead to incorrect estimation of gas consumption.

2.5.3 Best correlation

In all 26 instances there is seen to be a very high degree of correlation between gas demand and effective temperature. In 22 of the regression plots, three separate regression trend lines are obtained; in the remaining four regressions plots[46], two regression trend lines are obtained. An example of one of the three-segment plots is shown in Figure 20.
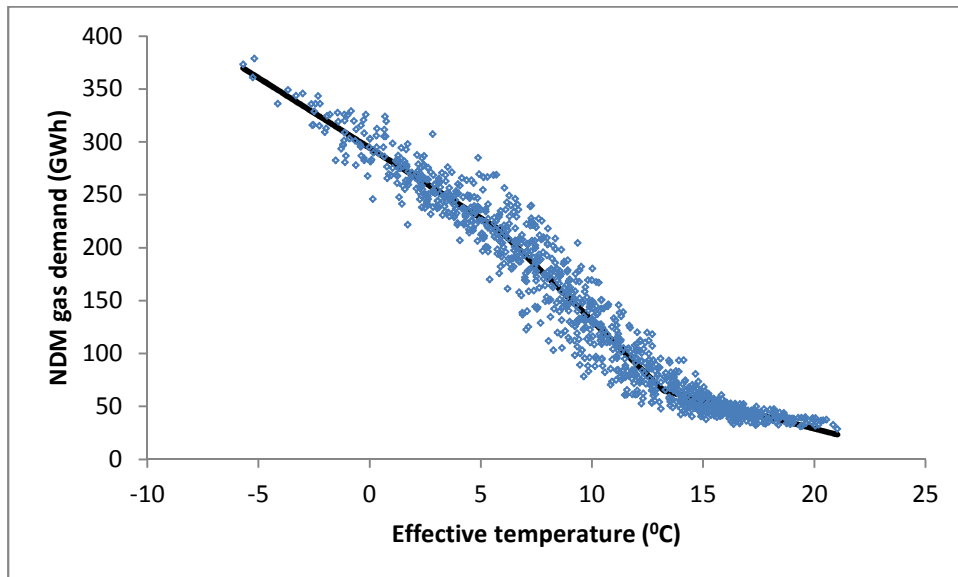
Figure 20 Regression plot of East Midlands LDZ daily weather-sensitive NDM gas demand against Waddington effective temperature showing three segmented linear regression trend lines (2008-2010)

Attention is drawn to the fact that the regression trend line for very high temperatures is seen to under-estimate demand, and the under-estimation would appear to become incrementally more significant the more that the regression trend line is extrapolated beyond the highest observed temperature (21.0 ^{0}C in the example given).   This is not considered to be unduly problematic, however, as there will also be a higher incidence of temperatures in the left portion of right-most regression trend line (13.2-17.5 ^{0}C in the example given) in which over-estimation tends to occur. What is more, given the fact that such a relatively small proportion of consumption occurs at high temperatures (less than 12% of consumption occurs for temperatures above 13.2 ^{0}C in the case of the East Midlands LDZ/Waddington regression above), errors in this part of the regression are of relatively lesser significance than elsewhere where consumption is greater.

Comparison of the multiple R^2 values, all very high in value and ranging from 0.933-0.973, allow one to determine which of the two regression plots for a single LDZ is best chosen as input for SHECMOBS. Table 5 shows these R^2 values, the correlations deriving from the weather stations shaded in grey being used as the SHECMOBS input[47].

---

[46] Three regression trend lines are discerned for the South West LDZ/Plymouth regression plot of Figure 19, which serves to give an indication of the power of the Segmented package.
[47] Note that in the course of writing up this thesis it was noted that the Weybourne correlation instead of the Marham correlation was incorrectly used as SHECMOBS input for the Eastern LDZ, and that the Manston correlation instead of the Herstmonceux correlation was incorrectly used for the South East LDZ. Since the R^2

Table 5 Coefficients of determination in the plot of NDM gas consumption against effective temperature for a segmented linear trend line for 26 LDZ/ weather station combinations

LDZ	Met Office Weather Station 1		Met Office Weather Station 2	
Scotland	Glasgow	0.9592	Edinburgh	0.9461
Northern	Boulmer	0.933	Albemarle	0.9448
North Western	Crosby	0.9467	Woodford	0.9455
North Eastern	Dishforth	0.9449	Linton-on-Ouse	0.9439
West Midlands	Coleshill	0.9512	Shobdon	0.9459
East Midlands	Waddington	0.9599	Coningsby	0.9557
Wales North	Valley	0.9234	Lake Vyrnwy	0.9374
Wales South	Sennybridge	0.9401	St Athan	0.9447
South West	Filton	0.9665	Plymouth	0.9344
South	Middle Wallop	0.9561	Solent	0.9493
Eastern	Weybourne	0.9463	Marham	0.9626
North Thames	Northolt	0.9644	Heathrow	0.9725
South Eastern	Manston	0.9545	Herstmonceux	0.9582

The results of the regression analysis of the Segmented package of R used in the formulation of the 13 resulting algorithms which characterise Great Britain consumption are presented in Appendix 5.3: Regression Algorithms, as are the algorithms themselves.

2.5.4 Application to Future Climates

Future estimates of annual consumption are calculated by applying the 13 composite regression trend lines to future weather data. The future weather data are obtained from daily weather generated from 100 runs of the UKCP09 Weather Generator for each of 117 ternions[48] constituted from:

  i. 13 locations - one for each of the 13 LDZs,
 ii. 3 time-slices -2030s (2020-2049), 2050s (2040-2069), 2080s (2070-2099)[49], and
iii. 3 emissions scenarios - high, medium, low.

With a single run of the Weather Generator producing a 99-year sequence of stationary[50] years of useable daily weather, the average annual energy consumption (E_t) for each ternion is calculated as

---

values are very high and very similar in both cases, it is considered that the impact of these errors on the final results from SHECMOBS is minimal.

[48] An example of a ternion is 'location - North Thames, time-slice - 2030s, emissions scenario - high'.

[49] The Weather Generator makes no distinction between years within a decade, e.g. output for the 2050s is as applicable for 2050 as it is for 2059.

[50] Stationarity – a statistical property which means that little statistical variability is exhibited over the time series, i.e. the 99th year is no less nor more likely to be warmer than the 1st year, any one of which years could represent any of the years within a given time-slice such as 2020-2049. There is no underlying trend (e.g.

shown in Equation 7 and Equation 8, where the average annual energy consumption in each ternion derives from 9,900 (100 x 99) sample years.

Equation 7

$$E_t = \left(\sum_{m=1}^{100} e \right) \Big/ 100$$

where

m = a single 99-year run of the Weather Generator

e = average annual energy consumption in a ternion measured over a 99-year run of the Weather Generator

Equation 8

$$e = \left(\sum_{n=1}^{99} C_{LDZ} \right) \Big/ \left(\frac{36159}{365.25} \right)^{51}$$

where

n = a sample year

C_{LDZ} = annual energy consumption for a sample year in a given ternion (see Appendix 5)

The average national annual space heating energy consumption (E_n) for a given decade in a given emissions scenario is finally calculated by summing the energy consumption totals of the 13 regional ternions specific to the particular decade and emissions scenario in question (*ter*) (Equation 9).

Equation 9

$$E_n = \sum_{ter=1}^{13} E_t$$

---

warming or cooling) in the weather of the 99-year sequence, but weather on one day is contiguous with the weather on the next day, i.e. the weather on a given day is not calculated in isolation, but bears a relation to previous days' weather, as occurs in reality.

[51] The UKCP09 Weather Generator produces years of 365 days, with a leap year every fourth year except for the hundredth year in any sequence, just as in the reality. Thus a sequence of 100 years has 24 leap years 76 non-leap year. There are 36,159 days in 99 years, and there are 365.25 days in a year on average.

2.5.5 SHECMOBS Results

Although principally an energy consumption model, SHECMOBS can also be used to give an indication of the reduction in greenhouse gas emissions resulting from decreased space heating in a future warmer climate. The impact upon energy consumption is reported in Section 2.5.5.1 and the impact upon greenhouse gas emissions is reported in Section 2.5.5.2.

2.5.5.1 Energy Consumption for Building Stock for Future Climate

The levels of NDM gas consumption in future warmer climates as predicted by the UKCP09 data are reported in Table 6, with the percentage reduction in consumption with reference to 2008-2010 being reported in Table 7

Table 6 NDM gas consumption for future warmer climates for different emissions scenarios relative to 2008-2010

	Consumption (GWh)		
	Emissions scenario		
	Low	**Medium**	**High**
Present day*	505540		
2030s	442882	442709	437406
2050s	423864	410471	401939
2080s	400420	374278	339137

2008-2010 average.

Table 7 Change in NDM gas consumption for future warmer climates for different emissions scenarios relative to 2008-2010

	Reduction in Consumption (%)		
	Emissions scenario		
	Low	**Medium**	**High**
2030s	12	12	13
2050s	16	19	20
2080s	21	26	33

The reduction in consumption is significant, with savings of 12-13% being achieved even by the 2030s. The particular emissions pathway followed is not seen to exert a significant effect until the 2050s, and the effect becomes increasingly pronounced the farther forward that one moves in time: by the time the 2080s are reached, NDM consumption levels are forecast to have reduced by fifth, a quarter or a third depending upon whether a low, medium or high emissions pathway is followed.

The actual decrease in space heating is proportionally even larger when one remembers that NDM consumption includes the non-weather-related elements of water heating and cooking (see Appendix 6. If future consumption of these latter two elements remains at the same levels as those of the present day, space heating is forecast to reduce by as much as 45% by the 2080s if heating systems were not to change (Table 8 and Table 10).

Table 8 NDM space heating gas consumption for future warmer climates for different emissions scenarios relative to 2008-2010

	Consumption (GWh)		
	Emissions scenario		
	Low	Medium	High
Present day*	370195		
2030s	307537	307365	302062
2050s	288519	275126	266595
2080s	265075	238933	203792

2008-2010 average.

Table 9 Change in NDM space heating gas consumption for future warmer climates for different emissions scenarios relative to 2008-2010

	Reduction in Consumption (%)		
	Emissions scenario		
	Low	Medium	High
Present day*			
2030s	17	17	18
2050s	22	26	28
2080s	28	35	45

NDM space heating consumption for 2007 calculates as 358,377 GWh. The reduction in space heating by 2050 under a medium emissions scenario calculates as 23%[52].

2.5.5.2 Reduction in Greenhouse Gas Emissions

Whilst the knowledge that a given rise in temperature will result in a given reduction in the demand for space heating is meaningful and the prognostication can be made with a certain the degree of confidence, unfortunately the same is not true with regard to forecasts concerning changes in emission levels. An increase in temperature of *x* resulting in a reduction of space heating energy consumption of percentage *y* for the year *z* would only result in a corresponding reduction of

---

[52] See Section 5.2.1 for the relevance of this information.

emissions of *y%* if the make-up of the energy generation and supply network in the year *z* had the same structure and fuel carbon intensities as that of the present day. But it is extremely unlikely that either the same split of fuels will be used in the future as for the present day as electric space heating becomes more widespread and gas-fired space heating declines, or that the carbon intensity of those fuels will be the same in the future as they are today. Indeed, the carbon intensity of electricity currently even varies on a daily basis, the price differential between coal and gas determining in large part how much of each fuel power stations use to meet the nation's electricity demand. Whilst, for example, 41% of electricity derived from the combustion of coal in 2006, the figure was 31% in 2009, increasing again to 34% in 2011 (DECC, 2012i). Therefore, caution must be exercised when evaluating the impact of climate change upon space heating in terms of emissions reductions.

Space heating GHG emissions for 2009, the last year for which there is a complete set of data, evaluate as 87 $MtCO_2$[53] (DECC, 2012c); space heating GHG emissions calculate as 15.5% of the nation's cross-sector total of 562 $MtCO_2$e for 2009 (DECC, 2012c). Taking account of the warning above, estimates of the reductions in emissions which would occur by the 2050s with reference to 2009 (if heating systems and fuel intensities were to remain unchanged) are shown in Table 10.

Table 10 Space heating emissions GHG emissions and reduction in emissions by the 2050s due to decrease in space heating compared to 2009 levels

	2009	2050s Emissions scenario		
		Low	Med	High
Space heating emissions ($MtCO_2$e)	92.5	72.1	68.8	66.6
Reduction in emissions (across built environment) (%)*		5.9	6.8	7.4
Reduction in emissions (across all sectors) (%)*		3.6	4.2	4.5

** Percentage reduction in space heating accords with the reduction in space heating in*Table 8 *(i.e. over the period 2008-2010 to 2050s). Space heating in the 2050s is assumed to have the same make-up as that of 2009.*

Although the values in themselves do not carry much significance, they do serve to lend a general perspective, giving an indication of the contribution that a reduction in space heating can make in achieving the 80% target of the Climate Change Act 2008: approximately 15.5% of the nation's emissions are currently due to space heating, and temperatures similar to those forecast for the 2050s would result in a reduction of emissions of the order of 4%.

2.5.6   Discussion of SHECMOBS

Of course, the understanding implied by these findings is that comfort taking, where people heat their homes to a higher level of comfort, do no negate or lessen the forecast reduction in space heating. This cannot be dismissed, in view of the finding that absolute levels of energy consumption have remained rather steady over the past 40 years or more, despite increasing levels of insulation. But whilst levels of central heating were very small in 1970, penetration is over 90% now. This

---

[53] Includes electricity emissions.

suggests that are homes are much better heated in the present day. Since, as a society, we are generally much more thermally comfortable than in the past, it is to be anticipated that levels of comfort taking will be less than in the past, thus limiting the size of any comfort taking (rebound effect).

Whilst a decrease in the level of space heating is not unexpected as the century progresses or as emissions levels increase, the extent of the diminution is perhaps rather surprising, especially that in the near term. The reduction in consumption between now and the 2030s (approximately 25 years) is forecast as being even larger than that between the 2050s and 2080s (approximately 30 years). One must ask the questions why the reduction in consumption is so large, and, in view of the fact that the greatest changes in air temperature associated with climate change are not forecast as occurring until the latter decades of the century, why in particular is the reduction by the 2030s so large.

2.5.6.1 Verification of Results

Deriving from millions of items of UKCP09 weather data in 1300 files, the process by which these raw data are converted by the algorithms listed in Appendix 5.3: Regression Algorithms into average annual consumption for ternions involves hundreds if not thousands of lines of Visual Basic for Applications (VBA) coding. In such a multi-step process there is a clear possibility of introducing error which not easily detectable. In consequence the results should be checked against other weather data.

As part of the Coincident Probabilistic climate change weather data for a Sustainable built Environment (COPSE) (ARCC, 2012), the University of Manchester have produced a number of future TRYs[54], developed from 3000 years of future weather data produced by the UKCP09 Weather Generator, the data being prepared in a manner following the ISO standard ISO BS EN ISO 15927 Part 4 (2005) (Watkins, et al., 2011). These future TRYs, comparable to conventional TRYs, provide a basis for checking the robustness of the procedure used in this analysis. Whilst the consumption forecast for a given ternion from SHECMOBS is the average consumption forecast of 9900 stationary years, the consumption forecast from a TRY year is the consumption deriving from a single year which can be described as a typical year, the typicality referring to its weather. Thus the averageness of the former is defined by its averageness in terms of its energy consumption, whilst the typicality of the latter is defined by the typicality of its weather. Therefore, although one would expect to find that energy consumption in a typical year would be close to average energy consumption, one would not necessarily expect to find that they were exactly equal. In essence, one "typical year" of weather could result in a level of energy consumption which is different from another year which might also be described as a "typical year" in terms of its weather, since typical does not mean average.

---

[54] A conventional TRY is a year of typical weather based on observations, calculated so as to incorporate an element of the variability seen in real weather, e.g. the daily mean temperature in a TRY, whether a conventional TRY or a future TRY, does not increase in an incremental fashion in contrast to an average weather year (where the daily temperature on a given day is calculated as the average of many years of data for that day).

When annual consumption calculated used the averaging process used in this analysis is compared against annual consumption using the future COPSE TRYs, the results are seen to closely resemble one another, but not equal one another, as one would expect; Table 11 shows the percentage difference in annual NDM consumption values calculated using the two different procedures for the eight different ternions which are available for cross-comparison.

Table 11 Percentage by which annual NDM gas consumption calculated using COPSE TRYS differs from annual gas consumption calculated using SHECMOBS averaging process

	London (Heathrow)		Manchester (Woodford/Ringway)	
	Emissions scenario		Emissions scenario	
	Low	High	Low	High
2050s	-1.2	-1.4	-4.0	-1.0
2080s	-1.7	1.3	-4.3	-2.3

Although the data for Manchester does show a little more variation than that for Heathrow, this is not unexpected because the weather station used for Manchester in the COPSE TRY (Ringway) is different to the Manchester weather station used in the averaging process employed by SHECMOBS (Woodford).

One can conclude, therefore, that the calculation method used to produce average weather years is robust.

2.5.6.2 Normalisation of Results

The reason, in part, why the decrease is in reduction is so large is because present day consumption is based on the period 2008-2010, a period during which the winters have been atypically cold. The winter months' CET for 2008-2010 records as 3.2 ^{0}C, which compares with a temperature of 4.1 ^{0}C for the period 1961-1990 (1970s) (baseline average used by UKCP09), since which time, on average, there has been a general increase in temperature, despite the atypicality of the period 2008-2010. The winter months' CET for the period 2000-2007 is almost 2 ^{0}C higher than that for the period 2008-2010, recording at 5.1 ^{0}C. If temperatures during the period 2008-2010 had been closer to the long-term average, then gas consumption during this period would have been lower, the outcome of which would be that the relative decrease in future consumption (especially that in the near term) would have been lower.

The temptation in such a case is to discard the period 2008-2010 as anomalous and attach the label "present day" or "normal" to data from the period 2000-2007. However, despite the winters being less cold, NDM gas consumption is seen to be no less during this period (Figure 21), the discrepancy being thought to derive from the continuing improvement in the thermal performance of the building stock. Thus the relative reduction in space heating is not reduced by using consumption data from the period 2000-2007 as the reference period against which to measure the change.
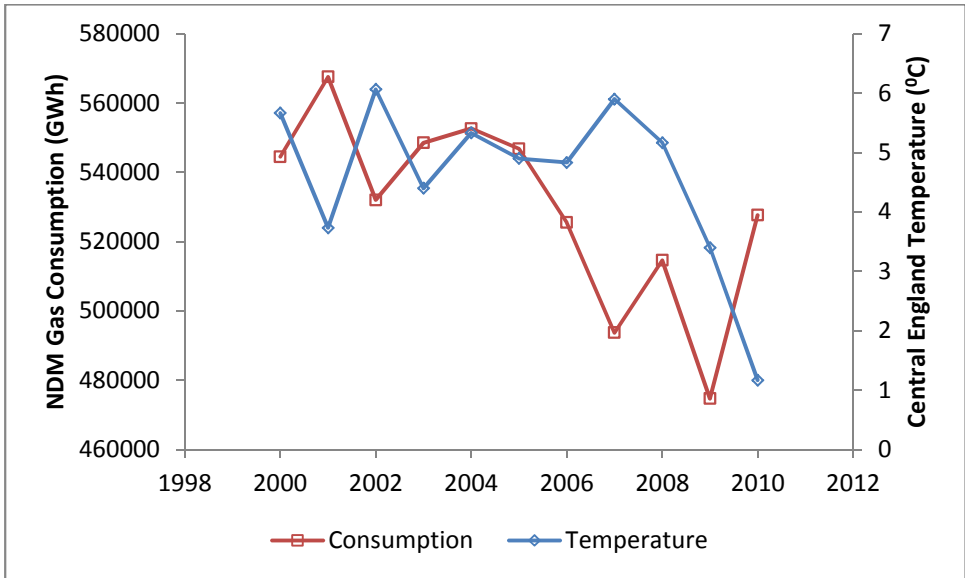
Figure 21 Comparison of NDM gas consumption and winter CET (December, January, February) (2000-2007)

An alternative approach is to replace the observed value for present day consumption with a normalised value calculated with regard to 2000-2011 average temperatures (Figure 22). Although present day consumption is not real, in the sense that it is only an estimate of what the consumption level in the present stock would be under the relatively warm climate of 2000-2011, it perhaps presents a more authentic picture of the effect of climate change upon space heating consumption in the present building stock.
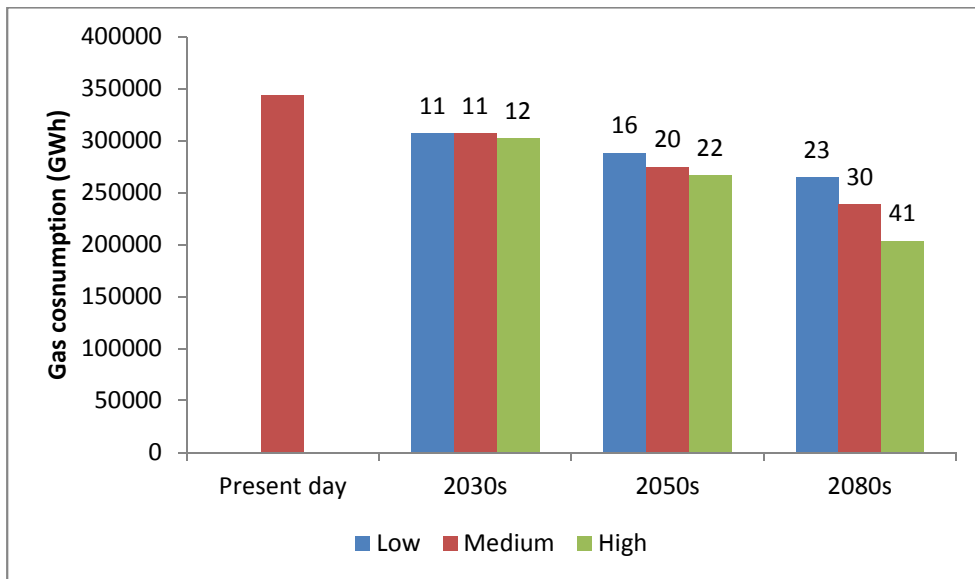
The numbers on top of the columns are the percentage reductions in NDM space heating gas consumption with reference to the 2000-2010 baseline average.

Figure 22 Normalised change in NDM space heating gas consumption for future warmer climates for different emissions scenarios relative to 2000-2010[55]

Nevertheless, the decrease in consumption by the 2030s, standing at 11-12%, still remains striking. This results from the fact that in a warming climate, a unit change in temperature produces a greater fall in consumption in the near term than the same unit change in temperature occurring later on, even where the relationship between consumption and temperature drop is perfectly linear. As this can be conceptually difficult to grasp, a stylised example which illustrates this principle is given in Appendix 7.

---

[55] Figures atop the bars indicate the percentage reduction in consumption.

3 Space Cooling Model

Having elucidated the relationship between climate and space heating energy consumption, one is left to consider whether a similar approach can be used to determine the levels of space cooling required to maintain comfort in response to a warming climate. In this instance, one could expect to see an increase in the amount of electricity used by mechanical cooling systems in response to elevated air temperatures since mechanical systems primarily run on electricity. Although the matter is complicated by the fact that mechanical cooling systems are predominated by air conditioning systems which not only cool the air but additionally condition it in the form of dehumidification and filtration, there nevertheless remains a good correlation between air temperature or degree-days and mechanical cooling energy consumption as later detailed in Section 4.2.

Government data are examined in Section 3.1 and National Grid data are examined in Section 3.2. Section 3.3 examines other models which have attempted to describe space cooling energy consumption. Sections 3.4-3.9 describe and present the results of a new space cooling energy consumption model for the residential sector, and Section 3.10 concludes with a discussion of the model.

Before embarking upon the analysis, it should be noted at this point that space cooling energy in the residential sector is the primary focus of this chapter. This is not to say that space cooling energy consumption in the non-domestic stock is unimportant, but rather that it presents a less definitive profile of climate change-related space cooling energy consumption. Growth in air-conditioning in business has been primarily attributed to the increasing use of Information Technology equipment and higher concentrations of staff (Carbon Trust, 2005), with levels of space cooling in the non-domestic sector being likely to be affected by the requirement to counteract the higher metabolic gains and higher equipment gains in a way that they are, for the most part, not in the residential sector. However, the large increase in air-conditioned commercial buildings in Europe is also ascribed to the perception that a non-air-conditioned office is not seen as being of investment quality (Guertler & Pett, 2008). Current levels of sales also suggest that climate is less influential with regard to the uptake of air-conditioning in the non-domestic sector, there being relatively high levels of sales in this sector (relative to residential use) in moderate climates (DGTREN, 2008). With the Building Services and Research Association (BSRIA) estimating the penetration rate of air-conditioning in the commercial market at 42% (in comparison to its figure of 3% for the residential market) (BSRIA, 2011), it is clear that the uptake of air-conditioning in the commercial sector is driven by further socio-economic factors which bear little influence in the residential sector.

3.1 Government Data

The Department of Climate and Energy Change (DECC) collects and releases national electricity consumption which are disaggregated by (i) time, (ii) region and (iii) end-use. These are examined in turn.

3.1.1 Time Disaggregated Data (Monthly Data)

In contrast to the Government gas consumption statistics which are reported no more frequently than quarterly, sectoral electricity consumption data are reported on a monthly calendar basis (DECC, 2012i). Its usefulness in a longitudinal analysis, however, is restricted by the fact that the monthly reporting only extends as far as the three sectoral groupings of (i) non-domestic & non-industry (NDNI) multi-sector[56], (ii) domestic and (iii) industry, and does not report upon end-use. When national NDNI electricity consumption is plotted against the Central England Temperature, rising temperatures show no sign of reciprocation in elevated levels of electricity consumption (Figure 23).

Figure 23 Relationship between adjusted electricity consumption[57] for NDNI multi-sector and mean monthly Central England Temperature (2005-2009)[58, 59]

---

[56] The NDNI multi-sector comprises the service, transport and agriculture sectors; electricity usage in this multi-sector is likely to be dominated by the service sector.

[57] Adjusted electricity consumption - the monthly consumption for a particular year is adjusted by the ratio of the annual consumption for that particular year to the average annual consumption over the entire period of the data., e.g. adjusted electricity consumption for June 2007 = electricity consumption for June 2007 x mean annual electricity consumption for period 2005-2009 ÷ electricity consumption for 2007. The principle is illustrated in Appendix 8.

[58] Data are also available for the period 1995-2004, but they are not contiguous with the data in Figure 23 since the former use the "statistical reporting period" which may be either four or five weeks long.

[59] The same pattern of diminishing electricity consumption as outdoor air temperature increases is seen in the domestic sector.

Although the electricity consumption has been trend adjusted to lessen the influence of non-climatic factors such as changes in the building stock, energy prices, appliance usage and efficiencies[57] (Sailor & Munoz, 1997; Sailor & Pavlova, 2003), consumption is actually seen to decrease as the air temperature increases. This is in contrast to data reported elsewhere where, depending upon location, electricity consumption can be seen to peak during the warmer summer months (Sailor & Pavlova, 2003; Sailor & Vasireddy, 2006). It is clear that air temperature-dependent increases in the amount of electricity consumed by mechanical space cooling systems in the UK are being masked by other intra-year factors[60] exerting a greater influence which the process of annual trend adjustment is incapable of isolating. However, when the relationship between adjusted electricity consumption and individual mean monthly CET is explored in individual plots for the months of June, July and August as a means of circumventing/minimising this problem, the level of correlation is remains low, even if consumption is seen to increase as air temperature increases (Table 12).

Table 12 Coefficient of Determination for the plot: adjusted electricity consumption versus mean monthly Central England Temperature for (i) the NDNI multi-sector and (ii) the domestic sector (2005-2010)

	NDNI multi-sector	Domestic sector
June	0.00	0.04
July	0.04	0.08
August	0.70[61]	0.16

3.1.2   Regionalised Data

Although electricity consumption is reported at the local authority level (of which there are 400) (DECC, 2012b), it suffers the same disadvantages as the monthly disaggregated data in that neither sub-sectoral nor end-use consumption are reported. In addition it is further disadvantaged by the fact that data are only reported annually.

Taking the local authority of Wealden in the south east of England as a typical example, the correlation between domestic electricity consumption and mean annual temperature (as represented by the local weather station of Herstmonceux (UK Meteorological Office, 2011)) is poor (Figure 24).

---

[60] e.g. the decrease in electrical heating and lighting as temperatures increase and the daytime becomes longer during the summer months.
[61] In view of the low R^2 values observed elsewhere, the disproportionately large R^2 value associated with August for the NDNI sector suggests that its high value is rather more likely to be due to chance than due to a causal nexus.
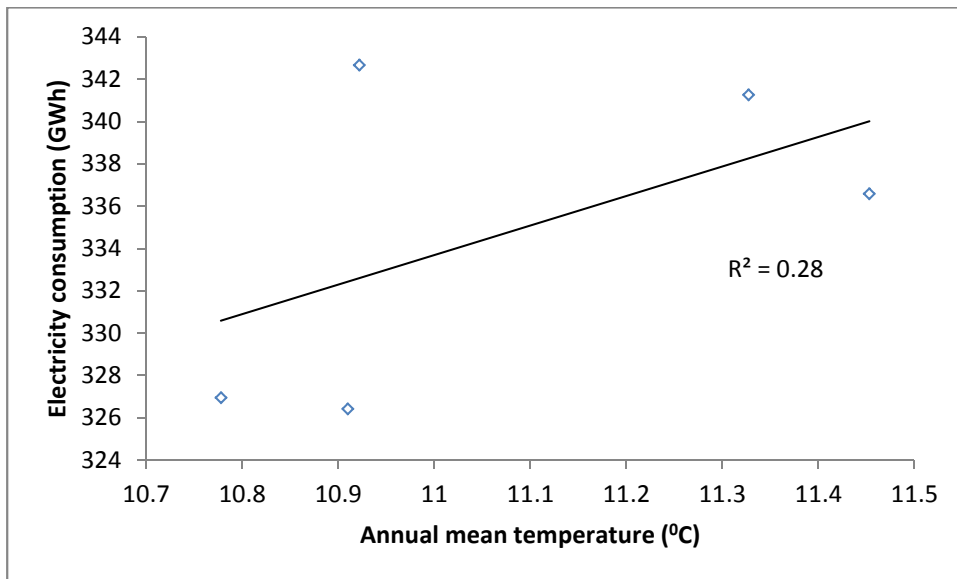
Figure 24 Relationship between electricity consumption in the domestic sector (Wealden) and annual mean temperature (Herstmonceux) (2005-2009) [62,63]

3.1.3 End-Use Data

Whilst a certain amount of electricity consumption is reported by end-use in the Government publication, Energy Consumption in the United Kingdom (DECC, 2011d), once again its usefulness is limited, being constrained by the facts that:-

   i.   only annual data are available ,

   ii.   the data are not disaggregated at a regional level,

   iii.   cooling and ventilation are grouped together as a single end-use[64],

   iv.   the end-use data derive from a secondary analysis of data from the Digest of United Kingdom energy statistics (DUKES), Office for National Statistics and Building Research Establishment (BRE) (i.e. the figures are derivations, rather than actual measures of consumption), and

   v.   cooling and ventilation data are reported only for the service sector, and not for the domestic and industry sectors.

In consequence, with regard to establishing whether or not there is a correlation between space cooling and air temperature, the best use that can be made of these Government data is to plot (a) cooling & ventilation electricity consumption within the service sector against (b) the CET (UK Meteorological Office, 2012a), the CET acting as a surrogate for "national temperature" (Figure 25).

---

[62] Data for 2003 and 2004 also exist, but are cited as being "experimental series".

[63] The R^2 value for the combined commerce & industry sector is 0.11.

[64] The Department of Energy and Climate Change (DECC) states that the Building Research Establishment (BRE) is responsible for the provision of these data (personal communication, Will Rose (DECC), 1 December 2011). A request was sent to the BRE asking for information on the split between the two components, but it failed to generate a response.
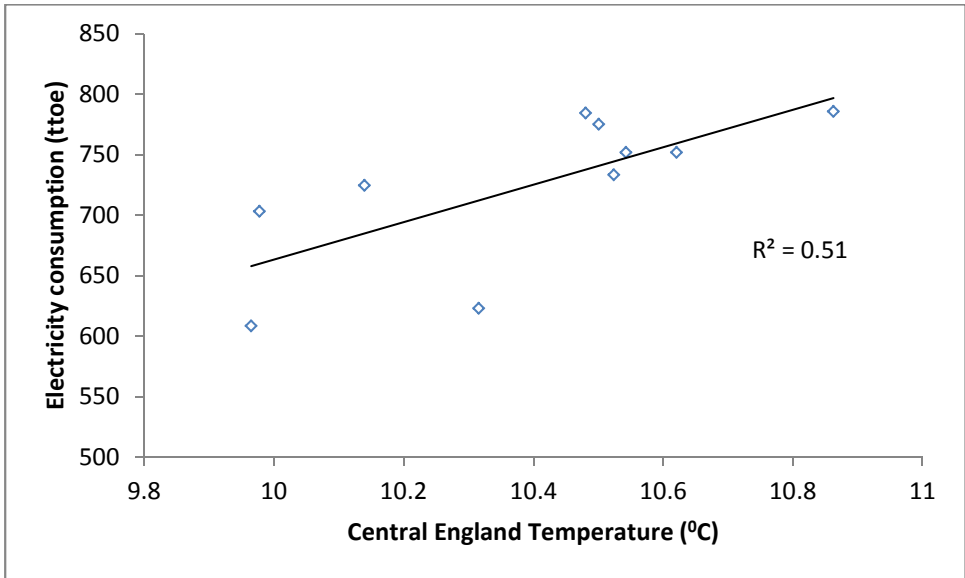
Figure 25 Relationship between cooling & ventilation electricity consumption for service sector and Central England Temperature (2000-2009)[65]

Although electricity consumption is seen to increase with temperature, the level of correlation is, however, rather too low (R^2 = 0.5) to further extend this stream of analysis.

3.2 National Grid

In addition to owning the previously mentioned gas National Transmission System (NTS), National Grid (NG) owns and operates the National Transmission Network (NTN) (more commonly, and perhaps somewhat confusingly, referred to as the National Grid), the NTN being the electricity analogue of the NTS (National Grid, 2012b). Whilst NG is not responsible for the transmission of all the electricity consumed within the UK, the great majority of electricity is transmitted through the NTN.

Although National Grid only reports upon England & Wales consumption (GWh) up to 2004, it does, however, continue to report upon demand (MW) at the half-hourly level. These data allow one to theoretically calculate energy consumption (MWh), where consumption for a particular day calculates thus:

Equation 10

$$daily\ consumption = \sum_{t=1}^{48} demand/2$$

---

[65] More than 95% of cooling and ventilation consumption in the service sector derives from electricity. Inclusion of additional consumption deriving from fossil fuels has negligible impact on the coefficient of determination: the R^2 value increases from 0.51 to 0.52 if fossil fuels are further included.

Using this method, the annual consumption for England & Wales for 2004 calculates as 309,557 GWh. Comparing very closely with the actual annual consumption for England & Wales as reported by National Grid (309,588 GWh), the calculation method is therefore considered robust.

The detailed nature of the data proffers a number of benefits over the Government data in providing an alternative means to elucidate the relationship between electricity consumption and air temperature by reducing the scatter in the plot:

i. *temporal disaggregation by day of the week* - consumption can be grouped by weekday or weekend, since the data reveal that consumption at the weekend (and on bank holidays) is noticeably smaller than that throughout the rest of the week, (Appendix 9),

ii. *temporal disaggregation by week* - daily consumption can be grouped into blocks so as minimise the "contaminant" effect caused by electrical lighting, where the summer period is divided into 13 consecutive blocks, each day in a single block having a similar number of daylight hours,

iii. *exclusion of non-climate-related consumption* - the electricity used by autogenerators, such as iron and steel works which generate and use their own electricity for non-climate-related industrial process (and so does not enter the grid), is omitted from the data,

iv. *daily running mean temperature* (t_{drm}) - the finding that comfort is related to thermal experience (CEN/BSI, 2007/2008; CIBSE, 2007) and thus is dependent upon the temperature on preceding days is easily exploited through the calculation of daily running mean (drm) temperature (see footnote 164).

However, when adjusted daily weekday electricity consumption is plotted against daily mean CET during summer, there is seen to be no correlation. Figure 26 shows an example of the relationship between adjusted daily Initial Demand Outturn (INDO) electricity consumption[66] and daily mean weekday CET for the month of July for the period 2005-2011.

---

[66] National Grid reports four sets of demand data, varying in the way that they include various electricity loads such as interconnector exports and power station load. The Initial Demand Outturn (INDO) dataset is chosen as being the most suitable dataset most responsive to a change in temperature in that it includes (i) power station generation, (ii) pump storage generation, and (iii) interconnector imports, but excludes (iv) station own load, (v) pump storage pumping and (vi) interconnector exports, for Great Britain. (It does, however, also include transmission losses.) Prior to 2005, INDO data referred to England and Wales.
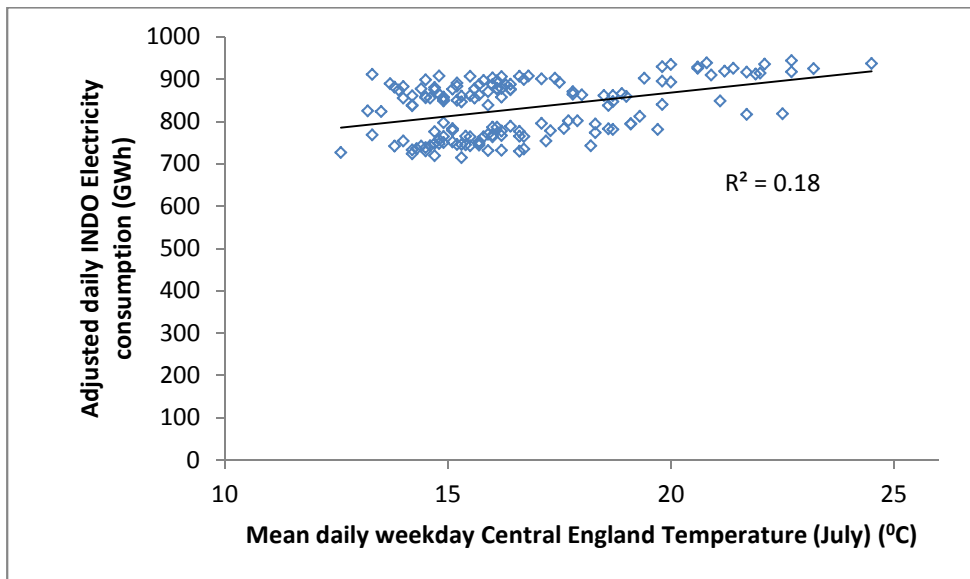
Figure 26 Relationship between adjusted daily INDO electricity consumption and daily mean Central England Temperature for weekdays (July, Great Britain, 2005-11) (^{0}C)

Even though weekend data have been removed from the plot in Figure 26, rather intriguingly, a split is seen to occur in the data[67] which even the process of trend adjustment (the aim of which is smooth out fluctuations arising from a change in price etc.), fails to remedy. Further analysis reveals that the high consumption band relates to the period 2005-2008, whilst the low consumption band relates to the period 2009-2011, though it remains unclear why the data should demarcate as such, with National Grid only stating there to be a difference between pre- and post-2005 data[66].

When the pre-2009 data are omitted from the analysis and the data are further refined[68], the initial results show signs of promise with an R^2 value as high as 0.72 being returned for the hottest block (29 June-5 July) when adjusted daily INDO electricity consumption is plotted against drm CET for a single week block[69] (Figure 27); and values exceed 0.6 for other warm blocks in mid-period (Table 13).

---

[67] i.e. the split coincides with the trend line, demarcating a relatively high consumption band to the upper side of the trend line, and a relatively low consumption band to the lower side of the trend line.

[68] Scatter should reduce as a consequence of the combined effect resulting from using (i) only post-2009 data, (ii) electricity consumption which has been adjusted, (iii) the drm weekday CET instead of the weekday CET, and (iv) a 5-day block featuring days with a similar number of daylight hours.

[69] Block 1 comprises all weekdays from 1-7 June over the period 2009-11 (i.e. 15 days in total), Block 2 comprises all weekdays from 8-14 June over the period 2009-11 (i.e. 15 days in total) …block 13 comprises all weekdays from 24-31 August over the period 2009-11. i.e. weekends and bank holiday Mondays are excluded.
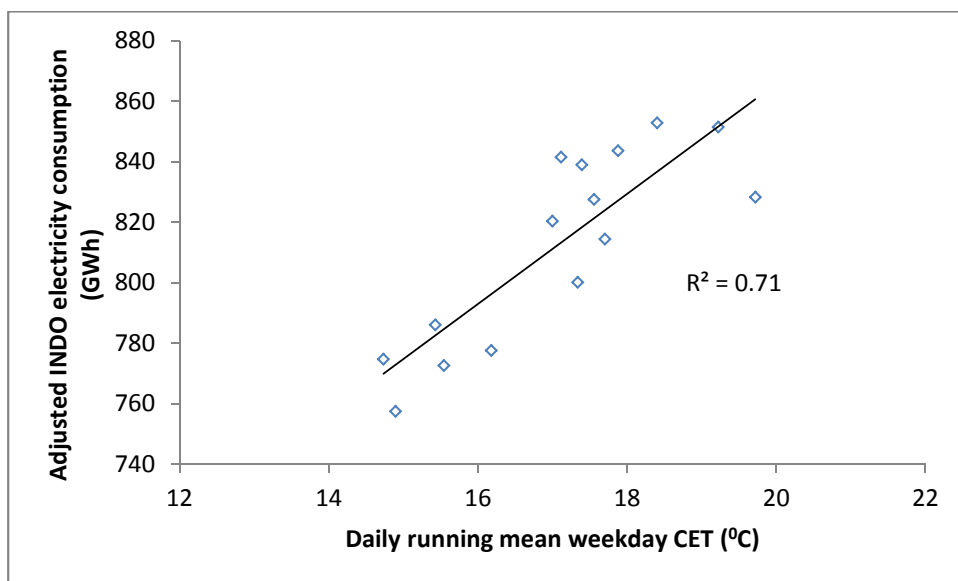
Figure 27 Correlation between adjusted daily INDO electricity consumption and daily running Central England Temperature for weekdays for Block 5 (29 June-5 July) (2009-2011, Great Britain)

Table 13 Distribution of R^2 values (showing correlation between adjusted daily INDO electricity consumption and daily running mean Central England Temperature for weekdays for 13 blocks of summer (June-August, 2009-2011, Great Britain)

Block number	1	2	3	4	5	6	7	8	9	10	11	12	13
R^2 value	0.25	0.26	0.19	0.03	0.71	0.45	0.64	0.63	0.54	0.11	0.40	0.20	0.01
drm CET (^{0}C)	14.0	12.7	14.0	16.5	17.9	15.6	15.9	16.0	16.3	16.4	16.0	15.7	14.3

Whilst it might be thought that the relatively high R^2 values observed occurring towards the middle of the 13-week period are simply anomalous, resulting from pure chance, the evidence suggests otherwise. When the same analysis is carried out for the pre-split data for the period 2005-2008, relatively high R^2 values are once again observed for certain weeks in the middle of the 13-week period (weeks 5, 6, 7 and 8), when the drm CET is generally at its greatest (Table 14).

Table 14 Distribution of R^2 values (showing correlation between adjusted INDO electricity consumption and daily running mean Central England Temperature for weekdays for 13 weeks of summer (June-August, 2005-2008, Great Britain)

Block number	1	2	3	4	5	6	7	8	9	10	11	12	13
R^2 value	0.00	0.03	0.19	0.73	0.60	0.48	0.75	0.75	0.12	0.00	0.2	0.30	0.03
drm CET (^{0}C)	13.8	15.2	15.3	14.9	16.4	16.2	17.7	17.5	17.0	16.2	15.7	15.9	15.7

When one considers that cooling & ventilation accounts for a mere 3% of electricity consumption in the UK[70] (c.f. electrical heating 12%, lighting & appliances 42%) (DECC, 2011d), the relatively high

---

[70] Excludes electricity used in transport sector, but includes that used in industry sector.

degree of correlation between electricity consumption and drm CET for certain of the warmer months is perhaps rather surprising. Although the increase in electricity consumption is unlikely to relate space cooling and ventilation alone, other end-uses unrelated to space cooling contributing towards the increase[71], unfortunately it is unknown how much of a contribution these other end-uses make towards the total increase in consumption.

Even though electricity consumption does seem to be influenced by air temperature with the coefficient of determination being quite high on occasion, the correlation remains rather too low for most of the weeks of summer to allow INDO data to be used as the basis of a space cooling model.

3.3   Space Cooling Models

The paucity of Government and National Grid data preventing the development of a space cooling model along the lines of the space heating model described in Chapter 2, an alternative approach is required. This is problematic, however, inasmuch as very few other data have been published elsewhere in relation to this matter. In meeting with this same impasse, other researchers have used a variety of means, with varying degrees of success, to characterise climate-related/future space cooling energy consumption. The climate-related aspects of these studies are critically assessed in turn, with a view to selecting the best features from each in order to construct a new Space Cooling Energy Consumption Model for the Residential Sector, tailored for use with data from the UK Climate Projections 2009 (UKCP09) (UKCP09, 2012f); for the sake of brevity, and to avoid later confusion with the eight models described in the literature below, this bespoke model is given the acronym SCECMORS.

3.3.1   Climate change and future energy consumption in UK housing stock (Collins, et al., 2010)

Using data from the UK Climate Impacts Programme 2002 (UKCIP02), the immediate predecessor of UKCP09, national energy consumption in the UK housing stock is estimated under a high emissions scenario to investigate the "worst case scenario" for future time-slices[72] (Collins, et al., 2010). Using synthetically generated weather years composed of hourly data for London for the 2050s and 2080s, a bottom-up model of the national housing stock is constructed from six representative dwelling types which comprise the bulk of the stock, the construction of which buildings are based on the stock average for the period 1981-1996. Endeavouring to describe the worst case scenario, the authors assume no technological advances in the efficiency of mechanical cooling systems take place, and similarly assume that no retro-fitting measures to improve the thermal performance of buildings are carried out.

Under typical patterns of occupancy, lighting and ventilation (including infiltration) which might be observed in the UK, the energy consumption of a split system air-conditioning system with a

---

[71] e.g. increased levels of refrigeration within the retail sector, and increased use of domestic electric showers.
[72] UKCIP02 reported a single temperature increase for each emissions level: under the high emissions scenario, an increase of 2.2 ^{0}C was forecast for the 2050s and an increase of 3.9 ^{0}C for the 2080s.

"relatively poor" nominal energy efficiency ratio (EER)[73] of 2.5 and cooling set-point temperature of 22.5 ^{0}C is estimated for each of the six dwelling types using the Virtual Environment suite of programs by Integrated Environmental Solutions. The six energy consumption values are multiplied by weighting factors which reflect the distribution of each of the dwelling types in the UK housing stock. The resulting data represent the stock consumption for a climate equivalent to that of London's. In order to calculate stock consumption for the UK as a whole, a further set of weighting factors are applied to the London-climate stock consumption data, the weighting factors deriving from the modelled cooling energy consumption of a semi-detached dwelling located in London, Cardiff, Manchester and Edinburgh. National cooling energy consumption is calculated for air-conditioning uptake rates of 50% and 100%.

Appraisal

In the absence of more detailed data, the model makes a good attempt to calculate national space cooling energy consumption. In its favour, the domestic dwelling stock is well represented by the six generic housing types which account for 98% of all homes, though the choice of basing their thermal performance on dwellings solely constructed in the period 1981-1996 is more contentious: over 75% of the housing stock was constructed prior to 1975, and 36% dates to the pre-war period (BRE, 2008) when the thermal performance of stock was considerably lower.

It could also be argued that four is a rather low number of regions on which to model a stock of 26 million dwellings in view of the rather large spread in the number of cooling degree-days forecast for different areas of the country as seen in Section 3.5. But the fact that the populous London area, the most densely-populated and warmest part of the country in summer, is included, serves to some degree to lessen any detriment arising from the smallness of the number, given the fact that a "pessimistic business-as-usual" scenario is the scenario being explored.

Inasmuch as the air-conditioning system used in the model is a split system, one cannot argue that this is not pessimistic, since the residential air-conditioning market is dominated, rather, by lower power rated moveable units which comprise 81% of sales (and 84% of the stock) (DGTREN, 2008). Perhaps a more realistic business-as-usual approach would be to include moveable units in the model which are likely to dominate the market for some time to come in view of their cheapness and ease of installation[74].

The choice of 50% and 100% for uptake of air-conditioning seems to have been arbitrarily chosen, and, indeed, an uptake rate of 100% would be very pessimistic, if not altogether very unlikely. Since the rate of uptake is apparently climate-related and bears such a very large influence upon the levels

---

[73] EER is dimensionless in Europe and is the ratio of the cooling output (kW) to the cooling input (kW), measured under specific conditions (e.g. temperature 35 ^{0}C, humidity 40%). It is functionally equivalent to the American EER which has units of BTU/hour/Watt, in which cooling output is measured in British Thermal Units/hour (BTU/hour) and input is measured in Watts. See the Glossary for further information regarding EER, Seasonal Efficiency Ratio (SEER) and usage made of them in this thesis.

[74] Moveable units are forecast to comprise 88% of residential (<12kW) air-conditioning systems by 2030, the last year for which a forecast is made (DGTREN, 2008).

of space cooling energy consumption (as detailed in Section 3.7 and as reported by Sailor and Pavlova (2003)), the authors' decision to err on the side of caution in describing the worst case scenario is, however, justified.

3.3.2 Air-conditioning energy use in houses in southern England (He, et al., 2006)

In this study, a bottom-up model estimating space cooling energy consumption from the housing stock of southern England using London weather data for the period 1 June 2004 - 30 September 2004 is constructed and modelled using the software package Tas (He, et al., 2006). The stock of southern England is modelled by the three most common house types (terraced, semi-detached and detached), which are modelled as having a design and size which are typically seen in the stock. Flats are excluded from the analysis. The construction of each of the dwellings is varied so as to accord with dwellings from three time periods (pre-1919, 1919-1964, post-1964). Thus the stock is modelled by nine representative buildings, and appropriate weighting values are applied in accord with the current distribution of these dwellings in southern England.

In line with the current distribution of air-conditioning systems in the UK stock, it is assumed that 85% of the dwellings with air-conditioning use moveable units, whilst the remaining 15% have split systems; the moveable units are assigned a seasonal energy efficiency ratio (SEER) of 0.8, whilst the split systems are assigned a SEER of 2.8[75]. Cooling control is assigned to the sitting room and the main bedroom, as previous research by the authors had shown these to be the rooms in which air-conditioning is most frequently installed, the set-point temperature being set at 22 ±2 ^{0}C. Various other set-point temperatures are also modelled. Uptake rates are based on a written answer to a question asked of the Department for Environment, Food and Rural Affairs (DEFRA) Minister in the House of Commons as reported in Hansard (Morley, 2005), where it was estimated that 0.5 million units were in existence at that time, and that, "based on continuation of current trends", numbers would increase to 2.3 million by 2050; the authors state that this is equivalent to an increase in uptake from 2.4% to 11% by 2050. In order to assess the impact of climate change upon the cooling energy consumption required for the bedroom, a final weighting factor is applied, where the weighting factor is the ratio of the number of cooling degree-days (CDDs) for the future climate[76] to the number of CDDs for the present climate[77].

Appraisal

The detail underpinning the important aspect of stock representation is very good: the thermal performance of aged dwellings is taken into consideration, and it is seen that the three generic dwelling types constitute 72% of the national stock (BRE, 2008).

---

[75] The EER is actually reported as 2.8. The SEER is assumed to have the same value as the EER, the SEER of a typical residential central cooling unit not being very different from the EER (personal communication, Ayub Pathan, 3 October 2012).

[76] The number of CDDs for the future climate are calculated using "morphed" weather years derived from UKCIP02 data.

[77] CDDs are calculated to a base temperature of 22 ^{0}C.

The set-point temperature band of 22 ± 2 ^{0}C is also recognised as being realistic, a study of dwellings in south east England showing an average switch-on temperature of 24.2 ^{0}C with temperatures being maintained at an average of 22.3 ^{0}C (Pathan, et al., 2008).

The decision to use a high percentage of moveable air-conditioning units in the model is also recognised as being realistic, although one might contend that the choice of using an EER of 0.8 is unrealistically low, and well below the stock Government Standard Average of 2.91 (Section 3.8.2.2): the value of 0.8 is apparently based on tests previously carried out by the authors on an a moveable air-conditioning unit bought at random and performed in a laboratory.

Whilst owning to the fact air-conditioning ownership statistics in the domestic sector are very limited in nature, and that this limitedness results in a wide range of uncertainty, one cannot comment on the dependability of the information relayed by the DEFRA Minister with any degree of authority, since the Minister did not quote its source. The fact that uptake is estimated to increase in a linear fashion between 2005 and 2050[78] leads one to question how much, if at all, climate change has been taken into account in making the prognostications.

Levels of future energy consumption are estimated as simple fractional multiples of the present day (2004) energy consumption using a multiplying constant, which is the ratio of the number of CDDs in the future to the present day number of CDDs (base year)[79]. Whilst this is the conventional method of using degree-days to forecast average future energy consumption, the authors have apparently erroneously used the London Design Summer Year (DSY) (1989) instead of the Test Reference Year (TRY)[80] (or the mean number of CDDs) as the base year (but it is not clear whether the future years are future DSYs, future TRYs or future average years): irrespective of which type of future year is used, the effect of using the 1989 DSY serves to result in a fallacious forecast of average future annual energy consumption.

What is more, it is not clear that a base temperature of 22 ^{0}C is appropriate for the calculation method used to forecast future consumption levels (Appendix 10), a base temperature in the region of 18 ^{0}C or 18.3 ^{0}C (65 ^{0}F) being the more usual choice.

It is also questionable whether climate data for London should be viewed as representative of the whole of southern England. As seen in Section 3.5, CDDs values are rather higher for London than they are for other regions in the country, even those other regions in the south of England.

3.3.3 Evaluation of the climate risks for meeting the UK's carbon budgets (AEA, 2011)

The top-down model presented in this report for the Committee on Climate Change uses London as a surrogate for the whole country in estimating the increase in cooling (and heating) demand in a future warmer climate (AEA, 2011). The model combines (i) data produced by the UKCP09 Weather Generator for London and (ii) present day monthly CDD totals obtained from 18 weather stations

---

[78] 2005: 0.5 million units, 2010: 0.7 million units, 2020: 1.1 million units, 2050: 2.3 million units.
[79] The model locks itself into using a base temperature of 22 ^{0}C.
[80] The DSY represents the summer weather of an atypically warm year (equating to the third warmest year in a series of 20), whilst the TRY is representative of an average year.

throughout the country (1970-2010). It is underpinned by the degree-day principle where electricity consumption is assumed to increase in linear fashion in response to increasing numbers of CDDs. CDDs are calculated to a base temperature of 22 ^{0}C, and the relationship between energy consumption and degree-days is described arithmetically, where the constant which determines the amount by which electricity consumption increases for a rise of 1 CDD is termed the 'elasticity of demand' (Appendix 10).

The model comprises a number of steps which can be distilled as follows, the first two steps being the establishment of assumptions:

i.   establish the 'reference' present day, cross-sector national cooling demand, which is taken as the 'cooling plus ventilation' figure for the service sector (DECC, 2011d),

ii.   establish the 'elasticity of demand' in response to temperature (i.e. the ratio of 'the percentage increase in electricity consumption' to the 'percentage increase in temperature', e.g. a 1% increase in temperature (number of CDDs) resulting in a 0.12% increase in electricity consumption has an elasticity of 0.12)

iii.   using the data from steps i and ii, calculate the actual increase in electricity consumption (GWh) per CDD increase

iv.   calculate the percentage increase in the number of CDDs for London between the present time and various time-slices in the future (using DECC/UKCP09 data)

v.   apply the London percentage increase in CDDs (from step iv) to present day data gathered from the 18 weather stations, in order to calculate the number of CDDs for each weather station for the various time-slices in the future

vi.   calculate the increase in electricity consumption (GWh) for each of the 18 weather stations for the various time-slices in the future (using the data calculated in steps iii and v).

Appraisal

The model assumes that cooling energy consumption will increase linearly in response to increasing numbers of CDDs. The simplicity of the model is commendable, but the authors realise that problems exist within it: its forecasts are correctly described as worst case scenarios.

The relatively big differences in air temperature forecast for different regions within the UK mean that the more that the CDD data are regionalised, the less chance of accruing error. As such, the current climate of the country is undoubtedly well represented by the data gathered from the 18 regional weather stations. The danger of using a limited number of weather stations to represent extensive areas of the country can be shown in Figure 28: in this example taken from UKCP09 source data, the daily mean summer maximum temperature for a medium emissions scenario in the 2080s for London at the 20% probability level[81] is forecast as 24 – 27 ^{0}C, which compares with the 21 – 24 ^{0}C seen in the immediate region, and a similar disparity is seen between Manchester and the North West.

---

[81] 20% probability level = (very) unlikely to be less than the stated temperature
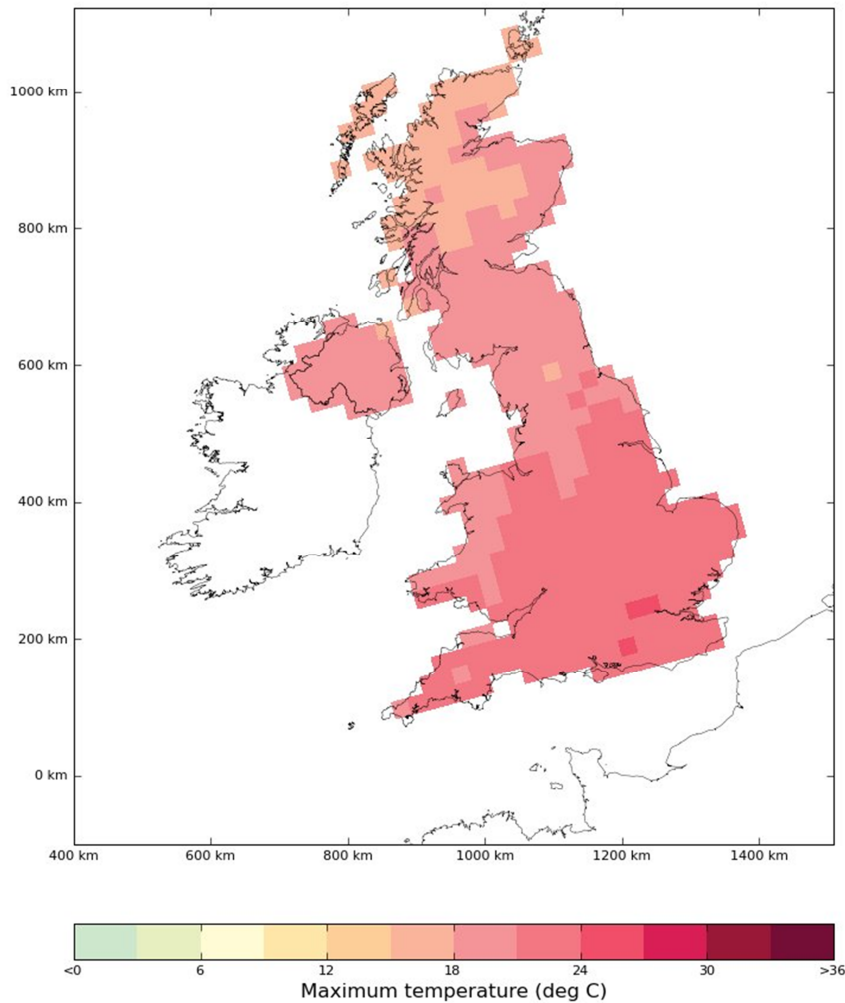
Figure 28 Daily mean maximum temperatures forecast for UK under a medium emissions scenario (2080s, summer, 20% probability level)

However, the premise that the space cooling energy consumption will increase at the rate stated (elasticity = 0.12) is suspect, as the authors, themselves, point out. It is based on the 0.12 figure used in the Department of Energy and Climate Change (DECC) Energy Model used for electricity demand in winter (i.e. a 1% increase in the prevalence of cold temperatures over winter results in increased electricity consumption of 0.12%) (Oxford Economics, 2008): the premise is that the elasticity of electric heating is of approximately equal value to the elasticity of electric cooling, as has been observed in the US. There is no significance, however, in the fact that the elasticity of electric heating in the United States averages out to equal the elasticity of electric cooling, there being no direct relationship between the two as seen in Section 3.3.5, where there is seen to be significant differences between the two values in different states. In brief, an increase in the elasticity of electric heating by *x* would not necessarily result in an increase in the elasticity of electric cooling by *x*, and vice versa.

It is also worth pointing out that the premise also assumes that the climate-dependent increase in space cooling electricity consumption will be cross-sectoral, where the increase in cooling demand in the service sector is assumed to be the same as the increase in demand in the domestic sector, since

service sector consumption is used as a surrogate for national consumption. This is doubtful since cooling in the service sector bears much less relationship with climate than does the domestic sector with climate, as previously mentioned at the beginning of the chapter.

It is also a concern that service sector "cooling plus ventilation" figures are used as a proxy for national cooling consumption, since ventilation consumption is erroneously included in the calculation.

Finally, the elasticity principle used in this approach makes no specific direct allowance for an increase in rates of penetration of air-conditioning as the climate warms. Elasticity is a composite measure of the overall increase in electricity consumption to an increase in temperature, that response resulting from the combination of both (i) prolonged and more intensive operation of air-conditioners currently in use, and (ii) increase in numbers of air-conditioners (increase in penetration). A refinement to the approach adopted here would be to disentangle the responses resulting from (i) and (ii), since it seems as though they increase at different rates in the future: whilst it may be correct to assume that (i) will increase linearly with respect to increasing number of CDDs, penetration rates do not seem to increase in the same linear fashion (see Section 3.7).

3.3.4   Cold Comfort for Kyoto? (Wu & Pett, 2006)

The increase in energy consumption and carbon emissions emanating from increasing residential demand for cooling in the south of England in a warming climate are estimated in this model (Wu & Pett, 2006). It uses data output from UKCIP02. The model, a variation on the conventional bottom-up approach, uses the degree-day principle as its fundament. Rather than use an 'elasticity of demand' factor to estimate actual energy consumption as in the previous model, it uses CDDs in a more direct manner, the result of which is that its estimations are presented as falling between a range of values which is dependent upon the choice of base temperature. In the case where the base temperature is known, one is not required to invoke the use of an 'elasticity of demand' constant (the uncertainty of which value has been described above) (see Appendix 10).

Rather than using dynamic simulation modelling (DSM) software to measure the energy consumption in a dwelling/set of dwellings which are representative of the stock as described in the previous bottom-up models, the approach taken is to calculate the energy consumption of an air-conditioning unit typically used in dwellings, and build up from there. As dwellings are not, for the most part, occupied during the hottest part of the day, it is assumed that an air-conditioner is used for 8 hours of each degree-day, the energy consumption being based on that used by the 0.8 kW power-rated De'Longhi air-conditioner, stated as having the capacity of cooling a south-facing 25 m^2 living room. The number of CDDs are calculated for a range of base temperatures (20, 22, 26 ^{0}C), and two different penetration rates (100% uptake, and an uptake of up to 45% chosen as reflecting that group of people wealthy enough to afford air-conditioning[82]). The equation describing the model can be summarised as follows:

Equation 11

$$E = (CDD_p \times r_u \times n_h \times p \times p_a)/(n_o \times 10^8)$$

---

[82] Taken as the percentage of households paying higher rates of council tax (bands D to H).

where,

E = national space cooling energy consumption (GWh)

CDD_p = population-weighted CDD[83] total for southern England

r_u = power rating of air-conditioning unit (i.e. power input = 0.8 kW)

n_h = length of time used for a typical period of operation (hours)

p = population

p_a = penetration rate of air-conditioning (%)

n_o = number of occupants/dwelling

Appraisal

In using the air-conditioning unit itself as the point of reference, the building block upon which all else is built, this model presents an interesting variation on the conventional building-as-base-unit bottom-up approach. The authors state that its output agrees in magnitude with that of the Market Transformation Programme, a DEFRA-managed programme, charged, amongst other responsibilities, with ensuring that reliable information on sustainable products (including air-conditioning) is available and used to inform policy decisions (MTP, 2012) (see Section 3.3.8). Citing the remarks made to the House of Lords Select Committee on Science and Technology by representatives of the Institute of Refrigeration that end-users commonly buy very cheap equipment rather than the best on the market and/or operate the equipment badly, the decision not to take the thermal performance of a generic dwelling/set of dwellings into account is perhaps more pragmatic and less bold than might be thought at first. The imagined worst case scenario by Wu and Pett where "the cheapest units, without adequate thermostatic controls, are left on in a bedroom overnight, with a window for 'cooling' breezes, and the sleeper wearily pulling a blanket over them in the comparatively chilly early hours rather than wake up sufficiently to turn off the cooler" is perhaps a better reflection of how air-conditioning is really used rather than the highly-regulated, artificial set-up used in DSM, with its set-point temperatures for switch-on and switch-off.

The principle underlying the energy calculation is that cooling is not called upon until the number of CDDs =1. At this point the air-conditioner is switched on, the typical length of operation being eight hours: thus eight hours' worth of energy is consumed. Since energy consumption is proportional to the number of CDDs, a doubling in the number of CDDs results in a doubling of energy consumption,

---

[83] CDD values must be weighted in proportion to population when considering uptake. This is easily seen in a country with extremes such as Canada, which, for the most part, is sparsely populated with a limited number of densely populated urban areas in the south: since it is clear that the greatest volume of air-conditioning systems will be bought in these areas of high population like the southern cities of Toronto and Montreal, an average CDD total for Canada would have to take more account of temperature in these cities than in the expansive lowly populated northerly regions where very few air-conditioners are installed.

with a value of 2CDDs resulting in 16 hours' worth of energy consumption, and so on (i.e. there are eight hours of consumption per CDD). In this way the annual energy consumption for the base year, comprising a total of *a* CDDs, is calculated. For a future year comprising of *b* CDDs, the increase in annual energy consumption is simply calculated as the ratio *b/a*, in accord with normal degree-day theory. Indeed, the choice of a run period of eight hours is not far removed from the 6.75 hours average (standard deviation of 3.1) observed for real usage recorded for nine rooms in dwellings in south east England in 2004[84], despite the wide range of

   i.   switch-on temperatures (22.3-27.9 ^{0}C),
   ii. system types (six different systems),
   iii. cooling capacities (2.45-6.7kW),
   iv. EERs (2.23 or less-3.38 or more),
   v.   dwelling type and location (from top-floor flat in central London to detached timber-framed house in East Sussex,
   vi. room type (all rooms in conventional house, including conservatory), and
   vii. dwelling age (1898-2001) (Pathan, et al., 2008).

However, despite the good reason underlying the choice of an eight-hour operating period, such a method results in what appears to be an unreasonably large total number of hours of operation over the course of the base year. With the present day national annual number of CDDs amounting to 47 for a base temperature of 18 ^{0}C (see Section 3.5), this amounts to annual usage of 376 hours, which is equivalent to almost 30 hours of use per week during the summer months of June, July and August. In a country where the vast majority of the population feel no need to use any air-conditioning at all in the home, these numbers not only appear unduly large, but are in discord with estimates with the Market Transformation Programme (MTP) (see Section 3.3.8). The high value for the annual number of hours of operation may partially reside in the fact that although an air-conditioner is switched on for eight hours, it may not be actively chilling the air for eight hours. Cycling between "chiller on" and "chiller off" where a thermostat causes a switch between the two once the comfort temperature is reached, it would seem that a large part of the eight-hour period may be spent in "chiller off" mode where minimal power is drawn. An improvement to the method of energy calculation would be to estimate the number of hours of annual consumption in the base year as a whole (as does the MTP), rather than attempt to construct it from the daily totals.

The decision to run the model for a number of different base temperatures shows how very important it is to choose the correct base temperature[85]: there is a three-fold (or more) difference in consumption levels for 2050 depending upon whether a base temperature of 20 ^{0}C or 26 ^{0}C is chosen. Although the difference in cooling energy consumption for base temperatures calculated to 20 ^{0}C and 22 ^{0}C[86] is much smaller, it, nevertheless, remains relatively high at approximately 50%.

---

[84] In one room, a kitchen, the average duration of a single operation was 45 minutes. Presumably the air-conditioning was, in this instance, used while cooking was in progress, and not primarily used as a response to warm weather per se. Ignoring this observation, the average operation time for the remaining eight rooms calculates as 7.5 hours (standard deviation of 2.2).

[85] The principle underlying the importance of choosing the correct base temperature is illustrated in Appendix 10.

[86] Such temperatures which are likely to be much closer to the real base temperature – see Section 3.3.5 and Section 3.3.6.

Although the text is unclear on this matter, it appears that CDD totals are not representative of average years, since very high present day CDD totals are reported - 310-320 (base temperature 22 ^{0}C) for southern England (c.f. the present day total for Heathrow calculates as 122 for a base temperature of 18.0^{0}C (see Section 3.5). It appears that the CDD totals used in this study are the CDD totals for the Design Summer Year, which represents a hot summer (the third hottest in a run of 20 years). This would also explain why the annual number of hours of operation is so high.

The uncertainty to which to attach to penetration rates is also problematic, since it can have such a large impact upon energy consumption (Section 3.7). Admitting to the fact that data from the USA show that there is little difference in uptake of air-conditioning between social classes, this necessarily disqualifies use of the penetration rate associated with wealthy householders. However, the alternative uptake rate of 100% is very unlikely: 100% uptake of air-conditioning is not even seen in the very hot, very humid climates of the USA (EIA, 2012).

3.3.5 Air conditioning market saturation and long-term response of residential cooling energy demand to climate change (Sailor & Pavlova, 2003)

In a seminal and much cited paper, two top-down models are presented in this study which investigates the effect of air temperature upon (i) residential electricity consumption, and (ii) market penetration[87] of air-conditioning systems in the residential sector (Sailor & Pavlova, 2003). Although the paper only examines data from the US, its findings nevertheless have a bearing upon the UK insofar as the present analysis is concerned since the information which it yields, even if not universally applicable, suggests where else more relevant data might be sought.

In the first of the two models the functional relationships between monthly electricity consumption and (i) mean monthly number of CDDs, (ii) mean monthly number of heating degree-days (HDDs) and (iii) mean monthly wind speed (w) are examined for four different states in diverse geographical locations using regression analysis. The electricity consumption is trend-adjusted to minimise the influence of non-climate factors (as described in Appendix 8), whilst the degree-day totals are population-weighted to better represent the climatic conditions experienced by energy consumers (see footnote 83). The residential per capita elasticity consumption (kWh/CDD) (base temperature

---

[87] The authors of this paper use the term "saturation" where others, including the author of this thesis, use the term "penetration", since "saturation" has different meanings for different people. In a country like the US which has extremely hot climates, this does not necessarily present a problem since 100% "penetration" may approach 100% "saturation", at least in the hottest and most humid regions. But it can be problematic for countries with milder climates where a saturated market, the point beyond which the market cannot grow any further, does not necessarily represent 100% penetration of the market. e.g. the climate in a cooler country (called *X-land)* might be such that the maximum number of dwellings which will ever install air-conditioning is 40%, such that a penetration rate of 40% is the same as 100% saturation. In this thesis, as elsewhere in the literature, the term "saturation" is used in this second sense, where a 10% penetration rate in *X-land* amounts to a saturation rate of 25%.

It should be pointed out the use of the word "saturation" in this paper may have been misinterpreted in yet a different way by the authors of the DGTREN (2008) report described in Section 3.3.7, where Sailor and Pavlova's "saturation" rate is correctly understood as a "penetration" rate, but whether deliberately or not, is also seemingly taken to represent 100% saturation. The reader is warned of the confusing multiple-usage of the term "saturation" in the literature.

18.3 ^{0}C[88]) is calculated in each of the four regressions[89]. R^2 values are found to range between 0.71 and 0.87. This increase in consumption due to more intensive and prolonged use of air-conditioning in response to increased temperatures (or number of CDDs) has been termed the "short-term response" to distinguish it from the "long-term response"; the long-term response is the increased consumption resulting from more air-conditioners being used as a consequence of increased temperatures (or number of CDDs).

In the second of the two models which examines ownership rates of air-conditioning in each of 39 cities[90], a single regression analysis finds that penetration rates are highly correlated (non-linearly) with the number of population-weighted CDDs[91] (base temperature 18.3 ^{0}C) across the range of cities: the curve shows an initial very steep slope (i.e. accelerated levels of uptake) which gradually diminishes as CDD values increase.

In the final part of the paper the two models are combined and the effect of a 20% increase in the number of CDDs on air conditioning electricity consumption is examined for a number of cities. For hot climates it is seen that the increase in per capita electricity consumption[92] is more important than the increase in electricity consumption deriving from increased saturation[93], but for less hot climates, the reverse is the case.

Appraisal

The two top-down models, which describe (i) cooling energy consumption and (ii) penetration in terms of CDDs, indicate that the choice of base temperature of 18.3 ^{0}C is good, in view of the high values for the correlations of determination.

The first model shows that there is a good deal of variation in the per capita electricity consumption, there being a considerable difference between the coefficients k_1 and k_2 for each state, k_1 being almost three times as large as k_2 for Ohio, for example. This highlights the danger in the method adopted in Section 3.3.3, a justification for the validity of its method being that the average electricity heating and cooling 'elasticity of demand' values are equal in magnitude in the US[94]. Since the per capita electricity consumption is shown to be city-specific (i.e. the per capita electricity

---

[88] An optimisation study revealed that no statistically significant improvement was gained by using alternative definitions for the base temperature.

[89] Per capita elasticity consumption for HDD and wind speed are also calculated, the total energy consumption (E) being calculated as: $E = k_1.CDD + k_2.HDD + k_3.w + constant.$

[90] Data obtained from the US Census American Housing Survey (typically 1994-1996). Honolulu on the mid-Pacific island of Hawaii is a notable anomaly, the explanation for the relatively low penetration being posited as a deriving from a combination of cultural differences, building practices and the presence of relatively strong trade winds.

[91] Data obtained from National Climatic Data Center.

[92] i.e. air conditioners being used for longer and more often as a consequence of hotter outdoor air temperatures (short-term response – see Glossary).

[93] i.e. more air-conditioning being used (long-term response – see Glossary).

[94] As there is so much variation in the way electricity is used in the US, with its plethora of climates, there really is no significance in the fact that average values for the heating and cooling 'elasticity of demand' values for the nation as a whole are of equal magnitude.

elasticity consumption constant varies considerably between cities) the first model has no application as a predictor of energy consumption outside of these cities.

But it is the second model to which most interest is attached. The finding that penetration rates are predictable and capable of being described by CDD values alone is initially viewed as remarkable. Despite the great variety of climates with differing levels of humidity, despite the different types of air-conditioning in use (both window units and central air-conditioning systems) and despite the great variety of construction types within the US housing stock, there appears to be a universality apropos the uptake of air-conditioning which can be described by air temperature alone.

The combined results of the models indicate that increases in consumption in hot climates are more strongly affected by an increase in service than an increase in penetration, with the reverse being true for less hot climates where an increase penetration contributes the majority of the increase in consumption. Taking the city of Buffalo in New York (with a penetration rate of 25%) as an example, a 20% increase in the number of CDDs from 282 to 338 would result in an increase in air-conditioning electricity consumption of over 60%, but the increase would only be 20% if the increase deriving from increased penetration were excluded. This compares with the much hotter city of Houston (penetration rate 94%) where a 20% increase in the number of CDDs would result in an increase in an increase in air-conditioning electricity consumption of 21%, where only 1% of the increased consumption derives from increased penetration.

In view of the facts that (i) the immature air-conditioning market in the UK is still some way behind the US market in terms of penetration[95], and (ii) the change in penetration is the more important aspect of climate-related change with regard to cooling energy consumption for climates similar to those predicted for the UK[96], it would seem that increased uptake of air-conditioning rather than increased service per se will most affect total consumption in the UK. In other words, the long-term response is likely to be more important than the short-term response for a warming UK climate.

3.3.6 Home air conditioning in Europe – how much energy would we use if we became more like American households? (Henderson, 2005)

This study focuses on the American experience of residential air-conditioning and applies it to several locations in Europe (Henderson, 2005). Although the UK is largely omitted from the analysis, the method used to estimate space cooling energy consumption is nevertheless applicable to the UK. In view of the high degree of maturity of the American market regarding air-conditioning, it may serve to indicate the pathway which the less mature Europe market will follow in the coming decades.

Using residential air-conditioning data from the 2001 US Residential Energy Consumption Survey (RECS) collected by the US Department of Energy's Energy Information Administration (EIA), the paper examines (i) the relationship between the number of CDDs and penetration (uptake) of air-conditioning, and also (ii) the relationship between CDDs and specific energy consumption (energy consumption/m^2).

---

[95] Penetration estimates vary between 3% (BSRIA, 2011) and 7.2% (following analysis of DGTREN (2008) data.
[96] By the 2080s, even under a high emissions scenario, the mean number of CDDs (calculated to a base temperature of 18.3 ^{0}C) forecast for Great Britain is only 312.

(i) The functional relationship between the uptake of air-conditioning systems and the number of population-weighted CDDs (base temperature 18.3 ^{0}C) mirrors the earlier work carried out by Sailor and Pavlova (2003), even though a different air-conditioning dataset is used. When the function is applied to a European context, it is seen that current penetration rates in locations throughout Europe are very small in comparison to the penetration rates which would ensue if the American pattern of uptake is followed. Whereas, for example, Italy was estimated as having a penetration rate of about 10% at the time of the European Commission's Energy Efficiency of Room Air Conditioners report in 1999, penetration could be expected to increase to over 70% using the relationship established between penetration and CDDs.

(ii) When cooling residential energy consumption per m^2 is plotted against CDDs calculated for the nine census divisions into which the country is divided (base temperature of 18.3 ^{0}C), a near linear relationship is observed between the two (Figure 29).
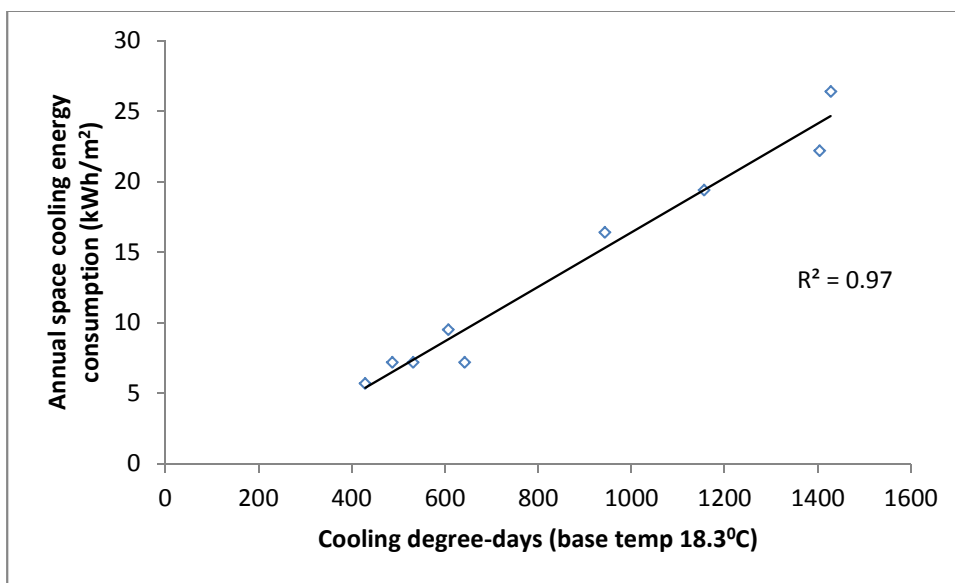
Figure 29 Relationship between space cooling energy consumption and CDDs (base temperature 18.3 ^{0}C) for the US using RECS 2001 data

Appraisal

This paper closely resembles the study by Sailor and Pavlova (2003), with both papers investigating the relationship between the number of CDDs and penetration. But whilst the former examines the per capita electricity consumption in relation to the number of CDDs, electricity consumption per m^2 in relation to the number of CDDs is examined in this paper. Very importantly, the paper sets out to estimate actual air-conditioning penetration rates rather than use judgement/scenarios to set these rates, as seen in previous models. The paper suggests that if the UK were to follow the American experience with air-conditioning, penetration rates would reach 50% when the annual number of CDDs was of the order of 300-350.

The extremely high degree of correlation between specific energy consumption and the number of CDDs is interesting because construction type apparently does very little, if anything, to disturb its linearity: even though dwellings in very hot locations which experience a high number of CDDs and

which are likely to have different construction types to those in cooler locations which experience few CDDs, the specific cooling energy consumption appears to be predictable for CDD values in the range 400-1400. This might suggest that the data are cross-transferable, and so equally applicable to the climate in the UK, whether now or in the future. Examination of the source data reveals, however, that these data are not transferable to the UK, as the relationship observed in Figure 29 does not derive from actual air-conditioning electricity consumption taken from field measurements. Rather, total electricity consumption is collected, and a statistical model is used to apportion the total amongst different end-uses, one of which is air-conditioning (EIA, 2012). In essence the consumption data have been fitted to a pre-defined distribution profile of air-conditioning systems and a pre-defined distribution profile of dwellings, and so it is perhaps not surprising that specific space energy consumption exhibits such a large degree of predictability. Whilst it is clear that the statistical model very well maps observed consumption patterns over the range of values examined, it does not necessarily reflect real air-conditioning consumption, and, moreover, it is not universally transferable for extrapolations of CDD values below 400[96]: although the extrapolated data would suggest that air-conditioning is not used at all for annual CDD values below 149 (base temperature 18.3 ^{0}C), data from both California (California Energy Commission, 2010) and Canada (NRCan, 2012; NCDIA, 2012) indicate otherwise, as does the fact that there is a limited amount of consumption within the residential stock even in the present climate of UK (40 CDDs for a base temperature of 18.3 ^{0}C).

3.3.7   Preparatory study on the environmental performance of residential room conditioning appliances (airco and ventilation)[97] (DGTREN, 2008)

The European Union's Ecodesign Directive (European Commission, 2005) is designed to improve the environmental performance of energy-using products through the harmonisation of the legislature in its constituent countries (European Commission, 2005). As part of its economic and market analysis, it has undertaken to estimate the sales and stock of room air-conditioning (<12kW) up until 2030, splitting the market into residential, office and retail sectors (DGTREN, 2008). The bottom-up model comprises two steps (Pout & Hitchin, 2009).

In the first stage of the model, the Bass diffusion model, which is reported as having successfully generated the technology uptake rates of a variety of electronic components including air-conditioning in the US, is used to estimate sales at various points in the future. Stock levels of different types of air-conditioning system are calculated on the basis of volume of sales for each type of air-conditioner, where the 2005 domestic stock is estimated to comprise of 84% moveable units and 16% split units. It involves the use of two coefficients: (i) the coefficient of innovation (advertising effect), the same value as that used for the US market being used, and (ii) the coefficient of imitation (word-of-mouth effect), the value of which has been adjusted so that actual sales match predicted sales. Knowledge of the percentage market saturation (see footnote 87) for a given year is also required in addition to the start year of the model. In the second stage, these sales data are then used to generate stock data, where account is taken of removals from the stock based on typical product lifetimes. Stock forecasts are generated at five-yearly intervals until 2030, where the split between residential, retail and office sectors is based on market research data for the most

---

[97] Note that although the study states that it is a "draft", it has apparently been accepted in this form as the finished report, requiring no further amendment (European Commission, 2012).

recent year available and assumed to remain constant in future years. A final adjustment brings model forecasts into alignment with forecast sales for the year 2010, it being noted, for example, that sales in the short term were being overestimated in presently small markets in northern and central Europe.

Appraisal

Although the report does not attempt to forecast energy consumption, its use of the Bass model to forecast uptake is recognised as credible. Like the paper by Wu and Pett (2006), it uses the air-conditioning unit itself rather than a dwelling on which DSM is performed. Its accuracy is dependent upon the value of the coefficient of innovation. It is unclear, however, whether this is appropriate, since a higher degree of innovation in the US, resulting from different a psyche, may have been a key factor in the speed of uptake of air-conditioning in the US compared to that in Europe.

In the short term, the Bass model may accurately reflect sales and subsequent stock levels, but forecasts beyond 2030 are not made. It appears that Sailor and Pavlova's equation (describing penetration in terms of CDDs) has been used to establish maximal saturation, which, as previously mentioned, is necessary for the function of the model. If so, this would be incorrect, and perhaps derives from Sailor and Pavlova's use of the word "saturation" (described here as "penetration") where calculated values have been interpreted as points of maximal saturation – see footnote 87. As mature as was/is the US air-conditioning market, analysis of the Residential Energy Consumption Survey (RECS) data shows that saturation had not been achieved by 2003, as market penetration has increased still further since Sailor and Pavlova's work was first published in 2003. Furthermore, there is no evidence available to show that Sailor and Pavlova's equation is applicable to any sector other than the residential sector, yet it is seemingly applied to the office and retail sectors.

Since the model is sales-based, future projections are prone to error in the case where anomalous patterns of sales take place. Indeed, "anomalous" sales may be the reason for the need of the final adjustment which brings modelled sales into alignment with 2010 sales. But the adjustment seems to be insufficient: when one considers that the model estimates that the residential sector contained almost 850,000 moveable units in 2005 and over 1.6 million in 2010, and will contain over 2.7 million in 2015 (i.e. a penetration rate of approximately 10%), it would seem likely that these figures are erroneously high[98]. The case for this argument, that stock estimates may have been based on abnormally large sales figures, is strengthened when it is recognised that the early- and mid-2000s featured some of the hottest years on record and that moveable units are usually "distress purchases" bought during a heat wave or similar (BRE (Butler), personal communication cited Wu and Pett (2006)).

3.3.8 Market Transformation Programme (MTP, 2012)

The Market Transformation Programme (MTP) is a DEFRA-managed programme which, amongst other things, has the responsibility of ensuring that reliable information on products covered by the

---

[98] c.f. the Building Services Research and Information Association (BSRIA), market research experts within this field, estimate penetration in the residential sector as 3% in 2010 and 3% in 2014 (BSRIA, 2011).

Ecodesign Directive (including air-conditioning) is available and used to inform policy decisions (MTP, 2012). It has produced a suite of Government Standard Briefing Notes (GSBNs), published in 2010, key of which, as far as this thesis is concerned, are the Briefing Note Packaged Air Conditioning (BNPAC) series, which model the future uptake of various air-conditioning systems in the non-domestic sector. The bottom-up model comprises three steps, in the first of which expert judgement is used to formulate a series of scenarios which envision different futures:

i. Reference Scenario - business-as-usual,
ii. Policy Scenario - following introduction of expected new policy and amendment to existing policy, and
iii. Best Available Technology Scenario (hypothetical realisation where the most efficient/lowest energy consuming technologies on the market or close to market are used)

Using (i) actual sales (2002-2007) and (ii) predicted sales (2007-2012) from market survey documents obtained from the BSRIA, sales extrapolations are made up to 2030. No detail is supplied but it is stated that the extrapolations consider "factors such as change in technology, economic forecasting and scientific opinion of warmer temperatures in the UK, as outlined by UKCIP02". From these sales data the stock size is generated where removals from the stock are generated by transposing a normal distribution of decay on to product lifetimes.

Energy consumption levels for each type of air-conditioning system for each size category (power rating) are estimated in the final stage of the model, where:

Equation 12

$$Cooling\ energy\ consumption = (n_s \times r_u \times n_h) / CoP$$

where,

n_s = number of units in the stock

r_u = average power rating (i.e. power input in kW), there being four size categories for household air-conditioners (which are defined as those with a power rating of less than 12 kW)

n_h = hours of effective usage per year[99]

CoP = Coefficient of Performance[100]

---

[99] For Equation 12 to be valid, n_h must refer to hours of effective usage, e.g. for an air-conditioner with a thermostat, if cycling between "chiller on" for 85% of the time and "chiller off" for 15% of the time, the number of effective hours refers is the length of time covered by the 85% figure.

[100] The MTP appears to use the term CoP where others use EER or SEER, all three terms being dimensionless measures of efficiency. (In the US, EER has unit of British thermal units/Watt.hour.) In Europe, for apparatus using the vapour-compression cycle (e.g. heat pumps and air-conditioners) CoP is mostly used to describe heating efficiency, whereas EER or SEER are mostly used to describe cooling efficiency. It is assumed that the

Appraisal

Scant detail is given with regard to the formulation of the stock churn aspect of the model: this prevents one from offering a critique, unless one considers this sentence itself as an indictment, since GSBNs are described as "public consultation documents that allow stakeholders to examine the data and assumptions behind the proposed Government Standards and related projections" (MTP, 2012). Since the model is sales-based, it would seem likely that the Bass model or similar is used to generate future sales data in a similar manner to the DGTREN (2008) analysis; the decision to model removals from the stock as a normally-distributed decay would seem to be more realistic however, and therefore offers an improvement. Like the DGTREN (2008) model, however, its reliance upon sales data to generate stock data serves to limit its usefulness beyond the short term (2030), and, moreover, may introduce error into estimates of future stock, where anomalous years of sales (the hot years of the early and mid-2000s?) are not recognised as being anomalous, and are therefore not recognised as being unsuitable as the basis of a stock model.

A key component of the energy consumption aspect of the model is the value attached to n_h, the constant which describes the number of hours that air-conditioning is used in a year. As such, energy consumption is calculated in a similar manner to that described by Wu and Pett (2006). Remembering that non-domestic air-conditioning is the focus of the documents, it is stated that whilst "the usage of many (domestic) units may only be a few tens of hours per year… in other domestic situations and offices this may extend to four, five or ten hours per day for up to 60 days in year may", with 250 hours being deemed a reasonable annual usage by the authors. However, whilst this assumption of 250 hours may be reasonable for packaged air conditioning systems in the non-domestic stock in the present climate, this model, unlike the Wu and Pett (2006) model, seems to take no direct account of the fact that as the climate warms (as the number of CDDs increase), usage will increase (i.e. increased short-term response)[101].

Although CoP is modelled so as to increase in increments in accord with the policy scenario under investigation, and in so doing incorporates another variable of unknown real magnitude which increases the margin of uncertainty associated with the final energy consumption output, it does serve, however, to offer alternative pictures of future consumption which stand in contrast to the worst case scenario formulated by other models.

The MTP states that whilst its data represent the best currently available information based on a bottom-up approach, DECC projections of the overall energy demand in the non-domestic sector are lower[102]. Thus, although energy consumption forecasts in DEFRA's *Saving Energy Through Better Products and Appliances* (DEFRA, 2009) use the MTP's air-conditioning energy consumption projections, they have been scaled down to match DECC's projections for overall energy demand in the non-domestic sector. Analysis reveals the value of this scaling factor to be 0.65. Since it is implicit that the DECC projections are correct, but that the MTP projections are not (even though its

---

authors actually mean EER instead of CoP. See Glossary for further information on use of the terms EER and SEER.

[101] It should be pointed out, however, that since the focus of this model is the non-domestic stock, penetration in which bears less relation with climate as previously mentioned, the modellers' decision not to take direct account of climate in estimating penetration is reasonable.

[102] It is stated that it is assumed that the differences arise from incomplete data with regard to stock, CoP and usage in the MTP model.

methodology is sound), it would seem that the DECC's projections may have been aligned with current overall measured consumption, perhaps reflecting actual use rather than ownership of air-conditioning. The fact that the MTP model over-estimates consumption is in keeping with the suggestion made above that its reliance on recent sales data could adversely affect future stock estimates.

3.3.9 Summary of Space Cooling Models

Of the eight models in the literature, five follow the bottom-up approach. Of these, two use the dwelling as the base unit from which to build, whilst the remaining three use the air-conditioning system as the base unit. The strengths and weaknesses of the models using the bottom-up approach are summarised in Table 15 and Table 16.

Table 15 Bottom-up models – dwelling is the base unit

	Stock	Penetration	Geographical Distribution	Energy calculation	Aspects suitable for use in SCECMORS
Collins et al (2010)	**Fair** dwellings well represented by type, but not in age	**Poor** 50% and 100% rates, no evidence to support such rates and bears no relation to climate	**Fair** division of country into four regions	**Good-Poor** good - DSM poor - based on energy consumption of relatively high energy-consuming 'split unit' which is not representative of the stock based on base temperatures of 22.5 ^{0}C and 26 ^{0}C	
He et al (2006)	**Good** dwellings well represented by type, and well represented by age	**Poor** 2.4-11% rate, based on remark made by DEFRA Minister, no evidence to support such rates	**Poor-Fair** southern England modelled from London data (no sub-divisions)	**Good-Fair** good - DSM good - based on sales' proportion of moveable and split units poor - EER value of 0.8 is too low based on base temperature of 22 ^{0}C	energy calculation dwelling stock

Table 16 Bottom-up models – air-conditioner is the base unit

	Stock	Penetration	Geographical Distribution	Energy calculation	Aspects suitable for use in SCECMORS
Wu and Pett (2006)	**Fair** air-conditioning systems represented by a single, typical moveable unit (moveable air-conditioning units dominate the stock)	**Poor** 100% rate and 45% rate representative of wealthy householders, no evidence to support such rates and bears no relation to climate	**Fair** only southern England is modelled as a single region (no sub-divisions)	**Good** sound methodology based on energy consumption of a typical moveable unit based on base temperatures of 20 ^{0}C, 22 ^{0}C and 26 ^{0}C	energy calculation
DGTREN (2008)	**Good** different air-conditioning systems are represented in proportion to sales' volumes	**Poor** over-estimation of uptake resulting perhaps from anomalous years' sales and/or incorrect coefficient of innovation insufficient account taken of climate dependence apparent incorrect estimation of maximal saturation	**Good** sales figures are national sales	**Not applicable**	air-conditioning stock
MTP (2012)	**Poor** different air-conditioning systems are well represented in proportion to sales' volumes, but relate to the non-domestic sector	**Poor** over-estimation of uptake resulting perhaps from anomalous years' sales and/or incorrect coefficient of innovation	**Good** sales figures are assumed to be national sales	**Poor-Fair** apparent over-estimation of energy consumption (when compared to DECC data) methodology is reasonable, but fails to take into account that a warming climate will result in a greater number of hours of operation	

The strengths and weaknesses of the three models using the top-down approach are summarised in Table 17.

	Robustness of source data	Robustness of methodology	Aspects suitable for use in SCECMORS
AEA (2011)	**Poor-Good** service sector 'cooling + ventilation' consumption is unsuitable, even though CDD data from DECC/UKCP09 is reliable	**Poor** elasticity of demand methodology is unreliable, and increase in use due to (i) prolongation + intensity is not demarcated from that due to (ii) penetration based on base temperature of 22 ^{0}C although data are regionalised to high degree, this is insufficient in itself	regionalisation
Sailor and Pavlova (2003)	**Good** penetration data from US Census American Housing Survey and climate data from the National Climatic Data Center (NCDA) energy consumption data believed to come from RECS.	**Good** good correlation between per capita electricity consumption and CDDs for base temperature of 18.3 ^{0}C specific account taken of climate-dependent penetration	penetration/CDD model
Henderson (2005)	**Good** penetration data from US Census American Housing Survey energy consumption data from RECS.	**Good** good correlation between per specific electricity consumption (i.e. consumption/m^2) and CDDs for base temperature of 18.3 ^{0}C, but cannot be applied to a UK context specific account taken of climate-dependent penetration	penetration/CDD model

Regarding the formulation of SCECMORS, the review makes clear that whilst certain procedures are best avoided (e.g. calculation of consumption based on 'elasticity of demand'), and others are

impracticable to use (e.g. calculation of consumption using per capita electricity consumption), others still can be gainfully employed. The most prudent course of action would be to develop both a bottom-up SCECMORS (of which there are two kinds), and a top-down SCECMORS, so that a comparison can be made. Unfortunately the lack of reliably disaggregated UK data at the stock level (Section 3.1 and Section 3.2) and the unsuitability of US data for application in the UK (the energy consumption aspects of the models in Section 3.3.5 and Section 3.3.6) means that the top-down approach cannot be pursued[103]: SCECMORS therefore uses the bottom-up approach alone.

3.4 SCECMORS

The two optimum bottom-up modelling formats for SCECMORS are set out in Table 18[104]. The first bottom-up approach uses the dwelling as the base unit (SCECdwell), and the second bottom-up approach uses the air-conditioner as the base unit (SCECair).

Table 18 Bottom-up approach modelling optimum formats – reference models

	Stock	Penetration	Distribution	Energy calculation
SCECdwell	He et al (2006)	Sailor and Pavlova (2003)	AEA (2011)	He et al (2006)
SCECair	DGTREN (2008)	Sailor and Pavlova (2003)	AEA (2011)	Wu and Pett (2006), MTP (2012)

In forecasting future levels of space cooling energy consumption, both SCECdwell and SCECair must take account of both (i) the short-term response factor (the ratio of the CDD numbers in the future to the present), and (ii) the long-term response factor (the ratio of penetration levels in the future to penetration levels in the present)[105]. Consequently, knowledge of the following is pre-requisite for their function:

i.   present day national annual CDD totals,
ii.   future national annual CDD total,
iii.   present day penetration rate
iv.   future penetration rates, and

The procedures describing the calculation of CDD totals are outlined in Sections 3.5-3.6, and Section 3.7 describes the method used to calculate future penetration rates[106]; SCECdwell is subsequently described in Section 3.8 and SCECair is described in and Section 3.9.

---

[103] Air-conditioning energy consumption data from Canada is also revealed to be an artificial construct, and therefore unsuitable for use in SCECMORS.
[104] Note that these represent the basic formats and not the actual formats, i.e. modifications are made to the methods described by the reference models, e.g. SCECdwell uses the same basic method as the He et al (2006) model for calculating energy consumption, but does not use the DSY since the DSY is not representative of the mean climate.
[105] The long-term response is the combined effect of the short-term response factor and the long-term response factor (see Glossary).
[106] Also see Section 3.7.4 for present day penetration rates.

3.5 Present Day National Annual CDD Total

Key amongst the extraneous factors[107] affecting space cooling energy consumption are the climate (CDDs) and the number of consumers. However, despite the relatively small size of the UK, the diversity of its climate is such that it cannot be represented by a point spot. A nationally representative CDD total can, therefore, only be formulated from the aggregation of regional data, where regional CCD totals are summed in proportion to the population (or, more correctly, the number of dwellings) contained within each region.

Since the bulk of energy consumption occurs within England, the "English region" (the highest tier of sub-national division used by central government) is used as the base regional unit (Figure 30). It broadly reflects the LDZ pattern of division used by National Grid which is used in the space heating model (Chapter 2), with the exception that the two separate LDZ regions of Southern and South East are represented by a single government region called South East.
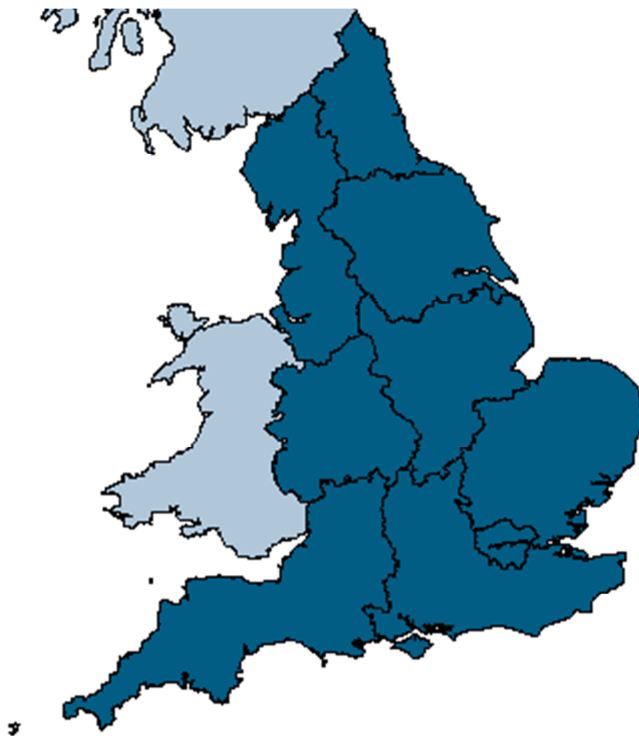
Figure 30 The nine English regions (UK National Statistics, 2012)

For reasons of consistency so as to accord with the LDZs, Scotland is treated as a single region and Wales is divided into a North region and a South region. The number of dwellings in each of the regions for the year 2010 is compiled from Government statistics (DCLG, 2012b; Scottish Government, 2012; Welsh Assembly Government, 2011).

As noted previously, CDD-based future energy consumption is calculated with reference to a base temperature. As SCECMORS is reliant upon North American data in order to calculate future rates of

---

[107] i.e. factors unrelated to the mechanical cooling apparatus (type, efficiency).

penetration (see Section 3.7), SCECMORS is bound into using the same base temperatures used in the North American data; whilst the US and Californian CDD data are reported to a base temperature of 65 ^{0}F (18.3 ^{0}C), the Canadian CDD data are reported to a base temperature of 18 ^{0}C[108]. This constraint, however, is not regarded as undesirable in view of the results of the optimisation study reported in Sailor and Pavlova (2003) (see footnote 88). Thus the annual number of CDDs are calculated with reference to both North American base temperatures, 18.0 ^{0}C and 18.3 ^{0}C.

The mean annual number of CDDs are calculated for the period 2000-10 for a single representative weather station located within each region using data from the British Atmospheric Data Centre (BADC) (UK Meteorological Office, 2011), the locations being the same as those previously successfully used in Section 2.5.3 to characterise regional space heating energy consumption (Equation 13 and Equation 14).

Equation 13

$$CDD_r = \left(\sum_{i=2000}^{2010} CDD_i \right) \div 11$$

where,

CDD_r = present day (2000-10) annual mean number of cooling degree-days in a region (K.day)

i = year

CDD_i = annual number of CDDs in a single year i (K.day)

Equation 14

$$CDD_i = \sum_{j=1}^{365} (t_m - t_b)$$

where,

j = day in year (extends up to 366 in a leap year, although equation only shows 365)

t_m = daily mean outdoor temperature, calculated as the mean of the daily maximum and daily minimum temperatures (^{0}C)

t_b = base temperature (^{0}C)

n = number of days in a year on which t_m is above t_b

---

[108] Canadian CDDs are also reported to base temperatures of 0 ^{0}C, 5 ^{0}C, 10 ^{0}C, 15 ^{0}C and 24 ^{0}C, but these are considered to be inappropriate since an incorrect base temperature can result in large over-estimation or under-estimation of energy consumption.

where,

$$t_m - t_b \text{ assumes a value of 0 if } t_b > t_m$$

The number of dwellings and annual CDD data for the present day for each of the 13 regions are reported in Table 19.

Table 19 Present day number of dwellings and annual CDD totals by region

Region	Number of dwellings	Weather station*	CDDs (base temperature 18.0 ^{0}C)	CDDs (base temperature 18.3 ^{0}C)
North East	1 160 000	Albemarle/Boulmer	8	6
West Midlands	2 348 000	Coleshill	45	38
Yorkshire and the Humber	2 283 000	Dishforth	25	21
South West	2 385 000	Filton/Yeovilton	48	40
Scotland	2 482 000	Glasgow	8	6
London	3 300 000	Heathrow	122	107
North Wales	357 000	Lake Vyrnwy	9	7
North West	3 103 000	Woodford/Ringway	33	28
South East 1**	3 661 000	Manston	63	53
South East 2**	3 661 000	Middle Wallop	44	37
South Wales	988 000	St Athan	26	21
East Midlands	1 950 000	Waddington	46	38
East of England	2 503 000	Weybourne	47	40
Great Britain	**26 519 000**		**47**	**40**

* For three of the weather stations, the data do not extend back as far as 2000 (Albemarle: February 2003, Filton: March 2001, Woodford: November 2003). The data from nearby weather stations (Boulmer, Ringway and Yeovilton respectively) are used in these instances where data are missing.

** Since two separate weather stations used in the previously described space heating model in Chapter 2 fall within the boundaries of the South East English government region, the data from each are used in the analysis: CDD data for the South East region are calculated as the mean of the data from Manston and Middle Wallop.

The present day annual cooling degree-day totals for Great Britain, weighted by dwelling population, ($CDD_{GB-2010}$), are shown in the final row of Table 19 above, having been calculated thus:

Equation 15

$$CDD_{GB-2010} = \sum_{r=1}^{13} CDD_r \times (n_r \div n_{GB})$$

where

r = region

CDD_r = annual number of CDDs in region r

n_r = number of dwellings in region r

n_{GB} = number of dwellings in Great Britain

It should be noted that the weather stations in Table 19 are located in rural locations. As such, the number of population-weighted CDDs reported for each region can be deemed to be the equivalent of the MIN population-weighted CDD values used for the Canadian data later reported in Section 3.7.3.

3.6 Future National Annual CDD Total

The procedure for calculating national annual CDD totals for different future time periods under different emissions scenarios uses the same regions, weather stations and weighting factors to those described in Section 3.5 above. The regional annual CDD totals are derived from daily weather generated by the UKCP09 Weather Generator for each of the 13 locations for the (i) 2030s, (ii) 2050s and (iii) 2080s under (i) low, (ii) medium and (iii) high emissions scenarios as previously described in Section 2.5.4. The Weather Generator is run 100 times for each of the 13 locations, with each run producing a 100-year sequence of useable data. The future annual number of CDDs for a ternion (CDD_t) is calculated from 10,000 years of data as:

Equation 16

$$CDD_t = \left(\sum_{n=1}^{100} CDD_i\right) \Big/ (100 \times 100)$$

where

n = Weather Generator run

CDD_i = annual number of CDDs in a single year i (see Equation 14)

The national number of CDDs in a future climate for a given decade in a given emissions scenario (CDD_{GB-fut}) is finally calculated by summing the annual CDD totals of the 13 regional ternions specific to the particular decade and emissions scenario in question (Equation 17).

Equation 17

$$CDD_{GB-fut} = \sum_{t=1}^{13} CDD_t$$

where

t = ternion

The annual number of CDDs for different future time-slices and different emissions scenarios are reported in Table 20 (base temperature 18.0 ^{0}C) and Table 21 (base temperature 18.3 ^{0}C).

Table 20 Annual CDD totals for future decades and emissions scenarios for regional weather stations (base temperature 18.0 ^{0}C)

Weather Station	2030s Emissions Scenario			2050s Emissions Scenario			2080s Emissions Scenario		
	Low	Med	High	Low	Med	High	Low	Med	High
Albemarle	30	27	32	44	54	62	66	108	172
Coleshill	86	95	84	118	137	155	145	237	329
Dishforth	59	57	58	82	88	108	102	153	237
Filton	108	113	120	155	178	228	203	306	411
Glasgow	25	24	26	40	47	55	55	79	167
Heathrow	201	195	210	273	291	309	310	432	600
Lake Vyrnwy	29	28	30	44	55	59	58	108	163
Woodford	73	79	79	110	133	144	122	196	315
Manston	118	124	134	172	193	213	197	308	389
Middle Wallop	99	101	115	149	167	188	186	245	406
St Athan	90	91	96	139	149	172	187	236	360
Waddington	82	77	83	121	126	139	133	227	299
Weybourne	61	62	69	87	95	110	115	185	280

Table 21 Annual CDD totals for future decades and emissions scenarios for regional weather stations (base temperature 18.3 ^{0}C)

Weather Station	2030s Emissions Scenario			2050s Emissions Scenario			2080s Emissions Scenario		
	Low	Med	High	Low	Med	High	Low	Med	High
Albemarle	24	22	26	37	46	53	56	94	154
Coleshill	74	82	72	103	120	137	128	214	302
Dishforth	50	48	48	70	76	93	88	135	213
Filton	93	98	104	136	158	205	181	277	379
Glasgow	21	19	21	33	39	46	46	68	148
Heathrow	179	174	187	248	264	282	282	398	561
Lake Vyrnwy	24	24	25	37	46	51	49	94	145
Woodford	62	68	68	96	117	127	107	175	287
Manston	102	107	116	152	171	189	174	279	356
Middle Wallop	86	88	100	132	149	167	165	221	375
St Athan	76	78	82	121	130	151	165	211	329
Waddington	71	66	71	107	110	122	117	204	272
Weybourne	51	52	58	74	82	95	100	164	253

Table 22 reports the population-weighted[109] national CDD totals for future time-slices under different emissions scenarios.

Table 22 Annual CDD totals for future decades and emissions scenarios (CDD_{GB-fut}) for Great Britain

Base temperature (^{0}C)	2030s Emissions Scenario			2050s Emissions Scenario			2080s Emissions Scenario		
	Low	Med	High	Low	Med	High	Low	Med	High
18.0	90	91	96	129	144	162	156	233	340
18.3	78	79	83	114	127	144	138	210	312

---

[109] The population distribution in the future is assumed to be the same as the present day.

3.6.1 Verification of Results

In the same way that the COPSE future TRYs are used to test the robustness of SHECMOBS (Section 2.5.6.1), they can also be used to test the robustness of the CDD calculation process used in SCECMORS. Whereas the gas consumption totals calculated from COPSE TRYs are, however, very similar to the consumption totals calculated using the averaging process used in SHECMOBS (Table 11), more variation is seen when CDD totals calculated from COPSE TRYs are compared with CDD totals calculated using the averaging process used in SCECMORS shown in Table 22 above: Table 23 shows the percentage difference in annual CDD totals calculated using the two different procedures.

Table 23 Percentage by which annual number of CDDs calculated using COPSE TRYS differs from annual number of CDDs calculated using SHECMOBS averaging process

	London (Heathrow)				Manchester (Woodford/Ringway)			
	Emissions scenario				Emissions scenario			
	Low		High		Low		High	
Base temperature (^{0}C)	18	18.3	18	18.3	18	18.3	18	18.3
2050s	-15.0	-16.9	-7.1	-8.3	-21.0	-23.4	-15.8	-17.1
2080s	-6.1	-7.0	-18.7	-19.7	13.3	14.3	-4.2	-4.7

In view of the relatively large discrepancy and in view of the ease with which error can be introduced into the VBA coding, the need to re-check the data is apparent. When the CDD total for the Heathrow-2080s-high emissions scenario ternion (base temperature of 18.3 ^{0}C) is re-calculated long-hand[110], however, exactly the same result of 561 CDDs is produced, the COPSE TRY continuing to return 19.7% fewer CDDs.

Part of the reason for the difference lies in the fact that there are so relatively few days in the course of a year when the mean temperature exceeds 18-18.3 ^{0}C (i.e. only hot summer days), that a small change in the number of hot days can result in a large percentage change[111]. Another reason for the difference is because of the aspect of variability which is incorporated within a TRY; whilst temperatures for the 2020s are forecast as being very similar whether or not a high emissions or a low emissions pathway is followed, both the COPSE Heathrow and Manchester high emissions TRYs return approximately 20% fewer CDDs than their low emission counterparts, even though one would have anticipated that the high emissions TRYs would return slightly more CDDs. Nevertheless, it would also seem that the daily temperatures in the COPSE TRYs do tend to be less hot than average weather for summer days (i.e. a lower preponderance of days where the mean temperature is above 18/18.3 ^{0}C), but discussion of this point lies beyond the scope of the present analysis. Whatever the causes of the COPSE TRY returning a lower than expected number of CDDs, the long-hand calculation that it prompted reveals that the VBA coding appears not to be at fault.

---

[110] i.e. calculated directly by inputting the data into Microsoft Excel spreadsheets, and processing the data directly in the spreadsheet without writing any VBA code – a laborious process.
[111] e.g. the 23% discrepancy for Manchester under a low emissions scenario (base temperature 18.3 ^{0}C) in the 2050s derives from a difference of only 23 CDDs (73 as opposed to 96).

3.7   Future Penetration Rates

The penetration profile (relationship between CDDs and penetration) is examined in this section using data from the United States, California and Canada. Although mentioned in the text on each occurrence, the reader is asked to be mindful of the fact that whilst the base temperature to which the US and Californian data refer is 18.3 ^{0}C (65 ^{0}F), the base temperature for the Canadian data is 18.0 ^{0}C.

3.7.1   United States

The air-conditioning market in the United States is long-standing and mature, price not being the same impediment to purchase for its inhabitants as it has been for the citizens of less wealthy countries. Whether fully mature or not (i.e. whether saturation has been achieved or not), the rapid rise in the uptake of air-conditioning over a relatively short period of time[112], is suggested as giving an indication of the pathway that uptake in the UK may follow in future years, especially since there is an observable correlation between penetration and the number of CDDs. Data are collated, and the relationship between the two is examined below.

3.7.1.1   Penetration data

The EIA periodically carries out a survey, the Residential Energy Consumption Survey (RECS), which, amongst other things, reports upon the extent of air-conditioning in the US. Analysis of RECS data from 1978 to 2009 shows a continuing upward trend of air-conditioning use (EIA, 2000; EIA, 2004; EIA, 2009; EIA, 2012), as shown in Figure 31.
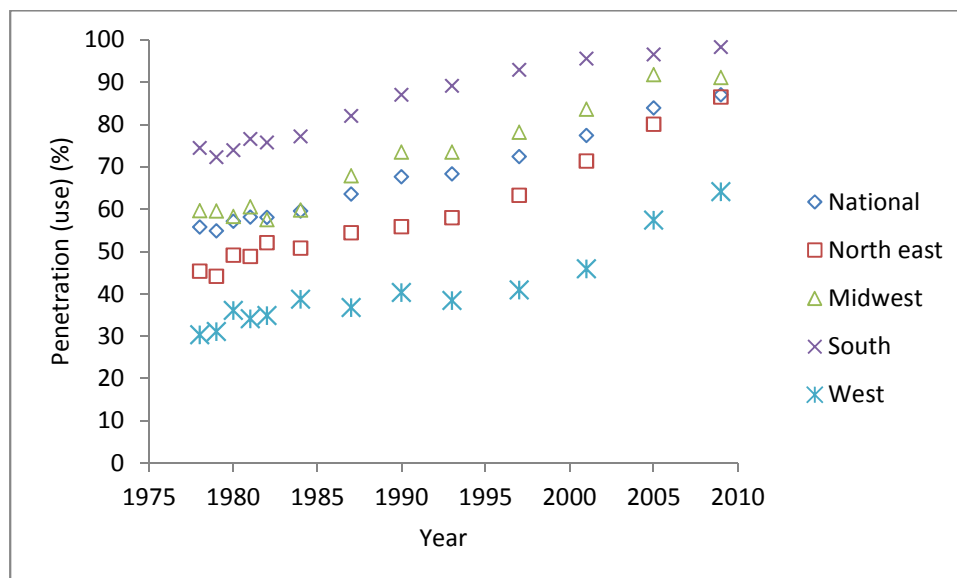
Figure 31 Increasing ownership (as percentage penetration) of air-conditioning in US regional divisions (1978-2009)

---

[112] The level of air-conditioning in American homes rose from less than 2% in 1955 to almost 59% in the 25-year period to 1980 (Biddle, 2008). Present ownership levels in the UK, (estimated at 3% (BSRIA, 2011) and 7.2% following analysis of DGTREN data), compare with those in 1950s America.

Although saturation has been achieved or almost achieved in certain of the divisions, the evidence suggests that penetration rates, on the average, are still on the rise.

In contrast to the data reported by Sailor and Pavlova (2003), the RECS dataset also provides details on air-conditioning use as well as ownership. This is a useful addition because not only is there a difference between the two (of the order of about 5%, but which extends to 10% and beyond for the less hot states such as Massachusetts (MA), Table 24), but also because energy consumption is likely to be more intimately linked to use rather than ownership.

Table 24 Penetration of air-conditioning by state/state grouping in the US residential sector*

State	Use Air Conditioner (%)	Use Air Conditioner (%)*	State	Use Air Conditioner (%)	Use Air Conditioner (%)*
CO	47	58	VA	93	-
CT, ME, NH, RI, VT	67	77	MO	100	-
MA	76	88	KS, NE	94	-
WI	78	83	TN	100	-
MI	82	87	NC, SC	94	-
ID, MT, UT, WY	70	75	NM, NV	71	71
IA, MN, ND, SD	87	92	GA	97	-
NY	74	81	AL, KY, MS	98	-
PA	90	94	AR, LA, OK	98	-
IN, OH	84	90	TX	96	99
NJ	91	-	AZ	91	96
IL	90	94	FL	96	-
CA	57	63	AK, HI, OR, WA	45	47
DC, DE, MD, WV	94	-			

Number of dwellings in US: 113.6M. Air-conditioning use and ownership is reported to 1 decimal place (100,000 homes). The accuracy of the penetration figures is therefore dependent upon the number of dwellings in a state or state-grouping; whereas the degree of error for the sparsely populated New Mexico-Nevada grouping is up to ±5%, the Californian data are accurate to less than ±1%.

*Data are omitted where the relative standard error (RSE) is greater than 50% (or fewer than 10 households were sampled). The RSE can be very large where there are few data. The survey does not report on the total number of dwellings which possess air-conditioning per se, but rather on the total number of dwellings which do not possess air-conditioning: i.e. the former is calculated from the latter. This is the reason why the air-conditioner ownership column contains more blank cells than the air-conditioner use column - the ownership column is calculated from "non-ownership" data, which, in a number of instances, contain few data.

3.7.1.2 Cooling degree-day data

The National Climatic Data Center (NCDC) publishes monthly population-weighted CDD data for the 48 conterminous states of the US to a base temperature of 65 ^{0}F for years back to 1992 (NCDC, 2012a). Table 25 reports average annual CDD totals for the period 1992-2010, reported to a base temperature of 18.3 ^{0}C (equivalent to a base temperature of 65 ^{0}F).

Table 25 Annual state CDD totals for the US (base temperature 18.3 ^{0}C)

State	Mean annual CDD total	State	Mean annual CDD total
Washington	122	Illinois	491
Maine	128	Indiana	499
Oregon	149	California	529
Montana	153	Nebraska	544
Vermont	157	New Mexico	562
Colorado	178	Maryland & DC	618
Wyoming	181	Virginia	618
New Hampshire	194	Delaware	627
North Dakota	241	Kentucky	684
Minnesota	279	Missouri	695
Massachusetts	280	Tennessee	779
Wisconsin	280	Kansas	797
Idaho	285	North Carolina	806
Rhode Island	314	Georgia	967
Michigan	316	Arkansas	1009
Connecticut	340	South Carolina	1041
New York	387	Oklahoma	1056
Pennsylvania	395	Alabama	1084
South Dakota	402	Nevada	1166
Ohio	431	Mississippi	1201
Iowa	445	Louisiana	1500
West Virginia	445	Texas	1522
Utah	452	Arizona	1741
New Jersey	482	Florida	1954

The number of CDDs for a state is population-weighted by state division, where the CDD value for each division within a state is weighted by its percentage of the total state population as adduced from the 1990 census data (NCDC, 2012a). Thus any effects deriving the urban heat island are necessarily taken into consideration.

3.7.1.3 Correlation between present day (2009) penetration rates and population-weighted CDDs

Figure 32 shows the correlation between present day air-conditioning penetration (use) and population-weighted CDDs for the 16 states/state groupings listed in Table 24, using the CDD data from Table 25[113]. The chart also shows (i) the predicted penetration (ownership) trend line using the functional relationship described by Sailor and Pavlova, and (ii) the best line of fit through the data using Microsoft Excel Solver to optimise Sailor and Pavlova's equation.
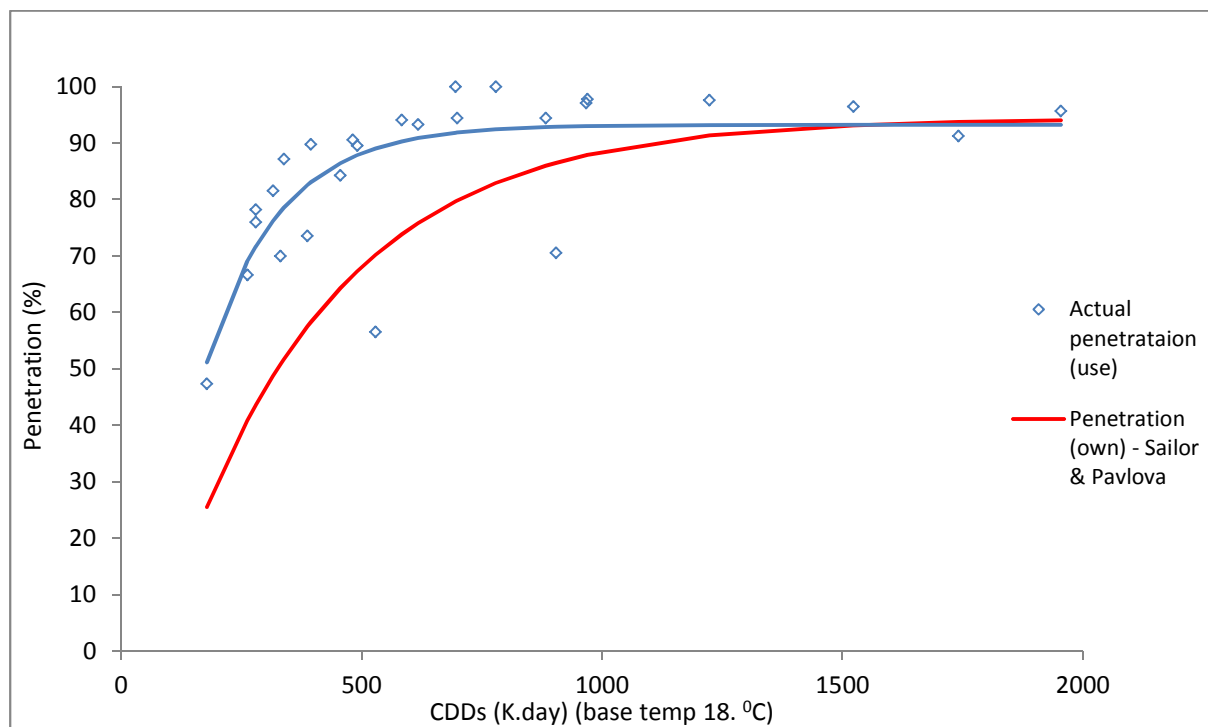
Figure 32 Correlation between penetration of air-conditioning use and annual population-weighted CDD total for 26 states/state-groupings in the US (base temperature 18.3 ^{0}C)

Even though the same general pattern of uptake is observed, actual penetration levels are higher than those predicted by the Sailor and Pavlova equation. For CDD values below approximately 1000, the increase in penetration which has occurred between the Sailor and Pavlova period of study (1994-1996) and 2009 would seem to be more significant than the fact that one regression examines

---

[113] The population-weighted CDD totals for a state-grouping is calculated by further population-weighting the population-weighted CDD totals of each state within that grouping using US census data (US Census Bureau, 2011).

ownership and the other regression equation examines use[114]. As suggested by Henderson (2005), however, the difference may in part arise from the fact that Sailor and Pavlova used the hourly method to calculate CDDs, rather than the daily mean temperature method used by the EIA[115]. Nevertheless, it is clear that little reliance can be placed on the accuracy of the left hand side of the curve for CDD values below 260 since its shape in this portion of the plot is largely determined by a single datum point of value 178 (i.e. Colorado). This is of particular importance insofar as the present analysis is concerned because CDD forecasts for the UK mostly remain below 260; only under a high emissions scenario in the 2080s do CDD forecasts exceed 260 (see Table 22, Section 3.6).

Two datum points clearly stand out as anomalous in Figure 32. When the use penetration/CDD regression data are re-plotted excluding these data, the Solver-derived best line of fit shows a very high coefficient of determination (R^2 = 0.87) (Figure 33[116]).

The following equations appear on the plot:

$$\mathit{Actual}: Penetration\,(use)\,(\%) = (96.7 - 160e^{(-0.00678.CDD)})$$

$$\mathit{Actual}: Penetration\,(own)\,(\%) = (95.7 - 167e^{(-0.00857.CDD)})$$
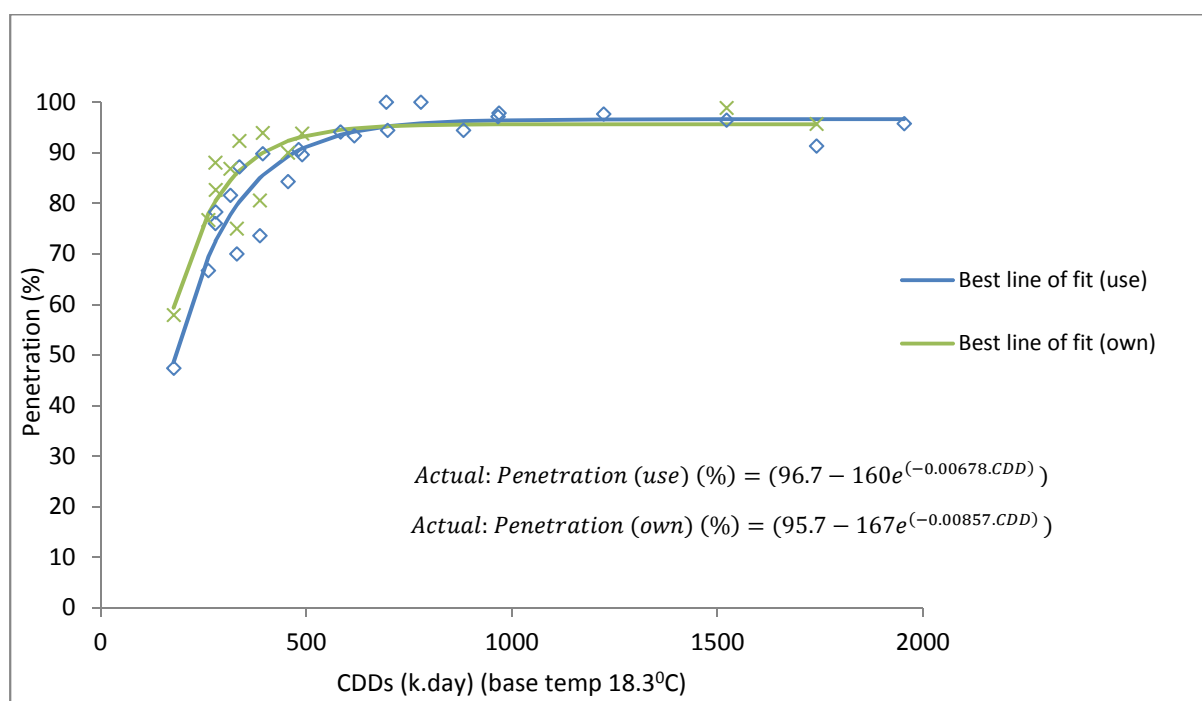
Figure 33 Correlation between penetration of air-conditioning (use & ownership) and annual population-weighted CDD total in the US (base temperature 18.3 ^{0}C) (anomalies removed)

This raises the question of the legitimacy of dismissing these datum points as aberrant. The datum points refer to the state-grouping of New Mexico/Nevada (CDDs = 905) and California (CDDs = 529).

---

[114] Table 24 shows that the difference in penetration between ownership and use is typically of the order of 5%, whilst Figure 32 reveals the penetration difference to be of the order of 20% for CDD values below approximately 500.

[115] Mean daily temperature method used by EIA – CDD totals are calculated from daily mean temperatures where only days in which the daily mean temperature exceeds the base temperature are included (see Section 3.5). Hourly method used by Sailor and Pavlova (2003) – CDD totals are calculated by aggregating hourly temperature differences and dividing by 24.

[116] The ownership penetration/CDD regression data and ownership best line of fit (R^2 = 0.77) are also shown for comparison.

New Mexico and Nevada experience extremely low levels of RH, afternoon levels in the summer (June-August) being of the order 25-38% for New Mexico and 14-21% for Nevada (NCDC, 2012b). The relatively low installation of air-conditioning in these states undoubtedly arises from the fact that "dry heat" is generally perceived as much less uncomfortable than "damp heat" to pale-skinned people, even be it that the air temperatures are the same in both instances. As such, although the New Mexico/Nevada data are not erroneous, they can be ignored since the UK neither currently experiences nor is forecast to experience such low RH values over the course of the next 60-70 years.

The picture is not so clear for the climatically-diverse California. Although much of the state is hot and dry like New Mexico and Nevada, some of the most densely populated coastal areas are not: afternoon RH levels reach up to 64% in San Francisco, whilst daily mean temperatures only average 16.3 ^{0}C in summer for the same city (June-August) (NCDC, 2012b). This is significant as far as the UK is concerned because the number of CDDs for parts of the UK is forecast to exceed that of the Californian average under a high emissions scenario by the 2080s (e.g. Heathrow, 561 CDDs, see Section 3.6). One cannot, therefore, safely disregard the California data as being irrelevant, and for this reason, California requires closer inspection.

3.7.2 California

The 2009 California Energy Commission (CEC) Residential Appliance Saturation Study (RASS) reports upon air-conditioning penetration in a similar fashion to the EIA's national RECS (California Energy Commission, 2010). Moreover, the CEC reports upon population-weighted CDDs to a base temperature of 65 ^{0}F (18.3 ^{0}C) for each of the 13 climatic zones which comprise the state, allowing one to examine the relation between air-conditioning penetration and CDDs. Figure 34 shows the correlation between the uptake of air-conditioning and CDDs, and overlays it with the US national best line of fit data obtained from RECS (using the equations presented in Figure 33).
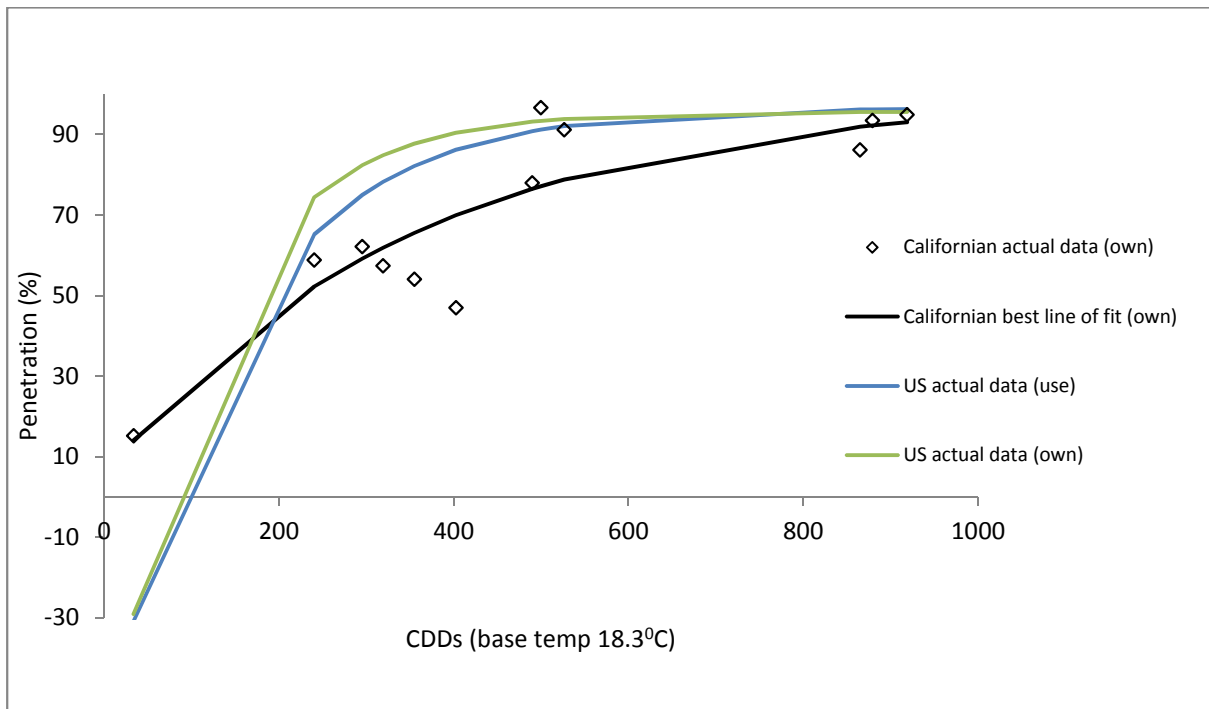
Figure 34 Correlation between penetration of air-conditioning (ownership) and annual population-weighted CDD total (base temperature 18.3 ^{0}C)

It is clear that at least as much diversity exists within California as exists in the rest of the country in terms of air-conditioning penetration and its relation to climate, with penetration rates as low as 15% in the San Francisco area, and higher than 90% in many inland areas. Although the R^2 value of 0.81 might suggest that CDDs act as a good predictor of penetration, closer examination of the data reveals that the correlation is very poor in the 200-400 CDD range; this is of especial significance because CDD values of this order are predicted for large parts of the UK by the 2050s under a medium emissions scenario (see Section 3.6). Furthermore, like the US data, the correlation is hampered by the fact that there is only single datum point with a CDD value less than 240.

The reason for the peculiarity of the Californian data would seem to be due, at least in part, to its geography. Indeed, Glen Sharp of the CEC states that, climatically, it is the most unique and diverse state in the US, citing the example of Sacramento in the Central Valley in which summer temperatures regularly reach the mid-90s (^{0}F), but which benefits from marine cooling almost every evening due to its proximity to the coast, with the result that it experiences very comfortable low temperatures at night (Sharp, 2012). Data from different locations in the San Francisco Bay area are startling when viewed from the cool maritime climate of north west Europe: whilst the average maximum temperature of the coastal town of Half Moon Bay records as approximately 18° C in July, it records as 31° C at Walnut Creek (only 25 miles inland) and 35° C at Tracy (only 50 miles inland). A similar diversity is seen in the Los Angeles area: the normal July maximum temperature for Santa Monica Pier is approximately 24° C, but the average increases to 35° F at Canoga Park in the San Fernando Valley only 15 miles to the north (Desert Research Institute, 2012). This is not to say that the Californian data give lie to the notion that there is a general relationship between penetration

and the number of CDDs, but rather that California is so exceptional that its data are likely to be unreliable for use in SCECMORS.

3.7.3   Canada

Given that the US data do not contain enough relatively low value CDD data (<300 CDDs), and that the uniqueness of the climate of California make it unsuitable as being representative of a more general relationship between CDDs and penetration, one is forced to look elswehere for source data which reveal the relationship between CDDs and penetration in a mature air-conditiong market. Canadian data are examined as meeting these criteria.

Usefully, the Canadian Government provides two sources which report upon the uptake of air-conditioning, each of which derive from separate surveys, and allows for cross-comparison of the data. The Comprehensive Energy Use Database (CEUD) , deriving from the annual Survey of Household Spending (SHS) (NRCan, 2011a), is published by the Department of Natural Resources (NRCan) and reports upon ownership levels for all ten provinces and one territory-grouping; the latest available data are for 2009 (NRCan, 2012). The Survey of Household Energy Use (SHEU)[117], also published by NRCan, only reports upon ownership levels for six regions, where the less populated states and territories are grouped together; the latest available data are for 2007 (NRCan, 2010).

Although NRCan also reports upon CDDs for each of the six 'Canadian regions', it is considered that the CDD data are not sufficiently accurate to reflect the climatic diversity of the country, as data from only 23 weather stations are used for this task (NRCan, 2011b)[118]. In consequence, population-weighted CDD data have been generated from comprehensive Canadian Government data (viz. CDD data: National Climate Data and Information Archive (NCDIA, 2012), and population data: 2006 Canadian census (Statistics Canada, 2008)). Provided that the CDD data are highly disaggregated by region and population-weighted accordingly, the number of regions or provinces/territories used to collect penetration data is of little importance so long as there is not an over-representation of anomalous data.

3.7.3.1 Calculation of Population-Weighted CDDs

There are a number of methods by which population-weighted CDD data can be calculated, the different methods yielding CDD values which may be significantly different from one another. As it is not clear which of the methods is most appropriate, all methods are used so that a comparison can be made. The population-weighted CDD calculation procedure is shown below.

---

[117] Not performed annually.

[118] A case in point which serves to illustrate the danger of using too few/incorrect weather stations to calculate a single CDD value (which is representative of a region) is seen in Montreal. Montreal possesses six weather stations, three of which are at airports, which return, in some cases, very different CDD totals, and in ways which are not immediately predictable. Montreal-Mirabel International Airport returns 158 CDDs. Montreal-Pierre Elliott Trudeau International Airport which is less than nine miles from downtown reports 242 CDDs, whilst the even more centrally located St-Hubert Airport, 7.5 miles from downtown, reports 218 CDDs. The remaining weather stations all report more than 300 CDDs with Montreal LaFontaine reporting 354 CDDs (base temperature 18 ^{0}C).

i.   Census data for all 144 *census metropolitan areas* (CMAs) and *census agglomerations* (CAs) (i.e. in essence, all towns with a population in excess of 10 000) are collated, to produce 148 individual population centres (PCs)[119].

ii.   Each PC is paired with the CDD total from the geographically closest weather station which reports at least 15 years of CDD data (base temperature 18 ^{0}C). 101 pairings are made in this way. For the remaining 47 PCs (for each of which there exists more than one weather station, e.g. Montreal CMA - footnote 118), the CDD total is recorded for each weather station. There exists four methods by which these remaining PCs can be paired with weather station CDD data:

   a. pair the PC with the CDD value from the weather station reporting the greatest number of CDDs (MAX),

   b. pair the PC with the CDD value from the weather station reporting the smallest number of CDDs (MIN),

   c. pair the PC with the average CDD value calculated from all the weather stations (i.e. all six weather stations in the case of Montreal) (MEAN), or

   d. pair the PC with the average CDD value calculated from the two weather stations reporting the maximum and minimum number of CDDs (i.e. Pierre Trudeau International Airport and LaFontaine in the case of Montreal) (MIDDLE).

iii. The population-weighted CDD total is calculated for (a) each of the 11 'province/territory-groupings' (for use with the CEUD air-conditioning data) or (b) each of the six 'Canadian regions' (for use with the SHEU air-conditioning data). This is achieved by summing all the weighted CDD values of the PCs within its boundaries, where the weighting factor is (a) the ratio of the PC population and the population of the 'province/territory-grouping', or (b) the ratio of the PC population and the 'Canadian region' population[120]. This is repeated for all four methods of calculating population-weighted CDDs where there exists more than one weather station for a PC.

Thus each 'province/territory-grouping' or 'Canadian region' has four separate population-weighted CDD values attached to it – MAX, MIN, MEAN and MIDDLE.

3.7.3.2 Relationship between Population-Weighted CDDs and Penetration

The benefit of using four different ways of calculating population-weighted CDDs is seen when penetration is plotted against population-weighted CDDs, and best-fit trend lines are mapped on to the data in order to establish the degree of correlation. In addition to fitting trend lines of the Sailor and Pavlova type based on the exponential function, linear trend lines are also mapped, since the regression data appears to be linearly related for relatively low CDD values as revealed by Table 26

---

[119] Four communities straddle province borders.

[120] See Section 3.5 for a description of the equation used in the weighting procedure. (Note that *number of dwellings* is used in the weighting factor in Section 3.5, whereas *population* is alternatively used in this instance in the absence of dwelling data at the level of the population centre; it is considered that the use of population data is not injurious to the analysis.)

and Table 27. (Indeed this accords with the US data, where the correlation also appears to be linear for relatively low CDD values.)

Table 26 Coefficients of determination (R^2 values) in the plot of air-conditioning penetration (ownership) against population-weighted CDDs calculated by different methods (air-conditioning data: 2009 CEUD) (base temperature 18 ^{0}C)

	Type of population-weighted CDD used in regression			
	MAX	MIN	MEAN	MIDDLE
Best fit trend line: exponential function	0.63	0.72	0.66	0.68
Best fit trend line: linear function	0.57	0.75	0.63	0.65

Table 27 Coefficients of determination (R^2 values) in the plot of air-conditioning penetration (ownership) against population-weighted CDDs calculated by different methods (air-conditioning data: 2007 SHEU) (base temperature 18 ^{0}C)

	Type of population-weighted CDD used in regression			
	MAX	MIN	MEAN	MIDDLE
Best fit trend line: exponential function	0.59	0.71	0.59	0.62
Best fit trend line: linear function	0.58	0.82	0.65	0.69

It is clear that air-conditioning uptake bears most correspondence with MIN population-weighted CDDs. The exponential-type and linear functions forecast very similar levels of penetration up to about 170 CDDs, such climates not being forecast until the second part of the century (see Table 22). However, whilst the R^2 value associated with the linear trend line is a little higher than that associated with the trend line using the exponential-type function for the MIN population-weighted CDDs, it must borne in mind that the the linear function becomes inaccurate for high CDD values since it takes no account of the fact that penetration plateaus as saturation is approached. This is seen in Figure 35 and Figure 36, where extrapolated penetration would exceed 100% for CDD values in excess of about 300, the significance of such a figure being that under a high emissions scenario the climate of the 2080s is forecast to return an even higher number of CDDs (see Table 22).
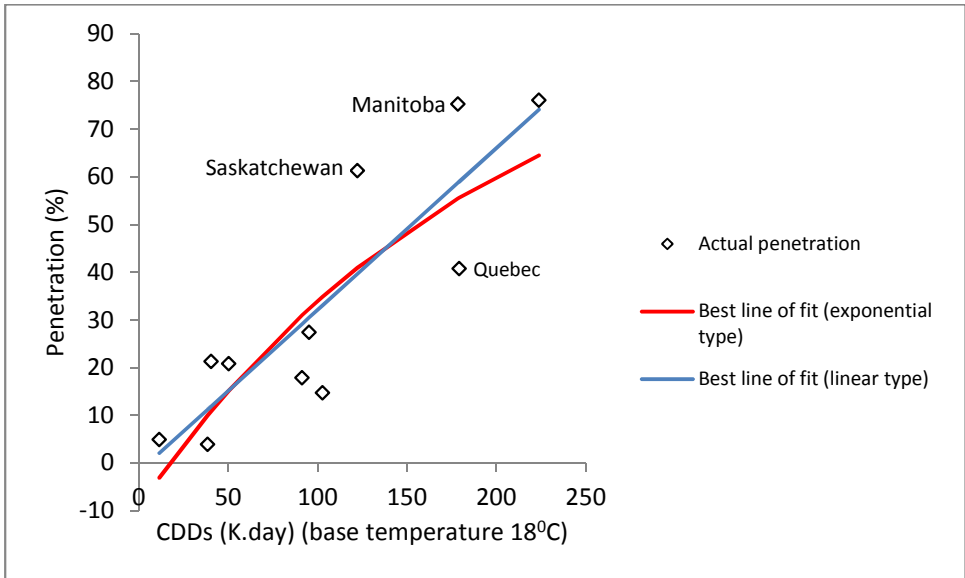
Figure 35 Correlation between penetration of air-conditioning (ownership) and annual MIN population-weighted CDD total using 2009 CEUD data (base temperature 18 ^{0}C)
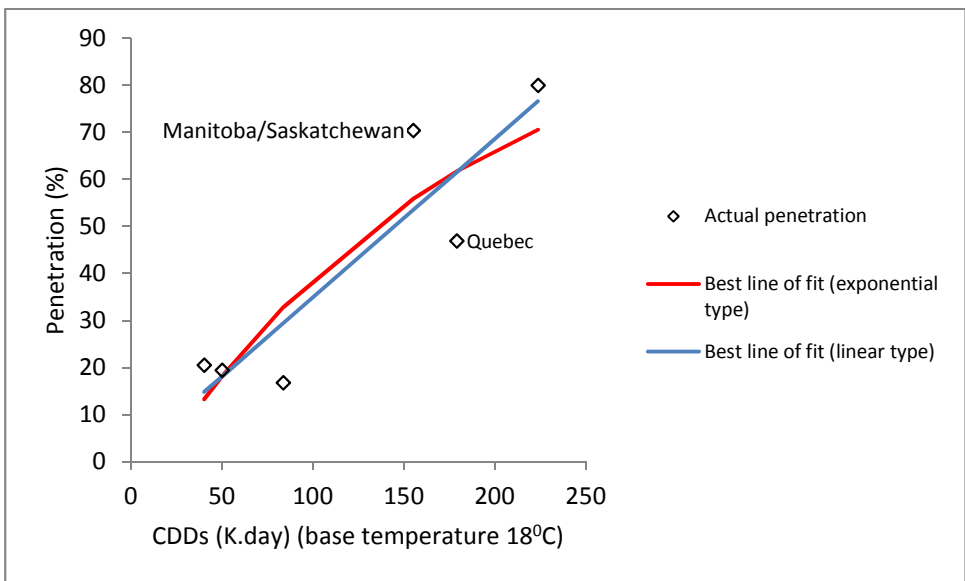
Figure 36 Correlation between penetration of air-conditioning (ownership) and annual MIN population-weighted CDD total using 2007 SHEU data (base temperature 18 ^{0}C)

The absence of accurate data for Canadian climates with relatively high CDD values disqualifies the straight-line function as a predictive tool of penetration for climates with high CDD values: simply, one should not extrapolate the linear function beyond the highest observed CDD value (= 224). The equations describing CEUD and SHEU penetration are shown below.

Table 28 Equations describing penetration as a function of CDD value using CEUD and SHEU data

Function type	Data source	Equation	
Exponential	**CEUD**	$penetration\ (\%) = 100 - (107.8e^{-0.00510 \times CDD})$	**Equation 18**
	SHEU	$penetration\ (\%) = 100 - (110.0e^{-0.00589 \times CDD})$	**Equation 19**
Linear	**CEUD**	$penetration\ (\%) = 0.3394\ CDDs - 1.8323$	**Equation 20**
	SHEU	$penetration\ (\%) = 0.3369 + 1.177$	**Equation 21**

The equations describing the relationship between penetration and CDDs from the CEUD and SHEU surveys are very similar. The SHEU data, however, is not altogether convincing for low-value CDD totals, and it is clear that there is a degree of spread in the data, even though the R^2 values are reasonably high. It is also a concern that there is such a large discrepancy in actual penetration rates for CDD values in excess of approximately 125, such values being typical of the forecasts for the southern parts of the UK by the 2050s, irrespective of which emissions scenario is followed. Were the UK to adopt the same pattern of uptake as Manitobans for example, one could expect penetration rates up to 17-18% larger than those predicted by the trend line, whereas an uptake pattern similar to those of Quebecers would result in an uptake of 16-18% less than that predicted by the trend line. Given the finding from the US that there can be differences between rates of ownership and rates of use (Table 24), it would seem that the discrepancy may arise in part from the fact that a plentiful number of Manitobans (and Saskatchewanians) have air-conditioning installed in their home but do not necessarily use it, which is perhaps not so much the case for Quebecers; in consequence, it is suggested that future penetration rates in the UK (i.e. penetration use) would perhaps find most correspondence in the ownership penetration rates of Quebec than Manitoba, which latter two provinces share the same number of CDDs.

3.7.4 Application of North American Penetration Rates to UK Climates

Although climate may be of primary importance concerning levels of penetration, and although the literature reveals that penetration rates can increase at considerable speed in prosperous economies, it would be incorrect to assume a step change in penetration rates from the present day's level to those forecast for the 2030s and beyond. Rather, it is likely that penetration will increase incrementally from the present level, estimated at 3% by BSRIA (BSRIA, 2011) and at 7.2% following analysis of DGTREN data (DGTREN, 2008). Even though the present analysis only endeavours to estimate penetration rates for the 2030s, 2050s and 2080s, it is of theoretical importance to take this pre-2030s trajectory into account since it has an effect upon the later trajectory. Figure 37 illustrates this point, showing three penetration trajectories deriving from the CEUD data for a medium emissions scenario using the exponential function.
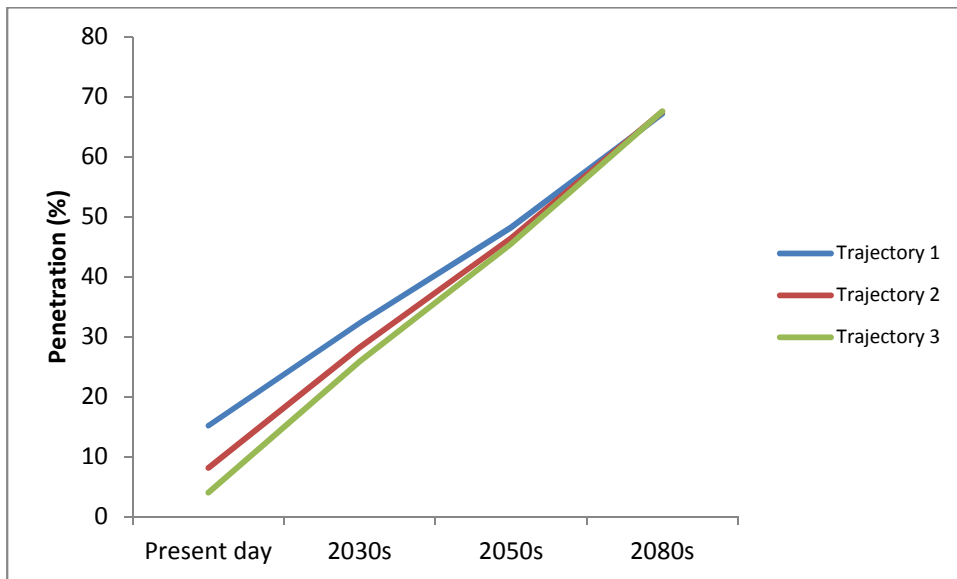
Trajectory 1 is described by the unamended function resulting in an over-estimate of the present day level of penetration. Microsoft Solver is used to amend the Trajectory 1 regression trend line by forcing it to align with the present day DGTREN estimate of penetration (±1%) resulting in Trajectory 2. Trajectory 3 is the regression trend line forced to align with the present day BSRIA estimate of penetration (±1%).

Figure 37 Forecast penetration levels of air-conditioning using the exponential function resulting from different initial estimates of present day penetration (medium emissions scenario, base data: CEUD)

Predictably, the initially relatively large differences in forecast penetration tend to diminish with time, so that by the time the 2030s are reached the difference is typically only of the order of 5%.

Table 29 and Table 30 compare forecast penetration rates for different time-slices under different emissions scenarios for Great Britain, using future CDD data reported in Table 22. The future penetration rates in columns 5-11 are calculated using the regression equations which describe the penetration data for the United States, California and Canada as a function of number of CDDs, the regression equations having additionally been forced to align with present day CDD and penetration levels in Great Britain (either the BSRIA estimate of penetration (Table 29), or the DGTREN estimate of penetration (Table 30))[121]. As a means of assessing their descriptive power, the coefficients of determination of these regression equations (bearing this additional forced alignment constraint), when re-fitted to the original datasets whence they derive, are also reported in the bottom row of each table.

---

[121] Columns 2 and 4 report the forecast number of CDDs for information purposes – the penetration forecasts which use the US and Californian regression equations use CDDs calculated to a base temperature of 18.3 °C, whilst the penetration forecasts which use the Canadian regression equations use CDDs calculated to a base temperature of 18.0 °C.

Table 29 Forecast penetration levels of air-conditioning resulting from initial estimate of present day penetration fixed at 3±1%[122]

| Time-slice | Emissions scenario | Base temperature | | Penetration* (%) | | | | | | |
| | | 18.3 °C | 18.0 °C | United States | | Calif | Canada linear function | | Canada exponential function | |
				Own	Use		SHEU data	CEUD data	SHEU data	CEUD data
Present day		40	47	2	1	4	4	4	4	4
2030s	Low	78	90	27	20	15	23	22	29	25
	Medium	79	91	28	20	15	23	22	30	26
	High	83	96	30	22	16	25	24	32	28
2050s	Low	114	129	45	34	24	39	38	46	41
	Medium	127	144	50	38	27	46	44	51	45
	High	144	162	56	44	31	54	52	57	51
2080s	Low	138	156	54	42	30	51	49	55	49
	Medium	210	233	71	61	44	84	82	74	68
	High	312	340	83	77	60	130	126	88	83
R²				**0.89**	**0.95**	**0.87**	**0.77**	**0.70**	**0.76**	**0.64**

* With the exception of the 'United States Use' column, all penetration rates refer to ownership rather than use.

[122] The equations from which the penetration data are produced use Microsoft Solver, where the constraint is set that penetration levels for the present day evaluate to within ±1% of the BSRIA estimate of 3%. (For the equation for the US 'use' data, present day penetration levels are set at ±1% of 2% rather than ±1% of 3% on the grounds that 'use penetration' levels are less than 'ownership penetration' levels (see Table 24) - 2% is 0.65 the value of the BSRIA estimate of 3%. The BSRIA estimate is multiplied by 0.65 as a means of converting present day 'ownership penetration' to 'use penetration' so as to concur with DECC estimates of energy consumption, which are 0.65 the value of the MTP estimates (see Section 3.3.8). The forecast penetration rates are very little affected by this intervention.)

Table 30 Forecast penetration levels of air-conditioning resulting from initial estimate of present day penetration fixed at 7.2±1%[122][123]

Time-slice	Emissions scenario	Base temperature 18.3 °C	18.0 °C	Penetration* (%) United States Own	Use	Calif	Canada linear function SHEU data	CEUD data	Canada exponential function SHEU data	CEUD data
Present day		40	47	6	4	8	8	8	8	8
2030s	Low	78	90	30	21	18	26	25	31	28
	Medium	79	91	30	22	19	26	25	32	28
	High	83	96	33	24	20	28	27	34	30
2050s	Low	114	129	46	35	27	41	40	47	42
	Medium	127	144	51	40	30	47	45	52	47
	High	144	162	57	45	33	54	52	57	52
2080s	Low	138	156	55	43	32	52	50	55	50
	Medium	210	233	72	61	46	83	80	73	68
	High	312	340	83	77	60	126	121	87	82
R^2				0.88	0.95	0.87	0.81	0.74	0.80	0.70

With the exception of the 'United States Use' column, all penetration rates refer to ownership rather than use.

Summary

In order to decide which of the seven regression equations[124] are best used to model future penetration, it must satisfy three criteria:

I.   the data from which the regression equation is drawn must be drawn from a climate returning a number of CDDs similar to that forecast for the UK for the coming decades of the 21st century,

---

[123] The equations from which the penetration data are produced use Microsoft Solver, where the constraint is set that penetration levels for the present day evaluate to within ±1% of the BSRIA estimate of 7.2%. (For the equation for the US 'use' data, present day penetration levels are set at ±1% of 4.7% rather than ±1% of 7.2% on the grounds that 'use penetration' levels are less than 'ownership penetration' levels (see Table 24) – 4.7% is 0.65 the value of the BSRIA estimate of 7.2%. The BSRIA estimate is multiplied by 0.65 as a means of converting present day 'ownership penetration' to 'use penetration' so as to concur with DECC estimates of energy consumption, which are 0.65 the value of the MTP estimates (see Section 3.3.8). The forecast penetration rates are very little affected by this intervention.)

[124] viz. (i) US (own), (ii) US (use), (iii) California, (iv) Canada (linear SHEU), (v) Canada (linear CEUD), (vi) Canada (exponential SHEU), or (vii) Canada (exponential CEUD)

II. the regression equations must not give unrealistic forecasts of penetration over the range of CDD values forecast for the UK for the coming decades of the 21st century, and

III. the degree of correlation between penetration and number of CDDs underlying the equation must be reasonably high.

Whilst the US data return very high R^2 values, and although the US ownership data compare very well with the ownership data from Canada in nearly all instances, its use must be disallowed in view of the fact that it mostly derives from climates which are considerably hotter than those forecast for the UK in this analysis. The penetration data from "anomalous" California, again with high R^2 values, cannot be used for the same reasons. Although the Canada data which uses the linear function returns high R^2 values, it is seen to grossly over-estimate penetration for high CDD values (high emissions scenario, 2080s), since it fails to account for the fact that the rate of uptake diminishes as saturation is approached. The Canada data which use the exponential function (cells shaded grey in Table 29 and Table 30) are considered as offering the most accurate representation of penetration levels, there being little difference in forecast penetration levels whether the SHEU data are used or whether the CEUD data are used. The R^2 values, although lower, are still relatively high. The equations describing penetration are shown in Table 31:

Table 31 Equations describing penetration as an exponential function of CDD value using Canadian penetration data

Present day penetration (%)	Data source	Equation	
3	CEUD	$penetration\ (\%) = 100 - (126.3e^{-0.00584 \times CDD})$	**Equation 22**
	SHEU	$penetration\ (\%) = 100 - (133.6e^{-0.00704 \times CDD})$	**Equation 23**
7.2	CEUD	$penetration\ (\%) = 100 - (119.3e^{-0.00558 \times CDD})$	**Equation 24**
	SHEU	$penetration\ (\%) = 100 - (125.6e^{-0.00666 \times CDD})$	**Equation 25**

In broad terms, the Canadian data suggest that penetration rates in the UK are likely to be of the order of 30% by the 2030s and 50% by the 2050s, whichever emissions pathway is followed. It is not until the 2080s that the full impact of different emissions pathways is revealed, where a low emissions scenario results in a level of penetration not very different from the 2050s, a medium emissions scenario results in penetration level of approximately 70%, and a high emissions scenario results in a penetration level in excess of 80%.

3.8 SCECdwell (bottom-up, dwelling as base unit)

In this model the cooling energy required to maintain thermal comfort in the sitting room and the main bedroom for a set of dwellings which are typical of the present day stock is estimated. Future space cooling energy consumption is calculated taking account of both the short-term and long-term responses to climate change. The model takes the following form.

i. A set of nine typical dwellings are modelled using climate data for London (1 June-30 September 2004) (base climate); the sitting room and the main bedroom in each dwelling are cooled using air-conditioning, and the space cooling energy demand totals from each are summed to calculate the total space cooling demand for the dwelling. These base data have been generated by He at al (2006) using the commercially available software package, Tas.

ii. The dwelling space cooling energy demand base data are used to generate the space cooling energy consumption of the present national residential stock for the base climate where account is taken of:

    a. dwelling stock profile (size of the dwelling stock and distribution of each dwelling by type and age)

    b. air-conditioning profile (penetration rates in the stock, distribution of each air-conditioning system by type and SEER).

iii. From the energy consumption data for the base climate of London in 2004, the stock energy consumption for the present day national climate is generated.

iv. Future stock consumption is calculated for each of nine different future climates (i.e. three different time-slices (2030s, 2050s, 2080s), under three different emissions scenarios (high, medium, low)). Account is taken of both (i) the short-term response factor (which is calculated as the ratio of the number of CDDs in a future climate to the number of CDDs in the present climate), and (ii) the long-term response factor arising from an increase in future penetration levels.

3.8.1 Space Cooling Energy Demand per Dwelling for Base Climate

The nine dwellings used in the modelling derive from three types (detached, semi-detached, terraced) and three time periods (pre-1919, 1919-1964, post-1964). The geometric features, floor plans, building construction and internal conditions (gains, infiltration and occupancy) are based on a combination of field study findings and review of the literature, being typical representations of those seen in the general stock (He, et al., 2006). The useable floor area (90 ± 5 m^2), number of bedrooms (three) and number of occupants per dwelling (2.5) compare well with the national average in England (92 m^2, 2.8 and 2.3 respectively) (DCLG, 2012a). The principal features of the dwellings, all double-glazed, are shown in Table 32, Table 33[125], Table 34, and Figure 38 shows the floor plan of the semi-detached house.

---

[125] The effect of dwelling age is revealed in the thermal performance of the building elements in Table 33.

Table 32 General dwelling model parameters

Model parameter	Description
Orientation	Sitting room and main bedroom: south-facing
Floor area	90 ± 5 m^2
Glazing	20% of total floor area
Sitting room area	detached: 22 m^2, semi-detached: 19 m^2, terraced: 12 m^2
Main bedroom area	detached: 15 m^2, semi-detached: 13 m^2, terraced: 12 m^2
Occupants	2.5 people/dwelling
Infiltration	0.5 air changes/hour
Maintained indoor temperature	22 ± 2 ^{0}C

Table 33 Construction and thermal performance of principal building elements

Element	Age	Description	U-value (W/m^{2}K)	Y-value (W/m^{2}K)
Walls	Pre-1919	Solid brick with 13 mm plaster finish	1.3	2.8
	1919-1964	50mm cavity brick with 13 mm plaster finish	1.2	2.7
	post-1964	cavity bricks with 55mm glass fibre insulation	0.36	1.7
Floors*	Pre-1919	Suspended timber floor with 500mm cavity on ground floor, wood floors on upper storey	0.5	2.1
	1919-1964	Suspended timber floor with 500mm cavity on ground floor, wood floors on upper storey	0.3	1.2
	post-1963	Concrete floors on ground floor, wood floors on upper storey	0.28	3.1
Roofs	Pre-1919	Slated roof with 70mm glass fibre insulation	0.46	1.3
	1919-1964	Slated roof with 100mm glass fibre insulation	0.32	0.48
	post-1963	Slated roof with 140mm glass fibre insulation	0.25	1.5

Ground floor U-values.

Table 34 Hours of operation of air-conditioning

	Weekdays	Weekends
Sitting room	7am – 9am 5pm – 11pm	10am – 2pm 5pm – 12 pm
Bedroom	9pm – 8am	10pm – 9am

131

Figure 38 Ground and first floor plans of semi-detached house

The resultant space cooling energy load (demand) consumption values for each room for the base climate are shown in Table 35.

Table 35 Space cooling energy load (demand) for sitting room and main bedroom for the base climate (He at al 2006)[126]

	Sitting room (kWh)			Bedroom (kWh)		
	Terraced	Semi-detached	Detached	Terraced	Semi-detached	Detached
pre-1919	29	72	85	141	124	159
1919-1964	54	121	150	160	144	185
post-1964	54	142	183	229	234	280

The simulated space cooling energy demand for a dwelling of type *i* and construction period *j* ($E_{i,j}$) is simply calculated as the sum of the demand values for the sitting room and bedroom for the particular dwelling type and construction period under consideration, where, for example, the energy demand for the pre-1919 terraced house evaluates as 170 kWh.

3.8.2   Space Cooling Energy Consumption for Dwelling Stock for Base Climate

The stock energy consumption is calculated as the modelled energy consumption of each of the nine dwellings extrapolated to the nationwide scale in proportion to observed dwelling and air-conditioning distribution profiles. The process involves converting energy demands to energy

---

[126] The terms "demand" and "consumption" are used by the authors of the (He, et al., 2006) paper in an imprecise manner on occasion. The data in the table above are termed (i) "cooling load" and (ii) "TAS simulated cooling energy", in a section contradictorily titled "Energy consumption for summer cooling of individual buildings". Extensive examination of the text and analysis of the data suggest to a very high degree that the figures are "demand" data. (Since the overall SEER of the model reported in the original paper calculates as 1.1, misinterpretation of the figures would only result in minimal consequence – an error of 10%.)

consumptions, and also adjusting the original SEER values used in the original simulations so as to more accurately reflect the efficiency of air-conditioning systems in the dwelling stock.

3.8.2.1 Dwelling stock profile

Government statistics report the number of dwellings by both type and by age as separate categories. Table 36 shows the stock profile by both dwelling type and dwelling age for England (DCLG, 2011).

Table 36 Actual distribution of dwellings by type and age in England (%)

Dwelling type[127]	%	Dwelling age	%
Terraced	29	pre-1919	21
Semi-detached	26	1919-1964	37
Detached	17	post-1964	42

A number of assumptions have to be made.

i. The patterns of distribution in Great Britain are assumed to be the same as those observed in England.

ii. It is assumed that the 72% of the stock represented by terraced, semi-detached and detached dwellings is representative of the whole stock[127]. The values in column 2 of Table 36 are thus multiplied by a factor of 1.39 so that these three-dwelling types constitute 100% of the stock.

iii. Since the number of dwellings of each type are not reported by age, it is assumed that the age distribution within a given type is the same as that observed across the stock as a whole.

The resulting pattern of distribution used in the modelling is shown in Table 37.

---

[127] The remaining 28% comprise bungalows - 9%; converted flats - 4%; purpose-built flats - 15%.

Table 37 Assumed distribution of dwellings by type and age used in the model (Great Britain) (%)

Dwelling type	Dwelling age	%	Number
Terraced	pre-1919	9	2 298 265
	1919-1964	15	3 927 437
	post-1964	17	4 481 053
Semi-detached	pre-1919	8	204 0590
	1919-1964	13	3 487 104
	post-1964	15	3 978 650
Detached	pre-1919	5	1 353 691
	1919-1964	9	2 313 283
	post-1964	10	2 639 366

Number of dwellings in Great Britain (n_s): 26 519 439 (DCLG, 2012b; Scottish Government, 2012; Welsh Assembly Government, 2011).

3.8.2.2 Air-conditioning stock profile

As noted previously, 2010 penetration rates of air-conditioning in the domestic stock are estimated at 3% by BSRIA (BSRIA, 2011), and at 7.2% following analysis[128] of DGTREN data (DGTREN, 2008).

The distribution of air-conditioning types and SEER values used in SCECdwell differ from those used in the He et al (2006) model. In both models the overall SEER value is the weighted sum of the constituent SEER values (Table 38).

Table 38 Distribution of air-conditioning systems and associated SEER values used in He et al (2006) model and SCECdwell - base climate

	Moveable		Split system		Overall[**]
	Distribution (%)	SEER	Distribution (%)	SEER	SEER
He et al (2006) model	85	0.8	15	2.8	1.1
SCECdwell[*]	84	2.9	16	2.95[***]	2.91

[*] *Distribution data are sourced from DGTREN (2008), and SEER data are sourced from Government Standard CoP (EER) data MTP (2012), where SEER values are assumed to approximate EER values.*
[**] *i.e. overall SEER in He et el model (2006) is proportional to [(0.85 x 0.8) + (0.15 x 2.8)]; overall SEER in SCECdwell is proportional to [(0.84 x 2.9) + (0.16 x 2.95)].*
[***] *MTP CoP (EER) estimate for 2010 for minisplits is 2.95, and that for "rooftops and ducted splits" is 3.0. As it is considered that minisplits are likely to exist in much greater number than ducted split systems in the domestic sector, the 2.95 value is chosen.*

---

[128] 1,898,951 units in dwelling stock of 26,519,439.

It is noted that the SEER values used in SCECdwell are EER values as noted in the legend of Table 38[129]. This approximation necessarily introduces error into the calculation and is further discussed in Section 3.10.

The equation describing the space cooling energy consumption for the national dwelling stock for the base climate (E_{L-2004}) (GWh) is described by the following equation:

Equation 26

$$E_{L-2004} = \sum_{i=1}^{3}\sum_{j=1}^{3} E_{i,j} \times n_{i,j} \times p_{2010} \times 10^{-10}/SEER_{SD}$$

where,

i = house type

j = construction period

m = air-conditioner of unit type

$E_{i,j}$ = simulated cooling energy demand for dwelling of type i, built in period j for base climate (kWh)

$n_{i,j}$ = the number of dwellings of type i, built in period j

p_{2010} = air-conditioning penetration in present stock (%)

$SEER_{SD}$ = overall SEER for SCECdwell (= 2.91)

The energy consumption deriving from use of these air-conditioners in the national dwelling stock in the base climate (E_{L-2004}) is shown in Table 39.

---

[129] See Glossary for description of these terms.

Table 39 Modelled air-conditioning energy consumption for dwelling stock for the base climate (London, 2004)

Dwelling type	Dwelling age	Dwelling stock (GWh)	
		penetration 3%	penetration 7.2%
Terraced	pre-1919	4.0	9.7
	1919-1964	8.7	20.8
	post-1964	13.1	31.4
Semi-detached	pre-1919	4.1	9.9
	1919-1964	9.5	22.9
	post-1964	15.4	37.0
Detached	pre-1919	3.4	8.2
	1919-1964	8.0	19.2
	post-1964	12.6	30.3
TOTAL		**78.9**	**189.3**

3.8.3 Space Cooling Energy Consumption for Dwelling Stock for Present Day Climate

Energy consumption for the national dwelling stock of the present day climate ($E_{GB-2010}$) (GWh) is calculated from the energy consumption for the base climate (E_{L-2004}) which is adjusted by the base climate adjustment factor, kL_{-2004} of value 0.511, the derivation of which is shown in Equation 27.

Equation 27

$$E_{GB-2010} = E_{L-2004} \times k_{L-2004}$$

where,

$$k_{L-2004} = CDD_{GB-2010} / CDD_{L-2004}$$

where

$CDD_{GB-2010}$ = number of CDDs in present climate (national population-weighted average, 2000-2010)[130]

CDD_{L-2004} = number of CDDs in base climate (London, 2004)[131] (92 for base temperature of 18 ^{0}C, 78 for base temperature of 18.3 ^{0}C)

Table 40 reports the present day space cooling energy in the dwelling stock.

---

[130] As derived in Section 3.5.
[131] As derived from analysis of the 2004 summer data for London (Heathrow) (UK Meteorological Office, 2011).

Table 40 Present day modelled space cooling energy consumption in the GB dwelling stock (GWh) (SCECdwell)

	Energy consumption (GWh)
$E_{GB\text{-}2010}$ (penetration 3%)	40.3
$E_{GB\text{-}2010}$ (penetration 7.2%)	96.8

3.8.4 Space Cooling Energy Consumption for Dwelling Stock for Future Climate

Future energy consumption must take account of both (i) the short-term response factor (the factor by which consumption would increase due to increased consumption of the present stock of air-conditioners alone) (k_{st}) and (ii) the long-term response factor (the factor by which consumption would increase due to increased penetration alone (k_{lt}).

Energy consumption for a future climate ($E_{GB\text{-}fut}$) (GWh) is calculated as follows:

Equation 28

$$E_{GB-fut} = E_{GB-2010} \times k_{st} \times k_{lt}$$

where

$k_{st} = CDD_{GB\text{-}fut} / CDD_{GB\text{-}2010}$

$k_{lt} = p_{fut} / p_{2010}$

where

$CDD_{GB\text{-}fut}$ = number of CDDs in future climate (national population-weighted average, where the future population shows the same geographical distribution as the present day)[132]

$CDD_{GB\text{-}2010}$ = number of CDDs in 2010 (national population-weighted average)[133]

p_{fut} = air-conditioning penetration in future stock (%)[134]

p_{2010} = air-conditioning penetration in 2010 stock (%)[135]

---

[132] As derived in Section 3.6.
[133] As derived in Section 3.5.
[134] As derived in Section 3.7.
[135] i.e. 3% (BSRIA estimate), 7.2% (DGTREN estimate).

Table 41 and Table 42 report both the short- and long-term response factors.

Table 41 Short-term response factor (k_{st})

	Emissions scenario		
	Low	Medium	High
2030s	1.9	1.9	2.0
2050s	2.7	3.1	3.4
2080s	3.3	5.0	7.2

Table 42 Long-term response factor (k_{lt})*

	Present day penetration – 3%			Present day penetration – 7.2%		
	Emissions scenario			Emissions scenario		
	Low	Medium	High	Low	Medium	High
2030s	8.5-9.7	8.6-9.9	9.3-10.7	3.9-4.3	3.9-4.4	4.2-4.7
2050s	13.5-15.4	15.1-17.1	17.0-19.1	5.8-6.5	6.5-7.2	7.2-8.0
2080s	16.4-18.4	22.5-24.7	27.6-29.3	6.9-7.7	9.4-10.2	11.4-12.1

Lower values derive from CEUD data and the higher values derive from SHEU data for each range.

Table 43 reports the resulting impact upon space cooling energy consumption as estimated by SCECdwell.

Table 43 SCEC-dwell: Present day and future space cooling energy consumption in the dwelling stock (GWh)

	Present day penetration – 3%			Present day penetration – 7.2%		
	Emissions scenario			Emissions scenario		
	Low	Medium	High	Low	Medium	High
2010	40	40	40	97	97	97
2030s	654-751	676-776	768-881	718-803	739-827	830-929
2050s	1495-1700	1866-2111	2361-2653	1546-1728	1910-2128	2395-2657
2080s	2182-2458	4504*4892	8036*-8534*	2220-2466	4487*-4892	7983*-8455*

Since a given number of CDDS returns a lower penetration rate for the "3% regression equation" than for the "7.2% regression equation" for low number of CDDS (e.g. in the present and near future), one might have expected the "3% regression equation" to return a lower penetration forecasts for high CDD totals as well. As the two regression equations are trained upon the same CDD data however, it is quite normal that "7.2% equation" which, in relative terms, "over-estimates" for low CDD values should under-estimate in relative terms, for high CDD values, since the nature of regression is that over-estimates in one part of a regression line are under-estimated at other parts as seen in the space heating logistic transformation analysis earlier. The asterisked higher energy consumptions seen with the "3% regression equation" in the table above are in direct correspondence with the higher penetration rates seen in Table 29 for the "3% regression equation, when compared to those for the "7% regression line" in Table 30 for high numbers of CDDs.

It is evident that cooling energy consumption in the domestic stock is forecast to increase sharply. Where the present day penetration is estimated at 7.2%, even under a low emissions scenario for the 2030s), a seven-fold increase in consumption from 97 GWh to at least 718 GWh is forecast as a minimum increase (Table 43). At its extreme, where the present day penetration is estimated at 3%, space cooling energy consumption may be more than 200 times as high as it is now by the 2080s under a high emissions scenario.

A DSM model such as this contains a number of assumptions, inaccuracy in which would obviously lead to an over- or under-estimation of energy consumption. The need to perform a sensitivity analysis in order to estimate the magnitude of the potential error associated with each of these assumptions is, therefore, important. Table 44 shows the impact of changing a number of key parameters associated with the building and the way in which it is used.

Model parameter	Change in energy consumption (%)
Set-point temperature: increased to 24 (±) 2 ^{0}C	-28
Set-point temperature: reduced to 20 (±) 2 ^{0}C	+45
Solar shading installed: window blind and oversized roof overhang*	-2

Overhang oversized to be unrealistically large (3m or more) (and therefore replicates the effect of shading).

3.9 SCECair (bottom-up, air-conditioner as base unit)

In this model the cooling energy consumption of an air-conditioner of a given type, operating under typical conditions over the course of a year, is calculated. Account is taken of the different types of air-conditioner and the numbers of each type in the present day stock, and future energy consumption is calculated taking account of both the short-term and long-term response to climate change. The model takes the following form.

   i.   The annual energy consumption of an air-conditioning unit is calculated, where account is taken of:
      a.   power rating of an air-conditioning unit (cooling capacity of an air-conditioning unit and EER), and
      b.   annual number of hours of operation (effective usage – see footnote 99)

   ii.   The air-conditioning unit energy consumption is used to generate the energy consumption of the present day residential stock , where account is taken of:
      a.   size of the dwelling stock,
      b.   air-conditioning penetration rates in the stock, and
      c.   proportion of each air-conditioning system used in the stock.

   iii.   Future stock consumption is calculated for each of nine different future climates (i.e. three different time-slices (2030s, 2050s, 2080s), under three different emissions scenarios (high, medium, low)). Account is taken of both (i) the short-term response factor (which is calculated as the ratio of the number of CDDs in a future climate to the number of CDDs in the present climate), and (ii) the long-term response factor arising from an increase in future penetration levels.

3.9.1 Annual Energy Consumption of an Air-Conditioner

The energy consumed by an air-conditioner of type m (E_m) (kWh) is calculated as the product of the electrical power used during operation (power rating, r_m) and the effective length of time it is in operation (n_h) [136]. The model assumes that each dwelling has no more than one air-conditioner, whether it be a split system or a moveable unit.

---

[136] i.e. hours of effective usage, when air is being chilled – see footnote 99.

3.9.1.1 Power used in Consumption (Power Rating)

The power consumed by an air-conditioner (power rating) is calculated as the ratio of the cooling capacity (cooling output) and its EER value.

Average Cooling Capacity of an Air-Conditioning Unit

The average cooling capacity of an individual air-conditioning unit is calculated as the ratio of the total cooling capacity of the stock and the total number of air-conditioners in the stock.

The average cooling capacity of each of the two types of air-conditioning unit which dominate the residential stock (c_m) are shown in Table 45, using data obtained from DGTREN (2006).

Table 45 Total cooling capacity, total number of air-conditioning units and average power rating of residential air-conditioning units in the UK[137] stock (2010)

	Moveable	Split system
Total cooling capacity of room air-conditioning units (output) (kW)	4270953	1572493
Total number of room air-conditioning units	1630135	268816
Average capacity/unit (c_m) (output) (kW)	2.62	5.85

Average EER of an Air-Conditioning Unit

Average EER values of air-conditioning units are the same as the Government Standard Average figures listed Table 38 of the previous section (MTP, 2012).

3.9.1.2 Annual Number of Hours of Operation

With regard to the assignation of a value for n_h, in accord with the MTP's statement that many (domestic) moveable units may only be used for a few tens of hours per year, the view is taken that annual effective usage in the domestic stock is likely to be of the order of 35 hours for the present day climate. As a means of testing whether or not 35 hours is a realistic choice for the annual number of hours of usage, a series of DSM experiments have been performed on a three-bedroom semi-detached house in which no mechanical cooling has been installed and as may be typically seen in the stock, in order to estimate the number of discomfort hours.

Validation of annual number of discomfort hours

The premise underlying the experimentation is that *the sum total of hours of discomfort in a free-running building* can be said to be equal to *the same number of hours that air-conditioning would be*

---

[137] Note that the figures refer to the UK rather than Great Britain. Since the number of air-conditioning units installed in the residential stock of Northern Ireland is likely to be very small, its inclusion in these data is deemed to make negligible difference.

used to prevent the occurrence of this discomfort if air-conditioning was installed instead (and the dwelling were not to free-run). Thus the number of hours during which the indoor temperature in the dwelling (running in free-running mode) exceeds the upper limit of the comfort zone is said to equal n_h[138].

Since air-conditioning is so little used within the domestic stock, occupants' perception of daytime comfort is considered to be best described by the Adaptive Comfort equations, the upper limit of the European adaptive standard EN 15251 (Category II) (see Section 4.2.2) being the threshold temperature above which discomfort is said to ensue. With regard to night time, since the Adaptive Comfort equations are not applicable because occupants lack adaptive opportunity, an indoor temperature of 24 ^{0}C is taken as the threshold temperature: CIBSE Guide A states that thermal comfort and the quality of sleep begin to decrease if the bedroom temperature rises much above 24 ^{0}C, at which point just a sheet is used for cover (CIBSE, 2007). The annual number hours for which air-conditioning would be used is therefore taken as the combined total of daytime hours and night time hours, when the dwelling is occupied, when the indoor temperature exceeds each of these temperature limits (discomfort hours). Designed in DesignBuilder running EnergyPlus software, a stock-representative three-bedroom semi-detached house is simulated in free-running mode in 16 different locations. Details of the building's construction and operation are shown Figure 39, Figure 40, Table 47 and Table 48.

Figure 39 Three-bedroom semi-detached house of typical design and construction used to model hours of discomfort

---
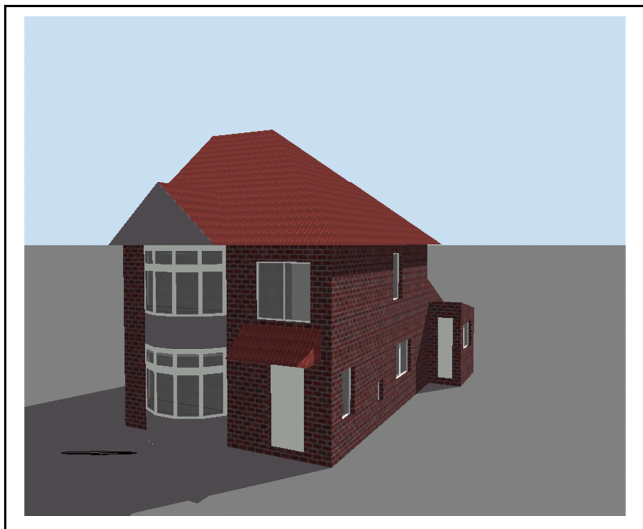
[138] n_h is the number of effective hours of operation (i.e. number of hours air-conditioner is switched on for an air-conditioner without thermostat; number of "chiller on" hours for an air-conditioner with a thermostat) - see footnote 99.

Figure 40 Plan layout of three-bedroom semi-detached house use to model hours of discomfort

Table 46 General model parameters

Model parameter	Description
Orientation	Front of house: north-facing. Conservatory: south-facing
Floor area	88 m^2
Glazing	30% glazing
Occupancy	0.02 people/m^2
Infiltration	0.7 air change/hour

Table 47 Construction and thermal performance of principal building elements

Element	Description	U-value (with bridging) (W/m²K)
Wall	Cavity wall with 80mm extruded polystyrene cavity, 13mm plaster finish	0.35
Floor*	150mm cast concrete ground floor slab on 130mm extruded polystyrene	0.24
Roof	Clay tile with 250mm medium weight stone wool insulation	0.16

Ground floor.

Table 48 Occupancy periods in which discomfort is monitored

Discomfort period	Weekdays	Weekends
Day	7am – 9am 6pm-12 midnight	9am – 12 midnight
Night	12 midnight – 7am	12 midnight – 9am

The default natural ventilation regime is set: when indoor temperatures exceed 22 ^{0}C and the house is occupied, the air change rate is increased to 12 air changes per hour (thus mimicking window opening).

All eight locations in Great Britain for which DesignBuilder provide hourly data have been used in the simulations. As each of these locations returns a CDD total which is less than the present day national population-weighted total ($CDD_{GB-2010}$) of 47, eight European locations with climates which are slightly warmer than that of Great Britain have also been simulated in order to achieve a balance[139]. Typical data output for the house at Gatwick are reported in Appendix 16: Model Output for Semi-Detached House at Gatwick.

---

[139] Great Britain locations: Jersey, Oban, Finningley, Hemsby, Aberdeen, Birmingham, Aughton, Gatwick. European locations: Nancy, Brussels, Amsterdam, Munich, Stuttgart, Cologne, Hamburg, Bremen.

Figure 41 shows the plot of discomfort hours against CDDs.
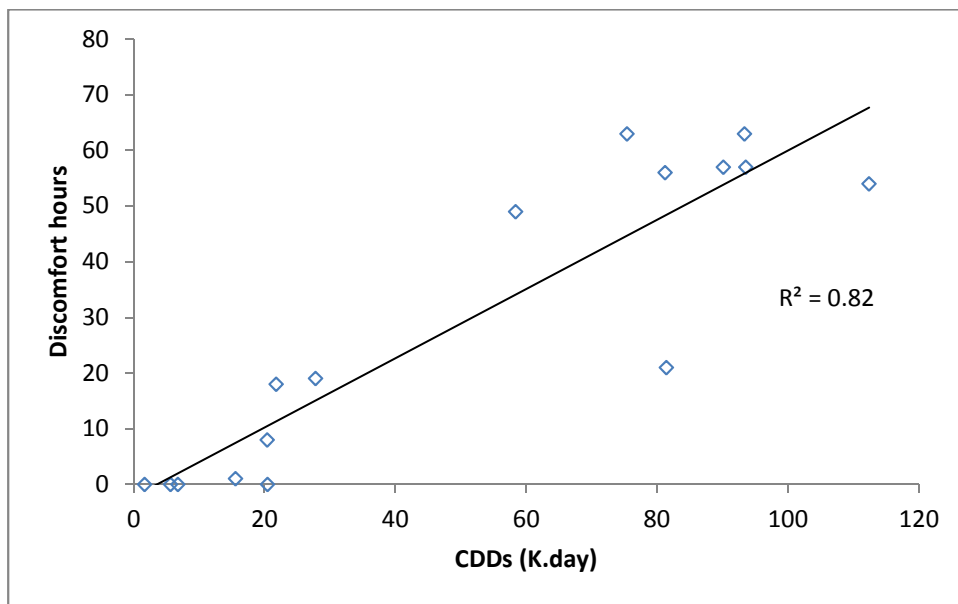
Figure 41 Plot of discomfort hours against CDDs (base temperature 18⁰C) for 16 locations for a stock representative semi-detached dwelling in a free-running mode

As the coefficient of determination is relatively high (and would evaluate at over 0.9 if the Cologne datum point were ignored), the method used here to estimate the number of discomfort hours from CDD totals appears to be satisfactory. The hours of discomfort for a CDD total of 47 ($CDD_{GB-2010}$) (base temperature 18 ^{0}C) evaluate as 27. In consequence, the value of 35 as a measure of the annual number of hours of operation of air-conditioning is deemed to be satisfactory: it is possible that there would be a degree of over-run on the limited number of occasions that the air-conditioner was used, where its use extended beyond the 27 hours since it is very unlikely that occupants would immediately switch off the air-conditioner as soon as the indoor temperature once again entered the comfort zone.

3.9.1.3 Modelled Annual Energy Consumption of an Air-Conditioner

The resulting average annual energy consumption values for each type of air conditioner m for the present day climate (E_m) (kWh), as described by Equation 29, are shown in Table 49.

Equation 29

$$E_m = r_m \times n_h$$

where ,

$$r_m = \frac{c_m}{EER}$$

145

	Moveable	Split system
Energy consumption (E_m)	43.7	69.4

3.9.2 Annual Energy Consumption for Dwelling Stock for Present Day Climate

The present day energy consumption in the dwelling stock is calculated as the average annual energy consumption of each air-conditioning type extrapolated to the nationwide scale in proportion to observed dwelling and air-conditioning distribution profiles. The dwelling and air-conditioning profiles are described in Section 3.8.2.

Space cooling energy consumption for the domestic stock for the present day climate ($E_{GB-2010}$) (GWh) is described by the following equation:

Equation 30

$$E_{GB-2010} \sum_{m=1}^{2} E_m \times n_s \times p_{2010} \times ac_m \times 10^{-10}$$

where

m = air-conditioner of unit type

E_m = average annual cooling energy consumption for an air-conditioner of type m for present day climate (kWh)

n_s = the number of dwellings in the stock

p_{2010} = air-conditioning penetration in present stock (%)

ac_m = proportion of air-conditioning stock of unit of type m (%)

The energy consumption deriving from use of these air-conditioners in the dwelling stock is shown in Table 50.

Table 50 Present day space cooling energy consumption in the dwelling stock (GWh) (SCECair)

	Energy consumption (GWh)
$E_{GB\text{-}2010}$ **(penetration 3%)**	30.0
$E_{GB\text{-}2010}$ **(penetration 7.2%)**	71.9

3.9.3 Energy Consumption for Dwelling Stock for Future Climate

Future energy consumption ($E_{GB\text{-}fut}$) is calculated by multiplying the present day energy consumption ($E_{GB\text{-}2010}$) by the short- and long-term response factors (k_{st} and k_{lt}) in exactly the same way as for SCECdwell as described in Section 3.8.4[140]. Table 51 reports space cooling energy consumption as estimated by SCECair.

Table 51 SCECair: Present day and future space cooling energy consumption in the dwelling stock (GWh)

	Present day penetration – 3%			Present day penetration – 7.2%		
	Emissions scenario			Emissions scenario		
	Low	Medium	High	Low	Medium	High
2010	30	30	30	72	72	72
2030s	486-558	502-576	570-654	533-596	549-614	617-690
2050s	1110-1262	1386-1568	1754-1970	1148-1283	1419-1581	1779-1973
2080s	1621-1826	3345-3665	5968-6338	1649-1832	3340-3633	5929-6280

The SCECdwell consumption forecasts are 26% larger than the SCECair forecasts. The fact that SCECdwell features two air-conditioners per dwelling (bedroom and sitting room) in contrast to SCECair which only features a single air-conditioner may partially explain why the SCECdwell forecasts are larger: there is a period of possible overlap when both air-conditioners are in operation in SCECdwell (19 hours out of 139 hours of possible operation, equivalent to a 14% overlap) (see Table 34). The smallness of the difference between their forecasts can be seen when it is considered that raising the annual number hours of operation in SCECair from 35 to 44 (equivalent to approximately 40 minutes per week for the 13 weeks of summer) would be sufficient to remove the discrepancy altogether.

3.10 Discussion of SCECMORS

When one considers the number of different assumptions underlying both SCECdwell and SCECair, and the sensitivity of the final results to changes in the value of some of these assumptions (SCECdwell -Table 44; SCECair - consumption increases by 26% for an additional nine hours of

---

[140] Note that the short- and long-term response factors (reported in Table 41 and Table 42) for SCECdwell are equally applicable to SCECair.

operation), it is striking that two such very different models should yield such relatively similar results.

Of particular importance is the error associated with the estimation of the SEER in SCECdwell, the EER being used as a surrogate for the SEER. If the value of the SEER is increased to accord with the observation that the SEER is often of the order 18% larger than the EER, the difference between SCECdwell and SCECair's estimation of space cooling energy consumption reduces to 13%. If the value of the SEER of the mobile unit is decreased to 0.8 to accord with the estimate by He et al (2006), the difference increases to 71%. Whilst a 71% difference may appear large, in absolute terms the difference remains small: taking a medium emissions scenario in the 2050s as an example, the 71% difference amounts to 3,358-3,829 GWh, which is the equivalent of 1.2-1.4% of the energy used for space heating in the residential stock in 2011[141].

Despite the uncertainty attached to the size of the error associated with estimation of current penetration rates, SEER values and number of hours that air-conditioning is in operation[142], their magnitude is put into perspective when compared against the influence borne by climate change, whether directly through the short-term response or indirectly through the long-term response. Moreover, it is also clear that the long-term response to climate change is of considerably more importance than the short-term response. Taking the medium emissions scenario for the 2050s as an example, where the present day penetration is estimated at 7.2%, total cooling consumption would increase by a factor of up to 3.1[143] if account is only taken of the short-term response (i.e. penetration remains at 7.2%); this compares with the 22-fold increase which may occur when further allowance is made for the fact that penetration is forecast to increase to approximately 50% in such a scenario[144]. (Even when using the low penetration Californian data which are considered to be anomalous, consumption would increase by a factor of more than 13, equivalent to an increase of 1,220%.)

Whilst it is clear that the analysis is most sensitive to changes in the value of the long-term response factor, this being the factor which most markedly affects consumption as shown in Table 42, it is also true that this is the factor to which the most uncertainty is attached (even though the analysis is statistically robust): not only is there a degree of spread in the Canadian penetration which, for example, could see penetration rates up to ±18% different from those reported for a CDD value of 180 (i.e. in the second part of the century)[145], but it is not certain that air-conditioning uptake will follow the same pattern as that observed in Canada. Perhaps penetration rates could remain relatively low as in present day Italy. Whilst this remains a possibility, it is important to remember that the Gross Domestic Products (GDP) per capita in most of regions of the hot Mediterranean basin have been relatively low by American standards until relatively recent times, air-conditioning, something of a luxury, being beyond the low purchasing power of the majority of consumers. In the relatively affluent present day UK, the cheapness of air-conditioning units, which can be purchased

---

[141] Space heating energy consumption in the residential stock (2011): 272,419 GWh (DECC, 2012h).
[142] Although the DGTREN penetration figure is 140% as large as the BSRIA penetration figure (7.2% as opposed to 3%), the initial large difference between estimates of future energy consumption rapidly declines: whilst the difference may extend up to 10% under a low emissions scenario during the 2030s, the difference extends to a maximum of no more than 1.7% by the time the 2080s are reached (but is typically less than 1%).
[143] Equivalent to an increase of 210%.
[144] Equivalent to an increase of 2,100%.
[145] This depends upon whether householders respond more like Manitobans or Quebecers (Section 3.7.3.2).

for about £300, somewhat removes this impediment to uptake. The example presented by China, where the number of air-conditioning units per 100 urban households rose from 0.34 in 1990 to 112.07 in 2010, shows how penetration levels can increase dramatically over a relatively short period of time in a buoyant economy (National Bureau of Statistics of China, 2011).

It is important to remember, however, that although levels of cooling consumption are forecast to increase by very large amounts **in relative terms** over the coming decades, **the absolute increase** in total national energy consumption is actually very low in consequence of the very low levels of current domestic consumption[146]. Even if the EER is increased form the modelled stock average of 2.91 to a value of between 6 and 7 as is forecast for 205 (see chapter 5), the approximate doubling in consumption still remains very low.

---

[146] The current levels of consumption do not register in Government statistics.

4 Adaptive Comfort Degree-Day Model

Summer temperatures are likely to increase significantly over the course of the century and that remedies must be sought if our buildings are to remain thermally comfortable. Whilst the installation of air-conditioning has been proposed as offering one solution to the problem, the Adaptive Approach to Thermal Comfort AATC) has been proposed as an alternative means of creating a thermally comfortable environment at little or no expense in terms of energy expenditure. Moreover, it is particularly well suited for application in buildings in the service sector, in which sector levels of air-conditioning have historically been considerably higher than in the residential sector and continues to be so in Canada[147]. A prescriptive low-energy modus operandi, the AATC eschews the view of thermal comfort as a fixed entity which is thrust upon the individual through the provision of a thermally comfortable environment; rather, it promotes the notion that comfort is borne of the individual, something which is personally attained. Provided that the individual is given the "adaptive opportunity" to do so, the AACT recognises that the individual will make the necessary changes to his/her local/personal environment in order to secure comfort. Whilst the AATC is most often applied in a cooling context, its use can be extended to the heating season in climates with very mild winters.

First described in the 1970s in the pioneering work of Humphreys and Nicol (Nicol & Humphreys, 1973), and greatly developed in a large and ever increasing body of work since this first paper, adherence to the AATC makes unnecessary the use of mechanical systems such as air-conditioning systems to secure a thermally comfortable environment and, indeed, actually forbids their use. Rather, thermal a thermally comfortable environment is primarily obtained by the opening and closing of windows, and also by changing the level of dress so as to accord with ambient outdoor conditions, the forbiddance of mechanical systems being a necessary constraint so that occupants' capacity to adapt to ambient conditions is not violated[148]. Whilst buildings which use mechanical heating or mechanical cooling systems customarily use broadly fixed temperature limits which are independent of outdoor air temperature to define the upper and lower boundaries of the zone of thermal comfort[149], the fluid temperature limits of the AATC are set in relation to the variant outside air temperature (ASHRAE, 2004; CEN/BSI, 2007/2008). Thus, the rising summer temperatures associated with climate change do not, therefore, inevitably lead to increased levels of discomfort in a well-designed building in free-running mode using the AATC.

Whilst the energy savings which are achievable with the AATC are calculated as the amount of energy which would otherwise be consumed by the mechanical heating/cooling systems displaced by it use, unfortunately future heating/cooling energy savings at the national level cannot simply be calculated as the heating/cooling energy consumption forecasts detailed in Chapter 2 and Chapter 3. As the AATC is only suitable for use in buildings with access to easily openable windows where the

---

[147] Whilst space cooling accounted for 1.6% (93PJ) of secondary energy use in the Canadian residential sector over the period 2005-2009, the figure was 3.6 times as high at 5.8% (335PJ) in the commercial/institutional sector over the same period. (NRCan, 2012).

[148] It is found that the use of air-conditioning in buildings reduces occupants' adaptive capacity by reducing the width of the zone of thermal comfort (the range of temperatures which an individual describes as comfortable) (de Dear & Brager, 2002).

[149] The Predicted Mean Vote (PMV) Model, as set out in BS EN ISO 7730:2005 (CEN/BSI, 2005/2006), is the standard typically used to define these limits.

occupants are engaged in near sedentary activities, quantification of energy savings at the national level is made impossible since the numbers of such buildings have not been determined[150]. For those free-running buildings which are capable of using the AATC, however, a metric which can reveal the level of potential savings achievable by the adoption of an adaptive comfort standard, in lieu of using an air-conditioning system (which employs the more restrictive Predicted Mean Vote (PMV) Model[151]), is an attractive notion.

This chapter introduces just such a metric, the *Adaptive Comfort Degree-Day (ACDD).* Moreover, such is the nature of the ACDD, that not only can it be used to provide a qualitative measure of potential energy savings deriving from use of the AATC, but it can do so without reference to the building's dimensions or building's thermal characteristics[152]; and in the special case where a building using a mechanical cooling system with a known cooling load is refurbished so that it can free-run during the cooling season after refurbishment, it, furthermore, provides a simple means of quantifying energy savings for any particular time in the future without the need to carry out a complex dynamic simulation modelling analysis.

The ACDD is analogous to the previously mentioned degree-day (CDD or HDD), the temperature difference/time composite used to quantify the amount of cooling/heating required to maintain thermal comfort using a given outdoor temperature as its base temperature; the differences between the ACDD and the CDD/HDD are that (i) ACDDs measure indoor temperature differences, and (ii) the ACDD base temperature is set so as to correspond with the upper and lower limits of the zone of thermal comfort of the PMV Model under typical conditions[153].

After explaining the concept of the ACCD in Section 4.1, Section 4.2 validates its capacity as an instrument for measuring climate/weather related energy savings. Section 4.3 and Section 4.4 investigate potential energy savings arising from implementation of the two adaptive standard options applicable within the United Kingdom, viz. (i) the ANSI (American National Standards Institute)/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) adaptive standard 55-2004[154] (ASHRAE, 2004), and (ii) the European adaptive standard BS EN 15251:2007[155] (CEN/BSI, 2007/2008) for future climates under different emissions scenarios over the

---

[150] For example, it cannot be used in deep-plan office buildings with sealed windows (i.e. primarily buildings specifically designed/adapted for use of air-conditioning systems), and it is additionally not suitable for use in in many retail premises where occupants spend a lot of time in non-sedentary activities.

[151] The PMV Model is traditionally used to set the temperature limits of the thermal comfort zone in indoor environments which are mechanically heated or cooled. It relates the six physical parameters affecting comfort (of which one is air temperature) to a comfort scale ranging from -3 to +3, as scored (voted) by the general population, where 0 represents the optimum level of comfort at which the greatest number of people are comfortable. For any combination of these six parameters in an indoor environment, the PMV Model predicts the average score (i.e. predicted mean vote) that the general population would attach to that particular environment. It additionally predicts the percentage of people that would be dissatisfied at any particular PMV value, where "predicted percentage dissatisfied" is given the acronym of PPD. Having decided upon an appropriate PMV or PPD range for the indoor environment in question, the PMV Model is used to set the maximum and minimum temperature limits for the particular values of the other five parameters.

[152] Heat loss coefficient, thermal capacity, infiltration rate, solar gains, internal gains.

[153] i.e. typical conditions as detailed in table A.5 of BS EN ISO 7730:2005 (CEN/BSI, 2005/2006).

[154] Section 5.3 - The Optional Method for Determining Acceptable Thermal Conditions in Naturally Conditioned Spaces.

[155] Annex A.2 - Acceptable indoor temperatures for design of buildings without mechanical cooling systems.

coming century. Section 4.5 discusses possible causes for the different results deriving from the two adaptive standards, before concluding with the summary in Section 4.6.

4.1 The Adaptive Comfort Degree-Day

A full understanding of ACDD theory requires a complete and exact understanding of the principles underlying conventional degree-day theory. Section 4.1.1 begins with an overview of conventional degree-day theory, before Section 4.1.2 goes on to explain the ACDD concept itself.

4.1.1 The Degree-Day

The degree-day concept is predicated on the notion that an energy balance is achieved in a building when the sum of the heat inputs equals the overall heat losses. Taking cooling as an example, and where there is no latent load, Equation 31 describes the heat balance equation.

Equation 31

$$Cooling: \qquad Q_c = Q_s + Q_i + Q_{f+v}$$

where,

Q_c = output from cooling system (kWh)

Q_s = solar gains (kWh)

Q_i = internal gains from people, equipment and lights (kWh)

Q_{f+v} = heat flux from outside to inside (sum of heat gains through building fabric + ventilation losses) (kWh)

where,

heat flux is proportional to indoor-to-outdoor temperature difference (i.e. $Q_{f+v} = k(t_o – t_i)$

t_o = mean outdoor temperature over the course of 1 day (^{0}C)

t_i = mean indoor temperature over the course of 1 day (^{0}C)

The underlying premise of the concept is that the incidental gains Q_s and Q_i, when averaged over a period of time, can be assumed to be constant (c). Equation 31 can thus be re-written as:

Equation 32

$$Cooling: \qquad Q_c = k(t_o – t_i) + c$$

Assigning the constant term, $t_i + (c/k)$, as the base temperature (t_b), the cooling degree-day equation can finally be written as:

Equation 33

$$Cooling: \qquad Q_c = k(t_o - t_b)$$

where,

t_b is the threshold outdoor temperature which calls the cooling system into operation[156]

Therefore, over the course of one day, the cooling energy output (Q_c) is proportional to the difference in temperature between the outdoor temperature on that day and the base temperature. Over the course of a longer given period of time (e.g. n days), the cooling load is proportional to the sum of the daily temperature differences in that given period of time (e.g. temperature difference on day 1 + temperature difference on day 2 + temperature difference on day 3 +….temperature difference on day n). The sum of these temperature differences - $n.(t_o - t_b)$ - are collectively referred to as the number of degree-days. Thus, the cooling energy demand over a given length of time of n days ($Q.n_c$) can be written as:

Equation 34

$$Cooling: \qquad Q.n_c = k.dd$$

where,

dd = number of degree-days over time period of n days

(based on (CIBSE, 2006)). Furthermore, a necessary adjunct of the concept, resulting from steady-state theory, is that, given enough time, the driving force applied by $(t_o - t_i)$ in Equation 32 would ultimately ensure that each degree rise/drop in outdoor temperature would result in a rise/drop in indoor temperature of equal magnitude in the situation where no mechanical system was in place to counteract the driver, $(t_o - t_i)$.

Thus the cooling degree-day (CDD) can be defined as the time integral of the mean daily outdoor air temperature above a particular base temperature (units: K.day, or more simply, CDD). Figure 42 illustrates the principle in graphical form where x is the base temperature which calls the cooling system into operation to maintain thermal comfort, such temperature corresponding with an indoor temperature of y (the upper limit temperature of the thermal comfort zone as set by the PMV

---

[156] i.e. when $t_o > t_b$, Q_c assumes a positive value, and thus cooling is required.

Model). It can be seen that the amount of cooling energy required to maintain the indoor temperature at *y* is in proportion to both (i) the number of cooling degree-days (Figure 42 (a)) and (ii) the number of quasi cooling degree-days (quasi DD) Figure 42 (b)) [157].
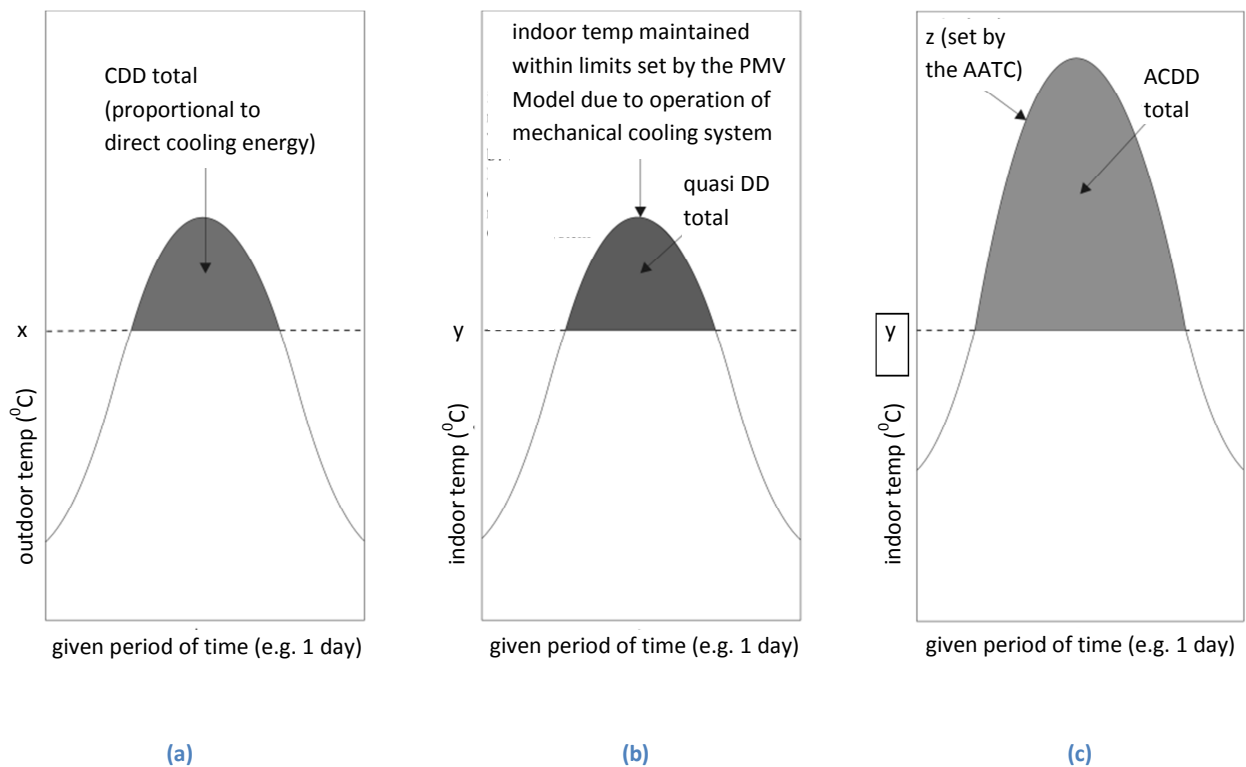
Figure 42 Adaptive Comfort Degree-Day concept explained by analogy with the traditional cooling degree-day – (a) Cooling degree-day total as a function of outdoor temperature and time, (b) Quasi cooling degree-day total as a function of indoor temperature and time, (c) ACDD total as a function of indoor temperature and time

Heating degree-days are calculated in an exactly analogous manner when the outdoor air temperature falls below the base temperature, the base temperature being the outdoor air temperature which calls the heating system into operation.

4.1.2   The Adaptive Comfort Degree-Day

The Adaptive Comfort Degree-Day functions in analogous fashion to the quasi degree-day, its value being in direct proportion to potential energy savings arising from use of the AATC in a building in place of the PMV Model. In this instance however, no mechanical system is in place to control the temperature. Taking cooling as an example again, whereas a building using the PMV Model must call upon an energy-consuming system once the indoor temperature of *y* is reached in order to prevent internal temperatures further rising above this limit Figure 42 b), the AATC may allow temperatures to extend beyond this limit whilst still maintaining thermal comfort. In such a case, the upper temperature limit of the thermal comfort zone set by the AATC (*z*) varies in accord with the varying mean outdoor air temperature (Figure 42.c). By simple analogy with the quasi degree-

---

[157] Note that the temperature scale for figure (a) is the outdoor temperature, whilst the temperature scales for (b) and (c) is the indoor temperature.

day, the potential energy savings which can be achieved by the AATC are in proportion to the area bound by *z* and *y*, (the amount of cooling energy which would otherwise be consumed by a mechanical system in maintaining an indoor temperature of *y*, and preventing it from reaching an indoor temperature of *z*)(units: cooling ACDD). The basic form of the equation used to calculate the annual number of ACDDs for a given location is described by Equation 35 and Equation 36

Equation 35

$$Cooling\ ACDDS\ (when\ AATC_{ul} > PMV_{bc}) \qquad ACDD_c = \sum_{i=1}^{n}(AATC_{ul} - PMV_{bc})$$

Equation 36

$$Heating\ ACDDS\ (when\ AATC_{ll} < PMV_{bh}) \qquad ACDD_h = \sum_{i=1}^{n}(PMV_{bh} - AATC_{ll})$$

where,

$AATC_{ul}$ = AATC upper temperature limit

PMV_{bc} = PMV base temperature for cooling season

$ACDD_c$ = annual number of cooling ACDDs

$AATC_{ll}$ = AATC lower temperature limit

PMV_{bh} = PMV base temperature for heating season

$ACDD_h$ = annual number of cooling ACDDs

n = length of time which number of ACDDs is measured

In similar vein to conventional degree-days, ACDD values calculated as having a negative value assume an actual value of 0, since the ACDD metric is only a measure of the extent by which $AATC_{ul}$ exceeds PMV_{bc} (cooling season) or $AATC_{ll}$ drops below PMV_{bh} (heating season).

It should be remembered that the cooling ACDD is a direct correlate of the non-latent (i.e. chilling) component of the energy consumption of a mechanical cooling system. As such, whilst the potential energy savings for systems involving no transfer of heat by latent loads (e.g. chilled beams/ceiling cooling system) are in direct proportion to the number of ACDDs, the level of the potential energy savings for other mechanical systems involving latent loads (e.g. fan coil systems) will be even greater than the number of ACDDs.

4.2 Validating the Concept of the ACDD

The concept of the ACDD is founded upon the notion that each degree rise in outdoor temperature would result in a rise in indoor temperature of equal magnitude in a free-running building under steady-state conditions. There will be many situations over the course of a year, however, where there is insufficient time for the steady-state equilibrium to be established. Indeed, it is this very premise that thermally slowly-responding heavyweight buildings exploit, where a large increase in the outdoor air temperature during the day does not result in a concomitant large increase in the indoor temperature during the day, the heat of the day rather being slowly released as temperatures drop during the night. Similarly, the temperature inside highly glazed buildings may far exceed the outdoor air temperature during the day, this being the principle underpinning the use of conservatories as solar collectors.

It is clear, therefore, that the ACDD concept must be tested under the non-steady-state conditions of the real world using real weather data. Whilst it may seem reasonable that there may be a close relationship between the number of ACDDs and potential energy savings in a quickly-responding building of very lightweight construction with a very low level of glazing with low solar gains, one has to examine if the relationship extends to other buildings of other construction types and different levels of glazing.

Taking cooling as an example, the ACDD concept states that potential energy savings (E_p) are proportional to the number of ACDDs:

Equation 37

$$E_p = k_1 \times ACDD$$

where,

E_p = potential energy savings on a given day

k_1 is a constant

$ACDD$ = number of ACDDs (either $ACDD_c$ or $ACDD_h$ depending upon whether cooling or heating is being examined) for the given daywhere the number of ACDDs is the summation of the 'temperature differences between the AATC upper limit and the PMV upper limit' over a given day as illustrated by Figure 42c. This is expressed in equation form as:

Equation 38

$$E_p = k_1 \times (AATC_{ul} - PMV_{bc}) \times T$$

where,

$T = 1$ (day)

Actual energy savings on a given day (E_a), as illustrated by Figure 42a, can be expressed as:

Equation 39

$$E_a = k_2(t_o - PMV_{bc}) \times T$$

where,

k_2 is a constant

t_o = mean outdoor temperature on the given day

This can be re-written as:

Equation 40

$$t_o = \frac{E_a}{(k_2 \times T)} + PMV_{bc}$$

Now, as seen later in Table 53 (Section 4.2.2), the $AATC_{ul}$ takes the following form for adaptive standards[158]:

Equation 41

$$AATC_{ul} = k_3 t_o + c_1$$

where,

k_3 and c_1 are constants

---

[158] ASHRAE adaptive standard 55: $AATC_{ul} = 0.31 \times t_o + 17.8 + x$.
European 15251 adaptive standard: $AATC_{ul} = 0.33 \times t_o + 18.8 + y$.

Substituting for $AATC_{ul}$ from Equation 41 into Equation 38 results in the following equation:

Equation 42

$$E_p = k_1\big((k_3 t_o + c_1) - PMV_{bc}\big) \times T$$

Substituting for t_o from Equation 40 into Equation 42 results in the following equation:

Equation 43

$$E_p = k_1 \left(\left(k_3 \left(\frac{E_a}{(k_2 \times T)} + PMV_{bc} \right) + c_1 \right) - PMV_{bc} \right) \times T$$

This simplifies as:

Equation 44

$$E_p = k_4 E_a + k_5 PMV_{bc} T + k_1 c_1 T - k_1 PMV_{bc} T$$

where k_4 and k_5 are constants

Since PMV_{bc} and T are also constant, it can be seen that E_p is proportional to E_a:

Equation 45

$$E_p = k_6 E_a + c_2$$

where k_6 and c_2 are constants

Substituting for E_p from Equation 37 into Equation 45 results in the following equation:

Equation 46

$$k_1 \times ACDD = k_6 E_a + c_2$$

This simplifies as:

Equation 47

$$E_a = k_7 ACDD + c_3$$

where

k_7 and c_3 are constants

The actual energy saved over the course of a year (E_y) calculates as:

Equation 48

$$E_y = \sum_{n=1}^{365} E_a$$

Substituting for E_a from Equation 47 into Equation 48 results in the following equation:

$$E_y = k \sum_{n=1}^{365} k_6 ACDD + c_3$$

This simplifies as:

$$E_y = k \sum_{n=1}^{365} ACDD + c$$

where k and c are constants

Thus actual energy savings over the course of a year are proportional to the number of ACDDs over the course of the year.

In other words, ACDD theory states that ACDDs are not only a measure of potential savings which can be achieved by implementing the AATC, but they are also a measure of actual savings. i.e. the number of ACDDs is also proportional to the actual energy consumed by a mechanical cooling system.

A series of modelling experiments have been performed to test the theory, where the relationship between annual actual space cooling energy consumption and the number of ACDDs is investigated: where a clear linear correlation exists between the two, one can assert that the ACCD concept is valid, and that ACDDs can therefore be used to estimate AATC potential energy savings[159].

Section 4.2.1 describes the modelling set-up used to calculate cooling energy consumption (cooling energy consumption being the equivalent of AAC T savings as previously mentioned). Section 4.2.2 describes the procedure for calculating ACDDs; since there are two adaptive standards available for use in the UK, the European adaptive standard EN 15251 and the ASHRAE adaptive standard 55, the numbers of ACDDs are examined for both. Section 4.2.3 presents the correlation results where cooling energy consumption is regressed against ACDDs, and Section 4.2.4 discusses the results.

---

[159] The modelling experiments only report upon space cooling energy consumption. The relationship between space heating energy consumption and heating ACDDs is discussed in Section 4.4.2.

4.2.1 Building Simulation

A range of simple, single storey office buildings of dimensions 15m x 25m x 3.5m of different thermal responsivenesses has been designed using the modelling software package, DesignBuilder. Five different construction types - (i) lightweight (LW) ,(ii) medium weight (MW), (iii) highly insulated medium/heavyweight (Insulated), (iv) medium weight with pitched roof (Pitched), (v) solid wall (Solid) - using five different levels of evenly-spaced glazing (10%, 30%, 50%, 70% and 90% wall coverage) are modelled; construction details are shown in Appendix 11. Each office building incorporates a fan-coil air-conditioning system with a set-point temperature of 26 ^{0}C (operative temperature). Thus a total of 25 buildings are examined, an example of one of which, the 30% glazed Pitched building, is shown in Figure 43.
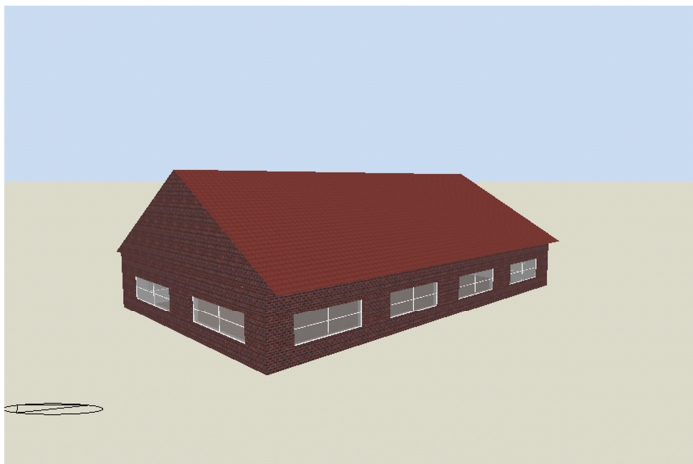
Figure 43 Pitched office building with 30% glazing

Simulations are carried out at time-steps of 10/hour for a total of 22 locations[160] under typical patterns of occupancy, equipment gains, metabolic activity, clothing, lighting and air-tightness for a generic office area using EnergyPlus software made available by the US Department of Energy using International Weather for Energy Calculations (IWEC) weather data[161] (Table 52).

---

[160] 550 simulations in total – 25 building types in 22 locations.

[161] Derived from up to 18 years (1982-1999) of hourly weather data observations, and supplemented by solar radiation data estimated on an hourly basis from earth-sun geometry and hourly weather elements, (particularly cloud amount information), the weather data constitutes weather conditions typical for the specific location (US Department of Energy, 2008), being the ASHRAE equivalent of the TRYs produced by the Chartered Institution of Building Services Engineers (CIBSE).

Table 52 Climate data for the 22 locations used in the building simulations and resultant effect upon total annual cooling energy consumption and window solar gains for MW building with 30% glazing

Location	Mean Dry Bulb Temp (°C)		Direct Normal (kWh/m²)		Total Annual Cooling Energy Consumption (kWh)	Solar Gains - Window (kWh)
	Summer (Jun-Aug)	Annual	Direct Normal	Diffuse Horizontal		
Aberdeen	13.3	8.3	483	616	732	21568
Oban	13.5	9.2	588	547	661	21209
Aughton	14.7	9.5	600	605	881	22376
Hemsby	15.3	9.8	690	641	1709	24411
Finningley	15.6	11.2	597	622	2011	22622
Brest	15.6	11.2	661	688	2229	24570
Birmingham	15.9	9.6	627	670	2264	24184
Jersey	16.2	11.2	891	633	2992	26499
Gatwick	16.3	10.1	743	593	3296	23803
Cologne	17.1	9.9	564	648	4428	22503
Brussels	17.1	10.3	509	630	4116	21352
Nancy	17.8	10.1	729	657	6064	24637
Frankfurt	18.2	10.1	723	615	5698	23866
Nantes	18.4	12.2	885	665	7073	27090
Paris	18.6	11.2	679	669	6382	24282
Dijon	19.1	10.7	812	682	7590	26257
Mannheim	19.2	11.1	727	638	7620	24255
Bordeaux	20.2	13.3	930	712	9672	28631
Odessa	21.1	9.9	831	701	10184	26659
Turin	21.5	12.4	1035	653	14927	28648
Montpellier	22.7	14.9	1320	666	15889	32531
Marseille	23.3	15.0	1504	615	17815	33737

The cooling energy consumption is noted in each of the 550 simulations, the input parameters[162] having been specifically chosen to present a very broad cross-section of the building stock, the intention being that the resulting annual cooling consumption totals should be equally broad in range. Indeed, this is seen to be the case, Figure 44, Figure 45 and Figure 46 giving an indication of the impact borne by construction type, level of glazing and location on consumption.

The space cooling energy consumption of the Insulated building is 2.7 times as much as that of the Pitched building for a 30% glazed building at Gatwick (Figure 44).

---

[162] viz. construction types, levels of glazing and location.
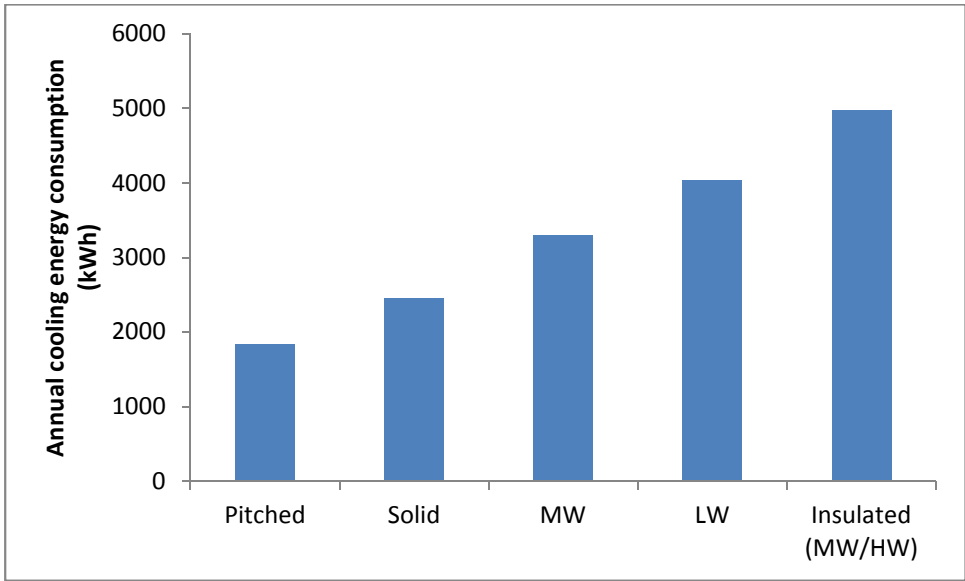
Figure 44 Variation in annual cooling energy consumption by construction type for a 30% glazed building at Gatwick

The space cooling energy consumption of the 90% glazed building is 25 times as much as that of the 10% glazed building for a MW building at Gatwick (Figure 45).
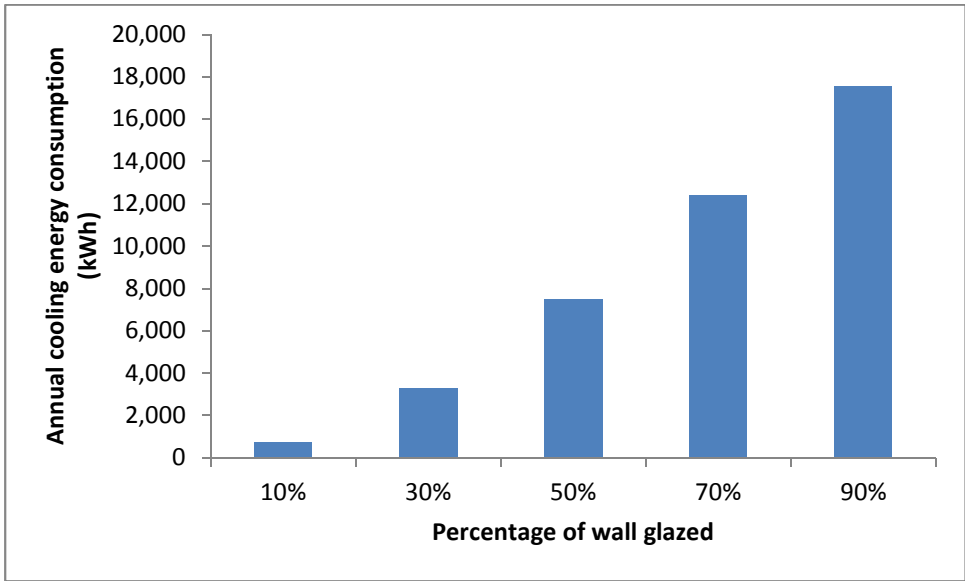
Figure 45 Increase in annual cooling energy consumption for a MW building at Gatwick as level of glazing increases

The space cooling energy consumption of the building in Marseille in the south of France is 27 times as much as that of the building in Oban in the west of Scotland for a MW building[163] (Figure 46).

---

[163] All seven of the IWEC locations on mainland United Kingdom (plus Jersey) are used in the analysis. Marseille is chosen as the extreme-most climate as its summer temperature (23.2 ^{0}C) approximates that
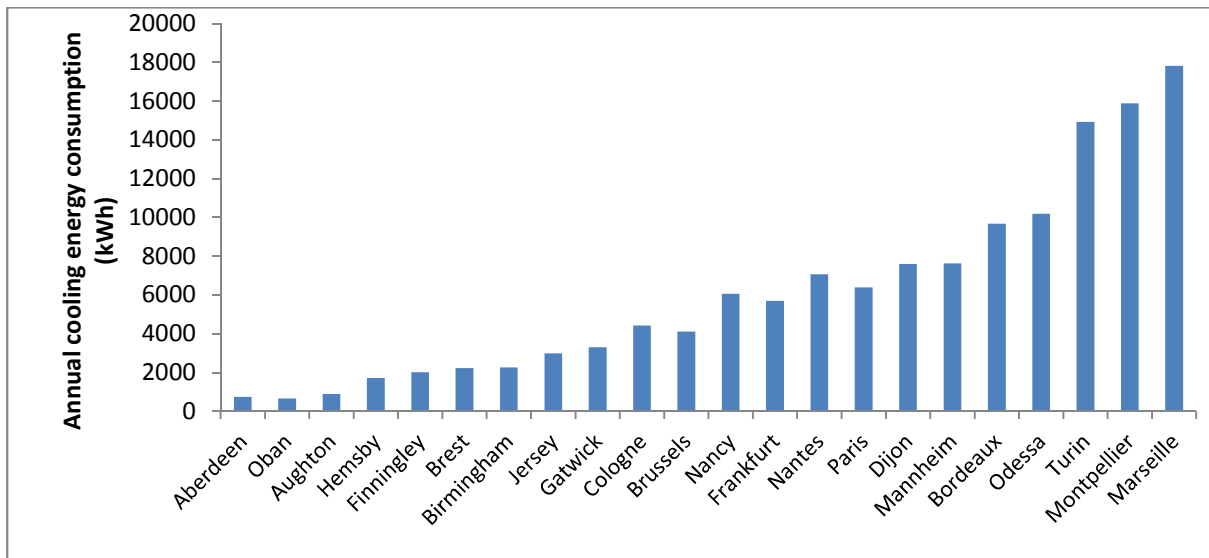
Figure 46 Annual cooling energy consumption in the MW building with 30% glazing (set-point operative temperature of 26 ^{0}C) across a range of 22 locations

4.2.2   Cooling ACDD Calculation

The European and ASHRAE adaptive standards are described by different equations which set different temperature limits for the thermal comfort zone. Since ACDDs are calculated with reference to the fixed upper temperature limit of the thermal comfort zone of the PMV Model, the ACDD concept provides an opportunity to compare one standard against the other on a like-for-like basis in terms of energy saving potential. This is particularly useful for designers and energy managers who wish to employ an adaptive standard in their buildings, but to whom little guidance is offered to help them make their selection.

Each adaptive standard sets an optimum temperature (neutral temperature), the temperature at which the greatest number of people find thermal satisfaction. Each adaptive standard also sets out acceptable deviations either side of the optimum temperature. The limiting temperatures of these deviations (*x* and *y*) mark the upper and lower limits of the thermal comfort zone (Table 53).

forecast for London under a high emissions scenario for the 2080s (22.7 ^{0}C at the 0.5 probability level). The remaining 13 European locations, primarily from western Europe, are chosen so as to ensure a good range of ACDD totals/temperatures. The results of all analyses are shown in Section 4.2.3 – no data are omitted.

ASHRAE adaptive standard 55*	
upper limit	*0.31 x t_{mm} + 17.8 + x*
lower limit	*0.31 x t_{mm} + 17.8 - x*
European 15251 adaptive standard	
upper limit	*0.33 x t_{drm} + 18.8 + y*
lower limit	*0.33 x t_{drm} + 18.8 - y*

* Note that the ASHRAE adaptive standard equations are not contained within the standard itself but can be found in other documents produced by the authors such as (de Dear & Brager, 2002) and (de Dear, 2007).

where,

t_{mm} = mean monthly outdoor air temperature

x = 2.5 or 3.5

t_{drm} = daily running mean outdoor air temperature[164]

y = 2, 3 or 4

As the adaptive standards each propose a number of different upper (and lower) temperature limits which allow for different levels of acceptable deviation (*x* and *y* in Table 53) from the neutral temperature, as does the PMV Model, the question arises as to which upper limits should be chosen. Section 4.2.2.1 sets out the method of selecting the upper temperature limit to be used in the comparison, and Section 4.2.2.2 describes the ACDD calculation process.

4.2.2.1 Selection of upper temperature limits

PMV Model

The PMV Model (BS EN ISO 7730:2005 standard) (CEN/BSI, 2005/2006) sets out three different comfort zones, Categories A, B and C, where PMV/PPD values can be used to delineate one category from another (see footnote 151) (

Table 54).

---

[164] Daily running mean temperature - a composite daily mean weighted temperature which takes account of the temperature on preceding days, the temperature weighting diminishing on a half-life basis the farther one moves back in time, i.e. temperature on day *n* (t_n) = 0.5t_{n-1} + 0.25t_{n-2} + 0.125t_{n-3} + ….

Table 54 BS EN ISO 7730:2007 categories of comfort

Category	PPD values (%) whole body discomfort	PMV
A	<6	-0.2 < PMV < +0.2
B	<10	-0.5 < PMV < +0.5
C	<15	-0.7 < PMV < +0.7

ASHRAE adaptive standard

The ASHRAE adaptive standard sets out two thermal comfort zones – one for 80% acceptability, and another for 90% acceptability. Since the 80% acceptability comfort zone used in ASHRAE adaptive standard 55 for buildings which employ mechanical cooling systems (and which uses the PMV Model) is based on a PPD value of 10 for general whole body thermal discomfort[165] (ASHRAE, 2004; Schiller Brager & de Dear, 2000) (Schiller Brager & de Dear, 2000), it is reasonable to attach this same value of PPD 10 for whole body thermal discomfort to the 80% acceptability limits of the ASHRAE adaptive standard.

European adaptive standard

BS EN 15251:2007 sets outs out both (i) the adaptive standard for buildings without mechanical cooling systems and the (ii) the standard for buildings which employ a mechanical cooling and/or heating system (i.e. PMV standard). The same comfort classification system is used for both the adaptive standard and the PMV mechanical appliance standard (Table 55)[166].

Table 55 BS EN 15251:2007 categories of comfort

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
II	Normal level of expectation and should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

---

[165] An allowance is made for an average of a further 10% dissatisfaction that might occur because of local thermal discomfort, in addition to the general whole body 10% dissatisfaction mentioned above.
[166] Whilst four different comfort zones are distinguished in Table 55, only the first three zones (Categories I, II and III) are used by the adaptive standard.

The BS EN 15251:2007 standard for buildings which employ a mechanical cooling and/or heating system is the same as PMV standard as BS EN ISO 7730:2005, where Categories I, II and III of BS EN 15251:2007 cross-correspond with Categories A, B and C of BS EN ISO 7730:2005, and the same PMV/ PPD values delineate one category from another.

Thus, Category B of the PMV Model (BS EN ISO 7730:2005) cross-corresponds with both (i) the 80% acceptability ASHRAE adaptive standard[167], and (ii) Category II of the European adaptive standard, which allows for a direct comparison between the standards[168]. In consequence, ACDDs are calculated with reference to the upper temperature limits of these three particular forms of each standard.

4.2.2.2 Application of Cooling ACDD Equations

Henceforth, the ASHRAE adaptive standard 55 (80% acceptability) is termed the AAS and the European 15251 adaptive standard (Category II) is termed the EAS for brevity.

In view of the fact that both the AAS and the EAS only apply to spaces where the occupants are engaged in near sedentary physical activities with metabolic rates ranging from 1.0 to 1.3 met, the adaptive standard comparison is limited to buildings such as offices, dwellings, schools and laboratories where the metabolic rate is of the order 1.2 met.

The resultant base temperature used in the calculation of ACDDs (which corresponds with Category B in

Table 54 and a metabolic rate of 1.0-1.3) derives from the PMV Model as detailed in Annex A.4 of BS EN ISO 7730:2005[169] (CEN/BSI, 2005/2006): the PMV base temperature for the cooling season (PMV_{bc}) calculates as 26.0 ^{0}C[170].

Regarding the necessity that comparison be made on a like-for-like basis, it is re-iterated that the AAS/EAS comparison is only valid for those buildings in which a mechanical cooling system is not present. Even though the EAS can, in general, apply to buildings in which a mechanical cooling system has been installed given the proviso that the system is not actually used to provide cooling, the comparison only remains valid for that sub-section of buildings completely lacking a mechanical cooling system so as not to invalidate the applicability of the AAS.

The annual number of cooling ACDDs ($ACDD_c$) are calculated for each AATC thus:

---

[167] Both share a whole body PPD value of 10.

[168] Noteworthy of mention are the facts that (i) the ASHRAE adaptive standard 55 (80% acceptability) is described as being intended for use in "typical applications" (ASHRAE, 2004) , and (ii) the European adaptive standard (Category II) is described as being intended for a "normal level of expectation and should be used for new buildings and renovations" (CEN/BSI, 2007/2008). In that they are both the "ordinary" forms of the standard therefore, this validates the rationale described above that these are the forms of each adaptive standard which should be compared against one another.

[169] The base temperatures refer to spaces under typical conditions of air velocity, relative humidity, clothing insulation and metabolic activity, where the air temperature is equal to the operative temperature.

[170] The PMV base temperature for the heating season (PMV_{bh}) calculates as 20.0 ^{0}C.

Equation 49

AAS

$$ACDD_c = \sum_{i=1}^{12}(AAS_{ul} - 26.0)$$

when $AAS_{ul} > 26$

where,

AAS_{ul} = AAS upper temperature limit

AAS_{ul} = (0.31 x t_{mm}) + 17.8 + 3.5

Equation 50

EAS

$$ACDD_c = \sum_{i=1}^{365}(EAS_{ul} - 26.0)$$

when $EAS_{ul} > 26$

where,

EAS_{ul} = EAS upper temperature limit

EAS_{ul} = (0.33 x t_{drm}) + 18.8 + 3

The annual number of heating ACDDs ($ACDD_h$) are calculated in an analogous manner.

4.2.3 Validation Results

In this section the results of the regression analyses are presented for the 25 buildings for the plot annual number of cooling ACDDs against annual total cooling energy consumption.

The correlation between the number of ACDDs and total cooling energy consumption shows a remarkable degree of consistency across the whole range of building types across the range of climates investigated, despite the fact that the cooling energy includes both the latent load in addition to the sensible load. (In humid climates where loads are high, one might find expect to find a diminution in correlation due to increased latent loads.) Ranging from a minimum value of 0.89 for the Pitched building with 10% glazing using the EAS, the coefficient of determination reaches a maximum of 0.99 for the Solid building with 30% glazing using the EAS and the Pitched building with 50% glazing using the AAS (Table 56 and Figure 47).

Table 56 Coefficients of determination for a range of buildings in the plot of annual number of cooling ACDDs against total annual cooling energy consumption

Level of glazing	LW		MW		Insulated		Pitched		Solid		Mean
	AAS	EAS	AAS	EAS	AAS	EAS	AAS	EAS	AAS	EAS	
10%	0.95	0.98	0.93	0.96	0.96	0.98	0.89	0.94	0.91	0.95	**0.95**
30%	0.98	0.98	0.97	0.98	0.98	0.98	0.96	0.98	0.97	0.99	**0.98**
50%	0.98	0.98	0.98	0.98	0.98	0.97	0.98	0.99	0.98	0.98	**0.98**
70%	0.98	0.97	0.98	0.97	0.97	0.97	0.98	0.98	0.98	0.98	**0.98**
90%	0.97	0.97	0.97	0.97	0.97	0.96	0.98	0.98	0.98	0.97	**0.97**
Mean	**0.97**	**0.98**	**0.97**	**0.97**	**0.97**	**0.97**	**0.96**	**0.98**	**0.96**	**0.97**	**0.97**
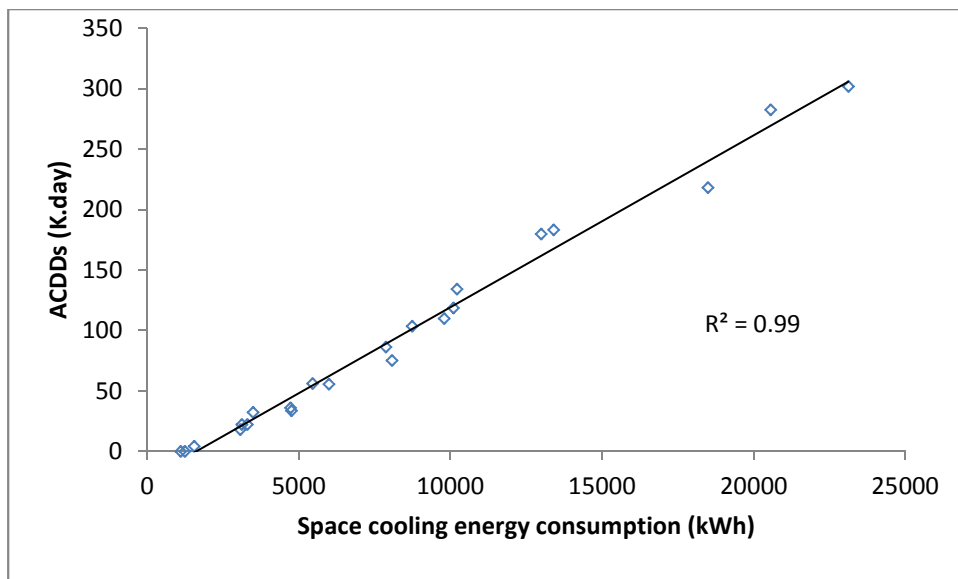
Figure 47 Correlation between annual number of cooling ACDDs using the AAS and total annual space cooling energy consumption for the Pitched building with 50% glazing for 22 different locations

Although the coefficient of determination is very high in each of the 50 regression analyses, it is noted that in two of the EAS analyses ((i) Pitched, 10% glazing, and (ii) Solid, 10% glazing) and one AAS analysis (Pitched, 10% glazing), the correlation starts to deteriorate if the demand for cooling is very low. Most clearly observed in the EAS Pitched, 10% glazing regression (Figure 48), the decline in the correlation can largely be ascribed to the fact that a zero demand for cooling energy does not correlate with zero ACDDs. Essentially, the mismatch results from the fact that although the AATC

would allow indoor temperatures to exceed 26 ^{0}C on occasion, buildings with very low levels of glazing in certain of the colder climates would either very rarely or never require the use of air-conditioning because indoor temperatures would very rarely or never exceed 26 ^{0}C. Whilst, for example, in neither Aughton nor Aberdeen would the Pitched building require a mechanical cooling system to maintain a temperature below 26 ^{0}C, the upper limit of the AATC (reflecting the number of ACDDs) does, periodically, stretch beyond 26 ^{0}C in both towns.
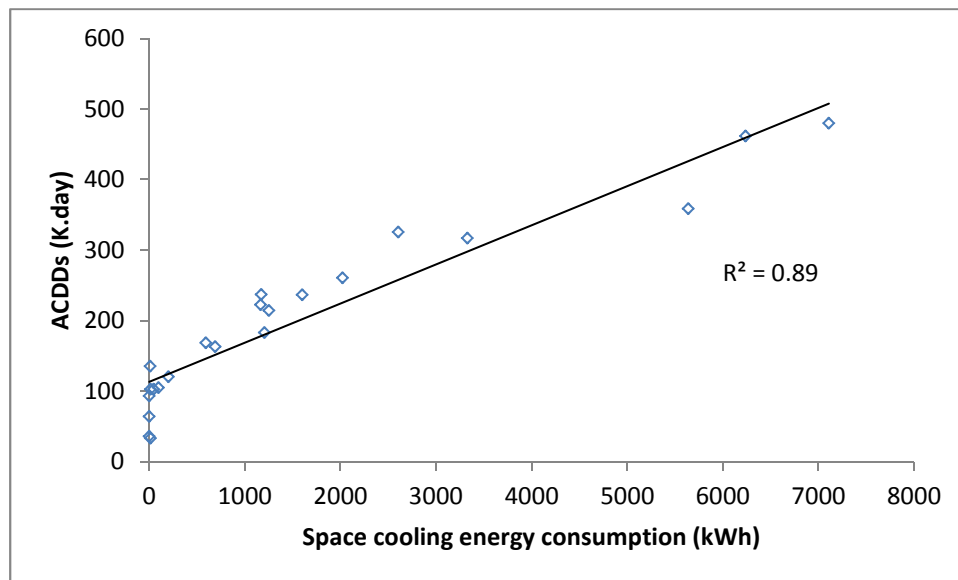
Figure 48 Correlation between annual number of cooling ACDDs using the EAS and total annual space cooling energy consumption for the Pitched building with 10% glazing for 22 different locations

Even though application of the AATC requires that there be access to openable windows, which may preclude its use in many of the more extreme construction types (e.g. 10% glazing and 90% glazing, such latter highly glazed buildings often likely to have been built so as to specifically incorporate an air-conditioning system and possessing sealed windows), the coefficient of determination across all buildings averages as 0.97 for both the AAS and the EAS.

4.2.4 Discussion of Validation Results

Thermal Responsiveness of Buildings

The fact that the correlation between cooling energy consumption and cooling ACDDs remains high for the whole range of construction types, irrespective of building construction (thermal responsiveness), indicates that the predictive capacity of the ACDD concept does not require attainment of the steady-state. The indoor temperature which would occur in the steady-state acts as no more than an alternative, convenient metric to measure the driving force of heat flux across the fabric of the building, where the greater the notional steady-state temperature, the greater the heat flux, such heat flux being equal and opposite to the applied cooling energy.

Having stated that the validity of the ACDD concept rests on no greater assumption than that there is a linear correlation between the notional steady-state indoor temperature and outdoor

temperature, it is worth noting that these results are, however, in close accord with Coley and Kershaw's finding of the close relationship between actual indoor temperature and outdoor temperature; modelling a number of different passively cooled building types using (i) weather data projected for the UK and (ii) observed weather data from a very wide range of climates including the humid Tokyo and Bangkok as well as London, a near linear relationship between actual indoor temperature and outdoor temperature is found (Coley & Kershaw, 2010).

Solar Gains

The finding that the coefficients of determination are largely uniform across all levels of glazing is indicative of the relatively much lesser importance of solar radiation than outdoor air temperature (and therefore ACDDs) in affecting indoor temperature. High levels of direct normal solar radiation are not translated into high levels of solar gains: despite the large differences in the levels of direct normal solar radiation across the range of locations investigated (coefficient of variation – 31%), the coefficients of variation for solar gains show a much higher degree of uniformity, the coefficient of variation being of the order of 5-7% for the summer months during which the cooling load is at its greatest, and 12% over the full course of the year (Table 57).

Table 57 Coefficients of variation for (i) solar radiation and (ii) solar gains through glazing for a range of buildings for 22 locations

	Coefficient of variation (Jun-Aug) (%)	Coefficient of variation (Jan-Dec) (%)
Direct Normal Solar Radiation	20.0	31.3
Diffuse Horizontal Solar Radiation	3.5	5.8
Glazing Solar Gains for a given level of fenestration (LW, MW, Insulated, Solid)	5.2	12.9
Glazing Solar Gains for a given level of fenestration (Pitched)	4.5 - 5.1*	12.4 - 12.7*

The reason why the coefficient of variation for glazing solar gains is lower for the Pitched building than it is for the other building types is because of the shading provided by the eaves.

Whilst, for example, Marseille receives 3.1 times as much direct normal solar radiation as Aberdeen, this translates into additional solar gains of only 56% for the MW building (30% glazing) (Table 52) since a large part of the additional Marseillaise sunshine occurs when the sun is high in the sky[171]. This dominance of air temperature over solar gains in determining indoor temperature/cooling load can be seen in any number town-town comparisons in Table 52: whereas, for example, the MW (30% glazing) building in Hemsby receives 36% more direct normal radiation than the same building in Brussels, its cooling load is 58% less in consequence of the fact that air temperatures are considerably lower in Hemsby than in the Belgian capital.

---

[171] Although solar gains for the 30%-glazed MW building in Marseille are only 56% higher than the same building in Aberdeen, the building in Marseille consumes over 24 times as much cooling energy.

Even though solar radiation is of lesser significance than air temperature, a further reason for the very good correspondence between the number of ACDDs and cooling energy consumption is that solar radiation is largely not antagonistic to this relationship, there being a similarly high correlation between the number of ACDDs and solar gains: the coefficient of determination falls in the range 0.79-0.81 for all building types and levels of glazing for both adaptive standards.

Latent Load

Even though latent loads are not negligible (typically constituting 10-20% of the total cooling load for the 30% MW building for example), (i) they are nevertheless significantly less than sensible loads and (ii) even though the degree of correlation is less, they also correlate with the number of ACDDs to a very high degree. These two facts combine so as to make the inclusion of latent load data within the total cooling data as being of negligible consequence.

Synopsis

Summarily, the regression analyses confirm the proposition that for (i) a given construction type, and (ii) a given level of glazing, there is a clear linear correlation between cooling load and the number of ACDDs, the accuracy of the prediction being most exact for buildings where the steady-state temperature more often exceeds 26 ^{0}C. The sequitur of this finding is that the ACCD can be used as a metric to forecast energy savings at different times in the future under a changing climate, thereby allowing one to compare the maximum potential savings deriving from the AAS and the EAS.

4.3 Application of the ACDD Concept to Future Climates

The Weather Generator is run 100 times for stationary 99-year time-slices centred on the 2030s, the 2050s and the 2080s under low, medium and high emissions scenarios for the city centres of three different locations - Edinburgh, Manchester and London - using the UKCP09 Weather Generator.

In order to investigate as broad a span of future climates as possible, ranging from a low increase in temperature in a climate at a northerly latitude to a relatively large increase in temperature in a climate at a southerly latitude, the three variables are grouped into ternions as shown in Table 58.

Climate	Outdoor temperature*	City	Time slice	Emissions scenario
I	coolest	Edinburgh	2030s	low
II	intermediate	Manchester	2050s	medium
III	hottest	London	2080s	high

The descriptors coolest, intermediate and hottest should be viewed as no more than relative terms.

The Weather Generator is also run for a 1970s control period (1961-1990) for each of the locations.

Thus 9,900 years of daily weather data are produced for each ternion and for the control period, averaging the daily mean temperatures of which gives an indication of future climate at the 0.5 probability level (Figure 49).
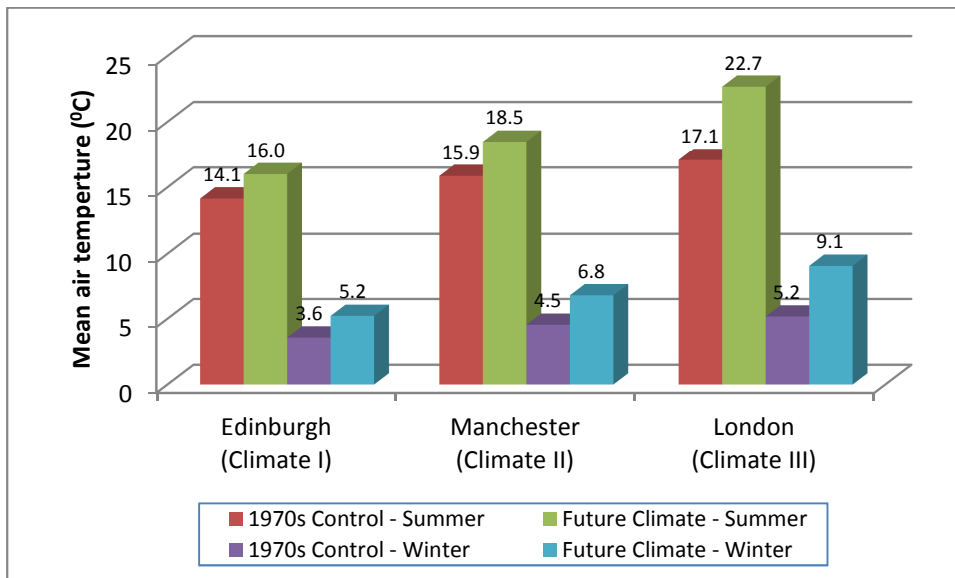
Figure 49 Mean air temperatures of future climates investigated

The annual number of cooling ACDDs ($ACDD_c$) resulting from implementation of the AAS and the EAS are calculated for the future climates and for the control period using the procedure outlined in Section 4.2.2.2. The number of heating ACDDs ($ACDD_h$) are calculated in a similar manner, heating ACDDs representing the extent to which the lower temperature limit of the AATC ($AATC_{ll}$) dips below the winter PMV base temperature (PMV_{bh}) of 20.0 ^{0}C. Table 59 summarises, in equation form, the procedure used to calculate the annual numbers of cooling ACDDs and heating ACDDs.

Table 59 Summary equations used to calculate ACDD totals from Weather Generator output

	Cooling ACDDs*[#]	Heating ACDDs*[~]
AAS	$$ACDD_c = \left(\sum_{i=1}^{12} (AAS_{ul} - 26.0) \right) \div 9900$$ where AAS$_{ul}$ = 0.31 x t$_{mm}$ + 17.8 + 3.5	$$ACDD_h = \left(\sum_{i=1}^{12} (20.0 - AAS_{ll}) \right) \div 9900$$ where AAs$_{ll}$ = 0.31 x t$_{mm}$ + 17.8 - 3.5
EAS	$$ACDD_c = \left(\sum_{i=1}^{365} (EAS_{ul} - 26.0) \right) \div 9900$$ where EAS$_{ul}$ = 0.33 x t$_{drm}$ + 18.8 + 3	$$ACDD_h = \left(\sum_{i=1}^{365} (20.0 - EAS_{ll}) \right) \div 9900$$ where EAS$_{ll}$ = 0.33 x t$_{drm}$ + 18.8 - 3

Indoor temperatures are operative temperatures.
[#]*When AAS$_{ul}$ and EAS$_{ul}$ > 26 ^{0}C.*
[~] *When 20 ^{0}C > AAS$_{ll}$ and EAS$_{ll}$.*

The relative performances of the AAS and the EAS are also investigated against 18 future COPSE TRYs to check the robustness of the procedure used in this analysis (c.f. Section 2.5.6.1 and Section 3.6.1).

- *Edinburgh Turnhouse (rural), high and low emissions scenarios, 2020s, 2050s, 2080s*

- *Manchester Ringway (rural), high and low emissions scenarios, 2020s, 2050s, 2080s*

- *London Heathrow (semi-rural), high and low emissions scenarios, 2020s, 2050s, 2080s*

The numbers of ACDDs calculated from the COPSE TRYs should be similar but different to those calculated for each of Climates I, II and III using the method described in Table 59: not only is the method of calculation different (see Section 2.5.6.1), but the COPSE TRYs are calculated for rural/semi-rural locations (airports) rather than city centres.

4.4 Future ACDD Results

The results reveal that rising temperatures in future climates have quite different implications with regard to application of the AATC in summer and winter.

4.4.1 Cooling Season – AAS and EAS

Figure 50 shows the number of ACDDs returned by the adaptive standards as the climate warms. Although both the AAS and EAS show an increasing return in the number of ACDDs as one moves from Climate I to III as expected, the differences between the actual numbers of ACDDs are marked: the EAS figures are considerably higher than their AAS counterparts for both the control data and the future climate data in all instances.
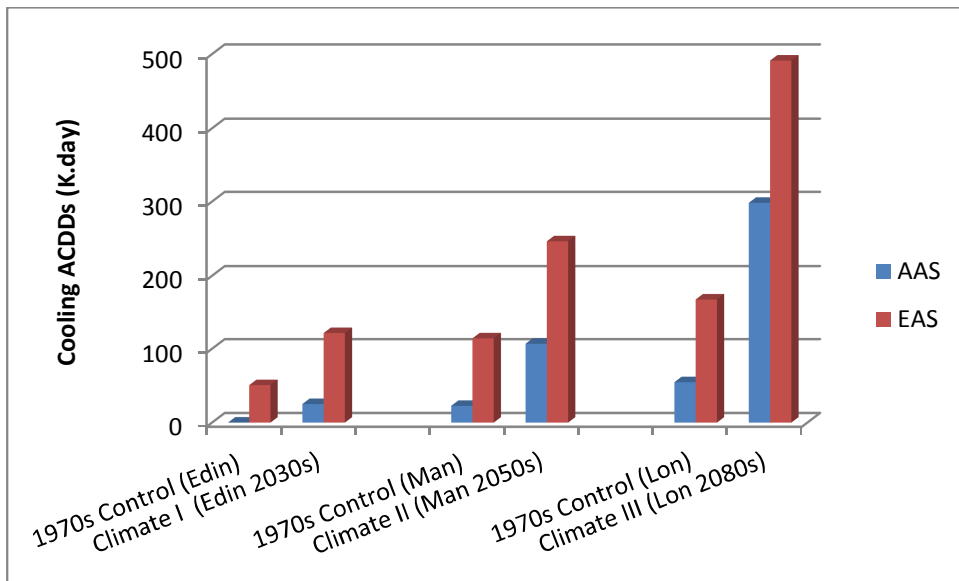
Figure 50 Annual number of cooling ACDDs for 3 climate types with reference to 1970s control

The EAS returns more ACDDs in Edinburgh in the 2030s than the AAS returns in Manchester in the 2050s; and the EAS even returns more ACDDs in Manchester in the 1970s than the AAS returns in Manchester in the 2050s.

The TRY data reveal similarly increasing numbers of ACDDs as the climate warms, but further show that the differences between low and high emissions scenarios does not start to become appreciable until the latter part of the century: whilst there is very little difference in the number of ACDDs returned between high and low emissions scenarios in the 2020s for all three locations, the difference is very significant by the time the 2080s is reached (Figure 51).
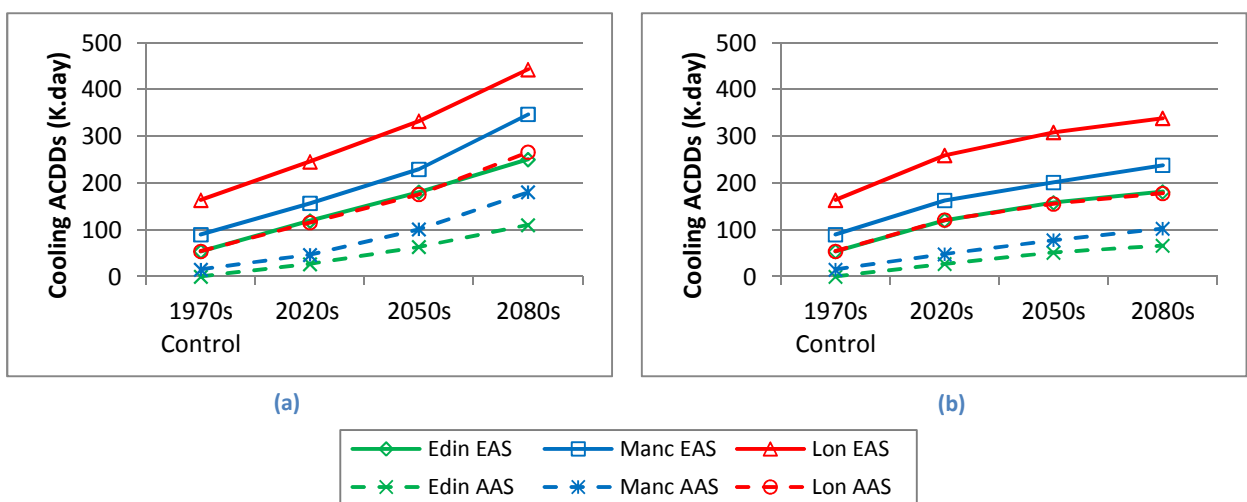
Figure 51 Annual number of cooling ACDDs following implementation of the AAS and the EAS using TRY data for (a) high and (b) low emissions scenarios for Edinburgh (Turnhouse), Manchester (Ringway) and London (Heathrow) for the 2020s, 2050s and 2080s

The data also reveal that, for any given city, potential savings achieved by the EAS (bold line) in any particular decade are not matched by AAS savings (dotted line) until decades later. Moving from left

to right in Figure 51a (high emissions scenario) it is seen that savings achieved in the 2020s by the EAS for either London or Manchester are only matched by the AAS in the 2080s; and Figure 51b (low emissions scenario) shows that EAS savings in the 2020s outmatch AAS savings in the 2080s for all three cities.

4.4.2 Heating Season – AAS and EAS

Insofar as the AAS only applies when the mean monthly outdoor temperature is greater than 10 ^{0}C, and the EAS only applies when the running mean outdoor temperature exceeds 15 ^{0}C, there appears to be limited scope for the implementation of either standard, in their current form, in winter, over the course of the next century. Analysis of 9,900 years of data from the Weather Generator shows that winter (December-February) mean monthly temperatures failed to reach 10 ^{0}C for any of the three climates (Table 60).

Table 60 Winter mean monthly temperatures for three climate types (December, January and February) (^{0}C)

	December	January	February
Climate I	6.1	4.8	4.7
Climate II	7.7	6.3	6.2
Climate III	9.7	8.8	8.7

Although the mean winter temperature fails to exceed the 10 ^{0}C threshold for Climates I and Climate II even at the 99th percentile (i.e. the top 1% mildest winters), the winter mean temperature does, however, manage to exceed the AAS threshold temperature for Climate III at the 71st percentile. Not surprisingly, the EAS threshold running mean temperature is only rarely exceeded: the incidence of such occurrence is negligible for Climates I and II, and is recorded, on average, on less than four winter days for Climate III.

4.5 Discussion of Future ACDD Results

At the outset of this discussion investigating why the AAS and EAS should yield such very different results in terms of the their energy saving capacity, it is important to remember that any free-running building using the AATC is zero-energy, whichever particular label is attached to the adaptive standard being used; a building operating in free-running mode will save exactly the same amount of energy using the AAS as the EAS. The difference between the two standards, insofar as energy savings are concerned, hinges on the matter of compliance. A building which may be EAS-compliant and can thus save energy through avoiding the use of a mechanical cooling system may not be AAS-compliant; where such non-compliance in the latter case disallows the use of the AAS with the result that a mechanical cooling system is alternatively used, no energy will be saved.

The findings that the upper temperature limits of the thermal comfort zones of the adaptive standards are higher than those of the PMV Model, and specifically, that those of the EAS are higher than the AAS, is expected – such a conclusion could be easily inferred by merely casting an eye over

the equations defining the respective comfort zones. The significance of the results lies in the reporting of the extent of the energy savings that can be achieved, and most specifically the speed at which they can be achieved through compliance. The approximate 0.9 ^{0}C higher limit of the EAS means that it can be applied to a greater number of buildings, these additional buildings being capable of achieving energy savings at a significantly faster rate than buildings which are merely AAS-compliant. As seen, the buildings using the EAS may achieve levels of energy savings in the 2020s which a merely AAS-compliant building could not achieve until the 2080s or later, irrespective of the emissions scenario chosen.

4.5.1 Disagreement between Adaptive Standards - Possible Causes

Given the universality of the perception of thermal comfort, it is curious that these two standards should yield such different zones of thermal comfort, the upper limit of the EAS being approximately 0.8-1.0 ^{0}C higher than the AAS over the range of climates investigated. Considering the fact that the upper limit of an adaptive standard is often no more than 0.8-1.0 ^{0}C higher than the upper limit of the PMV Model, such dissimilitude between the adaptive standards themselves is significant. Any claim that the 0.8-1.0 ^{0}C difference between the two adaptive standards is insignificant, that there is essentially very little difference between them, then logic dictates that the same argument should be applied to the AATC theory as a whole, that the 0.8-1.0 ^{0}C extension of the upper limit of the PMV Model offered by the AATC should also be ignored, so nullifying the very existence of any adaptive standard in so doing.

Therefore, despite the previously stated requirement that the two adaptive standards be compared on a like-for-like basis, it is apparent that this requirement is not being fulfilled. Two possible causes, one arising from differences in the sample populations[172]used to draw up the standards, and the other arising from differences in formulation of the adaptive comfort equations, suggest themselves as being responsible for the discrepancy.

4.5.1.1 Differences in Sample Populations

As the standards were drawn up from different population samples (either building types or occupants), it is possible that the building types used in constructing the ASHRAE adaptive standard were different to the building types used in constructing the European adaptive standard; or similarly, the difference could arise from the fact that the occupants of the buildings used in constructing the ASHRAE adaptive standard were en masse different to the occupants of the buildings used in constructing the European adaptive standard.

---

[172] i.e. different sample set of buildings and different sample set of occupants.

Differences in Building Types

Whereas the free-running buildings used to formulate the EAS may have included non-operational mechanical cooling systems[173], those of its AAS counterpart did not, since the ASHRAE adaptive standard outlaws their actual presence. In theory this difference could have expressed itself as differences in the degree of adaptiveness shown by occupants, occupants in the former group showing a lesser degree of adaptiveness borne as a result of having occupied the building at some time in the relatively recent past when it was mechanically cooled[174]. However, the fact that the method used to formulate the European adaptive standard, involving the use of the Griffiths constant[175], was designed to reduce the effects of adaptation, suggests that it is unlikely that such a difference could be an important factor in explaining the difference between the two adaptive standards.

Differences in Occupants

Whilst of course there is a great deal of thermal heterogeneousness within the human population at large, as evidenced by the fact that the neutral temperature differs from person to person, the mean neutral temperature of one large sample group will equal the mean neutral temperature of another large sample group if the sample groups have been chosen from the same population at large. If chosen from different populations however, then it is possible that each sample group will report different mean neutral temperatures. Thus differences between the sample groups used in the construction of each adaptive standard could ultimately result in different temperature limits for the AAS and the EAS.

Analysis of the neutral temperatures from occupants in buildings in four different countries used in formulating the EAS (Nicol & Humphreys, 2010) shows a degree of variance in the neutral temperature, being up to 1 ^{0}C or more in magnitude on occasion. In view of the large degree of variance amongst the handful of countries used to draw up the European adaptive standard, it is not inconceivable that at least as much variance might occur in the RP-884 database with its very broad national mix[176], and that the variance is averaged out differently in the two different databases, resulting in different neutral temperatures for the EAS and AAS. The cause of the disparity between the neutral temperatures could be due to randomness (deriving from too few data being used). It

---

[173] Indeed, there is a possibility that systems may have been in operation, at least for some of the occupants in some of the buildings for some of the time, since up to 10% of respondents could report a system as being in use before its status was changed from non-operational to operational.

[174] This lesser degree of adaptiveness would reveal itself as (i) a reduction in value of the slope of the regression trend line in the plot of comfort vote against outdoor (or indoor) temperature.

[175] When comfort vote is plotted against operative temperature in free-running buildings, it is seen that the regression coefficient (which can be taken as a measure of adaptiveness) differs from one analysis to the next, and it may derive from a number of different causes. The Griffiths constant is tantamount to the regression coefficient with the greatest slope (i.e. the plot where occupants show the least/no adaptation, and where account has been taken of the presence of error in the predictor variable), and has been based on analysis of both the European and ASHRAE adaptive standard databases of buildings (Nicol & Humphreys, 2010; Nicol, 2008).

[176] The worldwide database from which ASHRAE adaptive standard 55 was drawn, comprising sample populations from locations within Thailand, Indonesia, Singapore, Greece, the United States, the United Kingdom, Australia and Pakistan (de Dear & Brager, 2002) .

could also be due to differences in adaptive opportunity where perhaps cultural preferences/local protocol limit the extent to which dress code may be altered, noting that dress codes in the west may differ to those in different parts of Asia.

The disparity in neutral temperatures could also arise from differences in ancillary environmental conditions of the population samples. If, for example, the relative humidity was, on the average, higher in the buildings used to formulate the ASHRAE adaptive standard than in the buildings used to formulate the European adaptive standard, it would manifest itself in a lower neutral temperature. Considering the global nature of the RP-884 database used in formulating the ASHRAE adaptive standard 55, which includes buildings in tropical climates in south-east Asia and Australia (de Dear & Brager, 2002), such conjecture cannot be discounted.

Even though climate chamber experiments have reported age, sex and national-geographic (Danish/American) difference as having little effect upon the neutral temperature (Fanger, 1972), innate racial (physiological) difference is another possible cause for difference between the standards, with field studies having shown a difference between ethnic groups. A significant difference in neutral temperature was found between Japanese and non-Japanese (predominantly North American and European) office workers in Japan who had, on average, lived in Japan for 4.7 years and were thus likely to have acclimatised to local conditions: the difference in neutral temperature was most extreme (3.1 ^{0}C) when Japanese females were compared with non-Japanese males (Nakano, et al., 2002). Furthermore, although the magnitude of the effect was not quantified in terms of a temperature preference, studies reporting on the permanent sensation of cutaneous dryness in black-skinned people living in France as a consequence of reduced levels of sweating (Fotoh, et al., 2008) raise interesting possibilities that differences in physiology (i.e. race), even if only of secondary importance, may, in part, lead to differences in neutral temperatures: not violating the biological imperative to maintain a body core temperature of the order of 37 ^{0}C (such argument underlying the proposition that race cannot have an effect upon neutral temperature), dark-skinned people may find warmer temperatures comfortable because of an innate physiological preference to sweat more.

4.5.1.2 Differences in Formulation of Adaptive Comfort Equations

Inspection of the equations in Table 53 shows that differences in the number of ACDDs resulting from implementation of each standard may arise because of (a) differences in the neutral temperature for a given outdoor temperature (whether daily running mean (drm) or mean monthly), or (b) differences in the temperature bandwidth defining the comfort zone which extends either side of the neutral temperature.

(a) *Neutral Temperature*

Different approaches are employed in the derivation of the neutral temperature for each standard, the difference between neutral temperatures being in the range 1.3-1.5 ^{0}C.

ASHRAE adaptive standard

Its derivation can be simplified thus.

i. Comfort vote was plotted against indoor operative temperature for 36 different buildings.
ii. A trend line, weighted in proportion to the number of respondents, was fitted to the data in each of the 36 regression analyses and the mean neutral temperature (where comfort vote equals zero) was determined for each of the 36 buildings.
iii. The mean outdoor temperature for each of the 36 regression analyses was also noted.
iv. A meta-analysis was performed where the mean neutral temperature was regressed against the mean outdoor air temperature. A linear trend line was fitted to these data. The equation which describes the trend line is taken as the ASHRAE adaptive standard, allowing one to determine the neutral temperature for a given outdoor mean temperature (de Dear & Brager, 2002; de Dear & Schiller Brager, 1998). (The outdoor mean temperature actually used in the standard is the dry bulb mean monthly temperature.)

European adaptive standard

Its derivation can be simplified thus.

i. The European adaptive standard recognises that there is a linear correlation between comfort vote and indoor operative temperature when one is plotted against the other. The slope of the correlation trend line for which minimal/no adaptation has taken place (*G*) can described by the following equation:

Equation 51

$$G = \frac{(C-0)}{(t_{op}-t_n)}$$

where,

G = Griffiths constant (regression coefficient)

C = comfort vote at operative temperature t_{op}

0 = comfort vote at neutral temperature t_n

t_{op} = operative temperature

t_n = neutral temperature, the temperature at which most people are comfortable, according with a comfort vote of 0

179

Rearranging, the neutral temperature is described by the following equation:

$$t_n = t_{op} - (C/G)$$

G represents the maximum rate of change in comfort vote in response to change in operative temperature, resulting from the fact that minimal/no adaptation has taken place. Observation reveals G to have a value of at least 0.4 K^{-1}.

ii. Indoor operative temperature, comfort vote and outdoor drm temperature were recorded from 26 offices.

iii. For each operative temperature and comfort vote, the neutral temperature was calculated using Equation 52, where G is assigned a value of 0.4.

iv. The neutral temperature was plotted against outdoor running mean temperature for 26 offices in a single plot. A linear regression trend line was fitted to the data and its R^2 value was noted.

v. Steps iii and iv were repeated, where G is assigned a new value of 0.5.

vi. The regression trend line returning the greatest R^2 value is chosen as best characterising the relationship between neutral temperature and outdoor drm temperature[177]. The equation which describes the trend line is taken as the European adaptive standard, allowing one to determine the neutral temperature for a given outdoor mean temperature (Nicol & Humphreys, 2010).

The methods of neutral temperature derivation are considerably different, making it difficult to localise a specific factor or factors as being responsible for the discrepancy between the two adaptive standards. Nevertheless, five factors which have been identified as bearing an influence upon setting the neutral temperature, and these are discussed in turn.

1 Adaptation

It is clear that the neutral temperature, as reported by a group of occupants, will be lower on day *x* than it is on day *y*, even though the outdoor temperature and the group of occupants are the same on both occasions, if day *x* is preceded by a period of cold weather and day *y* is preceded by a period of hot weather. This creates a problem for the adaptive standard designer who simply wants to set a single neutral temperature in response to a single outdoor temperature from a regression of indoor temperature against outdoor temperature. The problem arises from the fact that adaptation has occurred, the occupants having responded to the thermal environment and made the changes necessary (e.g. opening windows) to secure a comfortable environment. In statistical terms, the data are autocorrelated, the value of a dependent variable being affected by the value of the preceding dependent variable.

Since a key requirement of linear regression analysis is that the data are free from autocorrelation, and since both adaptive standards are derived from linear regression analyses, it important to

---

[177] The best correlation is seen to occur when $G = 0.5$.

examine whether both standards have been successful in removing it from their formulation processes.

Whilst the effects of day-to-day adaptation (autocorrelation) will be manifest in any single building used in drawing up the ASHRAE adaptive standard[178], it will have no/little bearing upon the average neutral temperature of the building if the level of adaptation at high temperatures matches the level of adaptation at low temperatures since the regression line will still pass through the same neutral temperature mid-point. As the ASHRAE adaptive standard analysis eliminated those buildings which had uniformly hot or cold indoor temperatures (de Dear & Schiller Brager, 1998), it is, therefore, considered that the neutral temperature of the ASHRAE adaptive standard is unlikely to have been much influenced by the effects of day-to-day adaptation (autocorrelation) (see Appendix 12).

Since the European adaptive standard uses the Griffiths constant, tantamount to the regression coefficient showing the least/no adaptation, it is similarly not likely to have been much affected by day-to-day adaptation (autocorrelation). (The use of a daily running mean temperature, which additionally reduces the influence of autocorrelation, is further discussed in point 5 below.)

2 Errors in the Predictor Variable

Whilst the European adaptive standard endeavours to take specific account of errors arising from the measurement of the predictor variable (measurement errors and *equation errors[179]*) which may be present [180], the ASHRAE adaptive standard does not. Increasing the value of the Griffiths constant from 0.4 to 0.5 increases the value of the neutral temperature by about 0.2-0.3 ^{0}C over the range of temperatures forecast for the future. Although it is not possible to quantify the magnitude of the equation errors (Humphreys & Nicol, 2000), it is clear that the allowance made for them increases the disparity between the neutral temperatures of the adaptive standards.

3 Definition of Mean Monthly Temperature

The interpretation of *mean monthly temperature* for the ASHRAE adaptive standard is problematic, as raised by Nicol and Humphreys (2010). No guidance is given as to the length of time over which the mean should be recorded. The difficulty lies in the fact that as the climate warms, the mean monthly temperature increases – using a mean averaged over the preceding 10 years would result in a higher number of ACDDs than a mean averaged over the preceding 100 years. The assumption

---

[178] Adaptation reveals itself as a decrease in the regression slope when neutral temperature is plotted against outdoor temperature, i.e. the neutral temperature is increased for high outdoor temperatures and lowered for low outdoor temperatures.

[179] Error deriving from the fact that comfort cannot really be described by operative temperature alone, comfort being a psycho-physiological response to an environment shaped by a number of factors, of which operative temperature is but one.

[180] Increasing the value of the Griffiths constant from 0.4 to 0.5 (and which improves the correlation between neutral temperature and daily running mean temperature), is suggested as making an allowance for the presence of error in the predictor variable and error deriving from day-to-day adaptation.

implicit in the standard is that the mean is essentially static, that it represents the typical temperature that can be expected at a particular point in time and with which a person is familiar. As such, this criterion is fulfilled for the future climate in the present study, the mean monthly temperatures being calculated as the mean of that month in the decade under investigation (2030s, 2050s or 2080s) and deriving from 9,900 years of data; the mean is not calculated from preceding weather, but rather from weather that can be assumed to be typical of the time.

4 Comparison of Mean Monthly Temperature with Daily Running Mean Temperature

It has been suggested that the difference between the two standards arises as a consequence of the fact that the ASHRAE adaptive standard uses mean monthly temperatures whilst the European adaptive standard uses drm temperature in the calculation of the neutral temperature. Since the drm temperature on any given day incorporates a measure of the temperature recorded on preceding days, the mean monthly drm temperature will tend to be lower than the mean monthly temperature as the year warms (winter to summer), and higher than the mean monthly temperature as the year cools (summer to winter). Indeed, this is seen to be the case, the July/August boundary being the point where the mean monthly drm starts to exceed the mean monthly temperature (Figure 52).
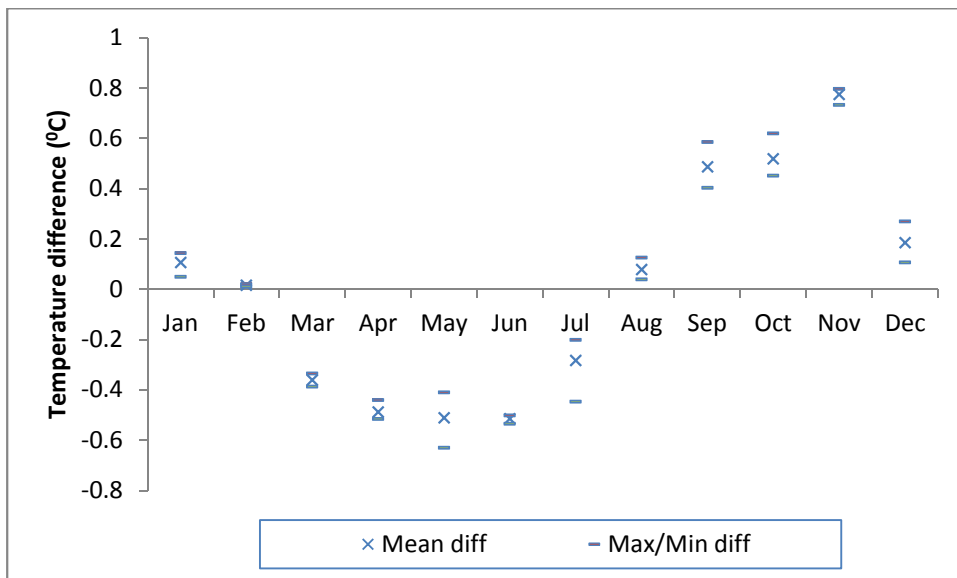
Positive value indicates that the drm temperature is greater than the mean monthly temperature.

Figure 52 Difference between mean monthly drm temperatures and mean monthly temperatures for 29,700 years of future weather data for Climates I, II and III

In the case where there is a substantial difference between the number of cooling ACDDs returned in the warming part of the year and the cooling part of the year, where the additional cooling ACDDs in the latter part of the year are not balanced by the relative reduction in cooling ACDDs in the first part of the year, the number of ACDDs returned by the drm temperature could be significantly

different to the number of ACDDs returned by the mean monthly temperature. However, the dailyness nature of the EAS seems to make only a limited additional difference: when EAS cooling ACDDs are recalculated using mean monthly temperatures instead of running daily mean temperatures for the 18 future TRYs, the average percentage reduction in the number returned is small (2.6%), especially when compared with the difference in number of AAS ACDDs (Table 61).

Table 61 Percentage change in number of cooling ACDDs returned by (i) EAS calculated using mean monthly temperature and (ii) AAS calculated using mean monthly temperature, with reference to EAS calculated using the drm temperature for 18 future TRYs

Change in number of cooling ACCDs with reference to EAS calculated using the drm temperature (%)	Average	Min	Max	Std. dev.
EAS ACDDs calculated using mean monthly temperature	-2.6	0.1	-6.1	2.0
AAS ACDDs calculated using mean monthly temperature	-58.9	-40.0	-77.7	10.6

(b) Width of Comfort Zone

The values x and y in Table 53 (i.e. width of the comfort zone) are calculated using different methods by the two adaptive standards. Both apply the knowledge of the PMV-PPD relationship where a PMV of given value results in a PPD of given value. The AAS defines the comfort zone width as the average of all the comfort zone widths arising at the 80% acceptability level of all the naturally-ventilated buildings used to create the standard (PMV of ±0.85), the resulting width calculating as ±3.5 ^{0}C[181]; the EAS, however, sets the width at directly ±3 ^{0}C of the neutral temperature, this width being that set by the PMV Model at a PMV of ±0.5 (PPD 10) under typical conditions[182, 183]. But rather than increase the difference between the two adaptive standards (and concomitantly increase the difference in the number of ACDDs returned between the two adaptive standards), the different methods used to calculate the widths of the comfort zone actually serve to reduce the difference between them: using a comfort zone of the same width would increase the difference between the upper limits from 0.8-1.0 ^{0}C to 1.3-1.5 ^{0}C[184].

Another possible reason for the difference may derive from the posited PPD value of 10 for whole body discomfort which is associated with 80% acceptability (i.e. overall PPD value of 20) for the AAS, such PPD value for whole body discomfort being used for the 80% acceptability category of the PMV

---

[181] The indoor temperatures coinciding with a comfort vote of +0.85 and -0.85 (equivalent to 80% acceptability) was noted in each building, and the temperature range noted. The average of these ranges calculated as 6.9 ^{0}C (de Dear & Schiller Brager, 1998) or 7 ^{0}C (de Dear & Brager, 2002).

[182] Typical conditions, as detailed in table A.5 of BS EN ISO 7730:2005, for occupants engaged physical activities with metabolic rates of the order 1.2 met (70W/m^2).

[183] Changes in levels of discomfort in free-running buildings are seen to very closely match changes in levels of discomfort in air-conditioned buildings using the PMV Model as temperatures depart from the neutral temperature (i.e. a shift in temperature of 3 ^{0}C from the neutral temperature of a free-running building will result in the same increase in the number of thermally dissatisfied occupants as a shift in temperature of 3 ^{0}C from the neutral temperature of an air-conditioned building, even be it that the buildings have different neutral temperatures).

[184] The difference between the lower limits is increased by the same margin.

ASHRAE adaptive standard 55[185]. Whilst one cannot actually, disentangle whole body comfort from local discomfort, accepting the same PPD value of 10 for whole body discomfort as in the PMV Model is, however, considered to be reasonable: what is more, use of the alternative 90% acceptability limit in place of the 80% limit for the ASHRAE adaptive standard would produces even more disparity between the upper limits, the current disparity of approximately 0.8-1.0 ^{0}C rising to 1.8-2.0 ^{0}C.

As intimated in the preceding paragraphs though, the discrepancy in the width of the comfort zone at the upper temperature limit of the comfort zone is of considerably lesser significance when compared to the difference in neutral temperatures; over the range of temperatures likely to be experienced over the next 70 years or more, neutral temperatures differ by 1.3-1.5 ^{0}C, whereas the values *x* and *y* differ by only +0.5 ^{0}C if the 80% acceptability limit is used or -0.5 ^{0}C if 90% acceptability limit of the ASHRAE adaptive standard is used.

4.6 Summary

Whilst it is very unlikely that winter temperatures will surpass the minimum thresholds necessary to permit use of either the AAS or the EAS during the heating season, the AACT is seen to bear considerable potential in curtailing an increase in space cooling energy consumption as the climate warms. In view of the fact that the relatively low upper temperature limit associated with the AAS restricts the scope of its application, in that fewer buildings will be able to achieve compliance with the standard, the EAS is seen to possess much the greater potential of the two adaptive standards, although this is necessarily incurred at the expense of a lower degree of thermal satisfaction on the average, even if the EAS deems itself as providing a comfortable thermal environment. In view of the urgency attached to not only the level but the speed at which carbon emissions must decrease if society is not to suffer the more extreme, deleterious consequence of climate change, the benefits conferred by the EAS are clear, the data revealing that, for any given city, potential savings achieved by the European adaptive standard in any particular decade are not matched by the ASHRAE adaptive standard savings until decades later.

It a cause of concern for proponents of the AATC, however, that two adaptive standards, which should deliver the same levels of comfort and same levels of energy saving, do not do so, since it lays itself open to criticism from detractors claiming that the AACT is too imprecise a tool to be considered as a robust alternative to the PMV Model. One cannot possibly discount the difference between the temperature limits of the two adaptive standards as being inconsequential, since the EAS often extends upon the temperature limit of the AAS to an even greater extent than the AAS extends upon the temperature limit of the PMV Model; such a line of reasoning, that the difference between the upper temperature limits of the thermal comfort zone is so small that it can be ignored,

---

[185] ASHRAE adaptive standard 55 sets the temperature limits for both free-running buildings and air-conditioned buildings. The 80% acceptability category for air-conditioned buildings (PMV standard) is actually based on a 10% general dissatisfaction criterion for the body as a whole based (corresponding to tests performed in the laboratory), allowing for an additional average of 10% dissatisfaction that might occur because of local discomfort (ASHRAE, 2004; Schiller Brager & de Dear, 2000).

would lead one to reject the AACT in entirety as an alternative to the PMV Model. Until such time as the two standards set temperature limits of equal value however, the EAS is seen as offering the greatest potential: not only are energy savings significantly higher with the EAS, but the upper temperature of the AAS may be unduly restrictive if further research reveals that the adaptive standards do err on the side of caution.

5 The Building Stock in 2050: Pathways to Securing a Reduction in Emissions of 80%

The Climate Change Act 2008 enshrines in law that UK GHG emissions in 2050 should be at least 80% lower than the 1990 baseline level (Climate Change Act, 2008)[186]. Since the built environment is responsible for a significant proportion of current emissions[187], it is clear that emissions from this sector must reduce significantly if the 80% target is to be achieved; and although specific sectoral targets have not been set, it is stated that the built environment will need to have an emissions footprint close to zero (DECC, 2011g). However, of the many pathways which may be followed in order to achieve this target, it remains uncertain which route represents the optimum choice in realising maximum benefit for least cost in terms of fiscal investment and social acceptability. The inter-connectedness of the sectors which contribute towards the UK's carbon budget means that the built environment cannot be considered in isolation, since decisions made in one sector can impose constraints or alternatively provide opportunities to exploit in another sector.

With regard to the built environment, such a case may be seen in its relationship with the power generation and supply sectors, which are likely to require extensive re-development in the coming years as electricity demand increases as end-user fossil fuel burning heating appliances are replaced by electrical heating appliances. It remains unclear which, if any of the three sources from which electricity can be generated in the future[188] will finally prevail, or even if a single technology will dominate the electricity generation market by 2050. Indeed, the Government is committed to developing all three technology streams at present, allowing the market to ultimately determine the eventual make-up of the electricity generation and supply sectors, where technologies with the lowest costs win the biggest market share (DECC, 2011g). In the instance where low carbon electricity can be generated and supplied at a lesser cost than the cost arising from minimising heating energy demand (primarily through the extensive installation of insulation, and the development and installation of low energy heating technologies[189]), energy consumption within the built environment could actually increase by 2050. Should the cost of delivering low carbon electricity be very low, then there is little advantage to be gained in making investment in reducing energy demand, when a more profitable yield from the investment could be returned elsewhere; should the cost of delivering low carbon electricity be very high, then efforts are best focussed on reducing energy demand; and there exists an extremely large number of possibilities between these two extremes, all of which are dependent upon the relative cost of low carbon electricity.

In consequence, a narrative which describes the state of the stock in 2050 where emissions have been reduced by 80% must draw reference from the power generation and supply sectors, key

---

[186] Emissions from international aviation and shipping are not currently included within the target. The Secretary of State must either include emissions from these sectors within the target before the end of 2012, or report to Parliament why the necessary regulation has not been issued.
[187] Over 26% of GHG emissions derive from the built environment (business, public and residential sectors, exclusive of emissions deriving from electricity sourced from fossil fuels) (2011 data) (DECC, 2012c).
[188] (i) Nuclear fission, (ii) fossil fuel combustion with carbon capture and storage (CCS) or (iii) renewables.
[189] e.g. micro combined heat and power (CHP) boilers, air-source and ground-source heat pumps (with/without underfloor heating), biomass boilers, smart meters, solar thermal.

determinants in shaping the future[190]. But since it is the Government's intention to see nuclear, carbon capture and storage (CCS) and renewables competing to deliver energy at the lowest possible cost until at least the 2020s, not knowing how costs will change over time (DECC, 2011g), the construction of a set of storylines in 2012 tailored to describe the building stock in 2050 is rendered problematic. Furthermore, since the 80% target relates to all GHG emitting processes en masse, a set of authentic storylines describing a particular future scenario, to be coherent, must similarly embrace all sectors collectively rather than focus upon individual sectors as independent entities, since emission totals in one sector must be traded off against emission totals in other sectors to ensure that the sector-wide reduction of 80% is achieved. An example of this is seen with the transport sector: if it starts to become apparent that emissions in this sector cannot be reduced as easily as emissions in other sectors, the built environment may be called upon to be a net electricity producer[191].

The construction of such a narrative requires the input of information from an immense number of diverse sources. Whilst the information revealed in this thesis is therefore insufficient in itself to form the basis of a narrative, it can be used however to help inform the Government's comprehensive multi-sector *2050s Pathways Analysis* (DECC, 2010a; DECC, 2011a; DECC, 2011b): deriving from the modelling output of the DECC 2050 Calculator, the analysis sets out 15 different possible scenarios which achieve the 80% reduction in GHG emissions, and provides the storylines which describe these scenarios. Pathway 1 takes a balanced approach spreading effort across many sectors thus avoiding extreme levels of ambition in any one area, and the remaining 14 pathways describe scenarios where efforts are variously concentrated in specific domains. (e.g. Pathway 2 presents the opportunities and constraints arising from concentrating efforts on reducing energy demand in order to achieve the 80% reduction, whilst Pathway 11 examines the scenario arising from concentrating efforts on meeting future electricity demand from renewable sources (DECC, 2011a)). Further pathways, including the (i) Nuclear, (ii) CCS, (iii) Renewables and (iv) MARKAL scenarios (see Section 5.3) are detailed within the DECC 2050 Calculator itself. More recently, the DECC 2050 Calculator has been used to inform *The Carbon Plan: Delivering our low carbon future*; presented to Parliament in December 2011, the plan sets out how the UK will achieve decarbonisation within the framework of its energy policy.

Section 5.1 gives a brief outline of the DECC 2050 Calculator used in the construction of the storylines. Section 5.2 compares estimates of space heating and space cooling energy consumption from the DECC 2050 Calculator with those from SHECMOBS and SCECMORS. In Section 5.4 four principal pathways forecast as achieving the necessary 80% reduction in emissions are run in the DECC 2050 Calculator for different forecasts of the climate in 2050, the results of a "basic" implementation of the Calculator being compared with those from an "adjusted" approach which is consistent with SHECMOBS and SCECMORS.

---

[190] The importance of planning for a future where electricity consumption is set to double by 2050 is explored in the Electricity Market Reform White Paper (DECC, 2011c).
[191] i.e. produce more electricity (through rooftop photovoltaic panels and/or micro-CHP) than it uses, the excess being exported to the grid, for consequent use in electric-powered vehicles and elsewhere.

5.1 DECC 2050 Calculator

The DECC 2050 Calculator estimates annual GHG emissions at five-yearly intervals up to 2050. It is a Microsoft Excel spreadsheet model comprising 73 worksheets, and functions by amassing the GHG emissions arising from each of 31 contributors exerting an influence upon the attainment of the 80% target in 2050. Ranging from the very large and immediately recognisable (e.g. biomass power stations, growth in industry, geosequestration) to the less obvious (e.g. marine algae, electrification of cooking in commercial premises), the cross-sector level of detail with which it has been suffused is extreme. Each contributor is constituted from several component parts (e.g. see Section 5.1.1 below) and plausible combinations of these component parts, which are based on expert analysis, are proposed for each of the 31 contributors; the user is free, however, to enter the input for different component parts on the relevant worksheet as he/she so desires. The ensuing effect upon total GHG emissions in the resulting bespoke scenario is reported in equivalent carbon dioxide (CO_2e) after each input of data, where account is taken of the emissions factor and global warming potential (GWP) for each GHG released into the atmosphere. The DECC 2050 Calculator uses 2007 as its base year, but since the totalled emissions from this bottom-up model for 2007 using the default input amount to only approximately 97% of the actual reported emissions for 2007, modelled GHG emissions for future years[192] are adjusted by a factor of 1.028.

With regard to space heating and space cooling, different methods of estimation are employed in different sectors, as described below.

Residential Sector Space Heating

The demand for space heating is calculated from a clearly defined bottom-up sub-model, elements of which can be changed by user.

Residential Sector Space Cooling

The demand for space cooling is reported as a bald number for the year under investigation for each of four penetration levels, and seems to be partially numerically derived. It is stated that (i) projected growth in number of dwellings, (ii) change in average dwelling heat loss, (iii) projected changes in outdoor temperature and (iv) the effect of changes to incidental gains have been taken into account (as for the residential space heating model) and that an indoor cooling set-point temperature of 23.5 °C has been assumed, but unfortunately the structural detail of the model is not given. Regarding penetration levels, (which, as seen in Section 3.8.4 (Table 42) and Section 3.10, is extremely important in determining actual levels of cooling consumption), default values have been set at (i) 100%, (ii) 67%, (iii) 33% and (iv) 0% (DECC, 2010a): the regularity of the figures suggests that no analysis has been deployed. The user may accept the default penetration rates or enter new values.

---

[192] Future temperature estimates are stated as being based on UKCP09 data at the 50% probability level under a medium emissions scenario.

Service Sector[193] Space Heating

Bald values for the space heating in the commercial sector are merely reported for the present and the future in the DECC 2050 Calculator. There are no foundation data (e.g. penetration levels, number of buildings, outdoor or indoor temperature) which can be modified. Of eight drivers and constraints listed as affecting non-domestic space heating and space cooling in the 2050s Pathways Analysis (e.g. increase in the number of buildings, increase in proportion of floorspace which is air-conditioned), no reference is made to climate (DECC, 2010a), which would tend to suggest that no direct account is taken of climate or climate change.

Service Sector[193] Space Cooling

Bald values for space cooling in the commercial sector are reported as for service sector space heating above.

Industrial Sector Space Heating

Energy consumption within the industry sector is reported en masse, with no end-uses being specified. The lack of detail, where space heating is not even itemised, would suggest that no direct account is taken of climate or climate change.

Industrial Sector Space Cooling

Space cooling is not itemised. See above.

The approaches used by the DECC 2050 Calculator in calculating space heating and space cooling in the residential sector are examined in more detail in Section 5.1.1 and Section 5.1.2 below; unfortunately, a lack of data, as explained above, precludes similar examinations for space heating and space cooling in the industry and service sectors.

5.1.1 DECC 2050 Calculator – Residential Sector Space Heating

The DECC 2050 Calculator estimates space heating demand. From that estimate the consumption is subsequently calculated.

---

[193] Insofar as the built environment is concerned, the service sector is usually described as composing of the commerce and public administration sub-sectors. The DECC 2050 Calculator mentions the commercial sector but not the public administration sector. Since the DECC 2050 Calculator is tasked with examining national emissions, its use of *commercial* is believed to be equivalent to the more widely recognised *service*. (The split of carbon emissions from the commerce and public administration sectors is approximately 50:50 (DECC, 2010a)).

5.1.1.1 Calculation of Space Heating Demand

The demand for annual space heating[194] for the residential stock in year y (D_y) (GWh) is calculated as the difference between the sum of annual seasonal heat losses and the sum of annual incidental heat gains (Equation 53).

Equation 53

$$D_y = \left(\left(\sum_{i=1}^{4} SL_y \right) - AIG_y \right) \times n_y \div 3.6 \times 10^{12}$$

where,

i = season (for each of the four seasons, 1 = winter (December-February), etc.

SL_y = average heat losses for a household in a season in year y (joules)

AIG_y = average annual useful incidental heat gains for a household in year y (solar radiation, metabolic, cooking, lighting & appliances, and water heating) (joules)

n_y = number of households in UK in year y

$1/3.6 \times 10^{12}$ = constant which converts Joules into GWh

where,

Equation 54

$$SL_y = HLC_y \times \Delta T_y \times t$$

where,

HLC_y = average household heat loss coefficient in year y (W/^{0}C)

ΔT_y = difference between mean seasonal outdoor temperature and mean indoor temperature in year y (^{0}C)

t = duration of season (seconds)

and,

---

[194] The amount of useful heat delivered by heating appliances.

Equation 55

$$AIG_y = AIG_{2007} \times \left(\sum_{i=1}^{4} SL_y \middle/ \sum_{i=1}^{4} SL_{2007} \right)$$

where,

AIG_{2007} = average annual useful incidental heat gains for a household for 2007 (solar radiation, metabolic, cooking, lighting & appliances, and water heating) (joules)

SL_{2007} = average heat losses for a household in a season in 2007 (joules)

The average heat loss coefficient (*HLC*) for a household, which takes account of losses through both the fabric and ventilation, is reported as 247 Watts/^{0}C for 2007. Its calculation is stated as being based on the Government's Standard Assessment Procedure (SAP)[195], account having been taken of the different age bands and built forms within the stock, but no further detail is given. The average annual useful gains for a household for 2007 (*AIG$_{2007}$*) is reported as 3.25 x 10^{10} joules and derives from 2006 stock data in the Domestic Energy Fact File 2008 (BRE, 2008).

Using Equation 53 , the DECC 2050 Calculator calculates residential space heating demand (*D*) for the present stock when input with its own default data for a 2050 climate (medium emissions scenario) calculates as 146.1 TWh[196], which compares with its estimate of 204.9 TWh for the present stock in 2007.

5.1.1.2 Calculation of Space Heating Consumption

Demand for annual space heating (*D*) also calculates as the sum of the demands (useful heat delivered) for the five separate heat sources (*j*) used for residential space heating:

Equation 56

$$C_y = \sum_{j=1}^{5} C_{y-j}$$

where,

C_y = total stock consumption in year y

j = heat source

---

[195] The SAP is based on the Building Research Establishment Domestic Energy Model (BREDEM) (BRE, 2011).
[196] i.e. this assumes that the present stock of 26.0M is not modified (the HLC remains at 247 Watts/^{0}C, and incidental gains remain the same).

1 = gas non-condensing boiler

2 = gas condensing boiler

3 = electrical resistance heating

4 = oil-fired boiler

5 = solid fuel boiler

C_{y-j} = stock consumption in year y for heat source j

The demand for space heating in the stock for a particular heat source j (D_j) is the ratio of stock space heating consumption (C_j) and efficiency (e_j) of that source:

Equation 57

$$C_{y-j} = \frac{D_{y-j}}{e_{y-j}}$$

where

D_{y-j} = stock demand in year y for heat source j

e_{y-j} = stock efficiency in year y of heat source j

The DECC 2050 Calculator assumes that a household is heated by a single heating source. Stock space heating consumption for a particular heat source (C_j) therefore calculates as the product of the stock consumption of all heating sources (C) and the penetration (p_j) of that particular space heating source in the stock:

Equation 58

$$D_{y-j} = D_y \times p_{y-j}$$

where,

D_y = total stock demand in year y

p_{y-j} = penetration in stock in year y of heat source j

Rearranging Equation 56 and substituting for C_{y-j} (from Equation 57) and D_{y-j} (from Equation 58), space heating consumption for the present stock in year y (C_y) calculates as:

192

Equation 59

$$C_y = D_y \left(\sum_{j=1}^{5} \frac{p_{y-j}}{e_{y-j}} \right)$$

Using Equation 59, the DECC 2050 Calculator calculates space heating consumption as:

i.   present day stock in the present day climate (2007): 252.7 TWh[197]

ii.   present day stock in the 2050 climate (medium emissions scenario): 180.3 TWh[198]

This corresponds to a drop of 29% between 2007 and 2050.

5.1.2   DECC 2050 Calculator – Residential Sector Space Cooling

Residential **demand** for space cooling (heat removed) within the residential sector is reported as a bald figure for the year under investigation, rising from a present day value of 0 (0% penetration) to a maximum of 49,700 GWh (if there was 100% penetration) in 2050 when the stock average CoP[199] assumes a value in excess of of6 if only electric air-conditioning is used, and the number of homes has risen to 39,954,879[200]. When penetration is set at 45-52%[201], the DECC 2050 Calculator therefore estimates that **consumption** across the entire stock of 40 million amounts to 3,700-4,300 GWh in 2050.

5.2   Comparison of DECC 2050 Calculator Output with SHECMOBS and SCECMORS Output

Unfortunately, the robustness of the DECC 2050 Calculator with respect to the service and industry sectors cannot be tested for the reason that the DECC 2050 Calculator does not seem to take specific account of climate change in these sectors. SHECMOBS and SCECMORS output can, however, be compared with that from the DECC 2050 Calculator with regard to estimating changes in space heating and space cooling energy consumption in the residential sector. The DECC 2050 Calculator output is compared with SHECMOBS output in Section 5.2.1.

---

[197] c.f. official Government (DECC) statistics, as reported in the DECC 2050 Calculator, estimate residential space heating consumption in in 2007at 286,223 GWh. There is some doubt about this figure (see later in this chapter.)

[198] i.e. this assumes that the present stock is not modified (the HLC remains at 247 Watts/^{0}C, incidental gains remain unchanged, and that both penetration and efficiency rates are the same as those of the present day).

[199] CoP – assumed to be EER (See Glossary).

[200] DECC 2050 Calculator estimate - based on Government projections for UK for period 1961-2033, and post-2031 growth is assumed to be 1.00% per annum, consistent with average trend 2006-2031 (DECC, 2012f).

[201] SCECMORS estimates penetration at 45-52% in the 2050s - see Section 3.7.4 (Table 29 and Table 30).

5.2.1 Residential Sector Space Heating: DECC 2050 Calculator versus SHECMOBS

The DECC 2050 Calculator estimates that the effect of a warming climate would be to reduce space heating consumption in the unmodified present UK stock by 29% by 2050 under a medium emissions scenario, and SHECMOBS estimates a reduction of 23% for Great Britain (see Section 2.5.5).

5.2.1.1 Estimate of Seasonal Mean Temperature

DECC 2050 Calculator supporting data states that mean temperatures are forecast to rise in winter/spring/summer/autumn by approximately 2/2.25/2.5/2.25 °C by 2050 compared to 1960-1990 average, and the UKCP09 website reference is given.   It is unclear, but it appears that the DECC 2050 Calculator may not use temperature data weighted in favour of areas of higher population. The danger of using non-weighted data is that the relative change in space heating consumption in a future warmer climate (compared to the present day) is under-estimated. This under-estimation results from the fact that the change in temperature during winter for less highly populated regions in the north, where total consumption is rather low, tends to be less than that in more densely-populated regions in the south where total consumption is high (i.e. temperatures may increase by up to 0.6 0C more in the south of the country than in the north of the country). Inputting Weighted Seasonal Mean Temperatures into DECC 2050 Calculator

In the evaluation of ΔT_y for each of the four seasons (Equation 54), it is important to establish whether or not the DECC 2050 Calculator uses correct values for seasonal mean temperature, appropriately weighted so that more account is taken of those regions of the country in which space heating consumption is greatest, since it can have a large impact on calculated energy consumption levels[202].

Weighted seasonal mean temperatures for the nation (Great Britain) as a whole are calculated for (i) 2007 and (ii) the 2050s under a medium emissions scenario, using raw temperature data obtained from the BADC and the UKCP09 Weather Generator respectively which are modified by NDM gas consumption weighting factors (see Appendix 13)[203]. These data are entered into the DECC 2050 Calculator, and the resulting space heating energy consumption for the present day stock is compared with the default DECC 2050 Calculator output (which uses the default seasonal temperatures) (Table 62).

---

[202] It is assumed that the reduction in space heating energy consumption for the UK is very similar to the SHECMOBS estimate of a 23% reduction in space heating energy consumption for Great Britain, since Northern Ireland dwellings comprise only 2.6% of the UK stock (DCLG, 2010).

[203] A weighting in accord with UK temperatures rather than Great Britain temperatures would be more accurate, but since the NDM data are only available for LDZs in Great Britain, a Great Britain weighting is used (see Appendix 13). There is likely to be only a very small difference between the two weightings.

Table 62 DECC 2050 Calculator comparison of space heating energy consumption of the present day residential stock using default seasonal temperatures and weighted seasonal temperatures for 2007 and 2050s (medium emissions scenario)

		Mean Outdoor Temperature (^{0}C)		Annual Space Heating Consumption (TWh)		Change in Space Heating 2007-2050s (%)
		2007	2050s	2007	2050s	
Default temperatures	**Winter**	5.6	6.0	252.7	180.3	29
	Spring	9.1	9.3			
	Summer	14.1	16.3			
	Autumn	9.9	11.3			
Updated weighted temperatures)	**Winter**	6.0	6.1	190.6	100.9	47
	Spring	10.1	10.4			
	Summer	15.3	18.0			
	Autumn	10.8	12.9			

Whilst there is only a relatively small difference between the default temperatures and the correctly weighted temperatures for winter (0.4 ^{0}C: winter, 2007 and 0.1 ^{0}C: winter, 2050s), the difference is marked for spring and autumn: 1.0 ^{0}C (spring, 2007), 1.1 ^{0}C (spring, 2050s), 0.9 ^{0}C (autumn, 2007) and 1.6 ^{0}C (autumn, 2050s). In fact the discrepancy associated with the spring temperatures (1.0-1.1 ^{0}C) is considerably more than the actual increase in temperature between spring 2007 and spring 2050s (0.3 ^{0}C). This is important because almost 50% of space heating currently occurs in these transition seasons[204].

Using these weighted temperatures, the reduction in the level of space heating changes from 29% to 47% (c.f. the SHECMOBS estimate is 23%). If the government figure of 286.2 TWh (quoted in the information pages of the DECC 2050 Calculator) is taken as correct, the forecast reduction in space heating increases to 65%. Significantly also, the estimation of consumption for 2007 changes so that it moves farther from the government figure, being 33% lower.

Since the insertion of correctly-weighted temperature data has a rather large effect upon its output for space heating in the residential sector, it is reasonable to ask whether it may be modified in order to bring its results into alignment with those from SHECMOBS (i.e. 23% reduction in space heating) and government statistics (i.e. reported value for space heating energy consumption for 2007). The following section examines where amendments can justifiably be made, and then compares its output with the output of the unamended Calculator[205] for a range of climates forecast for 2050 for a number of pathways prescribed as achieving an 80% reduction in GHG emissions.

---

[204] 25% of space heating occurred in spring and 22% in autumn over the period 2007-2010.
[205] i.e. unamended save for the insertion of correctly-weighted temperatures.

5.3 Pathways to the 2050 Target Reduction in Emissions

As mentioned in the introduction to this chapter, the future remains uncertain in that it remains unknown which direction policymakers will follow in choosing how best to achieve the UK target of an 80% reduction in emissions by 2050. Scenarios, envisioning how different possible futures may play out, provide a way of grappling with this uncertainty, allowing us to investigate alternative ways of securing the target. Indeed, the DECC 2050 Calculator is used for this very purpose, and, as noted earlier, a number of different pathways capable of bringing about the required 80% reduction in emissions have been proposed. However, all these scenarios consider but a single climate in 2050s, that resulting from the central estimate of the medium emissions scenario as detailed in UKCP09. Since the future climate remains uncertain, and since climate (air temperature) can so greatly affect levels of energy consumption (and, in consequence, levels of GHG emissions) in the built environment, it is important to assess the performance of the proposed pathways over a wider range of temperature forecasts.

This section sets out to perform this task, assessing four different pathways (described in the DECC 2050 Calculator and also set out in *The Carbon Plan: Delivering our low carbon future* (DECC, 2011g)) in a number of different future climates, which, taken as a whole, cover a large span of possibilities. The DECC 2050 Calculator is re-run with updated appropriately weighted climate data and other ancillary data, in order to assess the impact of different future climates on energy consumption in the built environment in 2050. The resulting impact on GHG emissions is also evaluated in order to ascertain whether the measures proposed in the pathways remain sufficient in steering the UK towards the cross-sector 80% reduction target the DECC 2050 Calculator fully being loaded with the remaining necessary data (such as numbers of buildings, growth in industry, fuel emission intensities etc.) so that the carbon economy of the nation in 2050 is fully represented.

It should be remembered, as stated in Section 5.1 that the DECC 2050 Calculator is constructed in such a way that only space heating in the residential sector is affected by these changes. The impacts upon space cooling in the residential sector, and both space heating and space cooling in the commercial and industrial sectors, are not affected. The commercial and industrial sectors are further discussed in Section 5.4.

Section 5.3.1 describes the pathways explored. Section 5.3.2 describes the procedures used to produce climate data and other necessary input data for the function of the DECC 2050 Calculator for the four pathways. Section 5.3.3 reports upon the results, comparing the results of two different formulations of the DECC 2050 Calculator – the Basic Model and the Adjusted Model. Section 5.4 concludes with a discussion of the results in insofar as the different sectors of the built environment are concerned.

5.3.1 Pathways

As previously noted in the chapter, of key importance in the determination of levels of future UK emissions is the method by which electricity is generated. Not only are 27% of current emissions due to electricity generation at power stations (DECC, 2012c), but in most forecasts of the future, electricity consumption is set to increase as use of end-user fossil fuel burning appliances decreases.

Four different DECC pathways, each relying upon a different primary source to produce the greater bulk of the nation's electricity supply, are investigated:

(i) Higher Nuclear, Less Energy Efficiency,
(ii) Higher Carbon Capture and Storage, More Bioenergy,
(iii) Higher Renewables, More Energy Efficiency, and
(iv) MARKAL Model ("core run"), a cost-optimising government model which uses a mix of electricity generation regimes (DECC, 2012g).

Taking into consideration the fact that the emission levels associated with a particular pathway are affected by further factors beyond electricity supply, these four pathways, as implied in their titles, are not differentiated from one another merely by choice of primary source of fuel for electricity generation; rather, they are distinct from one another in other aspects, being further populated with a set of additional parameters which are plausible/coherent. For example, whilst levels of insulation in homes are set at their highest in the Renewables pathway (average HLC of 118.5 W/^{o}C per dwelling in 2050), they are set at the lower 143.0 W/^{o}C in the Nuclear, CCS and MARKAL pathways. Similarly, levels of average indoor temperatures in homes are set to their lowest in the Renewables and MARKAL pathways (16 ^{o}C), at their highest in the Nuclear pathway (18 ^{o}C), with the CCS pathway being intermediary at 18 ^{o}C. The number of parameters and the values/settings assigned them which constitute a given pathway is extensive, covering all sectors which contribute to the nation's carbon balance. Those key elements directly concerned with this thesis which relate to the built environment are listed in Appendix 14.

5.3.2   Amendment of the DECC 2050 Calculator

The four pathways are modelled using two different approaches – the basic approach (Basic Model) and the adjusted approach (Adjusted Model).

Basic Model

When fitted with correctly weighted regional temperatures, the DECC 2050 Calculator tends to over-estimate space heating energy consumption in the domestic sector in the base year of 2007 (Table 62), and it is not unlikely that it over-/under-estimates consumption in other sectors in view of the great complexity involved in condensing the great array of factors which affect consumption into a single manageable model. Indeed, the DECC 2050 Calculator acknowledges its own imperfection in this respect, total cross-sector modelled emissions resulting from energy consumption in 2050 being adjusted by a multiplying constant equal in value to the ratio of actual emissions in 2007 to modelled emissions in 2007. There is an argument to be made, therefore, that this is sufficient remedy, that the adjusted level of emissions in 2050 give can be taken as giving an indication of what actual total cross-sector emissions will be in 2050. In consequence, the four pathways are modelled in this basic form in the DECC 2050 Calculator, unfettered save for the facts that (i) the DECC 2050 Calculator's default 2007 and 2050 temperatures are adjusted so as to correspond to more representative

weighted temperatures as described in Appendix 13[206], and (ii) a minor amendment is made to the way in which summer gains are handled (see below).

Adjusted Model

Whilst this basic approach may or may not give a fair representation of total-cross sector emissions, Section 5.2 makes clear that less confidence can be placed in the specific forecasts of energy consumption (and therefore emissions levels) in the residential sector. One approach to the problem is to use the method adopted the Building Research Establishment Housing Model for Energy Studies (BREHOMES), a multiple dwellings model of domestic energy consumption in Great Britain, the data from which has been used in a great many government statistics: rather than adjust final modelled results so as to accord with final actual results, parameters within the actual model which actually have an effect upon the results are adjusted, so that modelled results accord as near as possibly to actual results (DECC, 27/9/2011). Adjusting indoor demand temperature is the primary way by which this is done, energy consumption being most sensitive to adjustment of this parameter. However, other elements such as internal gains and HLC can also be adjusted so as to bring about the necessary reconciliation. Indeed, it would seem that the DECC 2050 Calculator even its present form makes use of this adjustment mechanism, the indoor temperature setting of 17.5 °C for 2007 cited in the DECC's *Great Britain's housing energy fact file* being based on modelled data generated by BREHOMES (DECC, 27/9/2011).

This adjusted approach not only allows one to reconcile (i) DECC 2050 Calculator modelled space heating energy consumption in the residential sector in 2007 with actual energy consumption, but also to reconcile (ii) DECC 2050 Calculator modelled Reduction in Space Heating (RISH) over the period 2007-2050 with the RISH as modelled by SHECMOBS. As such, one may be able to place more confidence in these results emanating from this adjusted form of the DECC 2050 Calculator.

Section 5.3.2.1 describes amendments made to both the Adjusted Model and the Basic Model in relation to input of data for the base year of 2007; the rationale and method of selecting temperatures so as to achieve a broad and representative set of possible future climates are described, as are the adjustments made to the DECC 2050 Calculator for summer gains. Section 5.3.2.2 outlines the amendments made to the Adjusted Model alone in relation to input of data for the base year of 2007, with a description of the methodology underpinning these adjustments. Amendments which are made to the 2050 input data for the Adjusted Model are explained in Section 5.3.2.3.

5.3.2.1 *Amendments made to both the Adjusted Model and the Adjusted Model - 2007 input*

---

[206] Note that the weighted temperatures in 2007 as calculated in Appendix 13 are very similar to DUKES weather statistics for 2007 (DECC, 2013), differing by only 0.04 °C, 0.05 °C, 0.07 °C and 0.03 °C for the four seasons winter, spring summer and autumn; this is in contrast to the DECC 2050 Calculator default temperatures which differ by 0.39 °C, 0.94 °C, 1.1 °C and 0.90 °C for the four respective seasons.

2007 Seasonal Temperatures

Since the DECC 2050 Calculator works on a seasonal temperature basis, it is necessary to calculate the mean temperature for each season of the year. The 2007 weighted mean temperature is calculated for each season as previously shown in Section 5.2.1.1, and substituted for the default temperatures of the DECC 2050 Calculator.

2050 Seasonal Temperatures

UKCP09 allows one to investigate future climates under each of three different global emissions scenarios – high, medium and low. Since the world economy is not currently bound on a low emissions pathway and since it is unlikely that there is enough time to make the necessary changes which will set the world economy on this pathway, one is left to consider the medium and high emissions scenarios as offering realistic projections of future climates.

Whilst the DECC 2050 Calculator, as currently set, only projects one vision of the future, that arising from the central estimate of the medium emissions pathway, the UKCP09 Weather Generator makes possible the investigation of future climates at percentiles other than the central estimate. Since actual temperatures are as likely to be above the central estimate as below the central estimate, it is useful to make use of this benefit of the Weather Generator as a means of establishing the range of energy consumptions/emissions in which actual values are likely to fall.

The Weather Generator is run 100 times for each of the 13 locations previously detailed in Section 2.5, resulting in 100 x 100 (10,000) years of weather data. The temperature data are sorted in order of increasing temperature by winter temperature for each of the thirteen locations. Winter temperature rather than annual temperature is used to sort the data because energy consumption in the built environment is greatest at low temperatures, with over 50% of NDM consumption occurring in the three months of winter for the period 2007-2010[207]. Thus 13 sets of data ranked by winter temperature are created.

The 30th, 50th, 70th and 90th[208] percentiles are selected in order to examine the likely occurrence of a given temperature being exceeded. The 30th percentile year for a given location is the 2,970.5th

---

[207] If ranked by increasing annual average temperature, it is entirely plausible that years at the 90th percentile, even though considerably warmer than those at the 30th percentile over the course of 12 months, could have annual space heating consumptions higher than those at the 30th percentile: this could arise when a very hot summer occurred in the same year as a cold winter. Since the aim of the analysis is to produce a series of data where one can say that energy consumption/emissions are likely to be no more than x% at a given percentile, it is important that the series of data exhibit as good a downward trend of energy consumption/emissions as possible, as temperatures increase. Essentially, winter temperature is more closely correlated with energy consumption/emissions than annual temperature, and so is the preferred option.

[208] Ideally the 10th percentile data would also have been investigated. It was noticed after running the simulations, however, that the temperatures for the 10th percentile had not been correctly weighted. In consequence these data have been omitted from the analysis. In view of the fact that we must prepare for future climates which are more likely to have a deleterious consequence, the loss of these data is less significant than it might otherwise have been: policymakers instituting safeguards in planning for the future are more likely to be interested in higher percentile data, to install safeguards for futures which are less likely to happen, but which may still nevertheless occur.

ranked year in the series for that particular location[209]. Whilst the winter temperature of the 2,970th year will be almost identical to the 2,971st winter temperature in any given series for a particular location, it is extremely unlikely that the spring temperatures will be almost identical in these two year, or that the summer and autumn temperatures will be almost identical. Thus while winter space heating consumption in ranked year 2,970 will be almost identical to winter space heating in ranked year 2,971, annual space heating is likely to be different in the two years, since a proportion of space heating occurs outside of the winter months. For this reason the 30th percentile is not selected as a single year. Rather it is selected as the series of 50 years from rank year 2,946 to rank year 2,995. Using a series of years rather than a single year is considered to more accurately reflect the 30th percentile, since consumption in the 2,970th or 2.971st year may be atypical of other nearby years, whereas consumption averaged over a period of 50 years is likely to more representative of the true 30th percentile consumption. The 50th, 70th and 90th percentile ranges are calculated in an analogous manner for each of the 13 series for the 13 locations.

The 50 years comprising the national 30th percentile are constructed from the 13 groups of 50 years which constitute the 30th percentile of each location, where the regional seasonal temperatures in each year are weighted, as described in Appendix 13, to produce nationally representative seasonal temperatures. Thus the first year of the 30th percentile at the national level (rank year 2,946) is constructed of rank year 2,496 from the series for location 1, rank year 2,946 from the series for location 2....rank year 996 from the series for location 13. The 49 remaining years of the national 30th percentile are calculated in an analogous manner, as are the years comprising the national 50th, 70th and 90th percentiles.

It is very unlikely that the 2,946th coldest winter in a series of 9,900 years in each of the 13 locations would all occur in the exact same chronological year in reality (e.g. 1479 A.D.). Such a method of calculating a percentile national year is, however, justified on the grounds that a shared weather pattern is generally seen throughout the country, such that when it is very cold in relative terms for one particular location, it is likely to also be very cold in most/all other locations around the country. This can be seen in Figure 7 which shows a very high degree of uniformity in temperature change between different locations. Using temperatures over a fifty-year sequence helps to minimise any non-correspondence between different locations: the impact of an anomalous year in a given percentile in a given location will only be small at the national level since it is only one of 650 years (13 x 50) which describe the given percentile for the nation as a whole, and as many anomalously high years are as likely to be balanced by anomalously low years.

---

[209] Note that only 9,900 years of data are used in this sorting process. Since a truly representative winter must consist of contiguous months (i.e. the December in year *n* and the January and February in year *n +1*), only 99 years of winter data are available for each run of the Weather Generator since the first year in each run must be omitted since there is no December with which to pair with its January and February. In contrast, the weighted 2007 base year data for the DECC 2050 Calculator base year refer to the calendar year 2007: since the base year data are not constrained as being representative of a typical winter, this is quite acceptable, and, moreover, the preferred option, since the default indoor temperature data for the DECC 2050 Calculator (which are used in the same equation as the outdoor temperature data to calculate energy consumption (see Equation 54)) apparently derive from calendar year data for 2007 (DECC, 27/9/2011).

These national weighted temperature data, calculated for different percentiles, are used in place of the default 2050 temperature data resulting from the central estimate of the medium emissions scenario.

Summer Gains

Analysis of the DECC 2050 Calculator reveals there to be a theoretical demand for space heating in the summer months both in 2007 and 2050 using the default temperature data. This results from the fact that the mean summer outdoor temperature is always less than the mean indoor temperature, meaning that that there would be an overall transfer of heat from indoors to outdoors during the summer months if a mechanical space heating system were not in place to counteract the heat loss (see Equation 53). If summer gains deriving from the summer outdoor-to-indoor temperature difference are removed, using correctly-weighted temperatures for 2007, the demand for space heating reduces from 154.5 TWh to 123.6 TWh, which would suggest that 20% of space heating in 2007 occurred in summer, the hottest summer on record. (Repeating the same task for winter (removing the demand for space heating in winter) results in a malfunction of the DECC 2050 Calculator, where a negative amount of space heating would be required over the course of the year. This results from the fact that gains exceed losses, furthermore suggesting that the overall annual gains estimate is too high, as is borne out by the Solver optimisation process carried below.)

However, when (i) correctly-weighted outdoor temperature data are used instead of the default outdoor temperature data[210], and most especially when (ii) outdoor temperatures deriving from more extreme forecasts (e.g. 90th percentile under a high emissions scenario) are used instead of the central estimate of the medium emissions scenario, situations arise where the summer outdoor temperature is higher than the indoor temperature: in the unamended form of the DECC 2050 Calculator, this results in unrealistic situations where the net flux of heat from outdoors to indoors in the summer erroneously acts to lessen the demand for overall space heating over the course of the year (see Equation 53 and Equation 54). Moreover, experience of the real world, even in the present relatively cool climate, teaches us that space heating is very rarely if ever used during the summer months of June, July and August.

Therefore, the DECC 2050 Calculator is amended so that no demand is made for space heating for the summer months of June, July and August.

5.3.2.2 Additional Amendments made solely to the Adjusted Model – 2007 input

As stated above, indoor temperature, internal gains and HLC can be amended in order to reconcile modelled data with actual data. The approach adopted is to amend each of these three parameters so that:

---

[210] Under a medium emissions scenario, the default DECC 2050 Calculator outdoor summer temperature (16.3 °C) is less than the indoor temperature (17.5 °C); the correctly-weighted mean outdoor temperature for the medium emissions scenario, however, stands at 18.0 °C,

(i)   DECC 2050 Calculator modelled energy consumption for the domestic sector for the year 2007 matches actual consumption for the year 2007 as reported in Energy Consumption in the UK (DECC, 2012i) as near as possibly, and

(ii)   DECC 2050 Calculator modelled percentage RISH over the period 2007-2050 matches SHECMOBS modelled percentage RISH for the period2007-2050 for the residential stock under a medium emissions scenario[211] as near as possibly.

Indoor Temperature

Although little research has been published with regard to actual mean indoor temperature (with the consequence that, the indoor temperature of 17.5 °C for 2007 cited in the DECC's *Great Britain's housing energy fact file* is based on modelled data generated by BREHOMES (DECC, 27/9/2011)), there is evidence to suggest that the figure of 17.5 °C is perhaps rather low. In a study of 1604 low income households over 2-4 weeks over two winters, the daytime living room temperature was reported at 19.1 °C and night-time bedroom temperature at 17.1 °C under a standardised outdoor temperature of 5 °C (Oreszczyn, et al., 2006). A study of 14 "low energy" homes over an 18-month period found a mean temperature of 19.8 °C for living rooms and 19.3 °C for main bedrooms under a standardised outdoor temperature of 5 °C (Summerfield, et al., 2007). Furthermore, an investigation of 25 homes in Northern Ireland revealed a mean temperature of 19 °C for the majority of the homes, varying between 18 °C and 22 °C (Yohanis & Modol, 2010)

Internal Gains

The data used for the useful internal gains, by the admission the authors of the source whence it derives (BRE, 2008), acknowledge that there is some uncertainty attached to its actual value. In consequence one need not feel overly-compelled to too strictly take its value of 836.3 PJ as definitive.

Heat Loss Coefficient

The DECC 2050 Calculator uses a value of 246.8 W/°C for the HLC for 2007. Examination of the Domestic Energy Fact File however reports the value for 2007 as 258.9 W/°C (DECC, 27/9/2011), the value deriving BREHOMES. Further examination of the data reveals that the HLC lowered steadily, year-on-year, from 1970 to 2008, as one would expect to find. In sharp contrast, the figure rose from 253.7 in 2008 to 294.7W/°C in2009, a value not previously seen since 1988. The reason for the abrupt increase is stated as arising from a change in modelling technology, the Cambridge Housing Model (CHM) being used to calculate the 2009 figure. But whereas BREHOMES uses a single national temperature in its modelling of the nation as whole, the CHM uses regional temperatures from regions, the model being weighted so as to take account of numbers of dwellings in each region (c.f. SHECMOBS which uses regional temperatures weighted by NDM space heating

---

[211] See Section 2.5.5.1.

consumption). There is reason to believe, therefore, that that the BREHOMES estimates of HLC and the DECC 2050 Calculator estimate of 246.8 errs on the low side.

Microsoft Solver is used to optimise the three parameters (indoor temperature, internal gains and HLC) above so that (i) the difference between DECC 2050 Calculator modelled residential space heating energy consumption in 2007 and actual residential space heating energy consumption in 2007 are minimised, whilst also (ii) maintaining the Calculator's derived RISH value for the period 2007-2050 to within acceptable limits of the SHECMOBS value for a medium emissions scenario. The starting values which Solver was initially loaded are the default settings of the DECC 2050 Calculator (viz. indoor temperature 17.5 ºC, internal gains 3.25×10^{10}J, HLC 246.8 W/ºC) and the SHECMOBS RISH value of 23%. Initially wide constraints (acceptable deviations either side of the starting values) are set for the three modelling parameters and the RISH value. The constraints are gradually increased for each run of Solver until Solver is no longer able to find a solution which satisfies all constraints. The final constraint values are set at ±7.5% for the three modelling parameters and ±5% for the derived RISH value. (In view of the greater confidence which can be placed in the RISH derived value on account of the robustness employed in its evaluation in SHECMOBS, narrower constraining limits are applied to it than to the three modelling parameters to which greater uncertainty is attached[212].)

Table 63 shows the resulting (i) the Solver-optimised values (for use in the Adjusted Model) for 2007 (column 1), and the (ii) original default DECC 2050 Calculator values (for use in the Basic Model) (column 2); Table 64 indicating the effects of these parameters on space heating energy consumption in 2007 and RISH over the period 2007-2050 (column 1) in comparison to the original, pre-optimisation parameters (column 2).

Table 63 Solver-optimised and Original values of indoor temperature, internal gains and HLC for use in the Adjusted Model and the Basic Model respectively

Parameter value (for 2007)	Solver-optimised value	Original value (default value)	Difference between starting value and Solver-optimised value
Indoor temperature	18.5 ºC	17.5 ºC	5.6%[213]
Internal gains	26.861 GJ	32.476 GJ	-17.3%
HLC	246.8 W/ºC	265.3 W/ºC	7.5%

---

[212] Since 2007 contains 365 days and since the energy consumptions deriving from the DECC 2050 Calculator are reconciled with actual 2007 data deriving from 365 days, the default setting of the DECC 2050 Calculator is adjusted to calculate consumption/emissions over 365 days instead of 365.25 days for the Solver optimisation exercise.   A more accurate optimisation may have been achieved if a setting of 365 days had been used for 2007 and 365.25 day used for 2050 (since 2050 is representative of the 2050s), but the difference would have been marginal.

[213] Caution should be exercised in evaluating this figure, since it is based on the Celsius scale. (Another scale would produce a difference percentage difference.)

Table 64 Effect upon RISH (2007-2050[214]) and space heating energy consumption (2007) for Adjusted Model and the Basic Model using the parameters detailed in Table 63

	Solver-optimised value	Original value (default value)	Difference between starting value and Solver-optimised value
RISH (2007-2050)	16.0 %	23.2 %	-9.5%*
Consumption (2007)	289.9 TWh	332.4[215] TWh	-12.8%

Like all the figures in this column, this figure is the relative difference, not the absolute difference between the default value and the Solver-optimised value.

5.3.2.3 Amendments made to the Adjusted Model -2050 input

Whilst certain of the data for 2050 are unaffected by these amendments (e.g. number of buildings), others (viz. indoor temperature, HLC and internal gains) are affected.

Indoor Temperature

The default indoor temperature for 2007 is 17.5 °C. The default indoor temperature for 2050 is determined by the level of *effort*, in the terminology of the DECC (DECC, 2010a), deployed in bringing about a reduction in emissions or save energy (see Appendix 15). The default temperatures correspond with the levels of effort assigned as 1, 2, 3 and 4 respectively, where 4 is the greatest level of effort. Thus, levels 1 and 2 are higher than the 2007 default temperature whilst levels 3 and 4 are lower. The default alternative indoor temperatures for 2050 are shown in the Table 65 below.

---

[214] i.e. the average forecast climate for the 2050s under a medium emissions scenario, as used in the Solver-optimisation exercise.

[215] This figure is the latest available figure for 2007 from the 2012 update of *Energy Consumption in the UK* (DECC, 2012i). Note that the default figure quoted in the DECC 2050 Calculator ("copied and pasted" directly into the Calculator in its information pages from an earlier version of *Energy Consumption in the UK*) for 2007 is 286.2 TWh. The difference of 46.2 TWh (13.9%) is considerable, bearing in mind that they are sourced from the same government publication and relate to the same year of 2007. A part of the reason for the difference lies in the fact that whilst *Energy Consumption in the UK* now includes data from (i) heat sold and (ii) bioenergy and waste in its space heating estimates, it did not used to do so; removing (i) and (ii) from the figure of 332.4 TWh, however, only makes marginal difference, since it only accounts for 5.2TWh. Note that the figure quoted for 2007 in the recently published *United Kingdom's Energy Fact File 2012* (December 2012) is 321.7 TWh. (DECC, 2012j). The Fact File data for 2007 have been reconciled with DUKES data. It is thought that perhaps the older data quoted in the information pages of the DECC 2050 Calculator (286.2 TWh) have not been reconciled, and this could be the reason for the discrepancy. Emails were sent to different people in the DECC for clarification of this matter, but no reply has been forthcoming. With the figure of 332.4 TWh being more recent than the figure of 286.2 TWh, and being in much closer agreement with the *United Kingdom's Energy Fact File 2012* figure of 321.7 TWh, it is considered to be the most reliable.

Table 65 DECC 2050 Calculator default temperatures for 2050

Level of effort	Relative change in indoor temperature (^{o}C)	Absolute indoor temperature (^{o}C)
1	+2.5	20
2	+0.5	18
3	-0.5	17
4	-1.5	16

The Renewables and MARKAL pathway set the highest level of effort (level 4), the CCS pathway sets a high level of effort (level 3), with the Nuclear pathway setting the level of effort at 2. Since the Adjusted Model sets a temperature of 18.5 ^{o}C instead of 17.5 ^{o}C for 2007, using the relative increase setting (column 2 in the table above) results in different indoor temperatures for 2050 compared to the absolute temperatures of column 3; the relative change setting results in indoor temperatures which are 1°C higher than the absolute values of column 3.

It is considered that the relative change in temperature offers the most authentic representation of the levels of effort, where levels 1 and 2 remain above the 2007 temperature, and levels 3 and 4 remain below the 2007 temperature. If one were to use the absolute temperatures of Table 65, not only would three of the four levels of effort represent a lessening in levels of comfort, but the level associated with the Renewables Pathway would be fully 2.5 ^{o}C below the 2007 setting of the Adjusted Model, both of which scenarios are considered unrealistic.

Heat Loss Coefficient

As for the indoor temperature, four alternative values are set for the HLC in 2050, the final figure in each instance lying at the end of one of four trajectories of gradually lowering HLC from the default 2007 value of 247 W/^{o}C as seen in Table 66.

Table 66 Average Heat Loss Coefficient per House – Default DECC 2050 Calculator Values (2007-2050)

Trajectory	2007	2010	2015	2020	2025	2030	2035	2040	2045	2050
1		233	223	217	211	206	200	195	190	186
2		230	214	201	192	185	180	175	170	165
3	247	228	203	188	178	169	160	152	147	143
4		225	194	171	158	147	137	127	123	119

As the figure for 2007 in the Adjusted Model has been increased by 7.5% to 265.3W/^{o}C, it would clearly be unacceptable to accept the absolute values in the table on account of the unrealistically large step decrease in HLC between 2007 and 2010. Applying the same 7.5% increase in value to HLC in all subsequent years, to correspond with the 7.5% increase in the 2007 figure is considered the most prudent course of action.

Internal Gains

As described by Equation 55, internal gains in any given year are calculated with reference to heat losses in that year, in the same 'gains to heat losses' ratio that is reported for 2007. Although not ideal, in the absence of an alternative, the same method of calculating gains in 2050 is used for both the Adjusted Model and the Basic Model. Gains in the Adjusted Model are, however, different to gains in the Basic Model since heat losses in 2050 are different for the two models[216].

Table 67 shows the values of the three constants, indoor temperature, internal gains and HLC, used as input for the DECC 2050 Calculator for the Adjusted Model and the Basic Model, for the four different pathways for 2007 and 2050.

---

[216] Heat losses are different because heat losses are calculated with reference to indoor temperature (see Equation 53and Equation 54).

Table 67 Indoor temperature, internal gains and HLC input for the DECC 2050 Calculator for the Adjusted Model and the Basic Model for the four different pathways for 2007 and 2050

Pathway	Parameter	Adjusted Model		Basic Model	
		2007	*2050*	*2007*	*2050*
Higher Nuclear, Less Energy Efficiency	*Indoor temp (ᵒC)*	18.5	19.0	17.5	18.0
	Internal gains (J)	26.861	13.413	32.476	20.046
	HLC (W/ᵒC)	265.3	153.8	246.8	143.0
Higher CCS, More Bioenergy	*Indoor temp (ᵒC)*	18.5	18.0	17.5	17.0
	Internal gains (J)	26.861	12.132	32.476	17.833
	HLC (W/ᵒC)	265.3	153.8	246.8	143.0
Higher Renewables, More Energy Efficiency	*Indoor temp (ᵒC)*	18.5	17.0	17.5	16.0
	Internal gains (J)	26.861	10.970	32.476	12.941
	HLC (W/ᵒC)	265.3	127.4	246.8	118.5
MARKAL "core run"	*Indoor temp (ᵒC)*	18.5	17.0	17.5	16.0
	Internal gains (J)	26.861	9.931	32.476	15.620
	HLC (W/ᵒC)	265.3	153.8	246.8	143.0

As a final note, it should be mentioned that two of the pathways mechanical cooling (in the form of air-conditioning) is used in two of the pathways (Nuclear and CCS), whilst natural ventilation is used for space cooling in the other two (Renewables and MARKAL). As such, these latter two pathways are manifestations of the AATC.

5.3.3   Results – Adjusted Model and Basic Model

The tables in Sections5.3.3.1 to 5.3.3.8 report the DECC 2050 Calculator output for 2050 from 3,200 runs for:

(i)   four pathways (Nuclear, CCS, Renewables and pathway analogous to MARKAL),
(ii)   medium and high emissions scenarios,
(iii) the 30th, 50th, 70th and 90th percentiles winter temperature, and
(iv)   the Adjusted Model and the Basic Model.

As previously noted the results derive from weighted temperature input into the DECC 2050 Calculator, where the results for a given tetrad (e.g. Nuclear pathway, medium emissions, 30th percentile, Adjusted Model) derive from 50 runs of the DECC 2050 Calculator, each run using a different set of seasonal temperatures.

Effective negative emissions in the residential stock arise from electricity generated by solid fuel community-scale CHP. The fossil fuel emissions generated from these CHP plants are accounted for in the residential space heating emissions total. The electricity generated is, therefore, effectively emissions-free. The negative emissions are calculated as the total emissions which would have been produced by the same quantity of grid-electricity.

Total cross-sector emissions (*Total UK Modelled Emissions*) calculated by the DECC 2050 Calculator do not concur exactly with reported emissions for the base year of 2007. The Calculator features an adjustment factor, a multiplying constant to bring the modelled emissions into alignment with actual emissions for 2007. Future modelled emissions are also adjusted by this same adjustment factor. The DECC 2050 Calculator uses the adjusted figure (*Total Adjusted UK Emissions*) in reporting the total cross-sector percentage reduction in emissions (*Reduction in Emissions Relative to 1990*).

For Table 68 to Table 83 the results appear in paired tables. The first table in a pair reports on the residential sector and the second table in a pair reports upon the total cross-sector emissions.   For example, the first column in Table 68 below shows that in the *Nuclear/30thpercentile/medium emissions scenario/Adjusted Model* tetrad, space heating emissions from the residential sector comprise 0.47 $MtCO_2e$ of the total of 154.70 $MTCO_2e$ for that tetrad (this latter figure appearing in the first column of Table 69).

In order to establish whether or not 50 runs is a sufficiently large of runs to produce results which can be said to be representative of a tetrad, the mean, maximum, minimum and standard deviation of set of five typical tetrads are shown in Section 5.3.3.9.

Space heating is referred to as SH, and space cooling is referred to as SC for brevity.

Finally, note that the key results for space heating demand and total cross-sector emissions are brought together in Table 88 and Table 89.

5.3.3.1 Medium Emissions Scenario 30th Percentile

Table 68 National demand, consumption and emissions from space heating and space cooling in the residential sector (30th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	208.85	164.69	186.77	136.45	109.57	83.73	96.65	69.37
SH Consumption (TWh)	84.02	66.26	187.19	51.17	44.08	33.69	96.87	26.01
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.47	2.64	47.86	1.11	0.25	1.34	24.98	0.96
SC Emissions (MtCO$_2$e)	0.04	0	0.16	0	0.04	0	0.19	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.14	0	0	0	2.70	0

Table 69 National cross-sector emissions (30th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.076	0.022	0.008	0.060	0.092	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.19	137.83	159.86	158.81	153.01	137.61	137.88	149.97
Total Adjusted UK Emissions (MtCO$_2$e)	154.70	139.83	162.22	161.11	162.22	146.60	146.93	159.77
Reduction in Emissions relative to 1990 (%)	80.65	82.52	79.71	79.85	79.71	82.50	81.62	80.02

5.3.3.2 Medium Emissions Scenario 50th Percentile

Table 70 National demand, consumption and emissions from space heating and space cooling in the residential sector (50th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	203.08	158.92	181.00	131.66	106.19	80.35	93.27	66.57
SH Consumption (TWh)	81.70	63.94	181.41	49.37	42.72	32.33	93.48	24.96
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.45	2.55	46.41	1.14	0.24	1.29	24.12	0.92
SC Emissions (MtCO$_2$e)	0.04	0	0.16	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.11	0	0	0	2.68	0

Table 71 National cross-sector emissions (50th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.077	0.023	0.008	0.060	0.093	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.20	137.84	158.44	158.10	153.02	137.63	137.05	149.99
Total Adjusted UK Emissions (MtCO$_2$e)	154.71	139.84	160.78	160.39	162.23	146.62	146.04	159.79
Reduction in Emissions relative to 1990 (%)	80.65	82.52	79.89	79.94	79.71	82.50	81.74	80.02

5.3.3.3 Medium Emissions Scenario 70th Percentile

Table 72 National demand, consumption and emissions from space heating and space cooling in the residential sector (70th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	195.78	151.63	173.70	125.62	101.92	76.08	89.00	63.03
SH Consumption (TWh)	78.77	61.00	174.10	47.11	41.01	30.61	89.20	23.64
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.44	2.43	44.57	1.17	0.23	1.22	23.03	0.87
SC Emissions (MtCO$_2$e)	0.04	0	0.16	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.08	0	0	0	2.65	0

Table 73 National cross-sector emissions (70th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.078	0.025	0.008	0.060	0.094	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.22	137.85	156.65	157.20	153.05	137.64	136.00	150.02
Total Adjusted UK Emissions (MtCO$_2$e)	154.73	139.85	158.96	159.48	162.26	146.64	144.92	159.82
Reduction in Emissions relative to 1990 (%)	80.65	82.52	80.12	80.06	79.71	82.50	81.88	80.01

5.3.3.4 Medium Emissions Scenario 90th Percentile

Table 74 National demand, consumption and emissions from space heating and space cooling in the residential sector (90th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	184.09	139.93	162.01	115.93	95.08	69.24	82.16	57.36
SH Consumption (TWh)	74.06	56.30	162.37	43.48	38.25	27.86	82.34	21.51
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.41	2.25	41.61	1.20	0.21	1.11	21.27	0.79
SC Emissions (MtCO$_2$e)	0.04	0	0.17	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.04	0	0	0	2.61	0

Table 75 National cross-sector emissions (90th percentile, medium emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.080	0.028	0.008	0.060	0.096	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.25	137.88	153.77	155.76	153.08	137.68	134.32	150.06
Total Adjusted UK Emissions (MtCO$_2$e)	154.76	139.88	156.04	158.02	162.30	146.67	143.13	159.86
Reduction in Emissions relative to 1990 (%)	80.65	82.52	80.49	80.24	79.70	82.50	82.10	80.01

5.3.3.5 High Emissions Scenario 30th Percentile

Table 76 National demand, consumption and emissions from space heating and space cooling in the residential sector (30th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	205.17	161.01	183.09	133.40	107.42	81.57	94.49	67.58
SH Consumption (TWh)	82.54	64.78	183.50	50.02	43.22	32.82	94.71	25.34
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.46	2.58	46.94	1.13	0.24	1.31	24.43	0.93
SC Emissions (MtCO$_2$e)	0.04	0	0.16	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.12	0	0	0	2.69	0

Table 77 National cross-sector emissions (30th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.077	0.023	0.008	0.060	0.093	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.20	137.84	158.96	158.36	153.02	137.62	137.35	149.99
Total Adjusted UK Emissions (MtCO$_2$e)	154.71	139.84	161.30	160.66	162.23	146.62	146.37	159.79
Reduction in Emissions relative to 1990 (%)	80.65	82.52	79.83	79.91	79.71	82.50	81.70	80.02

5.3.3.6 High Emissions scenario 50th Percentile

Table 78 National demand, consumption and emissions from space heating and space cooling in the residential sector (50th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	198.21	154.05	176.13	127.63	103.34	77.50	90.42	64.21
SH Consumption (TWh)	79.74	61.98	176.53	47.86	41.58	31.18	90.62	24.08
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.44	2.47	45.18	1.16	0.23	1.24	23.39	0.89
SC Emissions (MtCO$_2$e)	0.04	0	0.16	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.09	0	0	0	2.66	0

Table 79 National cross-sector emissions (50th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.078	0.024	0.008	0.060	0.094	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.22	137.85	157.25	157.50	153.04	137.64	136.35	150.01
Total Adjusted UK Emissions (MtCO$_2$e)	154.73	139.85	159.57	159.79	162.25	146.64	145.30	159.82
Reduction in Emissions relative to 1990 (%)	80.65	82.52	80.04	80.02	79.71	82.50	81.83	80.01

5.3.3.7 High Emissions Scenario 70th Percentile

Table 80 National demand, consumption and emissions from space heating and space cooling in the residential sector (70th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	**MARKAL**	**CCS**	**Renew**	**Nuclear**	**MARKAL**	**CCS**	**Renew**
SH Demand (TWh)	191.00	146.85	168.93	121.66	99.12	73.28	86.20	60.72
SH Consumption (TWh)	76.84	59.08	169.31	45.62	39.88	29.48	86.40	22.77
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.43	2.36	43.36	1.19	0.22	1.18	22.31	0.84
SC Emissions (MtCO$_2$e)	0.04	0	0.17	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.07	0	0	0	2.64	0

Table 81 National cross-sector emissions (70th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	**MARKAL**	**CCS**	**Renew**	**Nuclear**	**MARKAL**	**CCS**	**Renew**
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.079	0.026	0.008	0.060	0.095	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.23	137.86	155.47	156.61	153.06	137.66	135.31	150.04
Total Adjusted UK Emissions (MtCO$_2$e)	154.74	139.87	157.77	158.89	162.28	146.66	144.19	159.84
Reduction in Emissions relative to 1990 (%)	80.65	82.52	80.27	80.13	79.71	82.50	81.97	80.01

5.3.3.8 High Emissions Scenario 90th Percentile

Table 82 National demand, consumption and emissions from space heating and space cooling in the residential sector (90th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	181.42	137.26	159.34	113.72	93.51	67.67	80.59	56.07
SH Consumption (TWh)	72.99	55.22	159.70	42.65	37.62	27.23	80.78	21.03
SC Demand (TWh)	30.64	0	13.51	0	30.64	0	13.51	0
SC Consumption (TWh)	4.49	0	2.09	0	4.49	0	2.09	0
SH Emissions (MtCO$_2$e)	0.41	2.20	40.93	1.20	0.21	1.09	20.87	0.77
SC Emissions (MtCO$_2$e)	0.04	0	0.17	0	0.04	0	0.20	0
Effective Negative Emissions (MtCO$_2$e)	0	0	3.02	0	0	0	2.60	0

Table 83 National cross-sector emissions (90th percentile, high emissions scenario)

	Adjusted Model				Basic Model			
	Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.008	0.060	0.080	0.028	0.008	0.060	0.096	0.037
Total Modelled UK Emissions (MtCO$_2$e)	153.26	137.88	153.12	155.44	153.10	137.69	133.93	150.07
Total Adjusted UK Emissions (MtCO$_2$e)	154.77	139.89	155.38	157.69	162.31	146.68	142.72	159.88
Reduction in Emissions relative to 1990 (%)	80.64	82.52	80.57	80.28	79.70	82.50	82.15	80.01

5.3.3.9 Range of Values for a Sample of Typical Tetrads

The following four tables show the range of values and standard deviation for DECC 2050 Calculator output, a typical tetrad being shown for the 30th, 50th, 70th and 90th percentile winter temperature.

30th Percentile

Table 84 Mean, maximum, minimum and standard deviations for DECC 2050 Calculator output for a typical 30th percentile – Adjusted Model, Renewables pathway, Medium emissions scenario

	Mean	Maximum	Minimum	Standard Deviation
Residential SH Demand (TWh)	136.445	143.357	130.627	2.885
Residential SH Consumption (TWh)	51.167	53.759	48.985	1.082
Residential SC Demand (TWh)	0.000	0.000	0.000	0.000
Residential SC Consumption (TWh)	0.000	0.000	0.000	0.000
Residential SH Emissions (MtCO$_2$e)	1.114	1.148	1.067	0.018
Residential SC Emissions (MtCO$_2$e)	0.000	0.000	0.000	0.000
Residential Effective Negative Emissions (MtCO$_2$e)	0.000	0.000	0.000	0.000
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.022	0.023	0.020	0.001
Total Modelled UK Emissions (MtCO$_2$e)	158.808	159.833	157.936	0.427
Total Adjusted UK Emissions (MtCO$_2$e)	161.114	162.155	160.230	0.433
Reduction in Emissions relative to 1990 (%)	79.850	79.961	79.720	0.054

50th Percentile

Residential SH Demand (TWh)	Mean	Maximum	Minimum	Standard Deviation
Residential SH Consumption (TWh)	158.922	168.345	152.619	3.374
Residential SC Demand (TWh)	63.937	67.729	61.402	1.357
Residential SC Consumption (TWh)	0.000	0.000	0.000	0.000
Residential SH Emissions (MtCO$_2$e)	0.000	0.000	0.000	0.000
Residential SC Emissions (MtCO$_2$e)	2.549	2.700	2.448	0.054
Residential Effective Negative Emissions (MtCO$_2$e)	0.000	0.000	0.000	0.000
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.000	0.000	0.000	0.000
Total Modelled UK Emissions (MtCO$_2$e)	0.060	0.060	0.060	0.000
Total Adjusted UK Emissions (MtCO$_2$e)	137.836	137.863	137.808	0.011
Reduction in Emissions relative to 1990 (%)	139.838	139.866	139.809	0.012
Residential SH Demand (TWh)	82.516	82.520	82.514	0.001

70th Percentile

70th Percentile

	Mean	Maximum	Minimum	Standard Deviation
Residential SH Demand (TWh)	86.204	93.493	80.781	2.361
Residential SH Consumption (TWh)	86.398	93.704	80.963	2.367
Residential SC Demand (TWh)	13.510	13.510	13.510	0.000
Residential SC Consumption (TWh)	2.094	3.445	3.445	0.000
Residential SH Emissions (MtCO$_2$e)	22.312	24.178	20.922	0.605
Residential SC Emissions (MtCO$_2$e)	0.199	0.201	0.195	0.001
Residential Effective Negative Emissions (MtCO$_2$e)	2.635	2.681	2.599	0.015
Electricity Emissions Intensity (MtCO$_2$e/TWh)	0.095	0.096	0.093	0.001
Total Modelled UK Emissions (MtCO$_2$e)	135.314	137.107	133.980	0.581
Total Adjusted UK Emissions (MtCO$_2$e)	144.191	146.102	142.769	0.619
Reduction in Emissions relative to 1990 (%)	81.967	82.145	81.728	0.077

90th Percentile

Table 87 Mean, maximum, minimum and standard deviations for DECC 2050 Calculator output for a typical 90th percentile – Basic Model, Nuclear pathway, High emissions scenario

	Mean	Maximum	Minimum	Standard Deviation
Residential SH Demand (TWh)	93.514	98.829	89.152	2.440
Residential SH Consumption (TWh)	37.623	39.761	35.868	0.982
Residential SC Demand (TWh)	30.640	30.640	30.640	0.000
Residential SC Consumption (TWh)	4.494	4.494	4.494	0.000
Residential SH Emissions ($MtCO_2e$)	0.209	0.221	0.199	0.005
Residential SC Emissions ($MtCO_2e$)	0.037	0.037	0.037	0.000
Residential Effective Negative Emissions ($MtCO_2e$)	0.000	0.000	0.000	0.000
Electricity Emissions Intensity ($MtCO_2e/TWh$)	0.008	0.008	0.008	0.000
Total Modelled UK Emissions ($MtCO_2e$)	153.095	153.130	153.064	0.016
Total Adjusted UK Emissions ($MtCO_2e$)	162.310	162.348	162.278	0.017
Reduction in Emissions relative to 1990 (%)	79.701	79.705	79.696	0.002

5.3.4 Discussion of the DECC 2050 Calculator Results for 2050 - the Adjusted Model and the Basic Model

The sample results presented in Section 5.3.3.9, typical of all 80 tetrads, indicate that the method of using 50 runs to capture the breadth of winter temperatures across a given percentile is adequately robust, with low standard deviations for each output result. Thus the average results presented in Section 5.3.3.1 to Section 5.3.3.8 can be considered to be representative of a given tetrad.

In order to aid the presentation of the discussion the key results of these tables, residential space heating demand and cross-sector reduction in emissions, are summarised in Table 88 (medium emissions scenario) and Table 89 (high emissions scenario) below.

Table 88 Residential sector space heating demand (TWh) in 2050 and cross-sector reduction in emissions (%) 1990-2050 for the 32 tetrads under a medium emissions scenario

	%^{le}*	Adjusted Model				Basic Model			
		Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	30th	208.85	164.69	186.77	136.45	109.57	83.73	96.65	69.37
Reduction in Emissions relative to 1990 (%)	30th	80.65	82.52	*79.71*	*79.85*	*79.71*	82.50	81.62	80.02
SH Demand (TWh)	50th	203.08	158.92	181.00	131.66	106.19	80.35	93.27	66.57
Reduction in Emissions relative to 1990 (%)	50th	80.65	82.52	*79.89*	*79.94*	*79.71*	82.50	81.74	80.02
SH Demand (TWh)	70th	195.78	151.63	173.70	125.62	101.92	76.08	89.00	63.03
Reduction in Emissions relative to 1990 (%))	70th	80.65	82.52	80.12	80.06	*79.71*	82.50	81.88	80.01
SH Demand (TWh)	90th	184.09	139.93	162.01	115.93	95.08	69.24	82.16	57.36
Reduction in Emissions relative to 1990 (%))	90th	80.65	82.52	80.49	80.24	*79.70*	82.50	82.10	80.01

%^{le} - percentile

221

Table 89 Residential sector space heating demand (TWh) in 2050 and cross-sector reduction in emissions (%) 1990-2050 for the 32 tetrads under a high emissions scenario

	%le*	Adjusted Model				Basic Model			
		Nuclear	MARKAL	CCS	Renew	Nuclear	MARKAL	CCS	Renew
SH Demand (TWh)	30th	205.17	161.01	183.09	133.40	107.42	81.57	94.49	67.58
Reduction in Emissions relative to 1990 (%)	30th	80.65	82.52	*79.83*	*79.91*	*79.71*	82.50	81.70	80.02
SH Demand (TWh)	50th	198.21	154.05	176.13	127.63	103.34	77.50	90.42	64.21
Reduction in Emissions relative to 1990 (%)	50th	80.65	82.52	80.04	80.02	*79.71*	82.50	81.83	80.01
SH Demand (TWh)	70th	191.00	146.85	168.93	121.66	99.12	73.28	86.20	60.72
Reduction in Emissions relative to 1990 (%))	70th	80.65	82.52	80.27	80.13	*79.71*	82.50	81.97	80.01
SH Demand (TWh)	90th	181.42	137.26	159.34	113.72	93.51	67.67	80.59	56.07
Reduction in Emissions relative to 1990 (%))	90th	80.64	82.52	80.57	80.28	*79.70*	82.50	82.15	80.01

$\%^{le}$ - percentile

5.3.4.1 Attainment of 80%Reduction in Emissions Target

Whilst the demand for residential space heating varies considerably (according to percentile winter temperature, pathway, emissions scenario and model type (Adjusted or Basic)), the reduction in total cross-sector emissions is little affected. The target 80% reduction in emissions on baseline levels in 1990 is achieved in all instances except for those italicised in bold print above; and in these instances the target is only narrowly missed. Perhaps significantly, the only pathway which achieves the 80% target for all situations, is the MARKAL cost-optimising pathway which takes the balanced approach.

The reason why the level of residential space heating does little to interfere with the attainment of the 80% target,(i) despite the fact that cross-sector space heating currently accounts for 15.5% of GHG emissions and (ii) despite the fact that the demand for residential space heating remains considerable in 2050 (falling within the range 56-225 TWh, dependent upon tetrad[217]), is because in most instances, the demand for residential space heating in 2050 is met by electricity, the carbon intensity of which is forecast to be very low by 2050. Whereas the emissions intensity of electricity

---

[217] c.f. the Adjusted Model estimates demand in 2007 at 235.0 TWh and the Basic Model estimates it at 123.1 TWh.

is forecast to fall within the range 0.008-0.096 $MtCO_2e$/TWh by 2050, its value for 2007 is reported at 0.541 $MtCO_2e$/TWh, and that of gas is reported at 0.184 $MtCO_2e$/TWh[218] (DECC, 2011,19Aug). In essence, for the most pessimistic outcome of the four pathways (CCS pathway, where 45% of the residential space heating demand is met by solid fuel community-scale CHP plants) residential space heating emissions intensity are nevertheless twice as low as that of the present day where gas predominates. But, what is more, the relatively high emissions of the CCS pathway are offset by the effectively negative emissions of electricity produced by the CHP plants as previously explained, such emissions being the equivalent of 7-12% of residential space heating emissions for this pathway.

5.3.4.2 Adjusted Model Results Compared with Basic Model Results

Although total cross-sector emissions are very similar in value for the Adjusted Model and the Basic Model, the demand for residential space heating is approximately twice as high for the Adjusted Model in 2050. This ensues from the fact that demand in 2007 is twice approximately twice as high in the Adjusted Model as in the Basic Model (as previously noted in footnote 217). But whilst the resulting consumption from this demand in 2007 (289.9 TWh) compares favourably with the DECC estimate of 332.4 TWh (see Table 64) for the Adjusted Model[219], the Basic Model's estimate of 151.9 TWh for 2007 is less than twice the actual reported value for 2007 (see Table 62). This may suggest that more confidence can be placed in the Adjusted Model's output.

The most pessimistic forecast sees a reduction in residential space heating demand of 37% (30th percentile temperatures, Nuclear pathway, medium emissions scenario, Adjusted Model); the greatest reduction calculates at 83% (90th percentile, Renewables pathway, Basic Model, high emissions scenario, Basic Model).

5.3.4.3 Probability of Higher Temperatures

The spread of residential space heating demand values over the 30th-90th percentile winter temperature range is perhaps not as high as might have been anticipated. For the 90th percentile (where there is a 90% probability that winter temperatures will be less than the forecast value), demand is only about 15% higher[220] than at the 30th percentile (where there is a 30% probability that winter temperatures will be lower than the forecast value). The forecast percentage reduction in demand with reference to demand in 2007 is very similar for both models. For the 30th percentile, the Adjusted Model forecasts a minimum reduction of 4%, and the Basic Model forecasts a minimum reduction of 3%[221]; for the 90th percentile, both models forecast a maximum reduction of 11%[222].

---

[218] The emissions intensity of electricity is reported at 0.752 $MtCO_2e$/TWh or 1990. Although the value for gas for 1990 is not stated, it is likely to be of the same order as the value for 2007.

[219] Note that the Adjusted Models' estimate of 289.9 TWh is only 1.3% higher than the alternative DECC estimate of 286.2 TWh for 2007.

[220] Range 22-35%.

[221] Nuclear pathway/medium emissions scenario. Adjusted Model: demand falls from 235.0 TWh to 224.9 TWh; Basic Model: demand falls from 123.1 TWh to 119.0 TWh

223

5.3.4.4 Medium Emissions Scenario Results Compared with High Emissions Scenario Results

Even though a high emissions scenario would see a greater reduction in the demand for residential space heating energy in comparison to the medium emissions scenario, it is modest, falling in the range 2-4%. There is negligible difference between the two scenarios with regard to the reduction in total cross-sector emissions.   This is in agreement with findings that the deleterious consequences associated with higher emissions levels do not manifest themselves until the latter part of the century.

5.3.4.5 Pathways

The pathways are broadly effective as one another in achieving the 80% reduction in emissions target, whichever particular tetrad is used. Although the MARKAL pathway brings about a slightly greater reduction than the other pathways, it is not the pathway where the reduction in demand for residential space heating is greatest. This is not unexpected as total cross-sector emissions are affected by factors other than residential space heating. Indeed, residential space heating emissions are dwarfed by emissions from other sectors for all pathways except the CCS pathway; whilst residential space heating emissions in the MARKAL pathway typically constitute 1-2% of total cross-sector emissions by 2050, those from transport constitute 83% with agriculture & waste sector [223] accounting for the majority of the remainder, followed industrial processes.

Having said that, residential space heating emissions from the CCS pathway are very much greater: they comprise 26-29% of total cross-sector emissions in the Adjusted Model, and 15-17% of emissions in the Basic Model on account of the fact that 45% of residential space heating demand is met by community-scale solid fuel burning CHP plant. Despite the high emissions associated with this pathway, the reason why the 80% reduction target is achieved or almost achieved is because of the higher levels of bioenergy used in this pathway[224]. Therefore, in terms of net emissions, the CCS pathway should not be viewed as being a high emissions pathway, especially when it is considered that the electricity generated by CHP plant in this pathway produce effective negative emissions.

Note should also be taken of the fact that the CHP pathway, in addition to producing the most emissions, is also the most energy intensive, resulting from the fact that CHP, which meets 45% of the demand for residential space heating, is only 57% efficient, which compares with the 300% and

---

[222] Renewables pathway/high emissions scenario. Adjusted Model: demand falls from 235.0 TWh to 209.9TWh; Basic Model: demand falls from 123.1 TWh to 109.6 TWh

[223] It is interesting to note that only a very small proportion of the emissions from agriculture & waste are carbon dioxide, but are rather methane and nitrous oxide. The impact on emissions levels of processes other than the combustion of fossil fuels should not be under-estimated.

[224] Bioenergy is treated as a sector in its own right by the DECC 2050 Calculator, being a contributor of negative emissions. Negative emissions from bioenergy have the effect of negating positive emissions from other sectors. It should be noted, however, that bioenergy is taken into consideration in calculating the emissions intensity of electricity; therefore, the stated emissions levels associated with the Nuclear, MARKAL and Renewables pathways, which use only electricity or zero-energy forms of energy (district heating or geothermal heating) for space heating, can be regarded as accurate.

400% efficiencies associated with air-source heat pumps and ground-source heat pumps mostly used in the other pathways.

5.3.4.6 Space Cooling Forecast for 2050

As previously mentioned, DECC 2050 Calculator does not appear to take air temperature into direct consideration in forecasting space cooling demand. The Nuclear pathway calculates residential space cooling demand at 30.6 TWh and the CCS pathway calculates it at 13.5 TWh, whilst there is no demand for space cooling in the other two pathways.

SCECMORS does, on the other hand, directly consider climate change, and it serves as a useful exercise to compare SCECMORS results with the DECC 2050 Calculator's residential space cooling results on a like-for-like basis as near as possibly, viz:

i.   SCECMORS EER value is changed from 2.91 to 6.82 for the Nuclear pathway, and 6.45 for the CCS pathway[225]

ii.   the number of dwellings is raised from the SCECMORS 2010 value of 26.519M to 39.959M

iii. space cooling emissions are calculated using the average emissions intensities of electricity above from the Adjusted Model (e.g. the electricity emissions intensity of the Nuclear pathway for a medium emissions scenario is calculated from the average the four emissions from the 30th, 50th, 70th and 90th percentiles, which are all very similar).

As space cooling only occurs in the Nuclear and CCS pathways, emissions intensities from the MARKAL and Renewables pathways are not considered.

The results of these analyses are extensive, producing very similar data. A sample table is shown below, but the full set of results can be found in Appendix 17: SCECMORS Estimates of Residential Space Cooling Energy Consumption for different percentiles. In the discussion that follows, these results from SCECMORS are considered to be a part of the Adjusted Model.

---

[225] Electric air-conditioners are assigned a value of 600% efficiency by the DECC 2050 Calculator (i.e. EER of 6). A small proportion of space cooling is also provided by absorption coolers using free heat supplied from power stations, thus increasing the average EER value above 6. (Absorption air-conditioners supply 12% of the space cooling demand for the Nuclear pathway, and 7% for the CCS pathway.)

Table 90 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (50th percentile medium emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	51	10.46	11.05	1.533	1.620	0.012	0.126
SCECdwell SHEU 3%	58	11.74	12.41	1.722	1.820	0.014	0.141
SCECdwell CEUD 7.2%	52	10.61	11.21	1.555	1.643	0.012	0.128
SCECdwell SHEU 7.2%	58	11.76	12.43	1.724	1.822	0.014	0.142
SCECair CEUD 3%	51	7.77	8.20	1.139	1.203	0.009	0.094
SCECair SHEU 3%	58	8.72	9.22	1.279	1.352	0.010	0.105
SCECair CEUD 7.2%	52	7.88	8.32	1.155	1.220	0.009	0.095
SCECair SHEU 7.2%	58	8.74	9.23	1.281	1.353	0.010	0.105
Average	54.75	9.71	9.70	1.42	1.50	0.01	0.12

Although the demand is the same for both pathways, less energy is consumed by the Nuclear because of the greater EER value associated with this pathway because of its higher use of absorption air-conditioning using waste heat from power stations.

When amended with data from the DECC 2050 Calculator, SCECMORS (the Adjusted Model) tends to forecast a generally lower level of space cooling energy consumption than the default setting of the DEC 2050 Calculator. There is a degree of overlap, the Adjusted Model's estimate of cooling at higher levels of emissions sometimes exceeding that forecast by the Basic Model . Whilst the DECC 2050 Calculator estimates a consumption for space cooling of 4.5 TWh and 2.1 TWh for the Nuclear and CCS pathways, irrespective of the temperature percentile, SCECMORS estimates a consumption range of 1.3-2.3TWh for the Nuclear pathway and 1.4-2.5 TWh for the CCS pathway.

5.4 Energy Consumption and Emissions Levels in 2050

Residential Space Heating

With reference to present day levels of space heating (332.4 TWh), there is a marked difference between the pathways: he Adjusted Model forecasts a reduction in space heating consumption of 44-87%, and the Basic Model forecasts one of 71-94%. In all cases the reduction in consumption is smaller than for the CCS pathway than for the other pathways as a consequence of its heavy reliance upon less efficient CHP (in addition to electricity). However, there is seen to be virtually no difference between (i) the medium emissions scenario and the high emissions scenario, and between (ii) the 30th percentile and the 90th percentile. Whilst, for example, the 30[th]percentile/medium emissions scenario results in a 75% reduction in consumption, the 90th percentile/high emissions scenario results in a 78% reduction, for the Nuclear/Adjusted Model. The difference is brought about by choice of pathway and choice of model.

Differences in emissions levels show a much greater spread 16%[226] to 103%[227]. But in terms of cross sector-total emissions, the differences between the Basic Model and the Adjusted Model is negligible because emissions from space heating constitute such a small part of total emissions, typically less than 2% (if one excludes the CCS pathway with its artificially high levels of emissions since negative bioenergy emissions are accounted for elsewhere in the DECC 2050 Calculator, as previously mentioned).

Residential Space Cooling

Although the relative difference between the estimates of the Basic Model and the Adjusted Model can be large for cooler climates, in absolute terms the difference they are very small, amounting to no more than approximately 3TWh. Insofar as emissions are concerned, the differences between the models are insignificant since, even under a high emissions scenario at a penetration rate of the order of 70%, space cooling emissions amount to only 0.2 $MtCO_2e$.

Commercial and Industrial Sector Space Heating and Space Cooling

The manipulations made to the DECC 2050 Calculator only directly affect the residential sector. Its forecast for space heating energy consumption fall in the range 57.8 to 97.4TWh, and its forecasts for space cooling energy consumption fall in the range 13.5 to 47.7 TWh[228], depending upon the

---

[226] 30th percentile/Renewables/medium emission: Basic Model-0.96 $MtCO_2e$. Adjusted Model-1.11 $MtCO_2e$.
[227] 90th percentile/MARKAL/medium emission: Basic Model-1.11 $MtCO_2e$. Adjusted Model-2.25 $MtCO_2e$.
[228] A small note in the Calculator states that installed capacity in the commercial sector is assumed to increase in the future at a rate of 1GW per degree change in annual temperature with respect to 2007 values. Another note in the wiki refers to methodology issues and uncertainties between average annual demand and installed capacity. Confirmation that this is the method by which future demand in the different pathway in the Calculator is estimated was sought on two occasions, but no response was given.

pathway followed; these compare with present day values of 84.8 TWh and 8.8 TWh[229] (DECC, 2012i).

One can confer that emission levels of space heating and space cooling in the commercial sector would be similarly low across the range of percentile temperatures investigated. This is because space heating and space cooling in the commercial sector rely upon a similar distribution of low and zero carbon (LZC) technologies, dominated by electricity as seen in Table 91 and Table 92 (c.f. Appendix 14: Key Characteristics of Four Pathways Designed to Reduce GHG Emissions by 80% by 2050).

Table 91 DECC 2050 space heating technology mix for the commercial sector (%)

	Nuclear	CCS	Renewables	MARKAL
Geothermal (%)	1			
Electric Resistive heating (%)		7	10	
Air-source heat pump (ASHP) (%)	58	60	60	18
Ground-source heat pump (GSHP) (%)	30	30	30	30
CHP (%)				45
District heating (%)	11	3		

Table 92 DECC 2050 space cooling technology mix for the commercial sector (%)

	Nuclear	CCS	Renewables	MARKAL
Electric air-conditioning (%)	88	97	100	93
Absorption (%)	12	3		7

Since no information is given on levels of space heating and space cooling in the industrial sector, one cannot make any informed comment other than to say that they are likely to be small in relation to that of industrial process

---

(ii) average annual demand in the commercial sector is calculated from a given known ratio "annual demand/installed capacity" (mentioned in your contribution to the wiki).

[229] This is the figure for cooling and ventilation.

Summary

Considering the enormity of the task in successfully capturing the nation's carbon economy in single coherent model, it is remarkable that cross-sector modelled emissions for the base year of 2007 should so closely resemble actual emissions, an adjusting factor being used to align modelled emissions with actual emissions.

In the absence of an alternative, the application of the same adjusting factor to the year 2050 would appear to be justified, the same approach being used by BREHOMES to bring modelled energy consumption into alignment with government statistics. Consequently , the results produced by the Adjusted Model of the DECC 2050 Calculator, serve as useful comparisons to the results produced by the Basic Model, especially since the default set-up of the Calculator, when loaded with correctly-weighted temperature data under-estimates residential space consumption (190.6 TWh) by 43% for the year 2007[230].

Demand for space heating energy continues to remain significantly larger that the demand for space heating. When the demand for space cooling is at greatest (15.78 TWh) and penetration approaches 70%, the demand for space heating remains 5-10 times as large, depending upon whether the Basic Model or the Adjusted Model is used to estimate space heating.

The Basic Model estimates total space cooling demand across the residential and commercial sectors as falling between 13 and 78 TWh, depending upon pathway the followed, and the Adjusted Model estimates it as falling between 13 and 64 TWh. On a like-for like basis (i.e. same pathway, percentile temperature and same emissions scenario), the difference ranges between 0[231] and 22 TWh[232].

The Basic Model estimates total space heating demand across the residential and domestic sectors as falling between 114 and 207 TWh, depending upon pathway the followed, and the Adjusted Model estimates it as falling between 172 and 306 TWh. On a like-for like basis (i.e. same pathway, percentile temperature and same emissions scenario), the difference ranges between 58 TWh[233] and 99 TWh[234]

In terms of cross-sector emissions, all pathways across all tetrads secure or almost secure the 80% reduction target, but the Adjusted Model suggests that generational capacity may have to be increased to meet a projected shortfall in energy of up to 99 TWh in the heating season.

---

[230] The latest government figures for 2007 estimate residential space heating energy consumption at 332.1 TWh,

[231] Many different percentile/pathway/emission scenarios.

[232] 30th percentile/Nuclear/ medium emissions.

[233] 90th percentile/Renewables/high emissions.

[234] 30th percentile/Nuclear/medium emissions

6 Conclusion

Although it remains unclear to what extent the climate will change, it seems very likely that it will change. This will inevitably affect us all, bringing with it a range of both benefits and problems. Whilst we can expect to see a reduction in the demand for space heating in winter (as modelled by SHECMOBS in Chapter 2), we can also expect to see an increase in the demand for cooling in summer if we are to avoid discomfort and overheating in our buildings (as modelled by SCECMORS in Chapter 3, and the AATC in Chapter 4). The way that we deal with these changes will impact upon our consumption of energy, as will a plethora of other factors determined by the particular pathway that society follows, and these in turn will affect atmospheric levels of greenhouse gases. The realisation that greenhouse gas emissions must be reduced if we are to escape the most deleterious consequences of climate change later in the century has prompted the government into action, the Climate Change Act 2008 specifying an 80% reduction in emissions levels by 2050. It has further set out a number of different pathways which bring about the 80% reduction when modelled in the DECC 2050 Calculator, based on temperature projections at the 50% probability level under a medium emissions scenario. Using weighted temperature data, and data from SHECMOBS and SCECMORS, the DECC 2050 Calculator has been used to investigate a range of different future climates in addition to the central estimate projection under a medium emissions scenario (Chapter 5).

SHECMOBS

Recognition of the fact that a warmer climate will lessen the demand for space heating is often overlooked, with the focus of attention being rather more on the negative aspects of climate change. But given the fact that space heating accounts for 43% of energy consumption in the built environment, it is imperative that this end-use is examined in as great a detail as possible since even a small increase in air temperature can have a large impact upon the national energy budget. As gas accounts for 72% of space heating in the built environment, it is considered that SHECMOBS, the top-down cross-sector gas consumption model described in Chapter 2 performs just this task. Obviating the need to use incomplete or outdated data of uncertain quality deriving from a bottom-up analysis of a sample set of buildings which may or not be representative of the building stock, SHECMOBS relies on only temperature data and national gas consumption data, both of which have been regionalised to a very high degree. With the coefficients of determination of the 13 segmented regression analyses examining the past correlation between effective temperature and gas consumption averaging at 0.95, the method used by SHECMOBS to predict future levels of space heating energy consumption, involving application of the resulting 13 algorithms to UKCP09-generated future climate data as projected by UKCP09, is considered both appropriate and statistically robust.

The forecasts made by SHECMOBS reveal a diminution in the level of space heating as the century progresses, with a somewhat larger than anticipated reduction in the near term irrespective of which particular emissions pathway is followed. Despite the fact that the greater impact of climate change is not forecast as occurring until the latter part of the century, a reduction of between 11 and 12% is forecast by the 2030s compared to the generally relatively warm period 2000-10. (When

compared to the more recent but unusually cold period of 2008-2010, the reduction by the 2030s is between 17 and 18%.) A reduction of 16-22% is forecast by the 2050s, depending upon whether a low or high emissions pathway is followed (22-28% reduction with reference to 2008-10). By the 2080s the full impact of climate change begins to reveal itself, with the 23% reduction forecast under a low emissions scenario comparing to the 41% reduction forecast under a high emissions scenario (28-45% reduction with reference to 2008-10).

The value of SHECMOBS is twofold.

i. It gives an indication of the effect of climate change on our buildings in way that it immediately understandable, since the percentage change in consumption is the same as the percentage change in demand. An increase in temperature of $x\,^0$C by 2050 is intangible, an intrinsically difficult concept to understand, whereas a 16-22% reduction in the demand for space heating is immediately more arresting since it is something that we can understand. Knowledge that climate change is so large that space heating demand is likely to reduce by about a fifth by 2050, whichever particular emissions scenario is followed, is more likely to engage a sometimes sceptical public, to draw attention to the fact that climate change is real and close at hand.
ii. More importantly from an academic point of view, its output can be used to amend the DECC 2050 Calculator, so that changes in actual levels of consumption and emissions can be forecast.

SCECMORS

Although it is to be anticipated that a future warmer climate is likely to increase the demand for mechanical space cooling in the absence of measures designed to promote passive cooling systems, there are too few data to construct a cooling model along the lines of SHECMOBS. Whilst the level of space cooling in the residential sector has historically been so low as to prevent the discernment of a relationship between air temperature and energy consumption, space cooling in the service sector is also driven by factors other than climate, making the discernment between demand and air temperature difficult: 9% of electricity consumption in the service sector already derives from cooling and ventilation, with the penetration rate of air-conditioning in the commercial market being estimated at 42%, despite the present relatively cool climate.

Data from North America, however, suggest a pathway of uptake which residential air-conditioning may follow, data from the US showing that the long-term response (arising from increased penetration levels) is a more important factor than the short-term response (deriving from increased use of the existing stock) for relatively cool climates such as that of the UK. Using data from Canada, the current summer temperatures in which are similar to those forecast for the UK over the coming decades of the century, and penetration levels in which show a reasonable degree of correlation with the number of CDDs, SCECMORS estimates levels of space cooling energy consumption in the residential stock in a future warmer climate. (Since the Canadian penetration data derive from two independent surveys performed at different times and bear close resemblance, and since the number of CDDs are population weighted at a regional or provincial level to a very high degree, the Canadian data are regarded as being reliable surrogate data.) Although the SCECMORS forecasts

that penetration levels may increase markedly, data from elsewhere has shown that this is quite possible, with the level of air-conditioning in the US rising to almost 60% from less than 2% in less than 25 years, and with the number of air-conditioning units rising from 0.34 to 112.07 per 100 urban households in China over the course of 20 years.

Although SCECMORS is the generic term used to describe the space cooling model which estimates energy consumption in the residential sector, the bottom-up model actually comprises two sub-models, each performing the same task, but using different base units from which to build upwards. Whilst SCECdwell uses the dwelling as the base unit, SCECair uses the air-conditioner as the base unit, the constitution of each sub-model having been determined following an extensive review of the literature, but with each sub-model sharing common penetration levels based on the Canadian data.

Despite the very different methods each sub-model uses to calculate future levels of space cooling energy consumption, the sub-models' estimates are remarkably similar, differing by no more than 26% when compared on a like-for-like basis. In consideration of the fact that each sub-model contains a number of assumptions, the difference is not considered unduly large, especially since the actual levels of energy consumption forecast are so small in comparison to that deriving from space heating. Under a medium emissions scenario, penetration levels could reach 45-52% by the 2050s, resulting in a level of space cooling energy consumption which is the equivalent to 0.3-0.5% the quantity of energy used for space heating in the built environment in 2011[235]; and allowing for an approximate doubling in EER from the modelled value of 2.91 to a value of between 6 and 7 as is forecast for 2050, the approximate doubling in consumption still remains very low. Alternatively worded, if we were to follow the Canadian experience of uptake of air-conditioning, where half of all homes installed some sort of air-conditioning, under an average climate for a medium emissions scenario space cooling energy consumption in 2050 is likely to be of the order of 1% that currently used for space heating,. The data suggest that in spite of the anticipated large increase in ownership of air-conditioning, the level of space cooling energy consumption remains modest simply because the weather is unlikely to be sufficiently hot to warrant their use more often than occasionally. This finding is in keeping with data from Massachusetts, one of the less hot states of the US even though its current climate is considerably warmer than the climate forecast for the UK in the 2050s, in which latter climate the difference between ownership and use is likely to be very much higher than that in Massachusetts[236]. Like SHECMOBS, however, its greatest value lies in its application to future climates and different pathways as modelled in the DECC 2050 Calculator.

---

[235] 0.3% estimate derives from minimum SCECair estimate of 1,386 GWh; 0.5% estimate derives from maximum SCECdwell estimate of 2,128 GWh. (Space heating energy consumption across built environment in 2011: 399,540 GWh (DECC, 2012h)).

[236] The difference between ownership and use levels of air-conditioning in Massachusetts amounts to 12%. Whilst the Massachusetts climate returns 280 CDDs, the medium emissions scenario for the 2050s for Great Britain returns only 127 CDDs (base temperature 18.3 ^{0}C).

Adaptive Comfort Degree-Day Model

The threat posed by the expansion of air-conditioning, alongside the recognition that it may be avoided in many instances, has led to a renewed interest in the AACT as a means of reducing space cooling GHG emissions in the service sector in particular, its great benefit being that it remains a zero energy means of achieving thermal comfort despite increasing outdoor air temperatures.

The difficulty faced by facilities managers and designers in the UK who wish to avail of the AACT is that the two adaptive standards from which they can choose, the European adaptive standard EN 15251 and the ASHRAE adaptive standard 55, set different temperature limits, the necessary corollary of which is that they set different standards of thermal comfort, even though each is deemed to be satisfactory. The novel metric, the ACDD, has been developed as a means of comparing the two standards, allowing one to compare the maximum potential energy savings deriving from use of comparable versions of each[237]. Deriving from the same theory underpinning the conventional degree-day used by energy managers to estimate levels of space heating and space cooling, a series of modelling experiments performed on a set of office buildings has substantiated the validity of the ACCD concept as a metric for energy consumption: the coefficient of determination in 50 regression analyses investigating the correlation between the number of ACDDs and energy savings averages at 0.97. Of particular note are the findings that the ACDD's predictive capacity to estimate space cooling load is little affected by the fact that ACDD theory takes no direct account of the latent component which contributes towards the overall space cooling load, and that levels of fenestration and thermal responsiveness similarly little affect its predictive capacity.

When applied to a range of future climates, the ACDD data indicate that potential space cooling energy savings arising from use of the European adaptive standard are considerably more than those arising from use of its ASHRAE counterpart. The difference resides in the issue of compliance, where the higher upper temperature limits of the European adaptive standard make it available for use in a greater number of buildings, these additional buildings being barred from employing the AATC by the ASHRAE adaptive standard because of breach of its temperature limits. Such is the difference in the stringency applied by the two adaptive standards that potential space cooling energy savings achieved by the European adaptive standard in any particular decade are not matched by its ASHRAE equivalent until decades later. In view of the urgency attached to the speed at which carbon emissions must decrease if society is not to suffer the more extreme, deleterious consequences of climate change ,the benefits conferred by the EAS are clear. (The future climate data also reveal, however, that winter temperatures are unlikely to be sufficiently high, at least for the greater part of the century, to invoke use of an adaptive standard.)

It remains unclear why the two adaptive standards should set such different upper temperature limits (varying by about 0.8-1.0 ^{0}C) which result in such different levels of potential savings, with differences in both the sample groups and methodologies used to draw up each standard being explored. The difference is a cause for concern because, despite the methodological probity applied by both groups of authors in the establishment of neutral temperatures underlying each adaptive standard, such disparity lays the AATC bare to attack from critics citing a lack of understanding of the finer detail of the AATC as the root cause of the discrepancy.

---

[237] viz. ASHRAE adaptive standard 55 (80% acceptability) (AAS) and the European 15251 adaptive standard (Category II) (EAS).

With regard to its application to the DECC 2050 Calculator, its use is implicitly understood as constituting the means by which space cooling is achieved in the residential sector of the MARKAL and Renewables pathways, these being the two sectors which do not use mechanical cooling systems.

DECC 2050 Calculator

As useful as the information regarding space heating, space cooling and the AATC are, in isolation they are of only limited value in attempting to describe a future which has yet to write itself. Their greatest value lies in the contribution that they make to the government's DECC 2050 Calculator, a coherent, cross-sector, open access tool examining alternative pathways which result in an 80% reduction of GHG emissions. Its key importance lies in the way it allows alternative visions of the future to be projected because so many of the factors which will decide whether or not we are successful in achieving the target have yet to be decided. However, when loaded with correctly-weighted temperatures for its reference year of 2007 and its output for residential space heating consumption is compared against (i) official government statistics for 2007, and (ii) SHECMOBS forecast for a reduction in levels of space heating (2007-2050s), it is seen to under-estimate the former and over-estimate the latter. With outdoor air temperature greatly affect space heating energy consumption as shown by SHECMOBS, and with 15.5% of emissions currently derive from space heating, the need to use as accurate temperature data is clear, since it could result in pathways, presently described as successfully achieving the 80% reduction target, failing. Moreover, it is important to test pathways in a number of different future climates, rather than the single climate used in the Calculator, one based on temperature projections at the 50% probability level under a medium emissions scenario. When the DECC 2050 Calculator is re-run as both a Basic Model and as an Adjusted Model (where remedial action is taken so that its output accords with government statistics and SHEMOBS), it is seen that four widely divergent pathways result in four different levels of space cooling energy consumption. The Adjusted Model forecasts a reduction in space heating consumption of 44-87%, and the Basic Model forecasts one of 71-94%. This is not unexpected in view the fact neither the average indoor temperature nor heating technologies are consistent across all pathways. Of more significance is the finding that differences in future climates for 2050 little affect residential space heating energy consumption. Comparing extremes, the 30th percentile/medium emissions scenario with the 90th percentile/high emissions scenario, the difference averages at 3%, extending to a maximum of 7.5%.

Space cooling is still seen to be dominated by the he commercial sector in 2050. Whilst the Basic Model estimates a maximum increase in space cooling energy consumption from today's present value of near zero up to 4.5 TWh and the Adjusted Model forecasts a rise of up to 2.5 TWh, these compare with the forecasts of 14-48 TWh for 2050 for the commercial sector.

Despite the wide range of consumptions forecast for the residential stock for 2050, all the pathways initially prescribed as successfully achieving the 80% reduction in emissions, achieve a reduction of at least 79.7%. What is more, they continue to remain successful across eight future climates ranging from the 30th percentile medium emissions scenario to the 90th percentile high emissions scenario, their continued success mostly deriving from their reliance on electricity to provide space heating allied with its low emissions intensity.

The Adjusted Model suggests that generational capacity may have to be increased in order to meet the extra demand for space heating in the built environment, the shortfall between the Adjusted Model and the Basic Model ranging between 58 and 99 TWh for the heating season, depending upon which particular pathway is followed.

7 Bibliography

AEA, 2011. *Evaluation of the climate risks for meeting the UK's carbon budgets,* Didcot : AEA Technology plc (prepared by AEA Technology plc under contract to Committee on Climate Change).

ARCC, 2012. *COPSE: Coincident Probabilistic climate change weather data for a Sustainable built Environment.* [Online]
Available at: http://www.arcc-cn.org.uk/project-summaries/copse/
[Accessed 12 June 2012].

ASHRAE, 2004. *ANSI/ASHRAE standard 55-2004. Thermal Environmental Conditions for Human Occupancy,* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Biddle, J., 2008. Explaining the spread of residential air conditioning, 1955–1980. *Explorations in Economic History,* 45(4), pp. 402-423.

BRE, 2008. *Domestic Energy Fact File 2008,* Watford: Building Research Establishment.

BRE, 2011. *The Goverment's Standard Assessment Procedure fro Energy Rating of Dwellings,* Watford: Building Research Establishment.

British Gas, 1987. *Temperature/Demand Methodology for Planning Purposes - The TD76 Code of Practice,* s.l.: British Gas.

Bruhns, H., 2000. Property taxation for nondomestic buildings in England and Wales. *Environment and Planning B: Planning and Design B,* 27(1), pp. 33-49.

Bruhns, H., 2008. *Identifying determinants of energy use in the UK nondomestic stock.* Frankfurt, In: Improving Energy Efficiency in Commercial Buildings Conference, Building Performance Congress 2008, 10-11 April. Brussels: European Commission Joint Research Centre - Institute for Energy.

Bruhns, H., Steadman, P. & Herring, H., 2000b. A database for modeling energy use in the non-domestic building stck of England and Wales. *Applied Energy,* 66(4), pp. 277-297.

Bruhns, H. et al., 2000a. Types, numbers, and floor areas of nondomestic premises in England and Wales, classified by activity. *Environment and Planning B: Planning and Design,* 27(5), pp. 641-665.

Bruhns, H., Steadman, P. & Marjanovic, L., 2006. *A preliminary model of non-domestic energy use for England and Wales.* London, In: Proceedings of the Annual Research Conference of the Royal Institution of Chartered Surveyors Cobra 2006, 7-8 September 2006. London: RICS.

BSRIA, 2011. *World air conditioning - United Kingdom,* Bracknell: Building Services Research and Information Association.

California Energy Commission, 2010. *Residential Appliance Sauration Survey.* [Online]
Available at: http://www.energy.ca.gov/appliances/rass/
[Accessed 3 April 2012].

Carbon Trust, 2005. *Energy Saving Fact Sheet - Air Conditioning,* London: Carnpn Trust.

CEN/BSI, 2005/2006. *BS EN ISO 7730:2005. Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local comfort criteria,* Brussels/London: Comité Européen de Normalisation/British standards Institution.

CEN/BSI, 2007/2008. *BS EN 15251:2007. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics,* Brussels/London: Comite Europeen de Normalisation/British Standards institution.

CIBSE, 2006. *Degree-days: theory and application,* London: Chartered Institution of Builidng Services Engineers.

CIBSE, 2006. *Degree-days: theory and application,* London: Chartered Institution of Building Services Engineers.

CIBSE, 2007. *Environmental design - CIBSE Guide A.* London: Chartered Insitution of Building Services Engineers.

Climate Change Act, 2008. *Chapter 27,* Norwich: The Stationery Office.

Climatic Research Unit, 2010. *The Climatic Research Unit.* [Online]
Available at: http://www.cru.uea.ac.uk
[Accessed 21 December 2010].

Coley, D. & Kershaw, T., 2010. Changes in internal temperatures within the built environmetn as a response to a changing climate. *Building and Environment,* 45(1), pp. 89-93.

Collins, L., Natarajan, S. & Levermore, G., 2010. Climate change and future energy consumption in the UK housing stock. *Building Services Engineering Research and Technology s,* 31(1), pp. 75-90.

DCLG, 2010. *Live tables on household projections.* [Online]
Available at:
http://www.communities.gov.uk/housing/housingresearch/housingstatistics/housingstatisticsby/householdestimates/livetables-households/
[Accessed 31 July 2012].

DCLG, 2011. *English Housing Survey Housing Stock Report 2009.* [Online]
Available at: http://www.communities.gov.uk/publications/corporate/statistics/ehs2009stockreport
[Accessed 17 April and 29 July 2012].

DCLG, 2012a. *English Housing Survey - Headline Report 2010-11,* London: Department for Communities and Local Government.

DCLG, 2012b. *Housing - Live tables on dwelling stock (including vacants).* [Online]
Available at:
http://www.communities.gov.uk/housing/housingresearch/housingstatistics/housingstatisticsby/stockincludingvacants/livetables/
[Accessed 11 April 2012].

de Dear, R., 2007. *Adaptive Comfort Applications in Australia and Impacts on Building Energy Consumption.* Sendai, In: The 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings (IAQVEC), Oct. 28 - 31.

de Dear, R. & Brager, G., 2002. Thermal comfort in naturally-ventilated builidngs: revisions to ASHRAE standard 55. *Energy and Buildings,* 34(6), pp. 549-561.

de Dear, R. & Schiller Brager, G., 1998. Developing and Adaptive Model of Thermal Comfort Preference. *ASHRAE Transactions,* 104(1a), pp. 145-167.

DECC, 2010a. *2050 Pathways Analysis,* London: DECC.

DECC, 2011,19Aug. *2011 Guidelines to DEFRA/DECC's GHG Conversion Factors for Company Reporting,* London: DEFRA/DECC.

DECC, 2011a. *2050 Pathway Analysis - Response to the Call for Evidence - March 2011 - Part 1,* London: DECC.

DECC, 2011b. *2050 Pathways Analysis - Response to the Call for Evidence - March 2011 - Part 2,* London: DECC.

DECC, 2011c. *Planning our electric future: a White Paper for secure, affordable and low-carbon electricity,* Norwich: The Stationery Office.

DECC, 2011d. *Energy Consumption in the United Kingdom.* [Online]
Available at: http://www.decc.gov.uk/en/content/cms/statistics/publications/ecuk/ecuk.aspx
[Accessed 3 March, 16 May, 21 May, 22 May, 26 May, 28 May 2012].

DECC, 2011e. *Digest of United Kingdom Energy Statistics 2011.* Norwich: The Stationery Office.

DECC, 2011f. *Total Energy Statistics.* [Online]
Available at:
http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/source/total/total.aspx#
[Accessed 21 May 2012].

DECC, 2011g. *The Carbon Plan: Delivering our low carbon future,* London: DECC.

DECC, 2012b. *Sub-National Electricity Consumption Data.* [Online]
Available at:
http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/regional/electricity/electricity.aspx
[Accessed 28 May 2012].

DECC, 2012c. *UK Emissions Statistics.* [Online]
Available at:
http://www.decc.gov.uk/en/content/cms/statistics/climate_stats/gg_emissions/uk_emissions/uk_emissions.aspx#
[Accessed 15 July 2012].

DECC, 2012d. *Downstream Gas Statistics - data sources and methodologies.* [Online]
Available at: http://www.decc.gov.uk/assets/decc/Statistics/source/gas/368-gas-downstream-

statistics-methodology.pdf
[Accessed 20 August 2012].

DECC, 2012e. *Gas production and trade - upstream gas methodology note.* [Online]
Available at: http://www.decc.gov.uk/assets/decc/Statistics/source/gas/61-gas-upstream-statistics-methodology.pdf
[Accessed 23 May 2012].

DECC, 2012f. *2050s Pathways Analysis - The 2050 Challenge.* [Online]
Available at: http://www.decc.gov.uk/en/content/cms/tackling/2050/2050.aspx
[Accessed 16 July 2012].

DECC, 2012g. *Gas Statistics.* [Online]
Available at: http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/source/gas/gas.aspx
[Accessed 23 May 2012].

DECC, 2012h. *Energy consumption in the United Kingdom.* [Online]
Available at: http://www.decc.gov.uk/en/content/cms/statistics/publications/ecuk/ecuk.aspx
[Accessed 30 July, 11 July, 12 September, 14 September 2012].

DECC, 2012i. *Domestic Consumption in the UK (2012 update).* [Online]
Available at: https://www.gov.uk/government/publications/energy-consumption-in-the-uk
[Accessed 1 February 2013].

DECC, 2012i. *Electricity statistics.* [Online]
Available at:
http://www.decc.gov.uk/en/content/cms/statistics/energy_stats/source/electricity/electricity.aspx
[Accessed 3 March, 14 September 2012].

DECC, 2012j. *United Kingdom Hhousing energy fact file,* London: DECC.

DECC, 2013. *Table 1.1.9 Mean air temperatures (averages), 1970 to 2011 Great Britain.* [Online]
Available at: https://www.gov.uk/government/statistical-data-sets/dukes-2012-weather-statistics
[Accessed 31 January 2013].

DECC, 27/9/2011. *Great Britain's housing energy fact file 2012,* London: DECC.

DEFRA, 2009. *Saving Energy Through Better Products and Appliances,* London: DEFRA.

Desert Research Institute, 2012. *Climate of California.* [Online]
Available at: http://www.wrcc.dri.edu/narratives/CALIFORNIA.htm
[Accessed 4 September 2012].

DGTREN, 2008. *Preparatory study on the environmental performance of residential room conditioning appliances (airrco and ventilation),* unknowm location: Service Contract to Directorate-General for Mobility and Transport (European Commission).

Eames, M., Kershaw, K. & Coley, D., 2011. On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology,* 32(2), pp. 127-142.

ECI, 2010. *Degree days for energy management.* [Online]
Available at: http://www.eci.ox.ac.uk/research/energy/degreedays.
[Accessed 24 January 2011].

ECI, 2010. *Degree days for energy management.* [Online]
Available at: http://www.eci.ox.ac.uk/research/energy/degreedays.php
[Accessed 24 January 2011].

EIA, 2000. *Trends in Residential Air-Conditioning Usage from 1978 to 1997.* [Online]
Available at: http://www.eia.gov/emeu/consumptionbriefs/recs/actrends/recs_ac_trends.html
[Accessed 27 January 2012].

EIA, 2004. *Residential Energy Consumption Survey 2001 - Housing Characteristics Data Tables.*
[Online]
Available at: http://www.eia.gov/emeu/recs/recs2001/detail_tables.html
[Accessed 27 January 2012].

EIA, 2009. *2005 Residential Energy Consumption Survey--Detailed Tables.* [Online]
Available at: http://205.254.135.7/emeu/recs/recs2005/hc2005_tables/detailed_tables2005.html
[Accessed 27 January 2012].

EIA, 2012. *Residential Energy Consumption Survey (RECS).* [Online]
Available at: http://205.254.135.7/consumption/residential/data/2009/#undefined
[Accessed 23 March, 10 May 2012].

European Commission, 2002. *Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings,* Brussels: European Commission.

European Commission, 2005. *Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products and amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC,* Brussels: European Commission.

European Commission, 2011. *Commission Communication in the framework of the implementation of Commission Regulation (EU) No 206/2012 of 6 March 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for air ....*
[Online]
Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2012:172:0001:01:EN:HTML
[Accessed 28 August 2012].

European Commission, 2012. *Energy efficiency - Studies - Eco-design.* [Online]
Available at: http://ec.europa.eu/energy/efficiency/studies/ecodesign_en.htm
[Accessed 26 March 2012].

Fanger, P., 1972. *Thermal Comfort.* American edition ed. Copenhagen: McGraw-Hill Book Company.

Fotoh, C. et al., 2008. Cutaneous differences between Black, African or Caribbean Mixed-race and Caucasian women: biometrological approach of the hydrolipidic film. *Skin research and Technology,* 14(3), pp. 327-33.

Gakovic, B., 2000. Areas and types of glazing and other openings in the nondomestic building stock. *Environment and Planning B: Planning and Design,* 27(5), pp. 667-694.

Guertler, P. & Pett, J., 2008. *Cold Comfort for Kyoto:the link between air conditioning in commercial buildings and consumer lifestyle choices.* Frankfurt, In: Bertoldi, P., Atanasiu, B., eds. Proceedings of 5th Int. Conference on Improving Energy Efficiency in Commercial Buildings: IEECB Focus 2008, 10-11 April 2008 . Luxembourg: Office for Official Publications of the European Communities, 279-290.

He, J., Young, A. N., Pathan, A. & Oreszczyn, T., 2006. *Air conditioning energy use in houses in southern England.* Athens, In: Bloem, J. J. and Sutherland, G., eds. Proceedings of DYNASTEE 2005. Luxembourg: Office for Official Publications of the European Communities, 1 - 12.

Henderson, G., 2005. *Home air conditioning in Europe - how much energy would we use if we became more like American households?.* Mandelieu La Napoule, France, In: Attali, S., Tillerson, K., eds. Energy Savings: What Works and Who Delivers? ECEEE 2005 Summer Study, 30 May-4 June. Stockholm: European Council for an Energy Efficient Economy.

Hinnells, M., Layberry, R., Curtis, D. & Shea, A., 2008. *Transforming UK non-residential buildings:achieving a 60% cut in CO2 Emissions by 2050.* Frankfurt, In: Bertoldi, P. Atanasiu, B., eds. Proceedings of the 5th International Conference on Improving Energy Efficiency in Commercial Buildings: IEECB Focus 2008. Luxembourg: Office for Official Publications of the European Communities.

Humphreys, M. & Nicol, J., 2000. Effects of measurement and formulation error on thermal comforet indices in the ASHRAE database of field studies. *ASHRAE Transactions,* 106(2), pp. 493-502.

IPCC, 2000. *Special Report on Emissions Scenarios,* Cambridge: Cambridge University Press.

IPCC, 2007. Summary for Policymakers. In: S. Solomon, et al. eds. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK and New York, USA: Cambridge University Press.

Layberry, R. & Hinnells, M., 2007. *Transforming UK non-residential buildings: achieving a 60% cut in CO2 emissions by 2050.* La Colle sur Loup, France, In: Attali, S., Tillerson, K., eds. Saving energy - just do it! ECEEE 2007 Summer Study, 4-9 June. Stockholm: European Council for an Energy Efficient Economy .

Levermore, G. et al., 2012. *Deriving and using future weather data for building design from UK climate change projections – an overview of the COPSE Project,* Manchester, UK.: University of Manchester.

McGilligan, C., Natarajan, S. & Nikolopoulou, M., 2011a. Adaptive Comfort Degree-Days: A metric to compare adaptive comfort standards and estimate changes in energy consumption for future UK climates. *Energy and Buildings,* 43(10), pp. 2767-2778.

McGilligan, C., Natarajan, S. & Nikolopoulou, M., 2011b. *Comparison of energy savings achievable by adaptive comfort standards using the Adaptive Comfort Degree Day..* Brno, 2011, SOLARIS 2011 - Proceedings of the 5th International Conference on Solar Radiation and Daylighting,10–11 August 2011 Brno University of Technology, Czech Republic.

McGilligan, C., Natarajan, S. & Nikolopoulou, M., 2011c. *Use of Adaptive Comfort Degree-Days to compare energy savings from adaptive comfort standards for future UK climates.* Leicester, UK, CIBSE Technical Symposium, 6th and 7th September 2011 De Montfort University, Leicester,.

Morley, 2005. *Volume No. 434, Part No. 82, Written answers to Questions (7 June 2005) - Environment, Food and Rural Affairs (7 June 2005).* [Online]
Available at:
http://www.publications.parliament.uk/pa/cm200506/cmhansrd/vo050607/text/50607w05.htm#50 607w05.html_sbhd7
[Accessed 20 March 2012].

Mortimer, N., Ashley, A. & Rix, J., 2000a. Detailed energy surveys of nondomestic buildings. *Environment and Planning B: Planning and Design,* 27(1), pp. 25-32.

Mortimer, N., Maha, E. & Grant, J., 2000b. Patterns of energy use in nondomestic buildings. *Environment and Planning B: Planning and Design,* 27(5), pp. 709-720.

MTP, 2012. *Market Transformation Programme.* [Online]
Available at: http://efficient-products.defra.gov.uk/cms/
[Accessed 22 March 2012].

Muggeo, V., 2012. *Package 'segmented'.* [Online]
Available at: http://cran.r-project.org/web/packages/segmented/segmented.pdf
[Accessed 6 June 2012].

Nakano, J., Tanabe, S. & Kimura, K., 2002. Differences in perception of indoor environment between Japanese and non-Japanese workers. *Energy and Buildings,* 34 (6), p. 615–621.

Natarajan, S. & Levermore, G., 2007. Predicting future UK housing stock and carbon emissions. *Energy Policy,* 37(11), pp. 5719-5727.

National Bureau of Statistics of China, 2011. *China Statistical Yearbook 2011.* [Online]
Available at: http://www.stats.gov.cn/tjsj/ndsj/2011/indexeh.htm
[Accessed 26 March 2012].

National Grid, 2007. *Gas Demand Forecasting Methodology,* s.l.: National Grid.

National Grid, 2011. *Seasonal and Annual Data.* [Online]
Available at: http://www.nationalgrid.com/uk/Gas/Data/misc/
[Accessed 1 February 2011].

National Grid, 2012a. *Gas Demand Forecasting Methodology.* [Online]
Available at: http://www.nationalgrid.com/NR/rdonlyres/71CFD0F6-3607-474B-9F37-

0952404976FB/52071/GasDemandForecastingMethodologyFeb12.pdf
[Accessed 28 May 2012].

National Grid, 2012b. *National Grid.* [Online]
Available at: http://www.nationalgrid.com/uk/Electricity/
[Accessed 1 June 2012].

National Grid, 2012c. *Gas Consumer Information.* [Online]
Available at: http://www.nationalgrid.com/uk/Gas/
[Accessed 28 May 2011].

NCDC, 2012a. *Heating and Cooling Degree Day Data.* [Online]
Available at: http://www.ncdc.noaa.gov/oa/documentlibrary/hcs/hcs.html
[Accessed 13 February 2012].

NCDC, 2012b. *Comparative Climatic Data.* [Online]
Available at: http://ols.nndc.noaa.gov/plolstore/plsql/olstore.prodspecific?prodnum=C00095-PUB-A0001
[Accessed 24 March 2012].

NCDIA, 2012. *National Climate Data and Information Archive.* [Online]
Available at: http://www.climate.weatheroffice.gc.ca/Welcome_e.html
[Accessed 6 February 2012].

Nicol, F., 2008. *A handbook of adaptive thermal comfort – towards a dynamic model.* London: Low Energy Architecture Research Unit, London Metropolitan University.

Nicol, F. & Humphreys, M., 2010. Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Buildings and Environment,* 45(1), pp. 11-17.

Nicol, J. & Humphreys, M., 1973. Thermal comfort as part of a self-regulating system.. *Building Research and Practice,* 1(3), pp. 174-179.

NRCan, 2010. *Survey of Household Energy Use 2007,* Ottawa: Natural Resources Canada.

NRCan, 2011a. *(questions@nrcan-rncan.gc.ca), 14 November 2011,* Reply to your inquiry/Répondre à votre demande: email to C. McGilligan (cgm25@bath.ac.uk).

NRCan, 2011b. *(questions@nrcan-rncan.gc.ca), 6 December 2011,* Reply to your inquiry/Répondre à votre demande: email to C. McGilligan (cgm25@bath.ac.uk).

NRCan, 2012. *Comprehensive Energy Use Database, 1990 to 2009.* [Online]
Available at: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/comprehensive_tables/list.cfm
[Accessed 4 April, 17 September 2012].

ONS, 2012. *UK Standard Industrial Classification 2007 (UK SIC 2007).* [Online]
Available at: http://www.ons.gov.uk/ons/guide-method/classifications/current-standard-classifications/standard-industrial-classification/index.html
[Accessed 24 May 2012].

Oreszczyn, T. H. S., Ridley, I. & Wilkinson, P., 2006. Determinants of winter indoor temperatures in low income households in England. *Energy and Buildings,* 38(3), pp. 245-252.

Oxford Economics, 2008. *Review of the BERR Energy Demand Model,* Oxford: Oxford Economics.

Parker, D., Legg, T. & Folland, K., 1992. A new daily Central England Temperature Series, 1772-1991. *International Journal of Climatology,* Volume 12, pp. 317-342.

Pathan, A., Young, A. & Oreszczyn, T., 2008. *UK Domestic Air-Conditioning: A study of occupant use and energy efficiency.* Windsor, In: Proceedings of Air Conditioning and the Low Carbon Cooling Challenge, 27-29 July 2008. London: Network for Comfort and Energy Use in Buildings.

Pout, C., 2000. NDEEM: the national nondomestic buildings energy and emissions model. *Energy and Planning B: Planning and Design,* 27(5), pp. 721-732.

Pout, C., 2007. *Understanding energy use in the service sector.* Paris, In: New Energy Indicators for Buildings and Appliances: The Way Forward, 25-26 October. Paris: International Energy Agency.

Pout, C. & Hitchin, E., 2009. Future environmental impacts of room air-conditioners in Europe. *Building Research and Information,* 37(4), pp. 358-368.

Pout, C., MacKenzie, F. & Bettle, R., 2002. *Carbon dioxide emissions from non-domestic buildings: 2000 and beyond,* Watford: IHS BRE.

R Development Core Team, 2013. *The R Project for Statistical Computing.* [Online]
Available at: http://www.r-project.org/
[Accessed 8 February 2013].

Rickaby, P. & Gorgolewski, M., 2000. A classification system for services in nondomestic buildings. *Environment and Planning B: Planning and Design,* 27(5), pp. 695-708.

Sailor, D. J. & Munoz, J. R., 1997. Sensitivity of electricity and natural gas consumption to climate in the USA - methodology and results for eight states. *Energy ,* 22(10), pp. 987-998.

Sailor, D. J. & Vasireddy, C., 2006. Correcting aggregate energy consumption data to account for variability in local weather. *Environmental Modelling and Software,* 21(5), pp. 733-738.

Sailor, D. & Pavlova, A., 2003. Air conditioning maket saturation and long-term response of residential cooling energy demand to climate change. *Energy,* 28(9), pp. 941-951.

Schiller Brager, G. & de Dear, R., 2000. A Standard for Natural Ventilation. *ASHRAE Journal,* 42(10), pp. 21-28.

Scottish Government, 2012. *Housing Statistics for Scotland - Key Information and Summary Tables.* [Online]
Available at: http://www.scotland.gov.uk/Topics/Statistics/Browse/Housing-Regeneration/HSfS/KeyInfoTables
[Accessed 11 April 2012].

Sharp, G., 2012. *(gsharp@energy.ca.gov), 31 January 2012,* Re: Residential Appliance Saturation Survey: email to C.McGilligan (cgm25@bath.ac.uk).

Shorrock, L. & Dunster, J., 1997. The physically-based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK houisng stock. *Energy Policy,* 25(12), pp. 1027-1037.

Statistics Canada, 2008. *Population and Dwelling Count Highlight Tables, 2006 Cenuss.* [Online]
Available at: http://www12.statcan.gc.ca/english/census06/data/popdwell/Tables.cfm
[Accessed 6-15 February 2012].

Steadman, P., Bruhns, H. & Gakovic, B., 2000b. Inferences about built form, construction, and fabric in the nondomestic stock of England and Wales. *Environment and Planning B: Planning and Design,* 27(5), pp. 733-758.

Steadman, P., Bruhns, H., Holtier, S. & Gakovic, B., 2000a. A classification of built forms. *Environment and Planning B: Planning and Design,* 27(1), pp. 73-91.

Summerfield, A. et al., 2007. Milton Keynes Energy Park revisited: Changes in internal temperatures and energy usage. *Energy and Buildings,* 39(7), pp. 783-791.

UK Meteorological Office, 2010. *Met Office climate prediction model: HadCM3.* [Online]
Available at: http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadcm3
[Accessed 20 December 2010].

UK Meteorological Office, 2011. *MIDAS Land Surface Stations data (1853-current) - NCAS British Data Centre, 2006.* [Online]
Available at: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas
[Accessed 11 February 2011 - 18 April 2012].

UK Meteorological Office, 2012a. *Met Office Hadley Centre Central England Temperature Data.* [Online]
Available at: http://www.metoffice.gov.uk/hadobs/hadcet/data/download.html
[Accessed 3 March 2012].

UK Meteorological Office, 2012b. *UK 1971-2000 averages.* [Online]
Available at: http://www.metoffice.gov.uk/climate/uk/averages/19712000/areal/uk.html
[Accessed 24 May 2012].

UK National Statistics, 2012. *Find statistics for a local area or region in England.* [Online]
Available at: http://www.statistics.gov.uk/hub/regional-statistics/england/index.html
[Accessed 11 April 2012].

UKCP09, 2009. *UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87944&filetype=pdf
[Accessed 20 September 2012].

UKCP09, 2010. *UK Climate Projections: Briefing Report.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87867&filetype=pdf
[Accessed 22 June 2012].

UKCP09, 2011a. *Validation of Weather Generator outputs.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87941&filetype=pdf
[Accessed 25 September 2012].

UKCP09, 2011b. *An illustration of the effects of the revised Weather Generator.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/media.jsp?mediaid=87942&filetype=pdf
[Accessed 25 September 2012].

UKCP09, 2012a. *Wind or Wind speed.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/23197
[Accessed 22 June 2012].

UKCP09, 2012b. *Contributors.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/21691
[Accessed 22 June 2012].

UKCP09, 2012c. *Emissions Scenarios.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/23198
[Accessed 23 June 2012].

UKCP09, 2012d. *Online Weather Generator Report.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/22586
[Accessed 23 June 2012].

UKCP09, 2012e. *About the Climate change projections.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/22537
[Accessed 22 June 2012].

UKCP09, 2012f. *Home.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/
[Accessed 22 June 2012].

UKCP09, 2012G. *Maps and key findings.* [Online]
Available at: http://ukclimateprojections.defra.gov.uk/21708
[Accessed 10 2 2013].

United Nations Statistics Division, 2010. *Environmental Indicators.* [Online]
Available at: http://unstats.un.org/unsd/environment/air_greenhouse_emissions.htm
[Accessed 19 September 2012].

US Census Bureau, 2011. *The 2012 Statistical Abstract - The National Data Book.* [Online]
Available at: http://2010.census.gov/2010census/
[Accessed 25 January 2012].

US Department of Energy, 2008. *Building Energy Software Tools Directory - IWEC.* [Online]
Available at:
http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=369/pagename=alpha_list
[Accessed 22 December 2010].

Watkins, R., Levermore, G. & Parkinson, J., 2011. Constructing a future weather file for use in building simulation using UKCP09 projections. *Building Services Engineering Research and Technology,* 32(3), pp. 293-299.

Watkins, R., Palmer, J., Kolokotroni, M. & Littlefair, P., 2002. The London Heat Island:results from summertime monitoring. *Building Services Engineering Research and Technology,* 23(2), pp. 97-106.

Welsh Assembly Government, 2011. *Dwelling Stock Estimates, 2009-10,* Cardiff: Welsh Assembly Government.

Wu, A. & Pett, J., 2006. *Cold Comfort for Kyoto?,* London: Association for the Conservataion of Energy.

Yohanis, G. & Modol, J., 2010. Annual variations of temperature in a sample of UK dwellings. *Applied Energy,* 87(2), pp. 681-690.

Appendix 1: CaRB Results

The CaRB data for the industry sector report building-related energy consumption for England and Wales. DUKES data for the industry sector report the total of (i) process energy and (ii) building-related energy for the UK. Figure 53 shows the CaRB model data for 2004 and compares these data with actual Government DUKES statistics for 2004 (Bruhns, 2008).
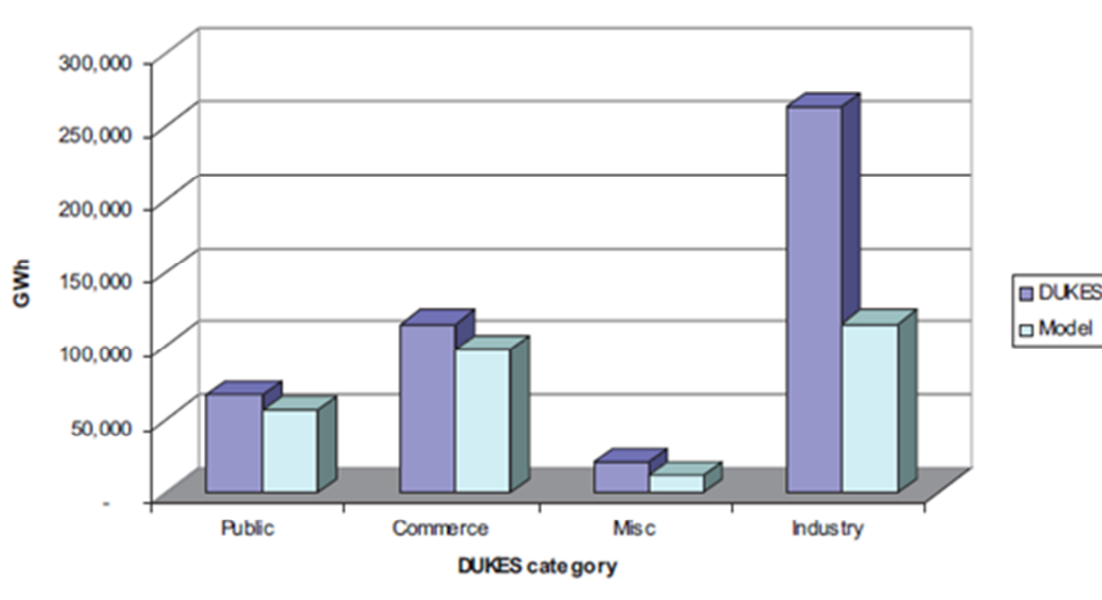
Figure 53 Comparison of energy consumption by as calculated by CaRB model with Government DUKES data (2004) (Bruhns, 2008)

Re-visiting the actual DUKES data for 2004 (DECC, 2011f) reveals a discrepancy, however, between the actual (correct) DUKES data and the DUKES data (apparently incorrectly) reported in Figure 53. Figure 54 shows the actual (correct) DUKES data for 2004 and reveals that whilst consumption for the public administration, commerce and miscellaneous sectors are in broad agreement with the figures reported by Bruhns (2008) in Figure 53 , the actual (correct) energy consumption for the industry sector is considerably larger[238].

---

[238] Note that the discrepancy between the figures for the industry sector does not derive from the erroneous inclusion of the power generation sector as an industry in Figure 54, but not in Figure 53: the data in Figure 54 (as for Figure 53) relate to secondary energy, not primary energy, and so transformation energy (energy lost in the in the process of converting primary fossil fuel energy to secondary energy (electricity) is not included. (Transformation losses in 2004 (620,000 GWh) dwarfed secondary energy consumption in the industry sector.)
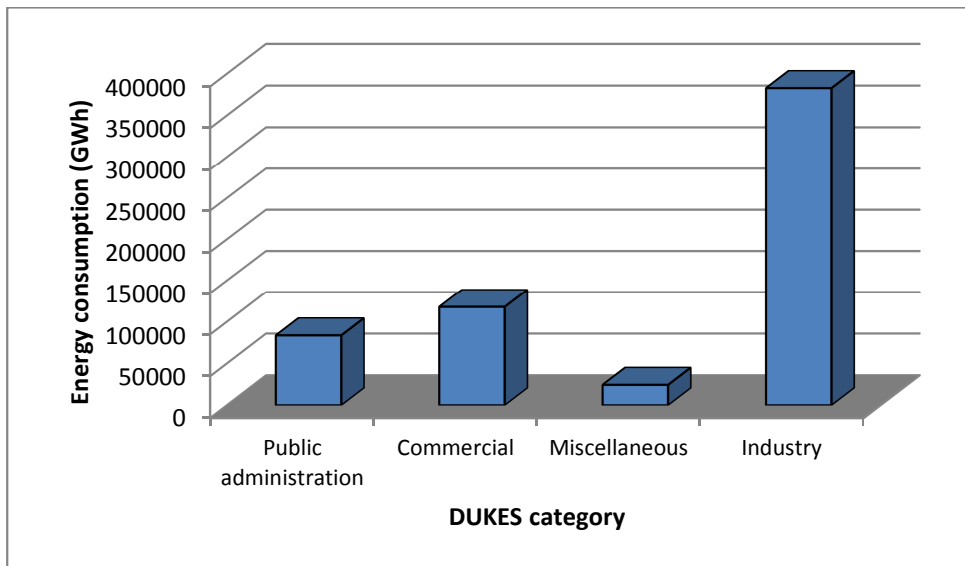
Figure 54 Actual energy consumption as reported in DUKES (2004)

Assuming that 90% of energy consumption in Great Britain occurs in England and Wales (90% of the population of Great Britain lives in England and Wales), the CaRB model estimates the building-related component of energy consumption in the industry sector at either (i) 49%[239] or (ii) 34%[240].

The possibility exists that the industry DUKES data have been updated since their initial publication in 2004, but the difference between the actual DUKES figure and the DUKES figure reported by Bruhns (2008) is so large that this is not considered likely, especially since the actual industry sector data for 2004 are of the same order as those in preceding and subsequent years. The discrepancy may be due to a simple arithmetic error; the actual DUKES data are reported in ttoe, but are converted to GWh in the Bruhns (2008) paper.

---

[239] i.e. 115,000 ÷ 260,000 ÷ 90% (where 260,000 = incorrect estimate of energy consumption in the built environment as reported in (Bruhns, 2008) (from Figure 53)
[240] i.e. 115,000 ÷ 375,000 ÷ 90% (where 375,000 = actual (correct) estimate of energy consumption in the built environment (Figure 54).

The totalled energy consumption of the four bulk activity divisions in the CaRB model (Figure 53) differs from the totalled energy consumption of the 11 primary activity classes (Figure 55) by 28%[241].
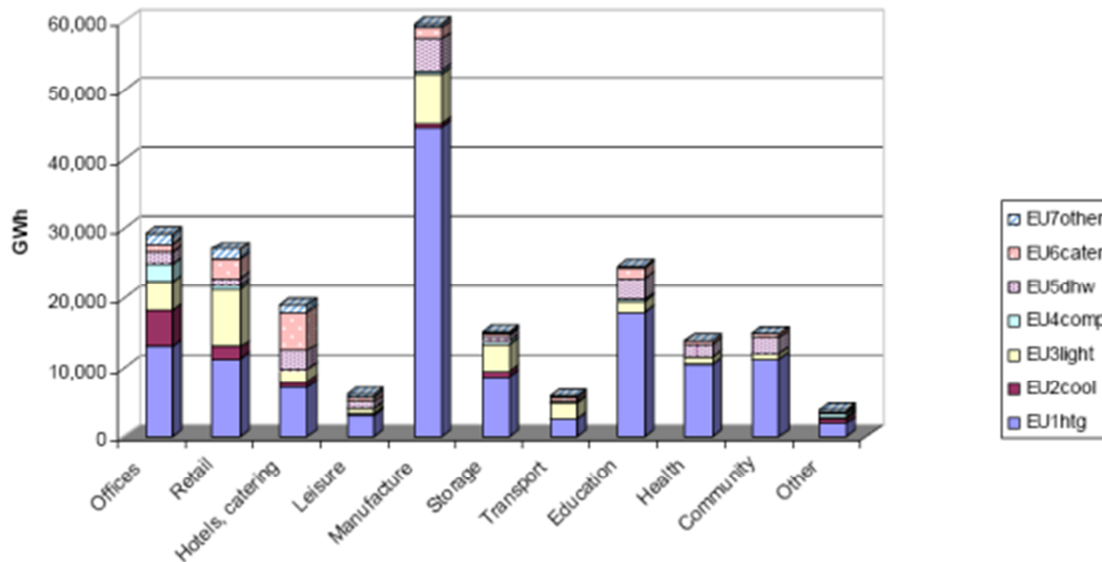
Figure 55 Energy consumption by activity class (and end-use) for England and Wales (Bruhns, 2008)

The reason for this difference is not clear, but the wording describing the energy model in Bruhns et al (2006) suggests that the energy consumption of a division (of which there are four) is calculated as the product of the floorspace and the average specific energy consumption of the division, rather than calculated as the sum of the 11 energy consumption totals from the 11 primary classes which constitute that division.

---

[241] Energy consumption of four bulk divisions: 270,000 GWh; energy consumption of 11 primary activity classes: 211,000 GWh.

Appendix 2: Approaches to Regressing Segmented Data

The following charts illustrate the importance of using the correct regression trend lines to map datum points in consumption/temperature regression plots.

Cold Weather Upturn

If a cold weather upturn exists, it is important that account is taken of it if energy consumption in a future climate is not to be over-estimated. Figure 56 shows a regression plot of consumption against temperature for the present day climate where there is a cold weather upturn.
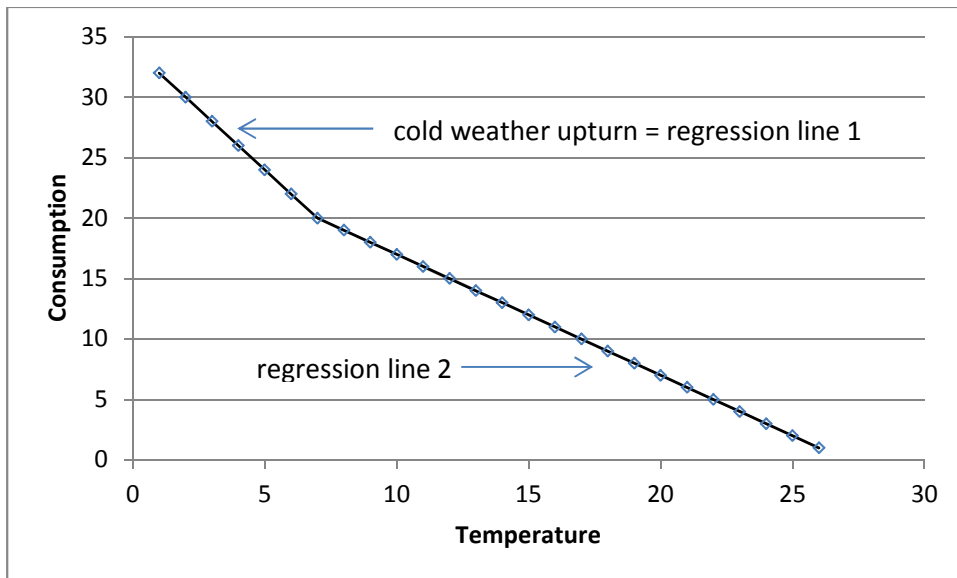
Figure 56 Plot of consumption against temperature for the present day climate showing a cold weather upturn (two regression trend lines)

Two separate regression trend lines correctly describe the regression data.

Figure 57 shows the same present day data, but a single regression trend line describes the data.
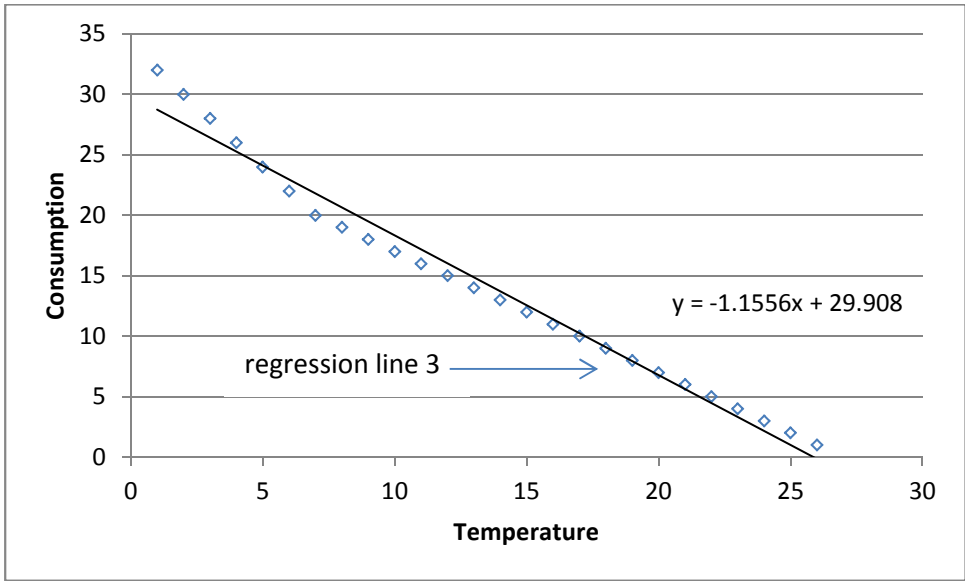
Figure 57 Plot of consumption against temperature for the present day climate showing a cold weather upturn (one regression trend line)

In Figure 57 the regression trend line under-estimates consumption for very cold and very hot temperatures but exactly balances out the under-estimation by over-estimating consumption for less cold temperatures in the mid-range. Regression line 3 has a gradient which is greater than that of regression line 2.

Figure 58 shows a future warmer climate, where there is no very cold weather and no cold weather upturn. Regression line 2 accurately maps the regression data, regression line 2 being the "normal" weather-sensitive regression trend line for temperatures in the mid-range seen in Figure 56.
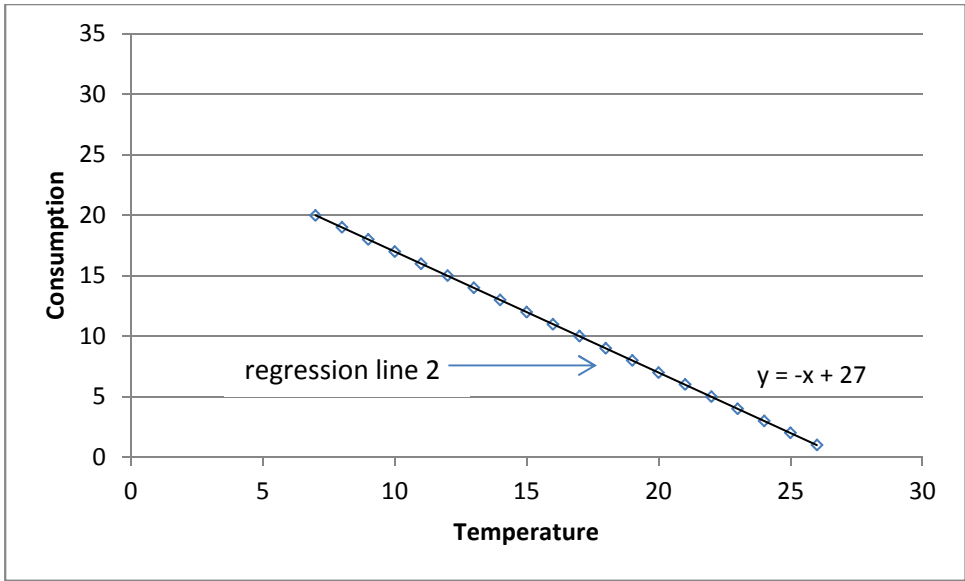
Figure 58 Plot of consumption against temperature for a future warmer climate accurately mapped by regression line 2

Figure 59 shows the same future data from Figure 58, overlaid with regression line 3 from Figure 57.

Figure 59 Plot of consumption against temperature for a future warmer climate incorrectly mapped by regression line 3

It is seen that using regression line 3 to forecast future consumption in the future warmer climate is incorrect. Consumption at low temperatures is over-estimated, but is not completely balanced by the under-estimation of consumption at higher temperatures (in the absence of the very cold weather data which were formerly also under-estimated).

Cold weather downturn
Note that exactly the same principle applies in the case where consumption is less than anticipated for very cold weather (cold weather downturn), a single regression trend line being insufficient to describe total consumption. Consumption at low temperatures is under-estimated by a single regression trend line, but is not balanced by the over-estimation of consumption at higher temperatures.

Summer cut-off
Where gas consumption levels off in warm weather, a single regression trend line constructed from present day climate data is inadequate to describe total consumption in a future warmer climate, if the regression trend line incorporates non-weather sensitive gas data.

Regression line 4 satisfactorily forecasts overall annual consumption levels in the present day climate where over-estimated data are exactly balanced by under-estimated data (Figure 60).
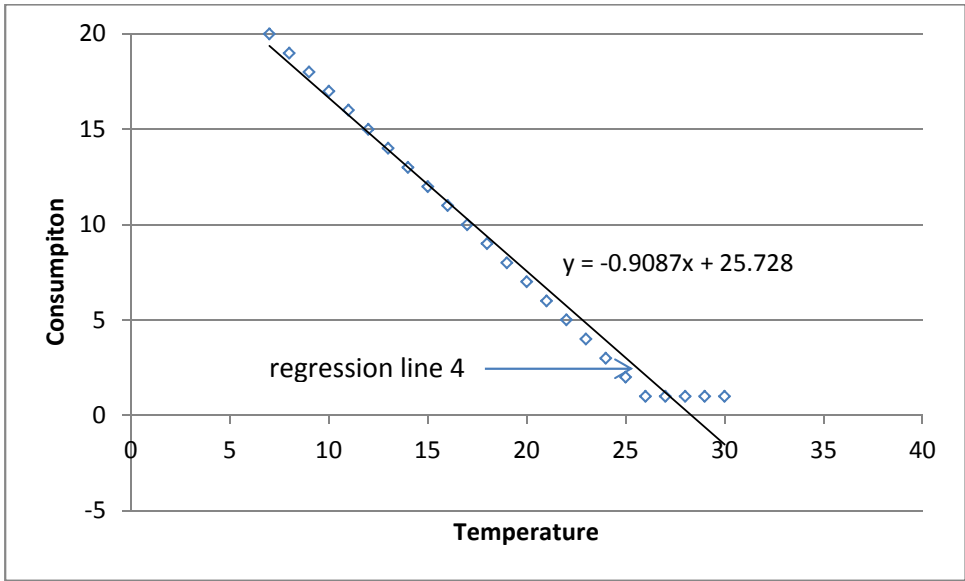
Figure 60 Plot of consumption against temperature for present day climate correctly mapped by regression line 4

In a future warmer climate, however, the distribution will not be the same, there being a higher incidence of warm temperatures; using regression line 4 to forecast future consumption levels results in an incorrect estimation of consumption levels since under-estimations are no longer balanced by over-estimations (Figure 61).
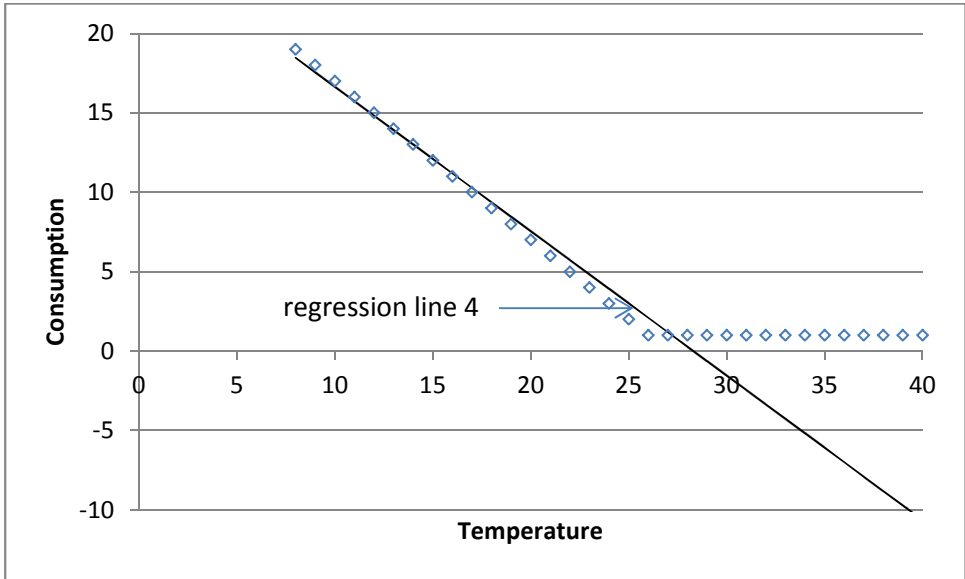
Figure 61 Plot of consumption against temperature for future warmer climate incorrectly mapped by regression line 4

The correct regression trend line (formulated from the present day climate) which can forecast future weather sensitive consumption (regression line 2) must omit the warm temperature non-weather sensitive data from its derivation (Figure 62).
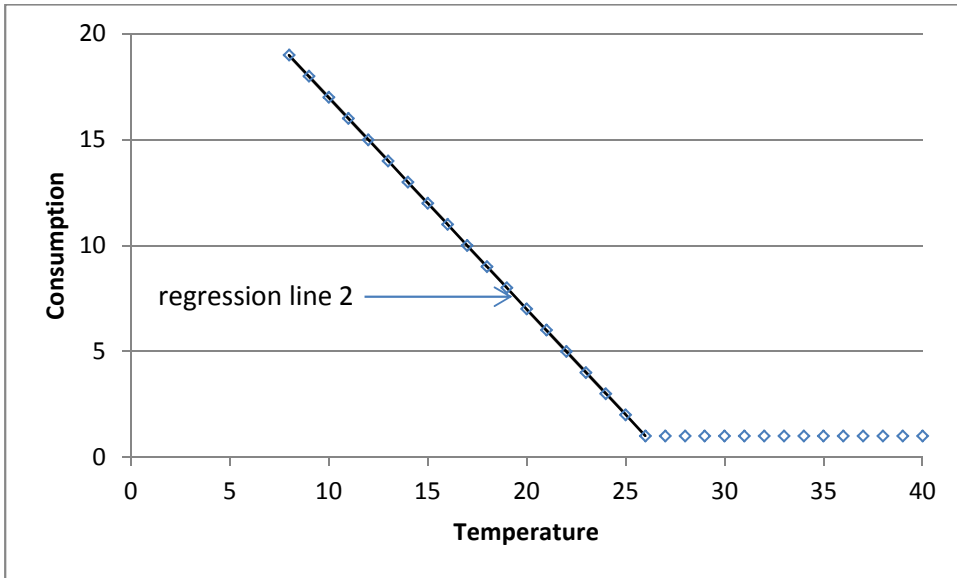
Figure 62 Plot of consumption against temperature for future warmer climate where weather sensitive consumption is correctly mapped by regression line 2

Reduced Weather Sensitivity in Warm Weather

In the case where consumption does not level off but some residual weather sensitivity remains for higher air temperatures, an additional regression trend line (regression line 5) must be used to describe consumption at these higher air temperatures (Figure 63) (c.f. cold weather upturn or cold weather downturn).
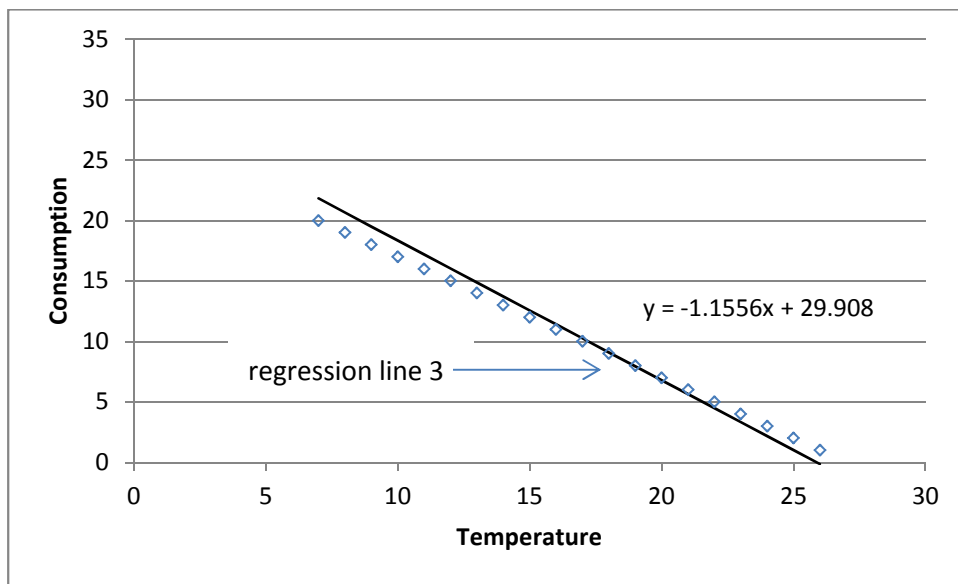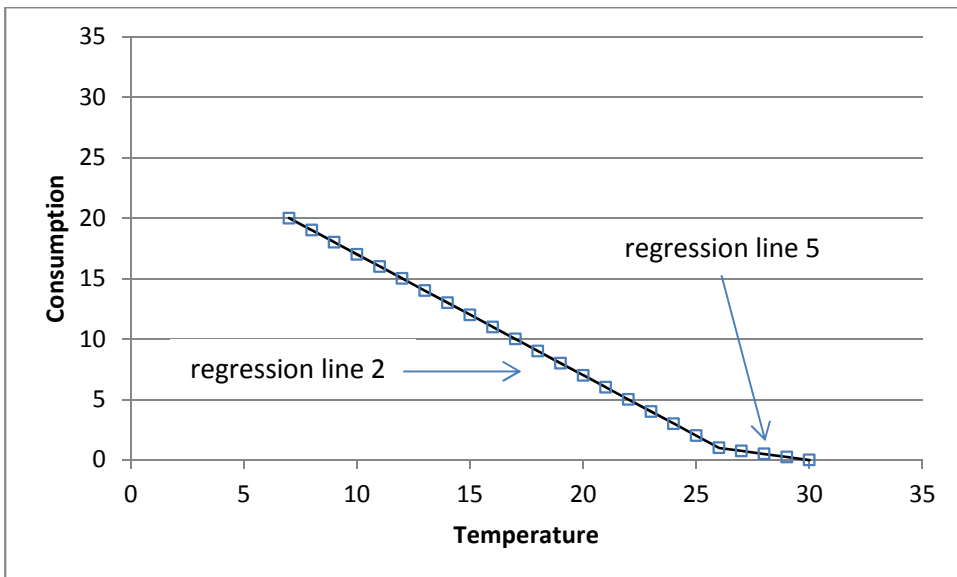

Figure 63 Plot of consumption against temperature for a future warmer climate correctly mapped by regression line 2 and regression line 5

Appendix 3: Daily Metered Gas Consumption Data

The decision to base SHECMOBS on NDM gas consumption is made on the grounds that NDM consumers are responsible for the bulk of space heating. However, despite the generally low values for the coefficient of determination in DM gas demand/effective temperature regression plots (Table 93), there is an argument that DM data should be used to further inform SHECMOBS since demand decreases in response to increasing effective temperature in 12 of the 13 LDZs.

Table 93 Coefficients of determination in the plot of DM gas demand against effective temperature (2008-2010)

LDZ	Met Office Weather Station	R^2
Scotland	Glasgow	0.05
Northern	Albemarle	0.16
North Western	Woodford	0.20
North Eastern	Dishforth	0.00
West Midlands	Coleshill	0.15
East Midlands	Waddington	0.09
Wales North	Lake Vyrnwy	0.02
Wales South	St Athan	0.03
South West	Filton	0.30
South	Middle Wallop	0.36
Eastern	Weybourne	0.55
North Thames	Heathrow	0.64
South Eastern	Manston	0.03

In particular, the degree of correlation between DM gas demand and effective temperature for the (i) North Thames LDZ and Heathrow regression plot (Figure 64), and (ii) Eastern LDZ and Weybourne regression plot is not so low that they can be ignored without comment.
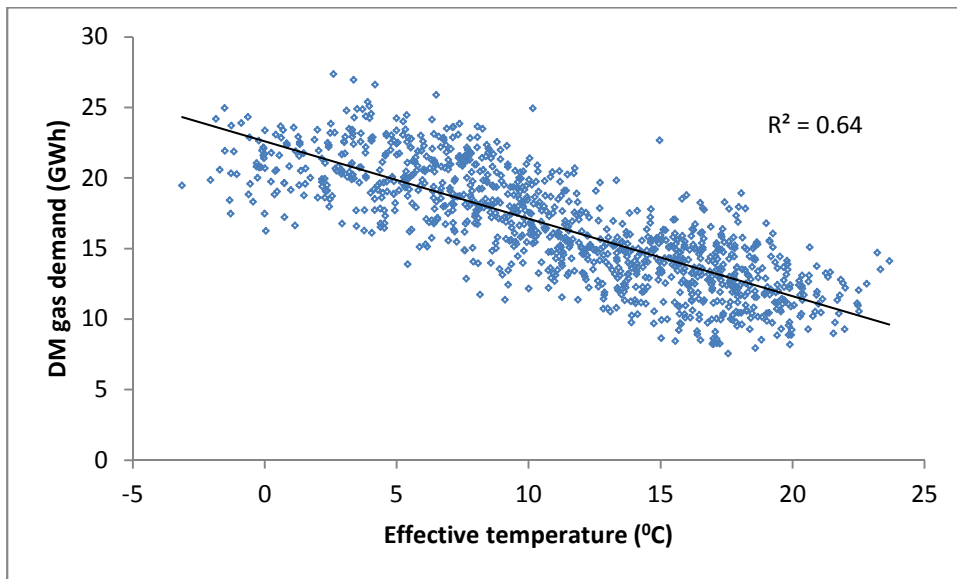
Figure 64 Regression plot of North Thames LDZ daily DM gas demand against Heathrow effective temperature (2008-2010)

Whilst the regression for North Thames LDZ/Heathrow shows a moderate degree of correlation between DM gas demand and effective temperature[242], it is not clear, however, to what extent the diminution in weather-related consumption is due to the reduction in space heating: if the diminution was primarily due to a reduction in the level of space heating, one would have expected to see consumption levels begin to taper at about 13-14 ^{0}C as is seen with the NDM stock (e.g. Figure 18, Figure 19 and Figure 20), but no such taper is seen. This suggests that the diminution is perhaps rather more due to weather-related industrial process. In consequence it would appear that any weather sensitivity that exists within the DM stock is dependent upon the nature of the industrial processes performed within the LDZ in question.

It is very likely that this diversity of industrial activity which is seen between LDZs is also responsible for the very high degree of scatter seen in the other LDZ DM gas demand/effective temperature regression plots, the range of gas demand values at any particular temperature typically being as large or larger than the maximum and minimum points on the regression trend line, as seen in the example below for the West Midlands LDZ/Coleshill regression plot (Figure 65).

---

[242] The Eastern LDZ/Weybourne regression plot has the same shape as that of the North Thames/Heathrow regression plot.

In brief, the inclusion of DM data as a weather-sensitive component does not bring any benefit to a space heating model. In practical terms, the DM gas demand can be said to be constant, its increase in magnitude in both absolute and relative terms from summer to winter being minimal in comparison to NDM demand: whilst DM increases only by 4% from 27,555 GWh to 28,596 GWh, NDM consumption increases by 370% from 43,155 GWh to 202,851 GWh (2008-2010 average).

Appendix 4: Importance of Using Correct Break Points in Segmented Regression

It is important that breakpoints of the correct value are chosen in fitting segmented trend lines to map the regression data, since temperatures in the future are likely to be warmer than those of the present day. An example is presented below to illustrate this point.

Figure 66 shows the regression plot of North West LDZ NDM gas demand against Woodford effective temperature for the present day climate. Two linear regression trend lines are fitted to the data, one for data above 10 ^{0}C (RL1), and another for data below 10 ^{0}C (RL2) (i.e. breakpoint of 10 ^{0}C). The two lines can be seen to be non-contiguous.
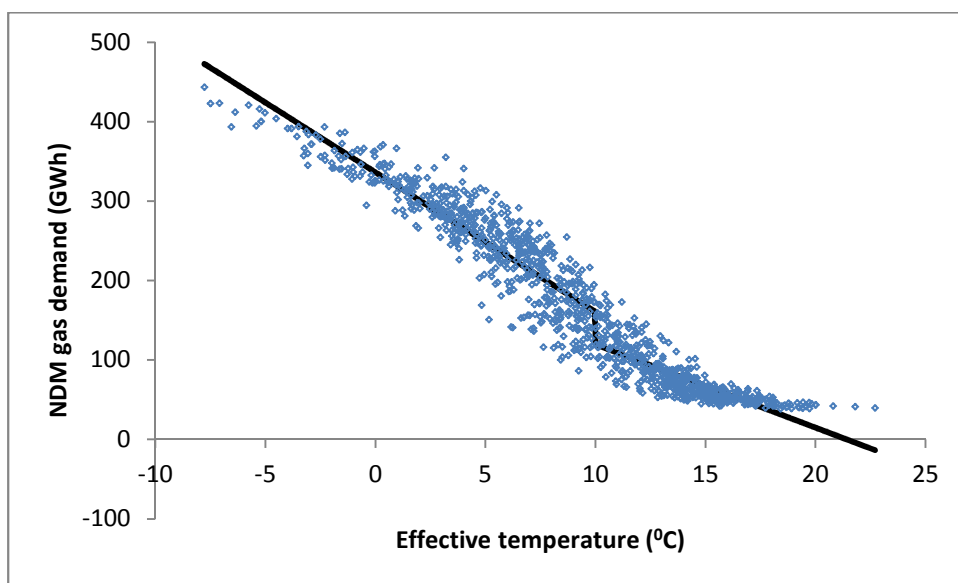
Figure 66 Regression plot of North West LDZ daily weather-sensitive gas demand against Woodford effective temperature showing two linear regression trend lines (break point 10 ^{0}C) (2008-2010)

The plot could be used to predict consumption over the course of a year for a climate like that of the present day because over-estimates and under-estimates of demand cancel out one another over the whole of the regression.

In a future climate, temperatures are likely to be warmer. Figure 67 re-presents the same data, but where datum points with effective temperatures less than -1 ^{0}C are omitted.
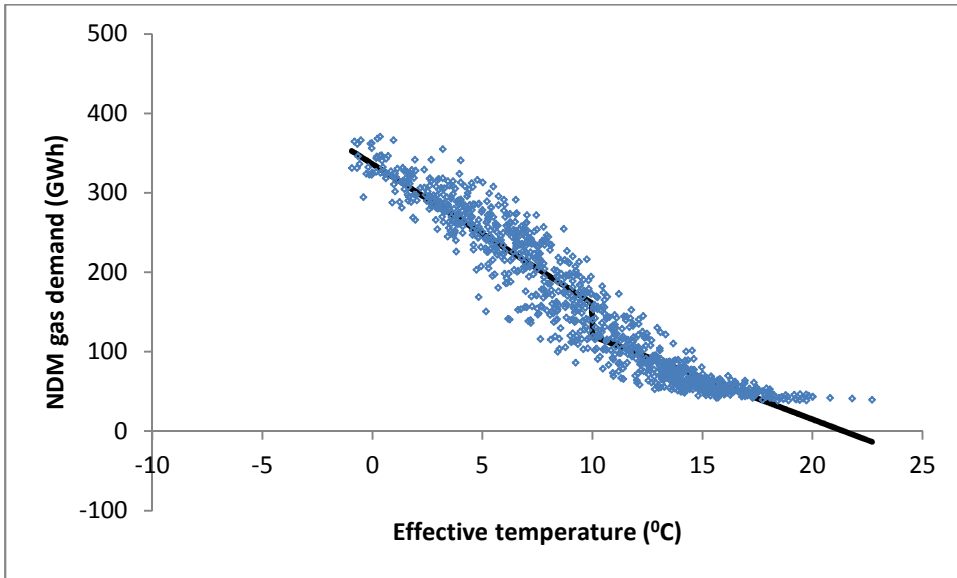
Figure 67 Regression plot of North West LDZ daily weather-sensitive gas demand against Woodford effective temperature showing the two original linear regression trend lines (break point 10 ^{0}C) (temperature > -1 ^{0}C)

With the omission of these data (the consumption of which the RL1 trend line previously over-estimated), the balance between over-estimation and under-estimations is lost, the end result of which is that overall consumption is under-estimated.

Figure 68 re-presents the present day climate data of Figure 66, where the data have been correctly segmentally regressed.
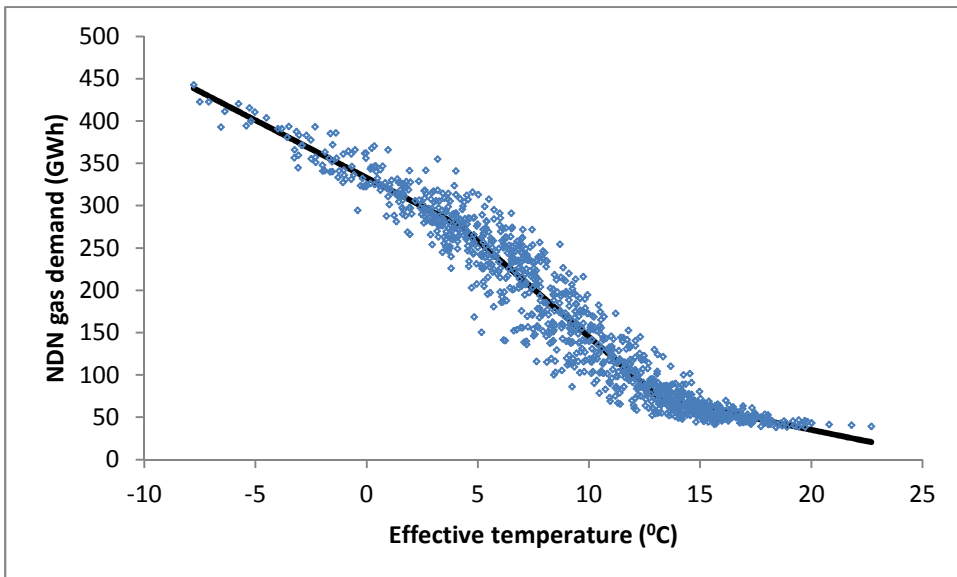
Figure 68 Regression plot of North West LDZ daily weather-sensitive gas demand against Woodford effective temperature showing three linear regression trend lines which are contiguous at the break points (2008-2010)

260

Figure 69 re-presents data of Figure 67 above, where datum points with effective temperatures less than -1 ^{0}C are omitted.
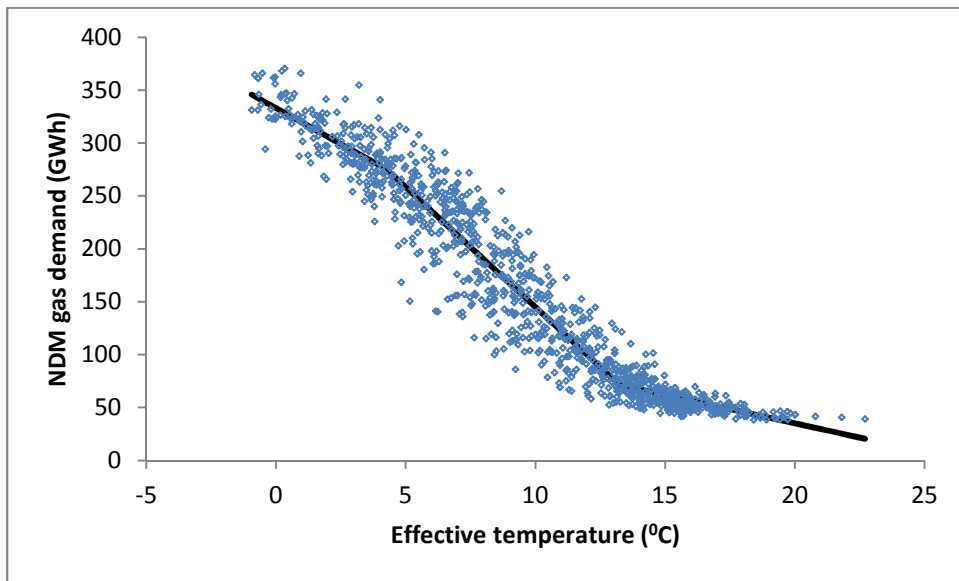
Figure 69 Regression plot of North West LDZ daily weather-sensitive gas demand against Woodford effective temperature showing the original three linear regression trend lines (temperature > -1 ^{0}C)

In this instance it is seen that the RL1 trend line continues to correctly map the data because approximately as many over-estimated as under-estimated datum points have been omitted.

Appendix 5: Segmented Package of R – Regression Results

This appendix presents the correlation data for the 13 LDZ/weather station regression plots used as input for SHECMOBS. The raw output of R is first presented. A brief discussion follows, in which the West Midlands LDZ/Coleshill correlation is scrutinised, and the latest version of the Segmented package (Version 0.2-9.1) is examined. Finally, the 13 algorithms underlying SHECMOBS are presented.

Appendix 5.1: R Output

Nomenclature

psi1.xx = first break point

psi2.xx = second break point (if applicable)

xx = slope of first regression trend line

U1.xx = difference between slope of first and second regression trend lines

U2.xx = difference between slope of second and third regression trend lines (if applicable)

West Midlands LDZ/Coleshill Regression

Break points	Estimate	Std. Error
psi1.xx	5.144	0.3734
psi2.xx	13.28	0.1694

t value for the gap-variable(s) V: 0.9796181 -0.1019985

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	263.1126	1.4233	184.86	<2e-16
xx	-11.7689	0.4479	-26.27	<2e-16
U1.xx	-6.544	0.5647	-11.59	NA
U2.xx	13.8264	0.6412	21.56	NA

Residual standard error: 17.71 on 1090 degrees of freedom

Multiple R-Squared: 0.9512, Adjusted R-squared: 0.951

Convergence attained in 20 iterations with relative change 0.0008017725

North East LDZ/Dishforth Regression

Break points	Estimate	Std. Error
psi1.xx	4.269	0.331
psi2.xx	13.32	0.1878

t value for the gap-variable(s) V: 0.2747137 -0.1914825

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	171.805	0.9035	190.16	<2e-16
xx	-6.6026	0.3321	-19.88	<2e-16
U1.xx	-5.2003	0.3922	-13.26	NA
U2.xx	8.9189	0.5242	17.01	NA

Residual standard error: 12.62 on 1090 degrees of freedom

Multiple R-Squared: 0.9449, Adjusted R-squared: 0.9446

Convergence attained in 6 iterations with relative change -4.963212e-05

South West LDZ/Filton Regression

Break points	Estimate	Std. Error
psi1.xx	6.252	0.4217
psi2.xx	13.77	0.1355

t value for the gap-variable(s) V: 0.6375837 -0.3045848

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	180.227	0.9101	198.03	<2e-16
xx	-8.893	0.2454	-36.232	<2e-16
U1.xx	-3.1077	0.3133	-9.919	NA
U2.xx	9.6064	0.3702	25.952	NA

Residual standard error: 9.555 on 1088 degrees of freedom

Multiple R-Squared: 0.9665, Adjusted R-squared: 0.9663

Convergence attained in 6 iterations with relative change -3.96351e-05

Scotland LDZ/Glasgow Regression

Break points	Estimate	Std. Error
psi1.xx	5.729	0.2638
psi2.xx	11.82	0.2016

t value for the gap-variable(s) V: 0.01651723 -0.06081112

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	234.3731	1.0648	220.1	<2e-16
xx	-10.3472	0.3043	-34	<2e-16
U1.xx	-7.2556	0.514	-14.12	NA
U2.xx	10.4725	0.627	16.7	NA

Residual standard error: 14.21 on 1090 degrees of freedom

Multiple R-Squared: 0.9592, Adjusted R-squared: 0.9591

Convergence attained in 13 iterations with relative change 5.368086e-06

North Thames LDZ/Heathrow Regression

Break points	Estimate	Std. Error
psi1.xx	5.956	0.4449
psi2.xx	15.13	0.1296

t value for the gap-variable(s) V: -0.08542935 -0.1465953

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	331.7197	1.7265	192.137	<2e-16
xx	-14.4692	0.4745	-30.491	<2e-16
U1.xx	-4.9752	0.5383	-9.242	NA
U2.xx	15.5551	0.5194	29.947	NA

Residual standard error: 15.31 on 1090 degrees of freedom

Multiple R-Squared: 0.9725, Adjusted R-squared: 0.9724

Convergence attained in 4 iterations with relative change -7.27188e-05

Wales North LDZ LDZ/Lake Vyrnwy Regression

Break points	Estimate	Std. Error
psi1.xx	12.57	0.1646

t value for the gap-variable(s) V: 0.01487558

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	30.00066	0.14237	210.72	<2e-16
xx	-1.93093	0.01929	-100.08	<2e-16
U1.xx	1.59472	0.11158	14.29	NA

Residual standard error: 2.26 on 1092 degrees of freedom

Multiple R-Squared: 0.9374, Adjusted R-squared: 0.9372

Convergence attained in 6 iterations with relative change -4.051843e-06

North West LDZ/Woodford Regression

Break points	Estimate	Std. Error
psi1.xx	4.251	0.3535
psi2.xx	13.24	0.1799

t value for the gap-variable(s) V: -0.2871866 0.07348583

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	333.0159	1.74	191.39	<2e-16
xx	-13.5695	0.5884	-23.06	<2e-16
U1.xx	-9.1093	0.718	-12.69	NA
U2.xx	17.2954	0.9057	19.1	NA

Residual standard error: 24.19 on 1090 degrees of freedom

Multiple R-Squared: 0.9455, Adjusted R-squared: 0.9452

Convergence attained in 8 iterations with relative change -2.080271e-05

South East LDZ/Manston Regression

Break points	Estimate	Std. Error
psi1.xx	14.22	0.1707

t value for the gap-variable(s) V: -0.1495534

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	341.5036	1.5949	214.13	<2e-16
xx	-19.6786	0.1821	-108.05	<2e-16
U1.xx	15.1282	0.6828	22.16	NA

Residual standard error: 20.28 on 1086 degrees of freedom

Multiple R-Squared: 0.9545, Adjusted R-squared: 0.9543

Convergence attained in 6 iterations with relative change -9.724161e-05

South LDZ/Middle Wallop Regression

Break points	Estimate	Std. Error
psi1.xx	14.29	0.1539

t value for the gap-variable(s) V: -0.1084723

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	222.1909	0.9742	228.09	<2e-16
xx	-12.8336	0.1133	-113.31	<2e-16
U1.xx	10.3205	0.5248	19.67	NA

Residual standard error: 13.41 on 1092 degrees of freedom

Multiple R-Squared: 0.9561, Adjusted R-squared: 0.9559

Convergence attained in 6 iterations with relative change -2.879268e-05

Northern LDZ/Albemarle Regression

Break points	Estimate	Std. Error
psi1.xx	3.257	0.3462
psi2.xx	12.35	0.1962

t value for the gap-variable(s) V: 0.03781496 0.09737832

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	141.1484	0.742	190.22	<2e-16
xx	-5.7433	0.3355	-17.12	<2e-16
U1.xx	-4.1591	0.3742	-11.11	NA
U2.xx	7.0119	0.4374	16.03	NA

Residual standard error: 10.23 on 1090 degrees of freedom

Multiple R-Squared: 0.9448, Adjusted R-squared: 0.9445

Convergence attained in 8 iterations with relative change 3.002456e-05

Wales South LDZ/St Athan Regression

Break points	Estimate	Std. Error
psi1.xx	5.321	0.632
psi2.xx	14.29	0.1923

t value for the gap-variable(s) V: 0.04076965 -0.1933543

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	110.0206	0.7553	145.659	<2e-16
xx	-5.1161	0.2343	-21.836	<2e-16
U1.xx	-1.6534	0.2599	-6.362	NA
U2.xx	4.9312	0.3581	13.771	NA

Residual standard error: 7.197 on 1089 degrees of freedom

Multiple R-Squared: 0.9447, Adjusted R-squared: 0.9444

Convergence attained in 7 iterations with relative change -1.946922e-05

East Midlands LDZ/Waddington Regression

Break points	Estimate	Std. Error
psi1.xx	5.801	0.3464
psi2.xx	13.22	0.164

t value for the gap-variable(s) V: 0.05429423 -0.1157591

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	294.304	1.5007	196.11	<2e-16
xx	-13.2472	0.4498	-29.45	<2e-16
U1.xx	-7.3134	0.6049	-12.09	NA
U2.xx	15.2424	0.672	22.68	NA

Residual standard error: 17.94 on 1090 degrees of freedom

Multiple R-Squared: 0.9599, Adjusted R-squared: 0.9597

Convergence attained in 9 iterations with relative change 1.55982e-05

Eastern LDZ/Weybourne Regression

Break points	Estimate	Std. Error
psi1.xx	0.8325	0.6122
psi2.xx	13.63	0.1646

t value for the gap-variable(s) V: -0.001210518 0.02283605

Intercept or slope	Estimate	Std. Error	t value	Pr(>|t|)
Intercept	256.5742	3.4263	74.884	<2e-16
xx	-6.9621	3.931	-1.771	0.0768
U1.xx	-8.8432	3.9348	-2.247	NA
U2.xx	12.5167	0.5365	23.331	NA

Residual standard error: 16.7 on 1062 degrees of freedom

Multiple R-Squared: 0.9463, Adjusted R-squared: 0.9461

Convergence attained in 6 iterations with relative change 3.321763e-05

Appendix 5.2: Discussion of West Midlands LDZ/Coleshill Correlation

West Midlands LDZ/Coleshill Regression
Note that even though the R^2 value for the West Midlands LDZ/Coleshill regression is high, considerably more iterations have been used to achieve this result. Investigation of these regression data reveals them to be slightly inferior to the other 12 regression plots. Although barely visible by eye, two of the regression trend lines exhibit a small degree of bias, the sum of positive residuals exceeding the sum of negative residuals for the mid-temperature and high temperature lines (Figure 70).
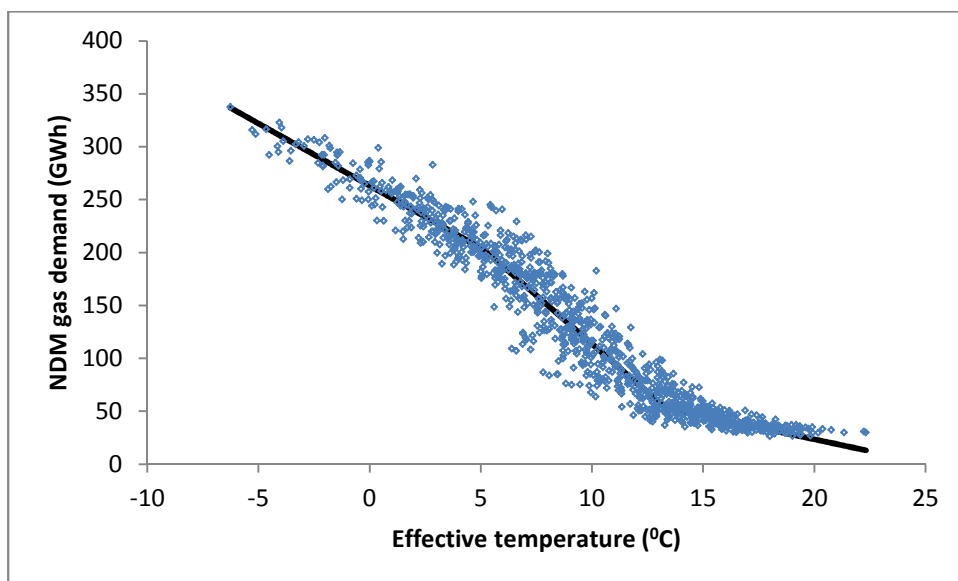
Figure 70 Regression plot of West Midlands LDZ daily weather-sensitive gas demand against Coleshill effective temperature showing slight bias in two of the three segmented linear regression trend lines (2008-2010)

The residual difference amounts to 2,120 GWh, which is the equivalent of a downward shift of the 3 lines by 2 GWh; overall, the trend lines under-estimate annual consumption by 1.5%. Since the analysis was originally performed a new Segmented package (Version 0.2-9.1) has been published by R (May 2012) (Muggeo, 2012), but identical results are produced after 20 iterations. Since West Midlands consumption only represents 9% of national consumption, this error of 1.5% is not considered to be significant.

Segmented package Version 0.2-9.1

Repeating the segmented analysis with the new package produces the same results as the former version for all the 3-line plots. However, the new package is able to discern a third line in the 2-line regression plots. The improvement in correlation is, however, only marginal and it is not considered to be significant (see table below).

Table 94 Improvement in R^2 value for 2-line regression plots transformed into 3-line regression plots

	R^2 value (Segmented package Version 0.2-8)	R^2 value (Segmented package Version 0.2-9.1)
Lake Vyrnwy	0.9374	0.9449
Manston	0.9545	0.955
Middle Wallop	0.9561	0.9582
Solent	0.9493	0.9725

Appendix 5.3: Regression Algorithms

Nomenclature

C = Annual consumption (GWh)

i = mean effective temperature on day i (^{0}C)

West Midlands LDZ

Equation 60

$$C = \left(\sum_{-\infty < i \leq 5.1} -11.8i + 263 \right) + \left(\sum_{5.1 < i \leq 13.3} -18.3i + 297 \right) + \left(\sum_{13.3 < i < \infty} -4.5i + 113 \right)$$

North East LDZ

Equation 61

$$C = \left(\sum_{-\infty < i \leq 4.3} -6.6i + 172 \right) + \left(\sum_{4.3 < i \leq 13.3} -11.8i + 194 \right) + \left(\sum_{13.3 < i < \infty} -2.9i + 75 \right)$$

South West LD

Equation 62

$$= \left(\sum_{-\infty < i \leq 6.3} -8.9i + 180 \right) + \left(\sum_{6.3 < i \leq 13.8} -12.0i + 200 \right) + \left(\sum_{13.8 < i < \infty} -2.4i + 67 \right)$$

Scotland LDZ

Equation 63

$$C = \left(\sum_{-\infty < i \leq 5.7} -10.3i + 234 \right) + \left(\sum_{5.7 < i \leq 11.8} -17.6i + 276 \right) + \left(\sum_{11.8 < i < \infty} -7.1i + 152 \right)$$

North Thames LDZ

Equation 64

$$C = \left(\sum_{-\infty < i \leq 6.0} -14.5i + 332 \right) + \left(\sum_{6.0 < i \leq 15.1} -19.4i + 361 \right) + \left(\sum_{15.1 < i < \infty} -3.9i + 126 \right)$$

Wales North LDZ

$$C = \left(\sum_{-\infty < i \leq 12.6} -1.9i + 30.0 \right) + \left(\sum_{12.6 < i < \infty} -0.3 + 10.0 \right)$$

North West LDZ

$$C = \left(\sum_{-\infty < i \leq 4.3} -13.6i + 333 \right) + \left(\sum_{4.3 < i \leq 13.2} -22.7i + 372 \right) + \left(\sum_{13.2 < i < \infty} -5.4i + 143 \right)$$

South East LDZ

$$C = \left(\sum_{-\infty < i \leq 14.2} -19.7i + 342 \right) + \left(\sum_{14.2i < \infty} -4.6i + 126 \right)$$

South LDZ

$$C = \left(\sum_{-\infty < i \leq 14.3} -12.8i + 222 \right) + \left(\sum_{14.3 < i < \infty} -2.5i + 75 \right)$$

Northern LDZ

$$C = \left(\sum_{-\infty < i \leq 3.3} -5.7i + 141 \right) + \left(\sum_{3.3 < i \leq 12.4} -9.9i + 155 \right) + \left(\sum_{12.4 < i < \infty} -2.9i + 68 \right)$$

Wales South LDZ

$$C = \left(\sum_{-\infty < i \leq 5.3} -5.1i + 110 \right) + \left(\sum_{5.3 < i \leq 14.3} -6.8i + 119 \right) + \left(\sum_{14.3 < i < \infty} -1.8i + 48 \right)$$

East Midlands LDZ

Equation 71

$$C = \left(\sum_{-\infty < i \leq 5.8} -13.2i + 294 \right) + \left(\sum_{5.8 < i \leq 13.2} -20.6i + 337 \right) + \left(\sum_{13.2 < i < \infty} -5.3i + 135 \right)$$

Eastern LDZ

Equation 72

$$C = \left(\sum_{-\infty < i \leq 0.8} -7.0i + 257 \right) + \left(\sum_{0.8 < i \leq 13.6} -15.8i + 264 \right) + \left(\sum_{13.6 < i < \infty} -3.3i + 93 \right)$$

Appendix 6: Derivation of Annual NDM Space Heating Consumption from Annual NDM Consumption

Annual NDM consumption (E_{NDM}) is calculated as the total of annual space heating (E_{SH}) and annual non-weather-sensitive consumption (E_{NW}). It is assumed that no space heating occurs on the very hottest days of the year. The gas demand on these days can be attributed to other non-weather sensitive end-uses alone such as cooking and heating water. Indeed, inspection of the demand on these hot days does reveal a rather high level of constancy (and there is also a good distribution of both weekdays and weekend days amongst these hottest of days, as one might expect).

The gas demand on the thirty warmest days of the period 2008-2010 for each LDZ is averaged. This daily average value is multiplied by 365.25 in order to calculate the annual non-weather sensitive consumption for a given LDZ (E_{LDZ-NW}).

Annual space heating energy consumption for a particular LDZ (E_{LDZ-SH}) is calculated as $E_{LDZ-NDM} - E_{LDZ-NW}$, where $E_{LDZ-NDM}$ is the total annual consumption for that particular LDZ. National space heating consumption (E_{NAT-SH}) is calculated as the sum of the 13 regional E_{LDZ-SH} values.

Appendix 7: Effects of a 1^0C Increase in Outdoor Temperature on Space Heating Consumption

In a warming climate, the impact of an increase in outdoor temperature of 1 ^{0}C on annual space heating energy consumption will be more pronounced in the near term than later on: the cooler the climate, the greater the reduction in space heating per degree change in outdoor air temperature. This is shown in the example below, where temperatures increase by 1 ^{0}C on two separate occasions: the first increase occurs between the present day and the 2030s, and the second increase occurs between the 2030s and the 2080s.

Consider the following example, deliberately exaggerated to so to aid clarity, where a very well insulated building only requires heating when temperatures drop below 6^0C.

In Figure 71 it is seen that in the present day, where the temperature only drops below 6^0C on five days of the year on average, space heating consumption amounts to 15 units (5 + 4 + 3 + 2 + 1), where each day is represented by a different symbol (rectangle, triangle etc.).
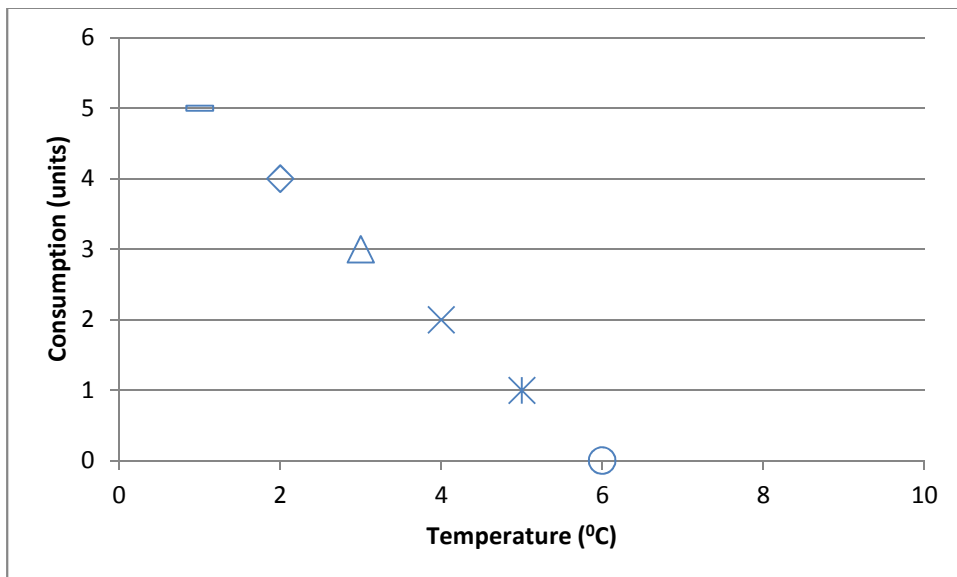
Figure 71 Base case gas consumption - present day

Following a 1 ^{0}C rise in temperature by the 2030s, every day is 1 ^{0}C warmer (Figure 72). Thus the day on which the temperature was 1 ^{0}C (symbol: elongated rectangle in Figure 71), now has a temperature of 2 ^{0}C (elongated rectangle in Figure 72). Similarly, every other day is 1 ^{0}C warmer. In this new climate, there are only four days when the temperature drops below 6 ^{0}C. Space reduces to 10 units (4 + 3 + 2 +1), amounting to a reduction in heating of 5 units (15 − 5).
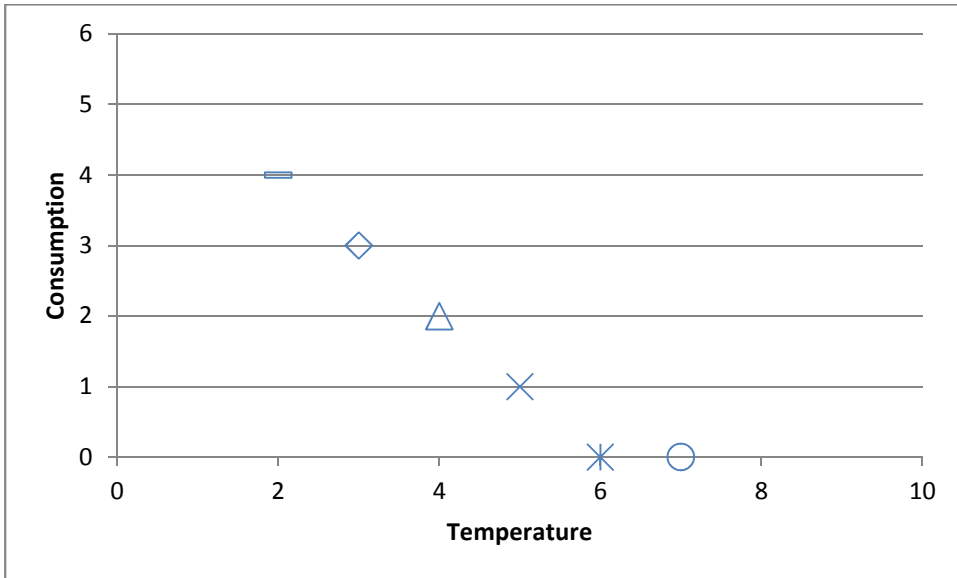
Figure 72 Gas consumption following a 1 ^{0}C rise in temperature - 2030s

A further increase in temperature of 1 ^{0}C occurs by the time the 2080s are reached. Space heating consumption now amounts to 6 units (3 + 2 + 1), amounting to a reduction in heating of only 4 units (10 – 6) (Figure 73).
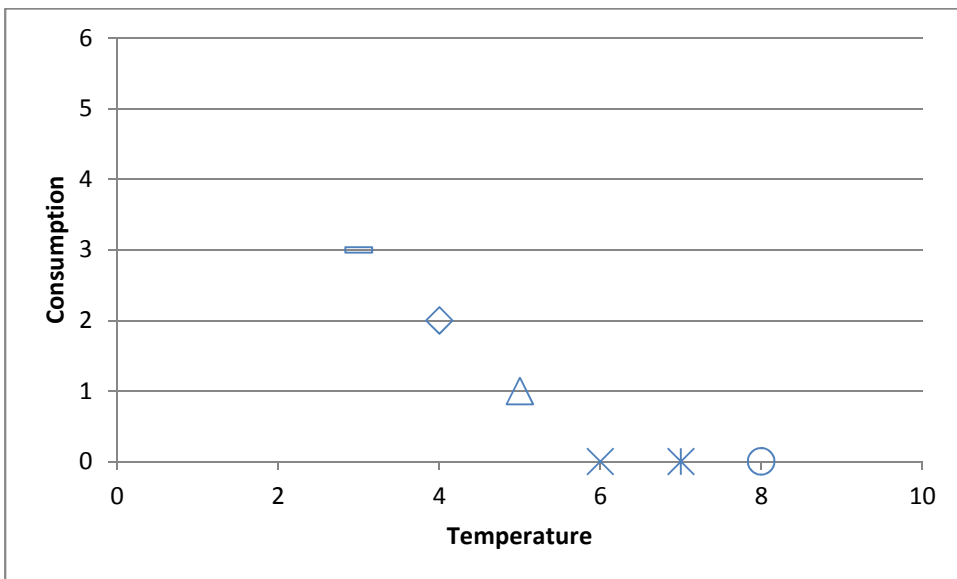
Figure 73 Gas consumption following a further 1 ^{0}C rise in temperature - 2080s

In this example, the reduction in consumption precipitated by a 1 ^{0}C rise in temperuture is 25% larger in the near term (5 units) than later on (4 units) when overall consumption is lower.

Appendix 8: Trend Adjustment to Lessen the Influence of Non-Climatic Factors in Regression Analyses

Trend adjustment can be used to lessen the influence of non-climatic factors in regression analyses. In the following hypothetical example below, electricity consumption (E) is examined over a period of three years. Electricity consumption is determined by air temperature (t) and two additional factors, a and b.

The equation describing electricity consumption in month m is described as:

Equation 73

$$E_m = 2t_m + 2a_m + 2b_m$$

Adjusted monthly electricity in year n (*Adj $E_{m.n}$*) consumption is described by the equation:

Equation 74

$$Adj\ E_{m,n} = E_{m,n} \times Adj\ F_n$$

> where,
>
> $E_{m,n}$ = electricity consumption in month m of year n
>
> $Adj\ F_n$ = adjustment factor in year n

The adjustment factor for year n is calculated as:

Equation 75

$$Adj\ F_n = \left(\frac{E_{y1} + E_{y2} + E_{y3}}{E_n} \right)$$

> where,
>
> E_n = electricity consumption in year n
>
> E_{y1} = electricity consumption in year 1, etc.

The table below presents the monthly data for the three year period.

Table 95 Determinants of monthly electricity consumption and adjusted monthly electricity consumption over a period of three years

Year	Month	Air Temp (*t*)	Factor *a*	Factor *b*	Electricity consumption	Adjusted electricity consumption
1	Jan	2	12	10	48	40.11707
1	Feb	3	12	10	50	41.78862
1	Mar	5	12	10	54	45.13171
1	Apr	9	12	10	62	51.81789
1	May	11	12	10	66	55.16098
1	Jun	16	12	10	76	63.5187
1	Jul	21	12	10	86	71.87642
1	Aug	21	12	10	86	71.87642
1	Sep	20	12	10	84	70.20488
1	Oct	18	12	10	80	66.86179
1	Nov	11	12	10	66	55.16098
1	Dec	9	12	10	62	51.81789
2	Jan	2	8	10	40	41.40987
2	Feb	1	8	10	38	39.33938
2	Mar	4	8	10	44	45.55086
2	Apr	8	8	10	52	53.83283
2	May	9	8	10	54	55.90332
2	Jun	16	8	10	68	70.39678
2	Jul	17	8	10	70	72.46727
2	Aug	18	8	10	72	74.53776
2	Sep	16	8	10	68	70.39678
2	Oct	11	8	10	58	60.04431
2	Nov	9	8	10	54	55.90332
2	Dec	4	8	10	44	45.55086
3	Jan	0	4	10	28	33.43089
3	Feb	1	4	10	30	35.81882
3	Mar	3	4	10	34	40.59466
3	Apr	6	4	10	40	47.75842
3	May	8	4	10	44	52.53426
3	Jun	14	4	10	56	66.86179
3	Jul	19	4	10	66	78.80139
3	Aug	22	4	10	72	85.96516
3	Sep	20	4	10	68	81.18931
3	Oct	18	4	10	64	76.41347
3	Nov	7	4	10	42	50.14634
3	Dec	1	4	10	30	35.81882

When regression analyses are performed on the data, it is seen that a clearer correlation exists between adjusted electricity consumption and temperature than between electricity consumption and temperature (Figure 74 and Figure 75).
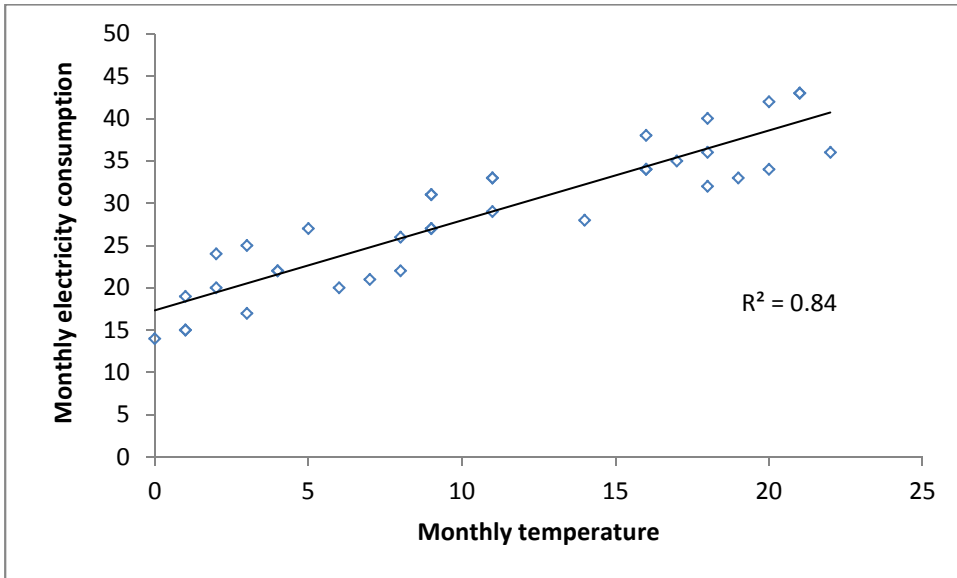
Figure 74 Relationship between monthly electricity consumption and monthly temperature over three year period
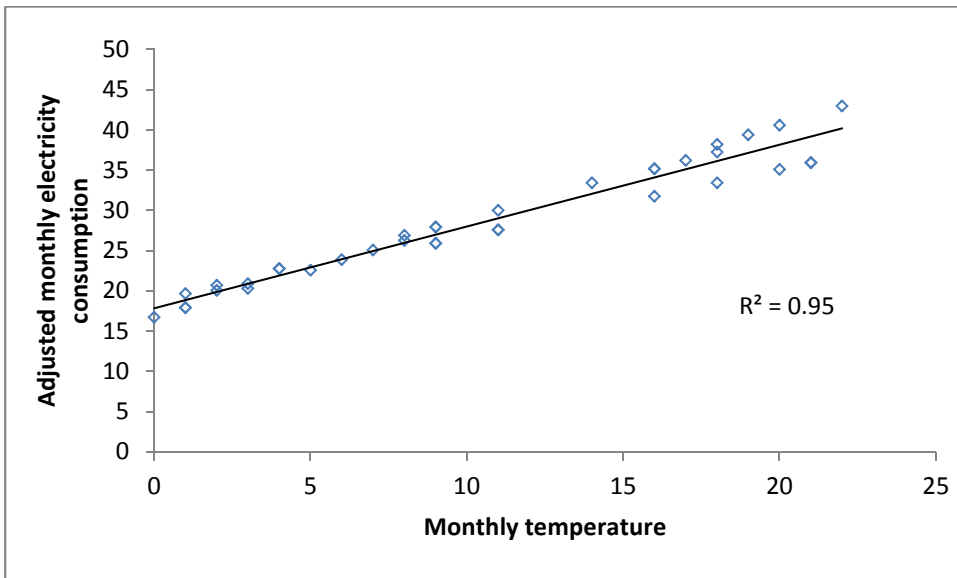
Figure 75 Relationship between adjusted monthly electricity consumption and monthly temperature over three year period

Appendix 9: Daily Variation of Electricity Consumption

The figure below shows the plot of INDO electricity consumption (see footnote 72) over a typical month in summer (August 2010, where 1 August is a Sunday). Electricity consumption is clearly reduced at the weekend and on the bank holiday Monday (30 August).
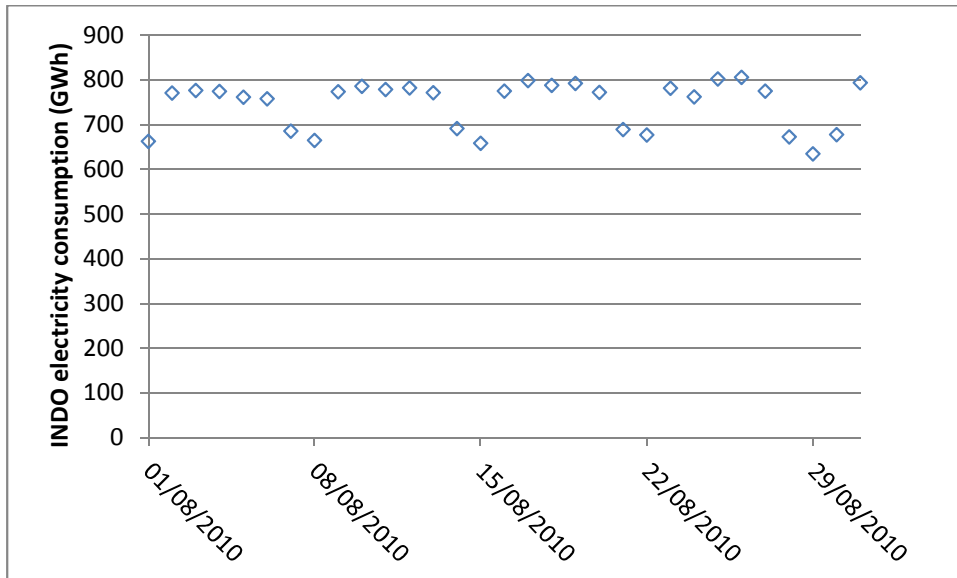
Figure 76 Plot of INDO electricity consumption for August 2010

Appendix 10: Importance of Using Correct Base Temperature When Determining Energy Consumption

The choice of base temperature can have important ramifications with regard to the calculation of energy consumption (Figure 77).
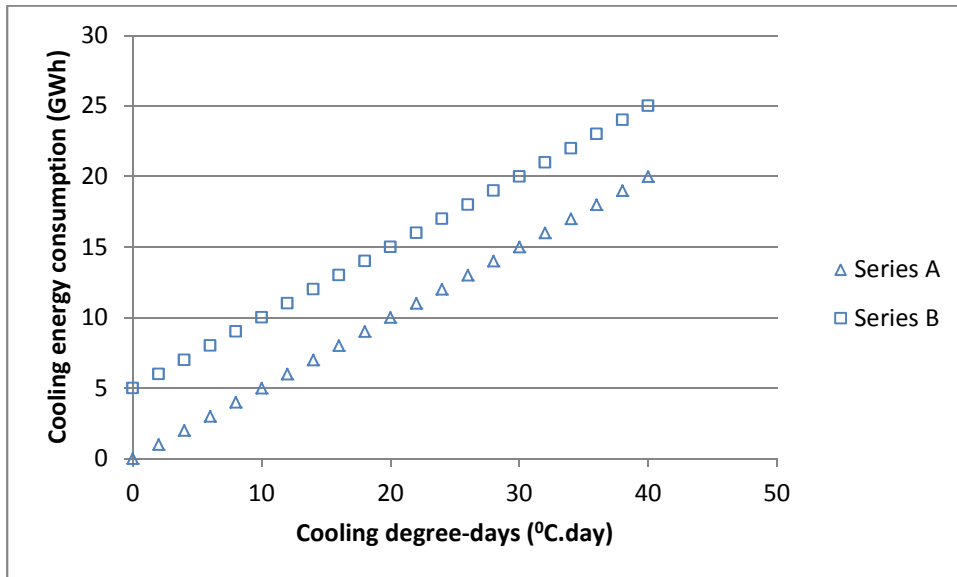
Figure 77 Relationship between energy consumption and cooling degree-days calculated to different base temperatures (^{0}C)

Series A

Cooling degree-days are calculated to a base temperature exactly equal to the trigger temperature which calls the air conditioning into operation (i.e. the correct base temperature has been chosen, since the graph passes through the origin). Each rise of 1CDD causes an increase in consumption of 0.5 GWh (elasticity = 0.5 GWh/CDD), where there is an exact correspondence between the number of CDDs and the cooling energy consumption (e.g. doubling the CDDs from 20 to 40, causes a doubling in energy consumption from 10GWh to 20GWh.)   In order to calculate the energy consumption for a given number of CDDs, knowledge of the elasticity (slope) is not required.

Series B

Cooling degree-days have been calculated to a base temperature above the trigger temperature which calls the air conditioning into operation. Each rise of 1CDD causes an increase in consumption of 0.5 GWh, but there is not an exact correspondence between the number of CDDs and the cooling energy consumption (e.g. doubling the CDDs from 10 to 20, does not cause a doubling in energy consumption, but rather a change from 15GWh to 25GWh.) Thus, where the correct base temperature is not known, knowledge of the elasticity is required in order to calculate the energy consumption for a given number of CDDs.

Appendix 11: Construction Details of Buildings Used in Cooling Energy Consumption Simulations

Table 96 Construction details of buildings used in simulations to investigate cooling energy consumption

---

LIGHTWEIGHT CONSTRUCTION, FLAT ROOF (LW)

Walls   (i) 6mm lightweight metallic coating, (ii) 88.9mm extruded polystyrene, (iii) 13mm gypsum plasterboard
Roof   (i) 10mm asphalt, (ii) 144.5mm glass wool, (iii) 200mm air gap, (iv) 13mm plasterboard
Windows   Double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

---

MEDIUM WEIGHT CONSTRUCTION, FLAT ROOF (MW)
Walls   (i) 100mm brickwork outer leaf, (ii) 79.5mm extruded polystyrene, (iii) 100mm concrete block (medium), (iv) 13mm gypsum plastering
Roof   (i) 10mm asphalt, (ii) 144.5mm glass wool, (iii) 200mm air gap, (iv) 13mm plasterboard
Windows   double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

---

MEDIUM WEIGHT CONSTRUCTION, PITCHED ROOF WITH EAVES (PITCHED)
Walls   (i) 100mm brickwork outer leaf, (ii) 79.5mm extruded polystyrene, (iii) 100mm concrete block (medium), (iv) 13mm gypsum plastering
Roof   (i) 25mm clay tiling, (ii) 10/20mm air gap, (iii) 5mm roof felt
Ceiling   (i) 10mm plywood (heavyweight), (ii) 139.1mm glass wool, (iii) 100mm cast concrete (lightweight), (iv) 13mm plasterboard

---

HIGHLY INSULATED MEDIUM/HEAVYWEIGHT, FLAT ROOF (INSULATED)
Walls   (i) 105mm brickwork outer leaf, (ii) 118.2mm extruded polystyrene, (iii) 100mm concrete block (medium), (iv) 13mm gypsum plastering
Roof   (i) 10mm asphalt, (ii) 251.2mm glass wool, (iii) 200mm air gap, (iv) 13mm plasterboard
Windows   double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

---

SOLID WALL CONSTRUCTION, SOLID FLAT ROOF (SOLID)
Walls   (i) 20mm external render, (ii) 50mm phenolic foam (foil-faced), (iii) 225mm brick, (iv) 13mm dense plaster
Roof   (i) 19mm asphalt, (ii) 13mm fibreboard, (iii) 204.7mm extruded polystyrene , (iv) 100mm cast concrete (lightweight)
Windows   double glazed clear glass (3mm) with 13mm air gap, painted wooden frame

Appendix 12: Effect of Adaptation on Neutral Temperature

In an analysis of the neutral temperature against outdoor temperature for a series of occupied buildings where the ultimate aim is to find the average neutral temperature of each building, it makes no difference whether or not adaptation has taken place amongst the occupants of a building, as long as the level of adaptation at high temperatures is balanced by the level of adaptation at low temperatures. Irrespective of the level of adaptation experienced by the building occupants, the same neutral temperature will be recorded for the building in question as seen in Figure 78.
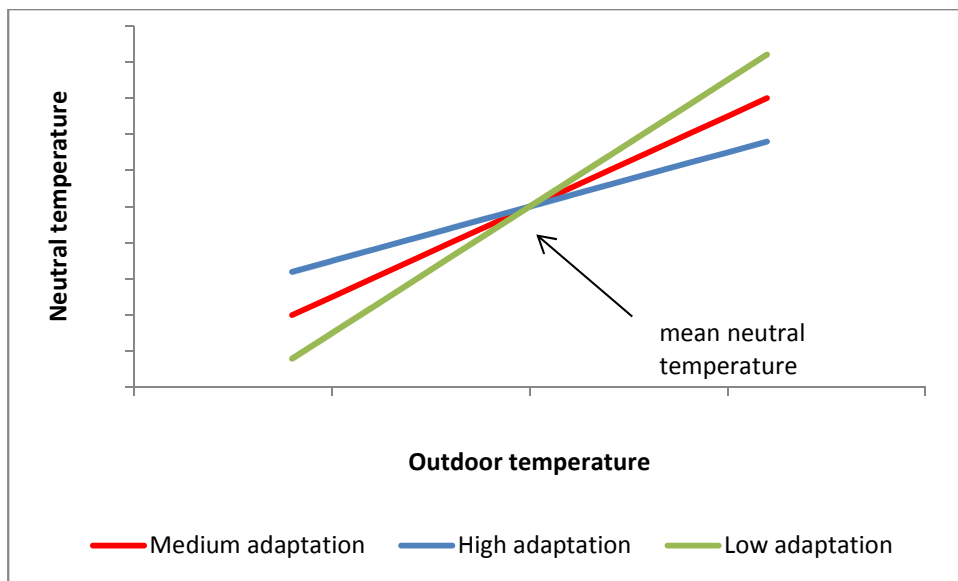
Figure 78 Chart showing that average neutral temperature of a building is unaffected by adaptation

Appendix 13: Calculation of Weighted National Seasonal Mean Temperatures for 2007 and the 2050s (Medium Emissions Scenario)

For each of the four seasons, a weighted national seasonal mean temperature for 2007 is calculated from regional unweighted 2007 seasonal mean temperatures which have been modified by 2007 seasonal weighting factors.

Weighted seasonal mean temperatures for the 2050s are calculated in a similar manner.

All data refer to Great Britain.

Appendix 13.1: Calculation of 2007 Weighted National Seasonal Mean Temperature

Appendix 13.1.1: Calculation of Unweighted 2007 Seasonal Mean Temperature

Daily mean temperatures are calculated from daily maxima and minima observations for 2007 for each of the 13 weather stations previously used in Section 2.5.4 and Section 3.6 (UK Meteorological Office, 2011), each station being representative of a different LDZ (i). From these daily data, the unweighted seasonal mean temperature is calculated for each of the 13 LDZs ($t_{LDZ-2007}$) for each of the four seasons[243].

Appendix 13.1.2: Calculation of 2007 Seasonal Space Heating Weighting Factor

The NDM daily gas consumption is obtained for each of the 13 LDZs corresponding to the weather stations above for 2007. The daily base level of gas consumption, when no space heating is used, is calculated as the average of the 10 lowest daily gas consumption values. This base value is subtracted from each NDM daily gas consumption total in order to calculate the NDM daily space heating gas consumption. These daily NDM space heating data are used to calculate the NDM winter space heating gas consumption for (i) each of the 13 LDZs (C_{LDZ}), and for (ii) the nation as whole (C). A winter space heating weighting factor for each LDZ for each season ($f_{LDZ-2007}$) is calculated as shown in Equation 76.

Equation 76

$$f_{LDZ-2007} = {C_{LDZ}}/{C}$$

where,

---

[243] Winter comprises January, February and December; spring comprises March, April and May, etc.

$$C_{LDZ} = \text{NDM winter space heating gas consumption in LDZ } i$$

$$C = \text{total NDM winter space heating gas consumption (total across all 13 LDZs)}$$

Space heating weighting factors are calculated in the same way for spring, summer and autumn.

Appendix 13.1.3: Weighted National Seasonal Mean Temperature

The weighted national mean temperature for winter for 2007 ($T_{w\text{-}2007}$) is calculated as shown in Equation 77.

Equation 77

$$T_{w-2007} = \sum_{i=1}^{13} (f_{LDZ-2007} \times t_{LDZ-2007})$$

where,

$f_{LDZ\text{-}2007}$ = space heating weighting factor for winter for 2007 for LDZ i

$t_{LDZ\text{-}2007}$ = unweighted mean temperature for winter for 2007 for LDZ i

The weighted national mean temperatures for 2007 for spring, summer and autumn are calculated in the same way.

Appendix 13.2 Calculation of 2050s Weighted National Seasonal Mean Temperature

Appendix 13.2.1: Calculation of 2050s Unweighted Seasonal Mean Temperature

The Weather Generator is run 100 times for stationary 100-year times-slices for each of the 13 locations previously used in Section 2.5.4 and Section 3.6 for the 2050s medium emissions scenario, with each run producing a 100-year sequence of data.

From the resultant 10,000 years of daily maxima and minima temperature data, the unweighted seasonal mean temperature is calculated for each of the 13 LDZs ($t_{LDZ\text{-}2050s}$), for each of the four seasons.

Appendix 13.2.2: Calculation of 2050s Weighting Factor

In order to eliminate the possibility that 2007 was anomalous with regard to gas consumption in different parts of the country, the weighting factor applied to regional temperature data for each of the four seasons for the 2050s ($f_{LDZ-2050s}$) is derived from NDM gas consumption data collected over the four year period 2007-2010, rather than just 2007. Otherwise, $f_{LDZ-2050s}$ is calculated in an analogous manner to $f_{LDZ-2007}$[244].

Appendix 13.2.3: Weighted National Seasonal Mean Temperature

The weighted national mean temperature for winter for the 2050s ($T_{w-2050s}$) is calculated as shown in Equation 78.

Equation 78

$$T_{w-2050s} = \sum_{i=1}^{13} (f_{LDZ-2050s} \times t_{LDZ-2050s})$$

where,

$f_{LDZ-2050s}$ = space heating weighting factor for winter for the 2050s for LDZ i

$t_{LDZ-2050s}$ = unweighted mean temperature for winter for the 2050s for LDZ i

The weighted national mean temperatures for the 2050s for spring, summer and autumn are calculated in the same way.

---

[244] The daily base level of gas consumption, when no space heating is used, is calculated as the average of the 40 lowest daily gas consumption values (rather than 10), since it derives from four years of data.

Appendix 14: Key Characteristics of Four Pathways Designed to Reduce GHG Emissions by 80% by 2050

	CCS	MARKAL	Nuclear	Renewables
Proportion of SH demand: Resistive heating (%)				10
Proportion of SH demand: ASHP (%)	18	58	58	60
Proportion of SH demand: GSHP (%)	30	30	30	30
Proportion of SH demand: Geothermal (%)		1	1	
Proportion of SH demand: Community-scale solid fuel CHP (%)	45			
Proportion of SH demand: District heating from power stations (%)	7	11	11	
Residential cooling demand (TWh)	13.5	0	30.6	0
Proportion of SC demand: Electric air-conditioning (%)	93		88	
Proportion of SC demand: Absorption chillers (%)	7		12	
HLC (W/^{0}C)	143	143	143	119
Indoor temp (^{0}C)	17	16	18	16

Efficiency: Electric resistive heating	1
Efficiency: ASHP	3
Efficiency: GSHP	24
Efficiency: Geothermal	0.85
Efficiency: Community-scale solid fuel CHP	0.57
Efficiency: District heating from power stations	0.9
Efficiency: Electric air-conditioning	6
Efficiency: Absorption chiller	0.7

Appendix 15: DECC 2050 Calculator Levels of Effort

The level of energy and emissions in 2050 depends in large part upon the level of *effort* deployed in trying to achieve the 80% reduction. The DECC 2050 Calculator recognises four levels of effort. Whilst certain of the parameters which affect energy consumption/emissions in 2050 are not affected by levels of effort (e.g. numbers of buildings), others such as changing mean indoor temperature and reducing the HLC are affected.

Level 1

Assumes little or no attempt to decarbonise or change or only short run efforts, and that unproven low carbon technologies are not developed or deployed.

Level 2

Describes what might be achieved by applying a level of effort that is likely to be viewed as ambitious but reasonable by most or all experts. For some sectors this would be similar to the build rate expected with the successful implementation of the programmes or projects currently in progress.

Level 3

Describes what might be achieved by applying a very ambitious level of effort that is unlikely to happen without significant change from the current system; it assumes significant technological breakthroughs.

Level 4

Describes a level of change that could be achieved with effort at the extreme upper end of what is thought to be physically plausible by the most optimistic observer. This level pushes towards the physical or technical limits of what can be achieved.

Appendix 16: Model Output for Semi-Detached House at Gatwick

Table 99 Modelling output for semi-detached house at Gatwick for May-September

		May	June	July	August	September
Glazing	kWh	-233.7915	-182.7561	-153.8783	-156.4212	-186.4301
Walls	kWh	-165.7996	-127.62	-72.79841	-97.88639	-121.8063
Ceilings (int)	kWh	-26.28305	-13.74676	34.72882	17.70824	-9.380915
Floors (int)	kWh	-38.77083	-32.68045	-32.3264	-39.85936	-26.01957
Ground Floors	kWh	-73.48812	-72.46283	-64.93794	-65.01604	-50.71343
Partitions (int)	kWh	9.425425	12.38849	36.05729	25.20742	15.8221
Roofs	kWh	-3.296976	-1.933995	-0.800889	-1.506162	-2.774776
Floors (ext)	kWh	-0.717617	-0.592174	-0.107814	-0.18152	-0.4057
Internal Natural vent.	kWh	-0.000001	-0.000001	0.000002	0.000002	-0.000001
Mech Vent + Nat Vent + Infiltration	ac/h	1.994726	2.990125	4.657084	3.830013	1.708539
External Infiltration	kWh	-337.2018	-259.8683	-207.2375	-216.335	-271.0081
External Vent.	kWh	-266.8593	-349.622	-613.6301	-501.6051	-240.1985
Zone Heating	kWh	66.72643	28.85005	4.073697	11.7493	57.00167
General Lighting	kWh	99.55117	100.1945	99.55117	101.2827	98.4629
Computer + Equip	kWh	225.6193	224.5452	225.6193	228.3667	221.7977
Occupancy	kWh	17.06792	16.18118	15.86253	16.259	16.66597
Solar Gains Exterior Windows	kWh	821.6042	741.496	809.4665	753.8649	564.0301
Zone Sensible Heating	kWh	66.72643	28.85005	4.073696	11.74929	57.00167
Air Temperature	°C	20.57786	21.48672	22.35192	21.98933	20.59904
Radiant Temperature	°C	21.31344	22.28704	23.55174	23.01351	21.21696
Operative Temperature	°C	20.94565	21.88688	22.95183	22.50142	20.908
Room Electricity	kWh	225.6193	224.5452	225.6193	228.3667	221.7977
Lighting	kWh	105.6663	105.8566	105.6663	107.3978	104.125
Auxiliary Energy	kWh	25.18134	24.36904	25.18134	25.18134	24.36904
Heat Generation (Gas)	kWh	115.0456	49.74147	7.023613	20.2574	98.27875
DHW (Gas)	kWh	99.12367	97.48912	99.12367	99.81585	96.79694
Outside Dry-Bulb Temperature	°C	12.47285	15.01125	17.31358	16.72406	13.84889

Appendix 17: SCECMORS Estimates of Residential Space Cooling Energy Consumption for different percentiles

The tales below present SCECMORS esimates of residential pace cooling energy consumption for different percentiles, updated with DECC 2050 Calculator settings of for the EER, numbers of buildings and emissions intensity of electricity. Note that the percentile temperatures used derive from the same ranking used for space heating (which used winter temperatures to establish the ranks). It is important that the temperature ranks are consistent with those used for space heating (which accounts for the vast majority of energy consumption within the residential sector), so that annual energy consumptions are representative of energy consumption – this would not be the case if summer temperatures were ranked independently (e.g. the probability of a 90th percentile summer occurring in the same year as the 90th percentile winter is very much higher than 90%).

Table 100 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (30th percentile medium emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	49	9.36	9.35	1.372	1.450	0.011	0.113
SCECdwell SHEU 3%	55	10.55	10.55	1.547	1.635	0.012	0.127
SCECdwell CEUD 7.2%	49	9.53	9.53	1.397	1.477	0.011	0.115
SCECdwell SHEU 7.2%	55	10.59	10.58	1.553	1.641	0.012	0.128
SCECair CEUD 3%	49	6.95	6.95	1.019	1.077	0.008	0.084
SCECair SHEU 3%	55	7.84	7.83	1.149	1.214	0.009	0.094
SCECair CEUD 7.2%	49	7.08	7.08	1.038	1.097	0.008	0.085
SCECair SHEU 7.2%	55	7.87	7.86	1.154	1.219	0.009	0.095
Average	52	8.72	8.72	1.28	1.35	0.01	0.11

Table 101 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (50th percentile medium emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	**Penetration (%)**	**Energy Demand (TWh)**		**Energy Consumption (TWh)**		**Emissions (MTCO$_2$e)**	
SCECdwell CEUD 3%	51	10.46	10.45	1.533	1.620	0.012	0.126
SCECdwell SHEU 3%	58	11.74	11.74	1.722	1.820	0.014	0.141
SCECdwell CEUD 7.2%	52	10.61	10.60	1.555	1.643	0.012	0.128
SCECdwell SHEU 7.2%	58	11.76	11.75	1.724	1.822	0.014	0.142
SCECair CEUD 3%	51	7.77	7.76	1.139	1.203	0.009	0.094
SCECair SHEU 3%	58	8.72	8.72	1.279	1.352	0.010	0.105
SCECair CEUD 7.2%	52	7.88	7.87	1.155	1.220	0.009	0.095
SCECair SHEU 7.2%	58	8.74	8.73	1.281	1.353	0.010	0.105
Average	55	9.71	9.70	1.42	1.50	0.01	0.12

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	56	12.80	12.80	1.877	1.984	0.015	0.154
SCECdwell SHEU 3%	63	14.28	14.27	2.094	2.213	0.017	0.172
SCECdwell CEUD 7.2%	57	12.90	12.90	1.892	2.000	0.015	0.155
SCECdwell SHEU 7.2%	63	14.24	14.23	2.088	2.206	0.017	0.172
SCECair CEUD 3%	56	9.51	9.51	1.394	1.474	0.011	0.115
SCECair SHEU 3%	63	10.61	10.60	1.556	1.644	0.012	0.128
SCECair CEUD 7.2%	57	9.58	9.58	1.405	1.485	0.011	0.115
SCECair SHEU 7.2%	63	10.58	10.57	1.551	1.639	0.012	0.127
Average	60	11.81	11.81	1.73	1.83	0.01	0.14

Table 103 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (90th percentile medium emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	62	16.03	16.03	2.351	2.485	0.019	0.193
SCECdwell SHEU 3%	69	17.73	17.72	2.600	2.748	0.021	0.214
SCECdwell CEUD 7.2%	62	16.07	16.06	2.357	2.490	0.019	0.194
SCECdwell SHEU 7.2%	68	17.62	17.60	2.583	2.729	0.021	0.212
SCECair CEUD 3%	62	11.91	11.90	1.746	1.845	0.014	0.143
SCECair SHEU 3%	69	13.17	13.16	1.931	2.041	0.015	0.159
SCECair CEUD 7.2%	62	11.94	11.93	1.750	1.850	0.014	0.144
SCECair SHEU 7.2%	68	13.08	13.07	1.918	2.027	0.015	0.158
Average	65	14.69	14.68	2.15	2.28	0.02	0.18

Table 104 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (30th percentile high emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	55	11.95	11.94	1.752	1.851	0.014	0.145
SCECdwell SHEU 3%	61	13.36	13.35	1.959	2.070	0.016	0.162
SCECdwell CEUD 7.2%	55	12.06	12.06	1.769	1.869	0.014	0.146
SCECdwell SHEU 7.2%	61	13.33	13.33	1.955	2.067	0.016	0.162
SCECair CEUD 3%	55	8.87	8.87	1.301	1.375	0.010	0.108
SCECair SHEU 3%	61	9.92	9.92	1.455	1.538	0.012	0.120
SCECair CEUD 7.2%	55	8.96	8.96	1.314	1.389	0.011	0.109
SCECair SHEU 7.2%	61	9.90	9.90	1.452	1.535	0.012	0.120
Average	58	11.04	11.04	1.62	1.71	0.01	0.13

Table 105 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (50th percentile high emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	57	13.34	13.34	1.956	2.068	0.016	0.162
SCECdwell SHEU 3%	64	14.86	14.85	2.179	2.303	0.017	0.180
SCECdwell CEUD 7.2%	58	13.43	13.42	1.969	2.081	0.016	0.163
SCECdwell SHEU 7.2%	64	14.81	14.80	2.171	2.294	0.017	0.180
SCECair CEUD 3%	57	9.91	9.91	1.453	1.536	0.012	0.120
SCECair SHEU 3%	64	11.04	11.04	1.619	1.711	0.013	0.134
SCECair CEUD 7.2%	58	9.98	9.97	1.463	1.546	0.012	0.121
SCECair SHEU 7.2%	64	10.99	10.99	1.612	1.704	0.013	0.133
Average	61	12.30	12.29	1.80	1.91	0.01	0.15

Table 106 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (70th percentile high emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	62	15.69	15.68	2.300	2.431	0.018	0.190
SCECdwell SHEU 3%	68	17.36	17.35	2.546	2.690	0.020	0.211
SCECdwell CEUD 7.2%	62	15.73	15.72	2.306	2.437	0.018	0.191
SCECdwell SHEU 7.2%	68	17.25	17.24	2.529	2.673	0.020	0.209
SCECair CEUD 3%	62	11.65	11.64	1.708	1.805	0.014	0.141
SCECair SHEU 3%	68	12.90	12.89	1.891	1.998	0.015	0.157
SCECair CEUD 7.2%	62	11.68	11.67	1.713	1.810	0.014	0.142
SCECair SHEU 7.2%	68	12.81	12.80	1.879	1.985	0.015	0.156
Average	65	14.38	14.37	2.11	2.23	0.02	0.17

Table 107 Residential space heating penetration, energy consumption and emissions for the 2050 stock – SCECMORS amended with DECC 2050 Calculator data (90th percentile high emissions scenario)

						Adjusted Model	
		Nuclear	CCS	Nuclear	CCS	Nuclear	CCS
Forecasting Model	Penetration (%)	Energy Demand (TWh)		Energy Consumption (TWh)		Emissions (MTCO$_2$e)	
SCECdwell CEUD 3%	64	17.27	17.26	2.532	2.676	0.020	0.210
SCECdwell SHEU 3%	71	19.03	19.03	2.791	2.950	0.022	0.231
SCECdwell CEUD 7.2%	64	17.28	17.27	2.534	2.678	0.020	0.210
SCECdwell SHEU 7.2%	70	18.89	18.89	2.770	2.928	0.022	0.229
SCECair CEUD 3%	64	12.83	12.82	1.881	1.988	0.015	0.156
SCECair SHEU 3%	71	14.14	14.13	2.073	2.191	0.017	0.172
SCECair CEUD 7.2%	64	12.84	12.83	1.882	1.989	0.015	0.156
SCECair SHEU 7.2%	70	14.04	14.03	2.058	2.175	0.016	0.170
Average	67	15.79	15.78	2.32	2.45	0.02	0.19

Postscript

DesignBuilder Update

The 550 simulations performed for the ACDD analysis described in Chapter 4 were performed using DesignBuilder version 2.4.1.009. After having completed the time-consuming ACDD analysis, the author was informed by the software provider of DesignBuilder that this particular version of the software contained a bug. DesignBuilder stated that the "bug in it related to metabolic rates which weren't being loaded correctly from the new NCM (National Calculation Methodology) databases. The net result was that internal gains from occupants were not included in simulations".

The bug has been fixed, and is not present in the updated version 2.4.2.015. A number of simulations we re-performed on a sub-set of buildings using the updated version in order to investigate how they might affect the results reported in Chapter 4. 22 re-simulations were carried out on the MW 30%-glazed building (one for each of the 22 locations), this building type having been chosen as being a typical building form, being the form likely to be most representative of the stock at large. A further 22 re-simulations were also carried out for the Pitched 10%-glazed building, this building type having been chosen as it shows the least degree of correlation between the number of ACDDs and space cooling energy consumption for simulations carried out in version 2.4.1.009 (see Table 56).

Although, the inclusion of occupancy gains necessarily affects the absolute level of total cooling energy reported in the new simulations, the results do not appear to be otherwise deleteriously affected, there continuing to remain a very high degree of correlation between the number of ACDDs and space cooling energy consumption. Indeed, the coefficient of determination actually improves for the Pitched 10%-glazed building: this results from the increased levels of cooling required in buildings originally observed as requiring little/no cooling, following inclusion of the metabolic gains.

Figure 79-Figure 82 compare regression plots deriving from use of the original version 2.4.1.009 with those deriving from use of the updated version 2.4.2.015.

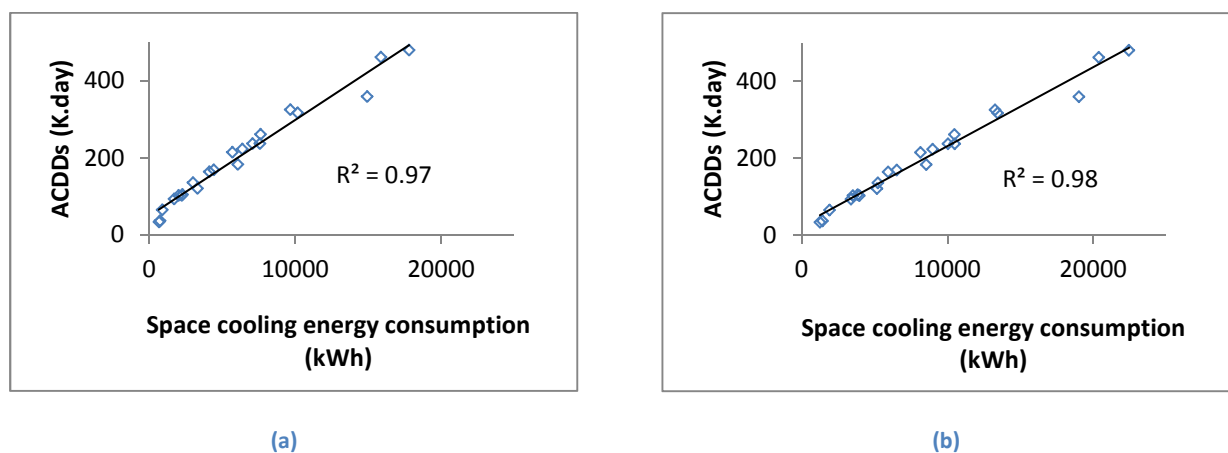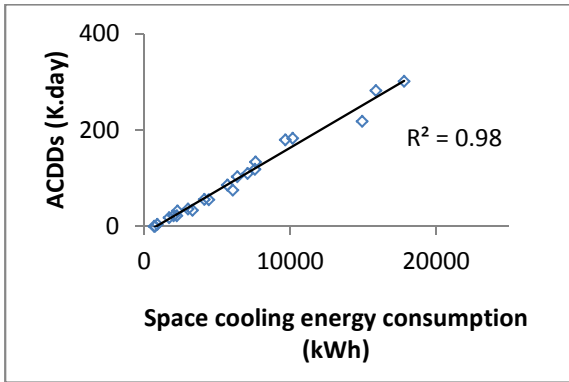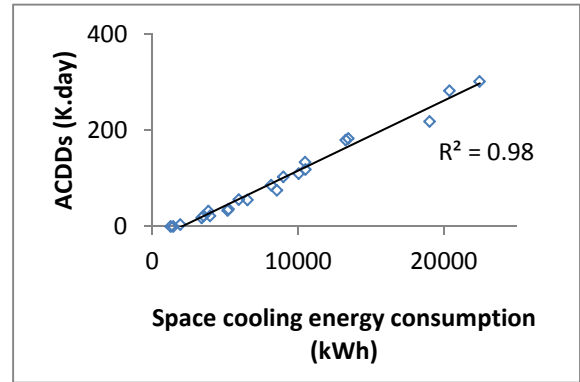(a)   (b)

Figure 79 Correlation between annual number of cooling ACDDs using the EAS and total annual space cooling energy consumption for the MW building with 30% glazing for 22 different locations – (a) version 2.4.1.009, (b) version 2.4.2.015
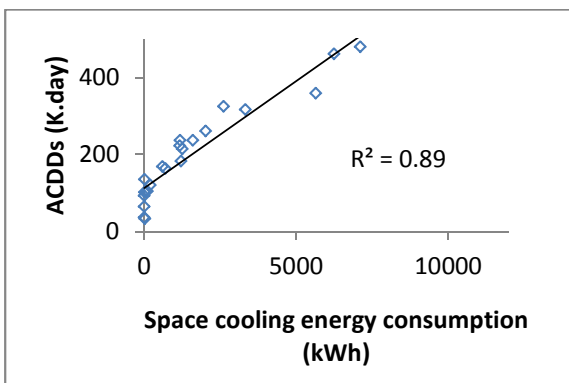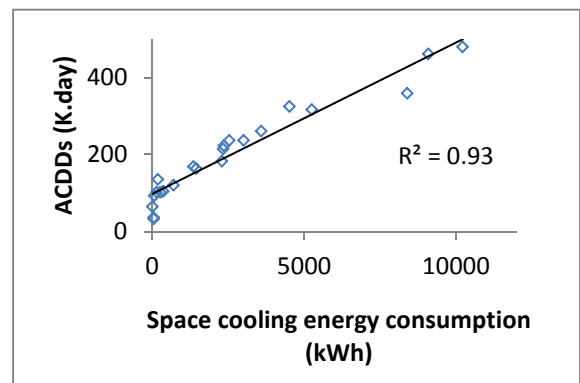
(a)
(b)

Figure 80 Correlation between annual number of cooling ACDDs using the AAS and total annual space cooling energy consumption for the MW building with 30% glazing for 22 different locations – (a) version 2.4.1.009, (b) version 2.4.2.015
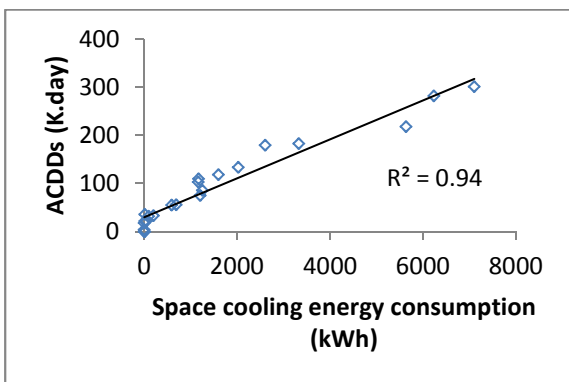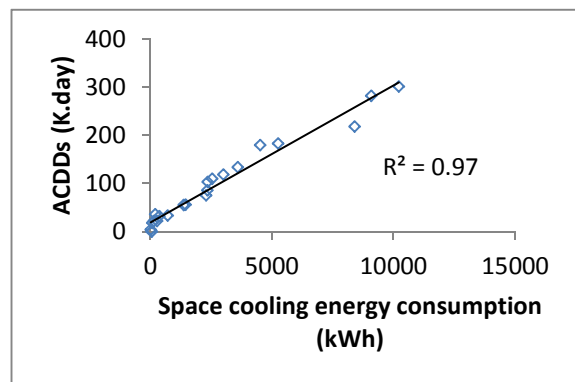

(a)
(b)

Figure 81 Correlation between annual number of cooling ACDDs using the EAS and total annual space cooling energy consumption for the Pitched building with 10% glazing for 22 different locations – (a) version 2.4.1.009, (b) version 2.4.2.015

(a)
(b)

Figure 82 Correlation between annual number of cooling ACDDs using the AAS and total annual space cooling energy consumption for the Pitched building with 10% glazing for 22 different locations – (a) version 2.4.1.009, (b) version 2.4.2.015

UKCP09 Weather Generator Update

The analyses described in Chapters 2, 3 and 4 all made use of data from the UKCP09 Weather Generator. During the compilation of this thesis however, the Weather Generator was updated, the principal improvements relating to rainfall extremes, temperature extremes, sunshine and vapour pressure (UKCP09, 2011b). Whilst the analyses in Chapters 2 and 3 used version 2.0, the analysis in Chapter 4 (and reported in (McGilligan, et al., 2011a)) used version 1. With version 1 lacking the improvement to heat wave duration incorporated in version 2.0 (this latter version appearing, on the whole, to increase the number of days reporting extreme temperatures), it would appear that the number of ACDDs estimated for future climates (Figure 50 and Figure 51) may have been under-estimated, since ACDDs are calculated from outdoor temperatures. Table 108 reports illustrative data comparing the number of days on which hot temperatures are recorded for version 1 (v1) and version 2.0 (v2.0) (UKCP09, 2011b).

	Hot day (>28 ^{0}C)				Hot day (>25 ^{0}C)			
	1970s		2080s Medium		1970s		2080s Medium	
	v 1	v 2.0	v 1	v 2.0	v 1	v 2.0	v 1	v 2.0
Heathrow	2	2	27	32	15	12	63	70
Yeovilton	0	1	21	28	7	8	54	63
Coltishall	0	0	10	11	4	4	37	37
Dale Fort	0	0	6	1	0	0	25	12
Ringway	0	0	9	9	3	2	30	29
Aldergrove	0	0	2	2	0	0	11	13
Eskdalemuir	0	0	1	3	0	1	8	12
Wick	0	0	0	0	0	0	4	0

Table 108 Number of days on which hot temperatures are recorded for versions 1 and version 2.0 of the UKCP09 Weather Generator at the 50% probability level for eight UK locations (1970s backcast and 2080s medium emissions scenario forecast)

The backcast for the relatively cool climate of the 1970s appears to show little difference in the number of hot days between the two versions. But it would seem that version 2.0 would be likely to return a greater number of ACDDs for both the European adaptive standard and the ASHRAE adaptive standard than version 1 for a future hot climate, because of the increased prevalence of hot days: in other words, energy savings from both the European adaptive standard and the ASHRAE adaptive standard would be likely to be higher in the future hot climate.

In view of the fact that the difference between the two versions is apparent in the hot 2080s climate but not in the cool past climate, it is considered that the results reported in Chapter 4 would have been little different if the analysis had been performed with version 2.0 instead of version 1, had it been available at the time: energy savings arising from the European adaptive standard in the near

term (e.g. the relatively cool 2020s) would be unlikely to be achieved by its ASHRAE counterpart until decades later.