UNDERSTANDING AND MODELLING THERMAL ENERGY DEMAND AND EMISSIONS IN URBAN ENVIRONMENTS

DAVID COWAN, MA, MSc

http://orcid.org/0000-0001-9113-2663

A thesis submitted in partial fulfilment of the requirements of London South Bank University for the degree of Doctor of Philosophy

February 2017

The School of the Built Environment & Architecture
London South Bank University

Supervisors

Professor Graeme Maidment and Dr Issa Chaer

Abstract

Refrigeration, air conditioning and heat pump (RACHP) systems currently account for nearly 20% of UK grid electricity use and over 7% of all UK greenhouse gas emissions. This research project has investigated the sources and levels of emissions from RACHP systems and how the cooling (and heating) energy and emissions from buildings might be reduced by optimizing the building's design, construction and operation.

Analysis of data from site surveys and maintenance logs confirmed that leakage of refrigerant can be a significant contributor to total RACHP emissions. TEWI (total equivalent warming impact) analyses showed that for RACHP systems with high GWP (global warming potential) refrigerants and annual leak rates of 10% or more, direct emissions from refrigerant leakage can exceed the indirect emissions associated with energy use. However, for heat pump and air conditioning systems, with typical leak rates of below 3%, using low GWP refrigerants (GWP = 500 or less), the direct emissions do not make a significant contribution to building emissions.

A new dynamic energy balance model and Excel based tool were developed to help improve the understanding of building energy use and emissions. The tool can be used to predict the sensitivity to different building design concepts, features and operation and the parameters of the installed RACHP plant. Results for an office building suggest that the building fabric (with the exception of the glazing) is not necessarily a key factor influencing the total energy use and emissions. However, relatively simple measures to reduce electricity use and to reduce solar gain could each reduce building emissions by 10% or more. Results for a dwelling built to 2006 Building Regulations demonstrated an overheating risk in summer, even with mechanical ventilation, but adding a 2 kW air conditioning unit could prevent overheating, with lower energy use and emissions than a similar dwelling incorporating mechanical ventilation.

Climate change simulations for the year 2080 predicted a net increase in energy demand and emissions of about 5% for the office building (mainly associated with the use of grid electricity), implying that the grid carbon factor is likely to be a key determinant of future emissions from such buildings. For dwellings without mechanical ventilation or air conditioning, internal temperatures might rise as high as 40°C in summer months, but a small air conditioning unit could maintain temperatures below 25°C with no increase in total energy use and emissions compared with the present day. For a grid electricity carbon factor reduction of 80%, total emissions for the simulated office building would fall by about 70% and for the dwelling by about 50%.

DECLARATION

I declare that the research described in this thesis is the original work of the author except where otherwise specified, or where acknowledgement is made by reference.

The work was carried out at the School of the Built Environment & Architecture, London South Bank University, under the supervision of Professor Graeme Maidment and Dr Issa Chaer.

This work has not been submitted for any other degree or award at any other academic or professional institution during the research program.

ACKNOWLEDGEMENT

This research was carried out in collaboration with the UK Institute of Refrigeration and funded by the Engineering and Physical Science Research Council (EPSRC), the London Development Agency (LDA) and the UK Institute of Refrigeration (IOR). Their sponsorship is gratefully acknowledged.

The author would like to thank in particular Mrs Miriam Rodway, Professor Graeme Maidment and Dr Issa Chaer for their encouragement, guidance and support throughout the research programme, from its original inception through to completion. I would also like to thank Dr Roberto Peixoto for reviewing my draft thesis - his comments were very helpful and much appreciated. The ideas and suggestions contributed by my fellow PhD candidates and other staff at LSBU and by other professionals in the refrigeration, air conditioning and heat pump sector are also gratefully acknowledged.

Finally I would like to thank my wife Margaret, who has supported and encouraged me throughout this endeavour.

Table of Contents

List of Figures

List of Tables

Glossary of Abbreviations

Abbreviation	Stands for
ach	Air Changes per Hour
ADE	(UK) Association for Decentralised Energy
ADL	Approved Document Part L (Building Regulations)
AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineering
ASHP	Air Source Heat Pump
BMS	Building Management System
BEMS	Building Energy Management System
BP	Boiling Point
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
BSRIA	Building Services Research and Information Association
CE	**C**onformité **E**uropéene (European Conformity)
CFC	ChloroFluoroCarbon
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CH_4	Methane
CIBSE	Chartered Institute of Building Services Engineers
CO_2	Carbon Dioxide
Coolth	Coolness (opposite to Warmth)
COP	Coefficient of Performance
CP	Critical Pressure
CT	Critical Temperature
DCLG	Department for Communities and Local Government
DEC	Display Energy Certificate
DECC	Department of Energy & Climate Change
DEFRA	Department for Environment, Food & Rural Affairs
DER	Dwelling Emissions Rate
DHW	Domestic Hot Water
DSY	Design Summer Year

DX	Direct Expansion
EC	European Community
EER	Energy Efficiency Ratio
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPSRC	Engineering and Physical Science Research Council
ETSU	Energy Technology Support Unit (Harwell, UK)
EU	European Union
Excel	Microsoft Excel Spreadsheet/ Workbook
F-Gas	Fluorinated Gas
FP	Freezing Point
GGIF	Greenhouse Gas Impact Factor
GGIR	Greenhouse Gas Impact Rating
GHG	Greenhouse Gas
GLA	Greater London Authority
GSHP	Ground Source Heat Pump
GWh	Gigawatt Hour
GWP	Global Warming Potential
HCFC	HydroChloroFluoroCarbon (Refrigerant)
HFC	HydroFluoroCarbon (Refrigerant)
HFO	HydroFluoroOlefin
HP	Heat Pump
HT	High Temperature
HVAC	Heating, Ventilation, and Air Conditioning
HWS	Hot Water Services
HX	Heat Exchanger
ICT	Information and Communications Technology
ID	Identifier
IEA	International Energy Agency
IES	Integrated Environmental Solutions
IES-VE	Integrated Environmental Solutions Virtual Environment
IGU	International Gas Union
IIR	International Institute of Refrigeration
IOR	Institute of Refrigeration
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

IT	Information Technology
kg	Kilogramme
$kgCO_2e$	Kilogrammes of CO_2 equivalent
kW	Kilowatt
kWh	Kilowatt hour
LCA	Life Cycle Analysis
LDA	London Development Agency
LED	Light Emitting Diode
LSBU	London South Bank University
LT	Low Temperature
MAC	Mobile Air Conditioning
MIS	Management Information System
MIT-3	(UNEP) Mitigation Scenario 3
MSc	Master of Science
Mt (or MT)	Million Tonnes
$MtCO_2e$ (or $MTCO_2e$)	Million Tonnes of CO_2 equivalent
MTProg	UK Market Transformation Programme
MWh	Megawatt Hour
N_2O	Nitrous Oxide
NH_3	Ammonia
ODS	Ozone Depleting Substance
ODPM	Office of the Deputy Prime Minister
ONS	Office for National Statistics
PCM	Phase Change Material
PED	Pressure Equipment Directive
PFC	PerFluoroCarbon
PRV	Pressure Relief Valve
PV	Photovoltaic
Rxxx (e.g. R134a)	Refrigerant Type (classified according to chemical composition)
RACHP	Refrigeration, Air Conditioning and Heat Pump
REAL Alternatives	Blended Learning for Alternative Refrigerants
REAL Skills Europe	Refrigerant Emissions and Leakage Skills for Europe
REAL Zero	Refrigerant Emissions and Leakage - Zero
RSE	REAL Skills Europe
RTOC	(UNEP) Refrigeration, Air Conditioning and Heat Pumps

	Technical Options Committee
SAP	Standard Assessment Procedure
SF_6	Sulphur HexaFluoride
SI	Statutory Instrument (UK legislation)
SOLIFTEC	Solid Fuel Technology Institute
STEK	Dutch national programme aimed at reducing refrigerant emissions
tCO_2(e)	Tonnes of Carbon Dioxide (equivalent)
TEAP	(UNEP) Technology and Economic Assessment Panel
TER	Target Emissions Rate
TEWI	Total Equivalent Warming Impact
TRY	Test Reference Year
TWh	Tera (10^{12}) Watt Hours
U (value)	Thermal Transmittance (rate of transfer of heat)
UHI	Urban Heat Island
UK	United Kingdom
UKCP09	UK Climate Projections (2009 and subsequent updates)
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
URS	URS Corporation Ltd.
US/ USA	United States of America
VP	Vapour Pressure
VRV	Variable Refrigerant Volume

Nomenclature

Symbol	Stands for
°C	Temperature (degrees Centigrade)
T_L	Evaporator temperature (°K)
T_H	Condenser temperature (°K)
K	Temperature (degrees Kelvin)
ΔT	Temperature difference (°K)
L	Refrigerant leakage rate per year (kg)
n	System operating time (years)
m	Refrigerant charge (kg)
R	Recycling factor (fraction of refrigerant charge lost)
E	Annual energy consumption (kWh)
CF	Carbon Factor (CO_2 equivalent emissions per kWh)
g	Grammes
Q_x	Thermal heat flow (kW)
Δθ	Rate of change of temperature (°C/h)
θ_t	Building internal temperature at time t
$\theta_{(t-1)}$	Building temperature at time (t-1)
C	Effective heat capacity (kWh/K)
h	Hour
t	Time (hour)
ΔQ_{del}	Thermal heat flow required to maintain energy balance (kW)
COP	Coefficient of Performance
EM_{RACHP}	RACHP emissions (tCO_2(e) per annum)
L_{em}	refrigerant leakage rate per year (% of the specific refrigerant charge)
U	Thermal transmittance (W/m^2K)
ach	Air changes per hour
l	Litre
Lt	Light transmittance factor (%)
g-value	Solar transmittance factor (%)
A	Area (m^2)

Published papers from this research

Gartshore, J. Rodway, M. Cowan, D. Chaer, I. Benton, S. Stacey, P. Blackhurst, D. Maidment, G. (2009) *REAL Zero – Refrigerant Emissions and Leakage in UK- Feedback from a UK Project.* IIR 1st Workshop on Refrigerant Charge Reduction, Cemagref Antony, France

Cowan, D. Chaer, I. Maidment, G. (2010) *F Gas Containment – Two UK Led Projects on Reducing Refrigerant Emissions and Leakage*. 1st IIR International Conference on the Cold Chain and Sustainability, Cambridge

Cowan, D. Gartshore, J. Chaer, I. Francis, C. Maidment, G. (2010) *REAL Zero – Reducing refrigerant emissions & leakage - feedback from the IOR Project*. Proc. Inst. R. 2009-10.7

Cowan, D. Chaer, I. Maidment, G. (2010) *Renewable Electrical Energy Strategies for Low and Zero Carbon Homes.* Energy in the City, Conference C92 of the Solar Energy Society, London

Cowan, D. Chaer, I. Maidment, G. (2010) *Reducing refrigerant emissions and leakage – an overview and feedback from two EU projects.* Keynote presentation at IIR 2nd Workshop on Refrigerant Charge Reduction, Stockholm, Sweden

Cowan, D. Chaer, I. Maidment, G. (2010) *REAL SKILLS EUROPE – a route to more sustainable cooling and heating.* Colloque AFCE Effet de Serre IX, Paris, France

Cowan, D. Lundqvist, P. Chaer, I. Maidment, G. (2011) *Refrigerant leakage and containment – overview of the activities of the IIR working party on the mitigation of direct emissions of greenhouse gases in refrigeration.* 23rd IIR International Congress of Refrigeration, Prague, Czech Republic August 2011

Cowan, D. Beermann, K. Chaer, I. Gontarz, G. Kaar, K. Koronaki, I. Maidment, G. Reulens, W. (2011) *Improving F-Gas containment in the EU – results from the REAL SKILLS EUROPE project.* 23rd IIR International Congress of Refrigeration, Prague, Czech Republic August 2011

Koronaki, I.P. Cowan, D. Maidment, G. Beerman, K. Schreurs, M. Kaar, K. Chaer, I. Gontarz, G. Christodoulaki, R.I. Cazauran, X. (2012) *Refrigerant emissions and leakage prevention across Europe – Results from the RealSkillsEurope project*. Energy, Volume 45, Issue 1, September 2012, Pages 71-80, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2012.05.040.

Cowan, D. Maidment, G. Chaer, I. (2014) *Estimation of cooling energy demand and carbon emissions from urban buildings using a quasi-dynamic model*. ASHRAE Winter Conference, New York, USA, January 2014

Cowan, D. Chaer, I. Lundqvist, P. Maidment, G. Coulomb, D. (2014) *24th Informatory note on refrigeration technologies: containment of refrigerants within refrigeration, air conditioning and heat pump systems*. International Institute of Refrigeration, Paris, France, January 2014

Colombo, I. Maidment, G. Cowan, D. (2014) *Investigation of whole life emission for air to water heat pumps.* 3rd International Conference on Sustainability and the Cold Chain, Twickenham, UK, June 2014

Colombo, I. Maidment, G. Cowan, D. (2015) *Investigation of whole life emission for air to water heat pumps.* 24th IIR International Congress of Refrigeration, Yokohama, Japan, August 2015

Chapter 1. Introduction

Historically, the primary energy demand has been for heat energy, used either directly (or indirectly by conversion into mechanical or electrical energy) for industrial processes, transportation, heating buildings and cooking food. The demand for cooling energy emerged in the early 1900s with the introduction of commercially viable vapour compression refrigeration and air conditioning systems for food storage and comfort cooling. Over the past century, cooling energy demands have increased dramatically, for several reasons, including:

1. The increasing use of refrigeration for food processing, freezing and storage, together with the high penetration of refrigerators and freezers in homes.
2. The trend for modern buildings to have lower thermal mass, higher levels of insulation and larger glazed areas than traditional buildings. This results in higher solar gain, with the heat less readily absorbed by the building fabric or lost through the walls.
3. The need to remove the additional internally generated heat from buildings that has arisen from the rapid growth in the use of IT and other electronic systems in offices and homes.
4. Increasing urbanization and building density in towns and cities, resulting in higher energy intensities and carbon emissions.
5. Increasing ambient temperatures, due to global warming and climate change.

In London and many other cities, the consequence of these changes is that even in winter the internal heat gains in many buildings can exceed the heat losses, so no additional heating is required. In some instances the heat gains in buildings are so large that they may require cooling measures throughout the year. However, it is not only buildings that require cooling: in the London Underground network, for example, the heat generated by the trains and passengers is absorbed by the ground and has raised its temperature to such an extent that cooling the underground has now become a major challenge.

The demand for cooling continues to increase and this study considers some options for reducing the cooling demand and emissions from buildings in cities such as London and delivering cooling energy in a more sustainable way.

1.1 Aims of the research

Because of the lack of good quality data, it has been difficult to logically target carbon emission reductions for the RACHP sector. There is limited authoritative information on why and where carbon emissions (from energy use and leakage) occur, or the most effective ways and the positive consequences of reducing these emissions. This research project was aimed at investigating and understanding the energy demand and carbon footprint of cooling in the urban environment, using two complementary approaches.

An investigation of the emissions from RACHP systems and the relative contributions between the direct emissions from refrigerant leakage and the indirect emissions associated with grid electricity use. Analysis of the relative emissions would help to identify the potential (and limitations) for future emissions reductions. Direct emissions due to leakage of refrigerant from systems contribute a significant percentage of total emissions from the RACHP sector. By developing a better understanding of the sources and causes of such leakage, effective measures to cut leakage and reduce refrigerant emissions might be implemented in a relatively short time frame. Reductions in the indirect (energy related) emissions from RACHP systems might be achieved through efficiency improvements (for example by using better technology), through the decarbonisation of the electricity grid, or by reducing the cooling energy demand (the thermal cooling load).

The aim of the second approach was to investigate the scope for reducing the cooling (and heating) energy demand in buildings, by developing a mathematical dynamic energy and emissions model that incorporates the RACHP plant and parameters for its performance and efficiency, refrigerant type and refrigerant leakage rate. Modelling the RACHP system within its operating environment should provide a better insight into its energy demand and emissions performance, since it assesses the dynamic response and utilisation factor, as well as how the RACHP system contributes to total building emissions. The model would be used to estimate the sensitivity of energy demand and emissions to alternative building designs, materials and features, different types of RACHP system and alternative strategies for managing the building, also the sensitivity to changes to the external environment associated with global warming. The results could be used to assess potential measures that could be incorporated in new and existing buildings, to reduce the cooling (and heating) energy demand and total building emissions.

1.2 Description of the chapters

A review of literature relating to cooling demand, climate change and mitigation follows in Chapter 2. Chapter 3 details the proposition and methodology used for the research, while chapter 4 describes work undertaken to investigate the emissions associated with RACHP systems, studies into refrigerant leakage and whole of life emissions in heat pumps, alternative refrigerants and the performance and efficiency of RACHP systems. Chapter 5 addresses the modelling of energy demand in buildings and describes a new quasi-dynamic energy model that has been developed to predict how the energy demand and emissions vary with changes to the design and operation. It also discusses sources of data for buildings, energy benchmarks and weather data for use in the model. Chapter 6 documents the results of simulations using the new model and compares results against an industry standard modelling tool (IES-VE), with established energy and emissions benchmarks and with an analysis of energy data from the analysis of ONS statistical data downloads. The sensitivity of energy and emissions to building design features and standards, operating parameters and climate change are reported in Chapter 7. Chapter 8 presents a discussion of the Excel model and the results of the simulations and sensitivity analyses, while the overall conclusions are presented in Chapter 9.

Chapter 2. Literature review

This chapter presents a review of literature relating to climate change and mitigation, the environmental impact of RACHP systems, current and future energy demand, the urban environment and demographic trends, studies into cooling energy and emissions, building energy benchmarks and low carbon cooling.

2.1 Carbon emissions and global warming scenarios

The IPCC 5th Assessment Report (IPCC, 2014) describes several alternative global scenarios and predictions of future anthropogenic emissions levels, along with their global warming impact. This latest report is built around the concept of Representative Concentration Pathways (RCPs) which are time and space dependent trajectories of concentrations of greenhouse gases and pollutants resulting from human activities, including changes in land use. RCPs provide a quantitative description of concentrations of the climate change pollutants in the atmosphere over time, as well as their radiative forcing in 2100 (for example, RCP 6 achieves an overall impact of 6 watts per square metre by 2100). Radiative forcing is the difference in the balance of energy that enters the atmosphere and the amount that is returned to space compared to the pre-industrial times and is determined by both positive forcing from greenhouse gases and negative forcing from aerosols (as the radiative forcing increases, the global temperature rises).

Gases and pollutants included in the RCPs are:

- Greenhouse gases - CO_2, methane, nitrous oxide, several groups of fluorocarbons and sulphur hexafluoride.
- Aerosols and chemically active gasses - sulphur dioxide, soot, organic carbon, carbon monoxide, nitrogen oxides, volatile organic compounds, ammonia.

Figure 2-1 shows radiative forcing estimates in 2011 relative to 1750 for the main drivers of climate change. The dominant factor is the positive forcing from CO_2, followed by methane (CH_4) and halocarbons, which include many current refrigerants. The chart also shows estimates for 1950 and 1980, indicating the rapid increase over the past 70 years.

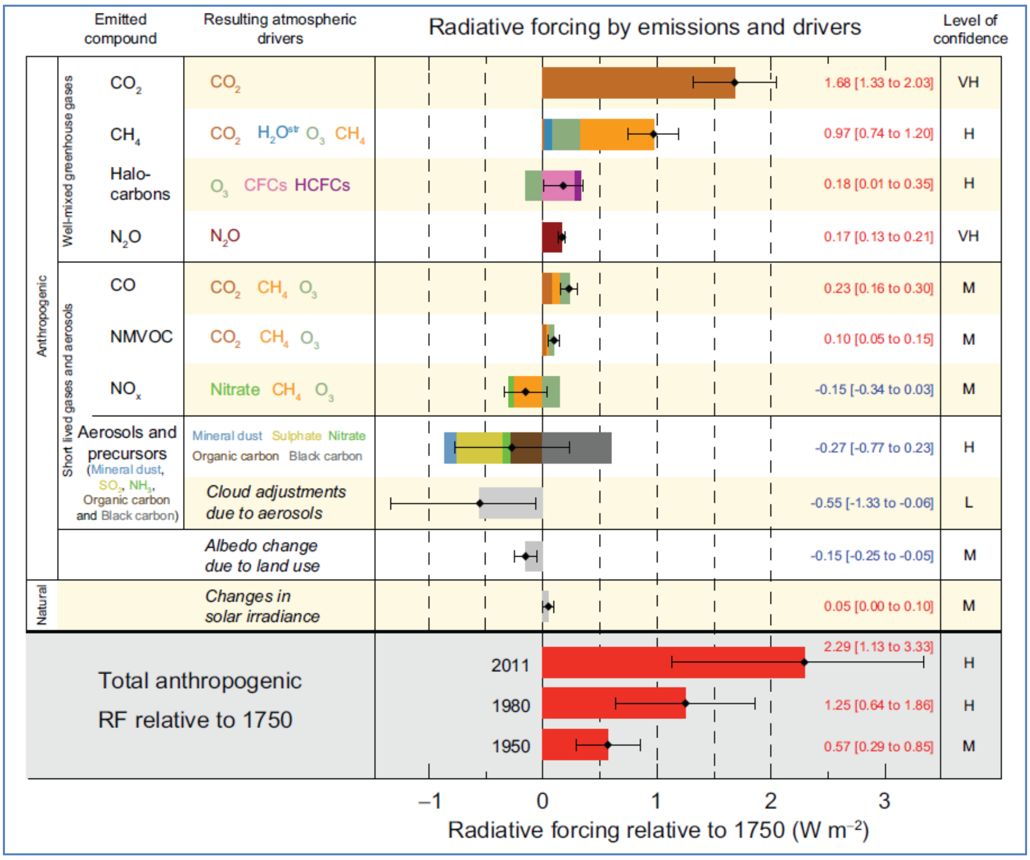


Figure 2-1. Radiative forcing estimates in 2011 relative to 1750

[Source IPCC (2013) Figure SPM.5]

The 4 RCP scenarios considered in the 5th Assessment were:

- RCP 8.5 – High emissions. This is consistent with a future with no policy changes to reduce emission, leading to three times today's CO_2 emissions by 2100, a rapid increase in methane emissions and increased use of croplands and grassland (driven by an increase in world population to 12 billion by 2100, lower rate of technology development, a heavy reliance on fossil fuels and high energy intensity.
- RCP 6 – Intermediate emissions. Radiative forcing is stabilised shortly after year 2100, which is consistent with the application of a range of technologies and strategies for reducing greenhouse gas emissions, a heavy reliance on fossil fuels, intermediate energy intensity, increasing use of croplands and declining use of grasslands and stable methane emissions. CO_2 emissions peak in 2060 at 75 per cent above today's levels, then decline to 25 per cent above today.
- RCP 4.5 – Intermediate emissions. Radiative forcing is stabilised by year 2100, consistent with a future with relatively ambitious emissions reductions: lower energy intensity; strong reforestation programmes; decreasing use of croplands and grasslands due to yield increases and dietary changes; stringent climate policies; stable

methane emissions. CO_2 emissions increase only slightly before decline commences around 2040.

- RCP 2.6 – Low emissions. Radiative forcing reaches 3.1 W/m^2 before it returns to 2.6 W/m^2 by 2100. This future would require: declining use of oil; low energy intensity; a world population of 9 billion by year 2100; use of croplands increase due to bio-energy production; more intensive animal husbandry; methane emissions reduced by 40 per cent. CO_2 emissions stay at today's level until 2020, then decline and become negative in 2100, while CO_2 concentrations peak around 2050, followed by a modest decline to around 400 ppm by 2100.

Figure 2-2 shows the total global mean radiative forcing for the four RCP scenarios out to year 2300 and the corresponding change in the global surface temperature. The charts indicate that by 2100 there could be a 1°C increase in temperature for the RCP 2.6 scenario, or a 2°C increase for RCP 4.5. These scenarios indicate that an ambitious emissions reduction programme will be needed to limit the temperature increase to 2°C or less.

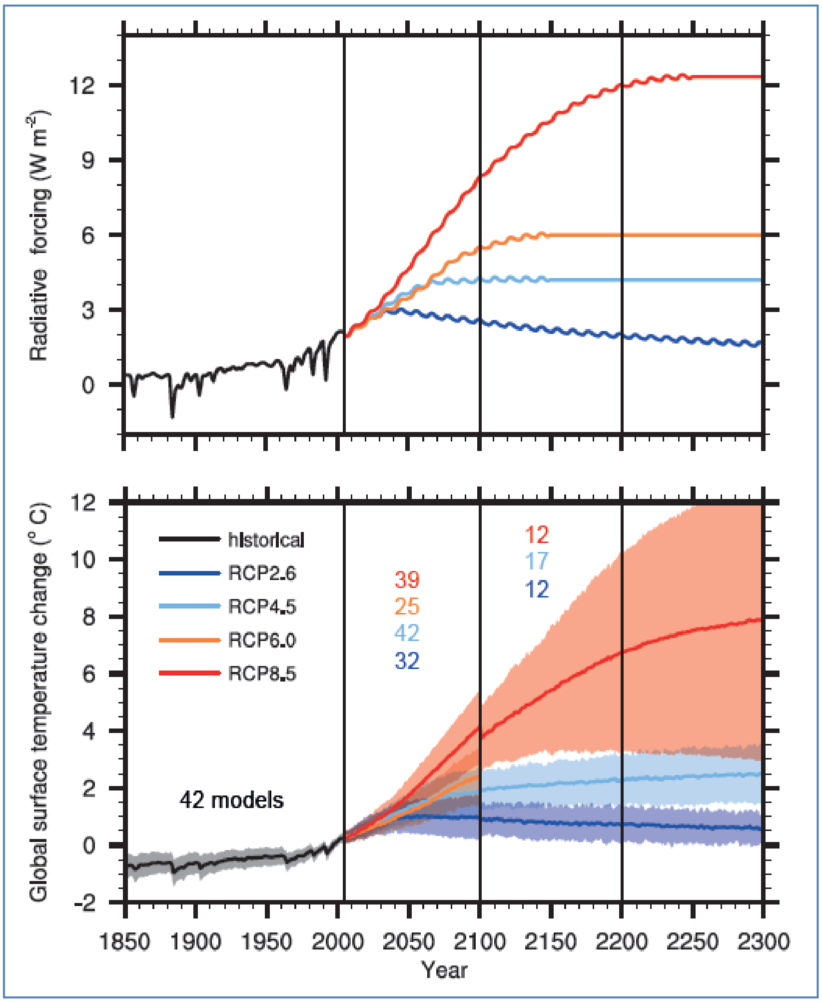


Figure 2-2. Predicted radiative forcing and temperature change for the 4 RCP scenarios

[Source: Stocker *et al* (2013) Figure TS.15]

Figure 2-3 charts the projected annual anthropogenic CO2 emissions and the warming against cumulative CO_2 emissions for the RPC scenarios and the associated scenario categories. Whilst the 5th Assessment Report projected a wide range of possible scenarios and outcomes, these charts demonstrate the criticality of reducing emissions at the fastest possible rate in order to limit the increase in global temperatures.

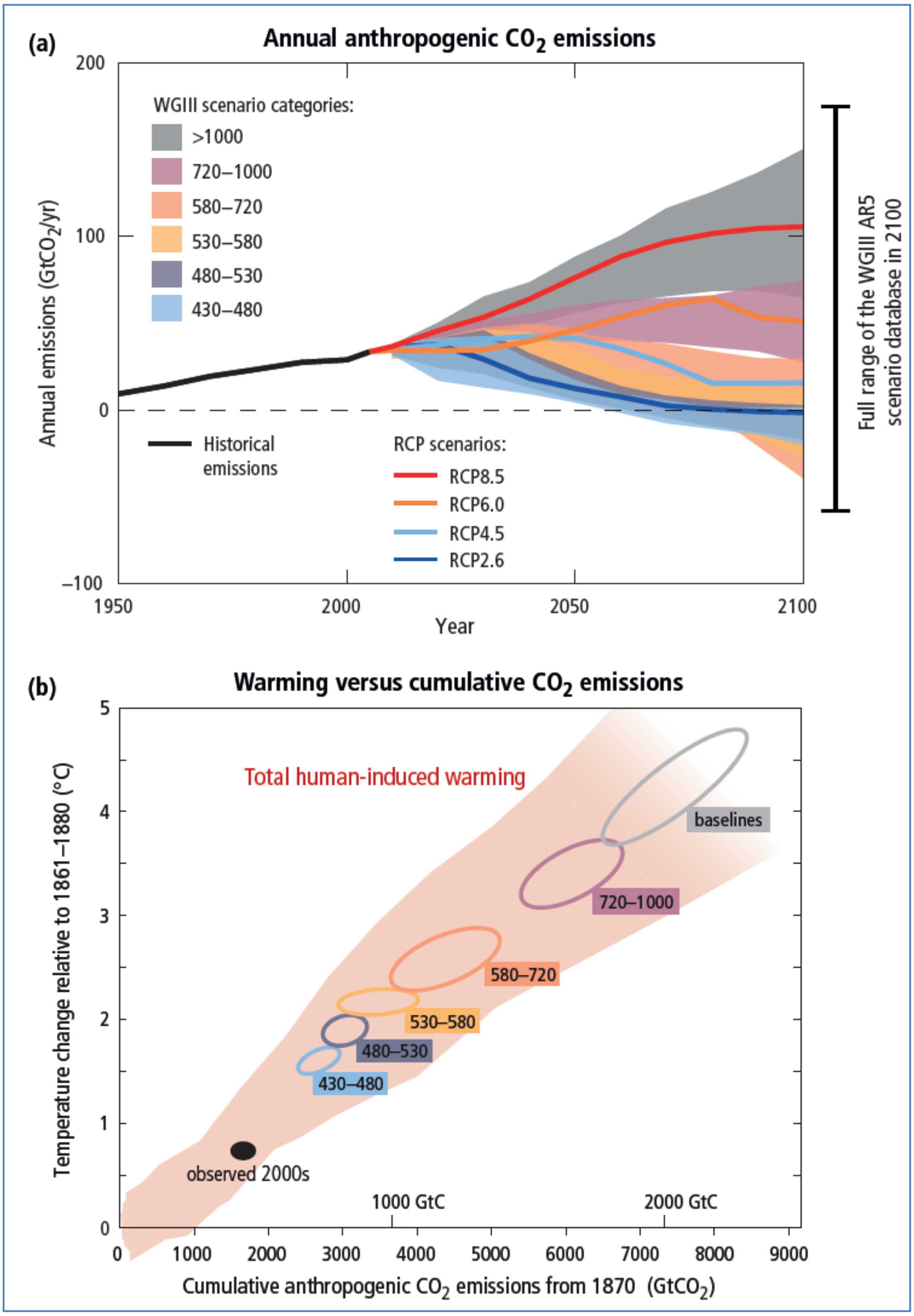


Figure 2-3. (a) Projected annual anthropogenic CO_2 emissions; (b) the warming vs cumulative CO_2 emissions

[Source: IPCC (2014) Figure SPM.5]

The most recent UK climate projections (UKCP09, 2014) include data for specific regions. The summary temperature projections for London are shown in Table 2-1, for the decades 2020s, 2050s and 2080s. The 'probability' columns indicate the probability that the temperature change (from the 1990 value) will be less than the figure shown in the relevant cell. The 'lowest change' and 'highest change' columns indicate the smallest and largest temperature changes that are likely under all the assessed emissions and probability scenarios. These show that by 2050 the increase in summer temperatures is most likely to be in the range 1.1°C to 5.2°C and by the 2080s could be as high as 8.1°C.

Table 2-1. UK temperature increase projections for London (from UKCP09)

Variable	Time period	Emissions Scenario	Change at 10% probability	Change at 50% probability	Change at 90% probability	Wider range (lowest change)	Wider range (highest change)
mean summer temperature (ºC)	2020s	High	0.5	1.5	2.7	0.5	2.8
mean summer temperature (ºC)	2020s	Low	0.7	1.6	2.8	0.5	2.8
mean summer temperature (ºC)	2020s	Medium	0.6	1.6	2.7	0.5	2.8
mean winter temperature (ºC)	2020s	High	0.6	1.4	2.2	0.5	2.2
mean winter temperature (ºC)	2020s	Low	0.5	1.3	2.1	0.5	2.2
mean winter temperature (ºC)	2020s	Medium	0.6	1.3	2.2	0.5	2.2
mean summer temperature (ºC)	2050s	High	1.4	3.1	5.2	1.1	5.2
mean summer temperature (ºC)	2050s	Low	1.1	2.5	4.3	1.1	5.2
mean summer temperature (ºC)	2050s	Medium	1.3	2.7	4.6	1.1	5.2
mean winter temperature (ºC)	2050s	High	1.4	2.5	3.8	0.9	3.8
mean winter temperature (ºC)	2050s	Low	0.9	2.0	3.1	0.9	3.8
mean winter temperature (ºC)	2050s	Medium	1.2	2.2	3.5	0.9	3.8
mean summer temperature (ºC)	2080s	High	2.6	4.9	8.1	1.3	8.1
mean summer temperature (ºC)	2080s	Low	1.4	3.0	5.1	1.4	8.1
mean summer temperature (ºC)	2080s	Medium	2.0	3.9	6.4	1.4	8.1
mean winter temperature (ºC)	2080s	High	2.0	3.7	5.7	1.4	5.7
mean winter temperature (ºC)	2080s	Low	1.4	2.6	4.0	1.4	5.7
mean winter temperature (ºC)	2080s	Medium	1.6	3.0	4.7	1.4	5.7

[Source: UKCP09 (2014)]

2.2 The environmental impact of RACHP systems

Although refrigeration, air conditioning and heat pump systems can be highly efficient "energy multipliers", converting low grade heat and coolth into useful heating and cooling energy with high efficiency, their environmental impact can be high, due to indirect emissions that are associated with generating the energy used to power the system and direct emissions associated with leakage of refrigerant.

It has been reported (IIR, 2015) that in developed countries the Refrigeration, Air Conditioning and Heat Pump (RACHP) sector consumes around 17% of all electricity. The IIR also reported that around 80% of the global warming impact of refrigeration systems is associated with generation of the electricity used by them (indirect emissions), while the remaining 20% is due to direct emissions from leakage of HFC (hydrofluorocarbon) greenhouse gas refrigerants (and HCFC or hydrochlorofluorocarbon refrigerants in countries that have not yet banned their use).

Global warming and climate change will tend to increase the demand for cooling, particularly in major cities in the UK, where the heat island effect has already been shown to increase ambient temperatures by 3°C or more (GLA, 2006).

The UK 2008 Climate Change Act (GOV.UK, 2008) mandates an 80% reduction in carbon emissions by 2050 (from a 1990 baseline). However, it could be a major challenge for the RACHP sector to reduce its emissions proportionality, because cooling demand will increase to combat the higher temperatures associated with global warming and the number of heat pump installations, which use technology and refrigerants that are similar to refrigeration and air conditioning systems, is forecast to increase dramatically.

Currently, the energy related (indirect) emissions from the RACHP sector are estimated from top down generalized estimates and not from analysis of actual energy use, since most RACHP installations do not include sub-metering on their electricity supply. However, the author has estimated (Chapter 4.2), from analysis of available data that nearly 20% of UK grid electricity consumption and more than 5% of all UK carbon emissions are attributable to the consumption of energy by RACHP systems (indirect emissions). The percentages could be higher within densely populated urban environments and cities, due to the high density of air conditioned commercial buildings and offices. However, the indirect emissions would be expected to decrease over time as the carbon emissions factor for grid electricity reduces, due to a lessening dependence on fossil fuel power generation and increasing power generation from renewable sources and nuclear power. Also, newer RACHP systems tend to have improved performance and efficiency, which should reduce the energy demand when existing installations are replaced.

In contrast to indirect emissions, the carbon emissions that are attributable to refrigerant leakage (direct emissions) can be estimated with somewhat better accuracy, based on the volume of refrigerant sold into the RACHP market (by assuming that the majority of this is used for replacing lost refrigerant). HFC refrigerant emissions are reported under the Kyoto Protocol (UNFCCC, 2014), whilst HCFC refrigerant data, which are controlled under the Montreal Protocol (UNEP, 2017) are reported via the Ozone Secretariat (UNEP, 1999). Since January 2015 the use of HCFC refrigerant is no longer permitted within Europe (and was banned for new installations in 2010) so recent HFC refrigerant use data are increasingly representative of all refrigerant emissions in the RACHP sector. For 2012, the reported figure for HFC refrigerant emissions from the RACHP sector in the UK was 11.3 million tonnes of CO_2 equivalent ($MtCO_2e$), or 1.96% of all UK GHG emissions in 2012 (GOV.UK, 2015).

According to the UNEP Refrigeration Air Conditioning and Heat Pumps Technical Options Committee 2010 Assessment (UNEP, 2011), there were some 280,000 supermarkets world-wide in 2006, with sales areas of between 400m^2 and 20,000m^2. Additionally there were estimated to be 20.5 million vending machines, 32 million other stand-alone equipments and 34 million condensing units. The world-wide refrigerant bank associated with these types of equipments was estimated to be 340,000 tonnes, split between 46% centralised systems, 47% in condensing units and 7% in standalone equipment. The split between refrigerant types was estimated to be 15% CFCs (chlorofluorocarbons - still used in 'Article 5' or developing countries), 62% HCFCs (hydrochlorofluorocarbons) and 23% HFCs (hydrofluorocarbons). At that time, HCs (hydrocarbons) and other alternative refrigerants were considered to be "not visible in terms of refrigerant bank".

In many countries the use of HCFC refrigerants is being phased out and low GWP natural refrigerants such as Hydrocarbons and CO_2 are increasingly replacing both HCFC and HFC refrigerants in new stand-alone equipment. A new class of synthetic refrigerants, hydrofluoroolefins (HFOs) are increasingly being promoted as replacements for HFCs such as R134a, offering similar cooling performance and efficiency, with much lower GWP. However, many alternative refrigerants cannot be used to retrofit existing systems, so HCFC and HFC refrigerants will continue to be used over the next 15-20 years, until the installed base has been replaced. Refrigerant leakage will therefore continue to be a significant contributor to the overall emissions from the RACHP sector for many years.

Annual leakage rates vary considerably for different system types and by geographical region. IPCC (2006) have produced guidelines for the typical range of values for operating emissions by equipment type, as indicated in Table 2-2. Legislation, fiscal measures, new technologies, alternative refrigerants and other initiatives have all helped to drive significant improvements in refrigerant leakage reduction and containment, particularly for supermarket chains that have taken a proactive approach to managing and containing refrigerant.

Table 2-2The table also provides an indication of the typical refrigerant charge, refrigerant losses during installation and the refrigerant recovered at end of life (decommissioning). The lower values for refrigerant emissions are more typically experienced in developed countries that are subject to tighter regulation and controls. The highest leakage rates tend to be associated with the commercial refrigeration (retail) and mobile air conditioning sectors, whereas domestic refrigerators (which are hermetically sealed), standalone commercial refrigeration systems, air conditioning systems and heat pumps all tend to have much lower leak rates.

Legislation, fiscal measures, new technologies, alternative refrigerants and other initiatives have all helped to drive significant improvements in refrigerant leakage reduction and containment, particularly for supermarket chains that have taken a proactive approach to managing and containing refrigerant.

Table 2-2. Range of values for charge and emission factors for RAC systems

Type of Equipment	Typical Range in Charge Capacity (kg)	Installation Emission Factor (% of initial charge)	Operating Emissions (% of initial charge/ year)	Refrigerant remaining at disposal (% of initial charge)	Refrigerant recovered (% of remaining charge)
Domestic Refrigeration	0.05 - 0.5	0.2 - 1.0	0.1 - 0.5	0 - 80	0 - 70
Stand-alone Commercial Applications	0.2 - 6	0. 5 - 3	1 - 15	0 - 80	0 - 70
Medium & Large Commercial Applications	50 - 2,000	0.5 - 3	10 - 35	50 - 100	0 - 70
Transport Refrigeration	3 - 8	0.2 - 1	15 - 50	0 - 50	0 - 70
Industrial Refrigeration (inc. food processing and cold storage)	10 - 10,000	0.5 - 3	7 - 25	50 - 100	0 - 90
Chillers	10 - 2,000	0.2 - 1	2 - 15	80 - 100	0 - 95
Residential and Commercial A/C including Heat Pumps	0.5 - 100	0.2 - 1	1 - 10	0 - 80	0 - 80
Mobile Air Conditioning	0.5 - 1.5	0.2 - 0.5	10 - 20	0 - 50	0 - 50

[Source: IPCC (2006) Vol.3, Table 7.9]

The relative contributions to global warming from the direct and indirect emissions vary according to the application, the system efficiency, the type of refrigerant, the actual leakage rate and the carbon intensity of the grid electricity used to power the system. Table 2-3. (Heap, 2001) shows relative indirect and direct contributions for a range of applications in the EU and indicates that indirect emissions are the main contributor to total RACHP emissions, while direct emissions represent 28% of the total in the retail sector. A similar study reported 10 years earlier that direct emissions in commercial and mobile air conditioning applications were more than 50% of the total equivalent carbon emissions (AFAES/DOE, 1991). This indicates the substantial environmental benefits that can be obtained by reducing refrigerant leak rates.

Table 2-3. Annual EU Emission ($MTCO_2e$) for HFC Systems

System type	Direct emissions $MTCO_2e$	Indirect emissions $MTCO_2e$	Total emissions (direct + indirect) $MTCO_2e$	Direct % related to total emissions
Retail	9.0	23.0	32.0	28%
Industrial	3.4	25.0	28.4	12%
DX AC	2.6	10.0	12.6	21%
Small commercial	1.8	12.0	13.8	13%
Chillers	0.7	12.0	12.7	6%

Other small	0.3	12.0	12.3	2.5%

[Adapted from Heap (2001)]

The EU F-Gas Regulations (EC, 2006), introduced in 2007 and amended in 2014, have played a significant role in reducing direct emissions by introducing mandatory requirements relating to the handling of HFC refrigerants to reduce leakage and emissions, requiring regular leak testing of RACHP systems, record keeping for test results and repair activity and mandatory training for installation, service and maintenance personnel.

A UK project (REAL Zero) undertaken by the Institute of Refrigeration and London South Bank University investigated the causes of refrigerant leakage and developed guidance and training on improving the containment of refrigerant (Cowan *et al.*, 2010). This helped to reduce refrigerant leakage in the UK supermarket sector by nearly 30% and the sector continues to reduce its direct emissions. A follow up pan European project (REAL Skills Europe) extended this work and developed enhanced training materials in several languages, while a more recent project (REAL Alternatives) has focused on alternative low GWP refrigerants.

2.3 The level of global emissions from leakage of refrigerant

The full impact of direct emissions from leakage of refrigerant is difficult to estimate because until the adoption of the Kyoto Protocol in 1997 there was no formal reporting system in place. There is also a lot of old equipment installed for which there is limited technical information and few maintenance records. Refrigerant emissions are an important aspect of the work undertaken for this study and reported in more detail in a separate chapter. However, the currently understood global scenario is summarized below.

The environmental damage caused by the release into the atmosphere of ozone-depleting substances (ODS) and greenhouse gases (GHGs) was first recognized in the 1970s. Monitoring stations had determined that the atmospheric concentrations of ozone depleting substances and other gases were steadily increasing as a result of increasing industrialization and the use of chemicals such as chlorofluorocarbons (CFCs) for refrigeration, air conditioning, foam blowing, aerosols and industrial cleaning. Depletion of the ozone layer increases the ultraviolet radiation at the earth’s surface, potentially leading to greater incidences of skin cancer and eye cataracts, as well as adversely affecting plants, crops, and ocean plankton.

The 1985 Vienna Convention for the Protection of the Ozone Layer led to the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP, 2017). The Montreal Protocol resulted in a 98% reduction in the consumption of CFCs between 1986 and 2008, whilst a regulatory adjustment in 2007 will result in a global phase out of HCFCs (hydrochlorofluorocarbons) by 2030. In the UK it has been illegal to use HCFCs to service refrigeration and air conditioning equipment since 1 January 2015. However, in many applications CFCs and HCFCs have been replaced by HFCs (hydrofluorocarbons), which are greenhouse gases with, in some cases, very high global warming potential (GWP).

In 1977 the first Wold Climate Conference took place and in 1988 the Intergovernmental Panel on Climate Change (IPCC) was set up. Its first report in 1990 led to the United Nations Framework Convention on Climate Change. Emissions from HFCs are monitored under the Kyoto Protocol (UNFCCC, 2014), which was adopted on 11 December 1997 and entered into force on 16 February 2005. It covers emissions of six main greenhouse gases:- carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Refrigeration and air-conditioning systems are the main source of HFC emissions.

Across the EU as a whole, the target for emissions reductions between 1990 and 2012 was -8%, but individual Member States agreed targets that ranged between a 28% decrease for Luxembourg and a 27% increase for Portugal. Following the Copenhagen Accord (UNFCCC, 2009), many countries set pledges for future GHG emissions reductions and the 2012 Doha Amendment (UNFCC, 2012) embodied these pledges and set new targets for the period 2013 to 2020. However, even with these pledges global GHG emissions continue to increase.

Data from a UNEP Technology and Economic Assessment Panel report (UNEP, 2009) suggests that the replacement of HCFC refrigerants with HFC alternatives will not result in a significant reduction in either the global refrigerant bank of HCFC refrigerants, or HCFC emissions, for many years. Figure 2-4 (which is based on a mitigation scenario whereby refrigerant loss is reduced and recovery rates increased) shows that global HCFC refrigerant banks and emissions are predicted to change by only a small amount between 2002 and 2020, while at the same time HFC refrigerant banks and emissions are forecast to increase by 400% and 137% respectively. The combined HCFC and HFC refrigerant emissions projections indicate an increase of nearly 50% in the global warming impact associated with refrigerant emissions between 2001 and 2020 and represent around 2% of all global warming emissions in 2015.

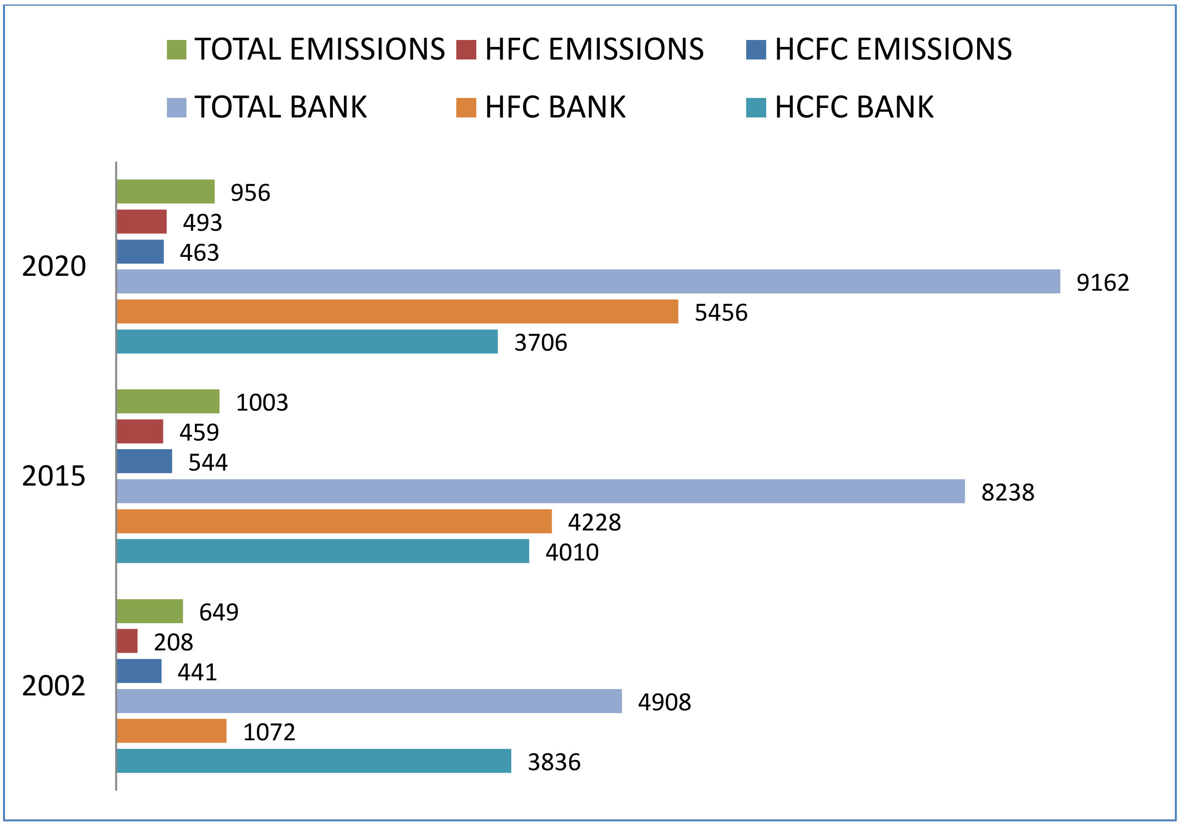


Figure 2-4. Global Refrigerant Banks and Emissions Projections 2002 – 2020 ($MTCO_2e$)

[Adapted from: UNEP (2009)]

A more recent report (UNEP, 2016) suggests that for the non-Article 5 (developed) countries, HFC emissions from servicing demand (refrigerant leakage) will peak at just under 200 $MTCO_2e$ between 205 and 2020 (Figure 2-5), while for the Article 5 (developing) countries they will peak at about 400 $MTCO_2e$ between 2020 and 2025 (Figure 2-6). These predictions are based on the MIT-3 scenario, whereby manufacturing in developed countries has completed a transition to lower GWP refrigerants by 2020 and developing countries start transitioning from 2020 onwards.

Summing the HFC emissions for 2020 suggests that the combined total from non-Article 5 and Article 5 countries will be around 520 $MTCO_2e$. This compares with a figure of 493 $MTCO_2e$ from the UNEP 2009 projections. The highest emissions are predicted to come from stationary air conditioning systems.

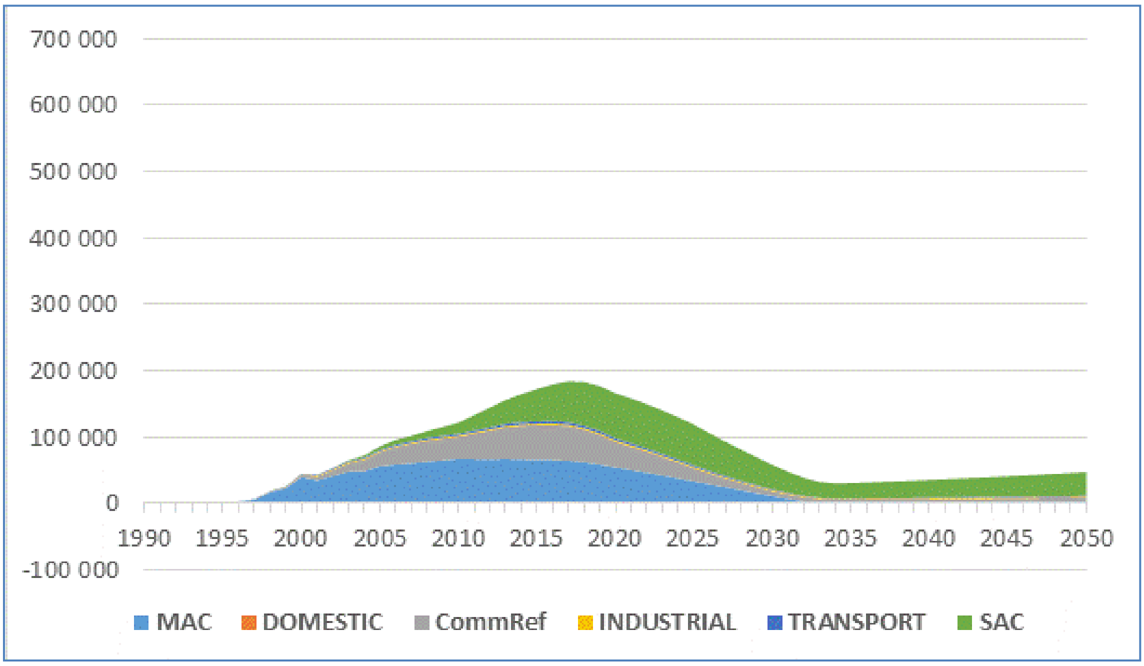


Figure 2-5. HFC emissions from servicing demand (ktCO_2e) for non-Article 5 countries (MIT-3 scenario)

[Source: UNEP (2016)]

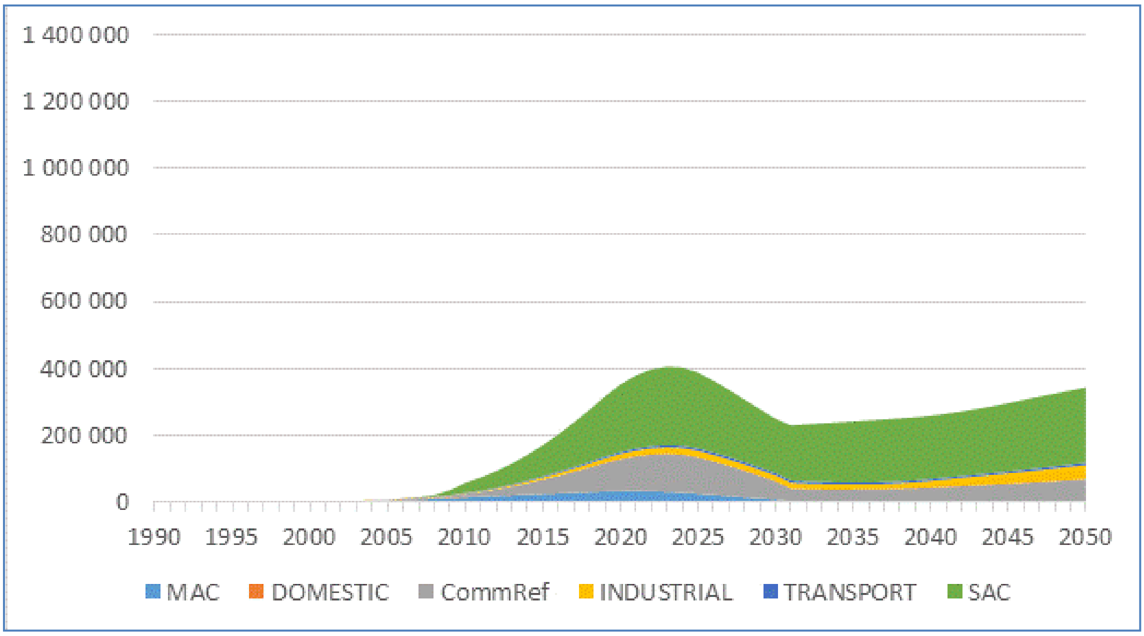


Figure 2-6. HFC emissions (ktCO_2e) from servicing demand for Article 5 countries (MIT-3 scenario)

[Source: UNEP (2016)]

2.4 The impact of the F Gas Regulations and HFC phasedown on direct emissions

The original F Gas Regulations EC 842/2006 (EC, 2006) came into force in July 2007 and were aimed at improving the handling of F Gas refrigerants in order to reduce leaks and associated carbon emissions. They (and related legislation) addressed:

- Leak testing
- Refrigerant recovery
- Refrigerant use records (F Gas logs)
- Training and certification - individuals and companies)

In 2009 the ODS (Ozone Depleting Substance) Regulations EC 1005/2009 were updated (EC, 2009) to place additional controls on ozone depleting HCFC refrigerants. They included:

- A ban on the use of virgin R22 from Jan 2010 (recovered refrigerant could still be used)
- The phase out of HCFCs for servicing from January 2015

Although HCFC refrigerants continue to be used in other parts of the world they are now banned in the UK and Europe and the environmental impact of any remaining systems (which can no longer be serviced) is small.

Air conditioning systems for mobile and transport applications were not covered by the original F Gas Regulations but were instead covered by the MAC (Mobile Air Conditioning) Directive (2006/40/EC). This placed a ban on new systems using a refrigerant with a GWP of greater than 150.

A review of the impact of the F Gas Regulations and the MAC Directive (COM, 2011) predicted that the combined effect would be to reduce carbon emissions by a total of 88 million tonnes of CO_2 equivalent ($MtCO_2$(e)) by 2050, compared with the emissions expected without these measures (Figure 2-7). However, this would at best result in a level of emissions that was similar to the level in 2010, indicating almost zero progress towards the 80% target reduction in emissions by 2050 and that further measures would be required. It was concluded that the only way to achieve this level of reduction would be via a phase-out or phase-down of high GWP refrigerants.

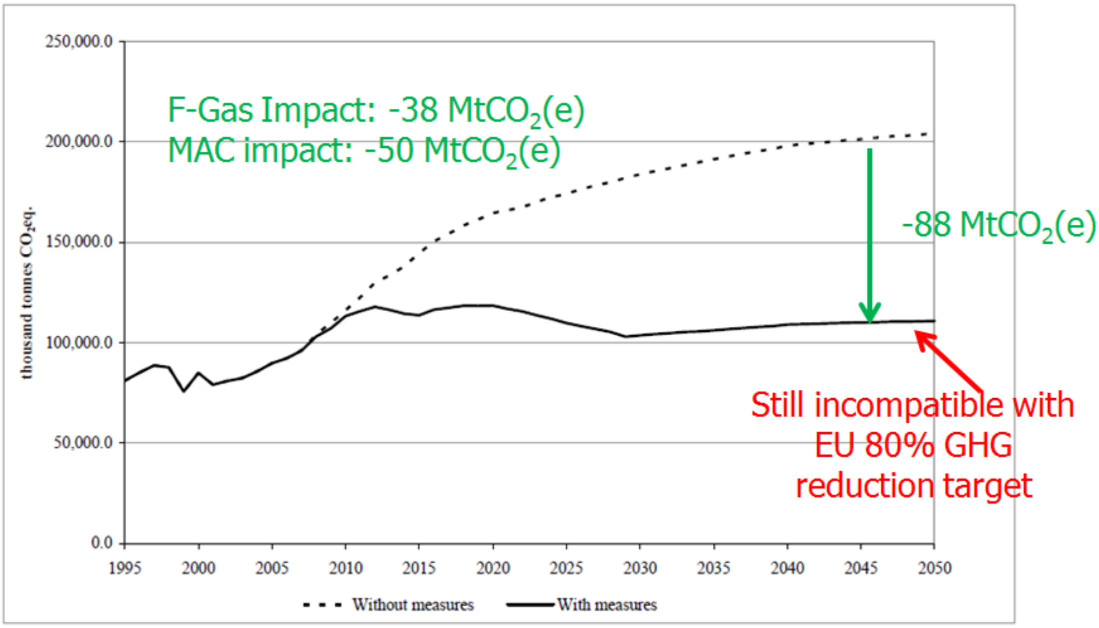


Figure 2-7. The impact of the F Gas Regulations and MAC Directive on EU F Gas emissions to 2050

[Source: COM (2011)]

Revised F Gas Regulations EC 517/2014 (EC, 2014) were therefore introduced in 2014 and came into force on 1 January 2015, when the original Regulations were withdrawn. The provisions included:

- A transition to lower GWP technologies
- A reduction in the use of F Gases (phase down) between 2015 and 2030. The amount of HFCs that producers and importers can place on the market must reduce to 21% of the 2015 value (in terms of tonnes of CO_2 equivalent amount) by 2030. This is the most significant measure and will be the key driver for the use of low GWP refrigerants.
- Extended scope to include transport refrigeration
- Amended leak test requirements (based on the CO_2 equivalent global warming potential of the refrigerant charge (mass x GWP) rather than the mass of refrigerant in the system
- Improved monitoring (new reporting provisions)
- Improve containment and recovery via extension of the training and certification requirements and the development of EU standards and best environmental practices

The expected impact of the additional measures is indicated in Figure 2-8, which demonstrates compliance with the 80% emissions reduction by 2050 target. However, as indicated by the TEWI examples presented in Chapter 4, the indirect (energy related) emissions predominate over the direct (refrigerant leakage) emissions for most systems, apart from those with very high leak rates, so these measures represent only one step towards reducing RACHP emissions. It will still be necessary to find a way of achieving a major reduction in indirect emissions to ensure that the RACHP sector contributes fully to the UK's 80% emission reduction target.

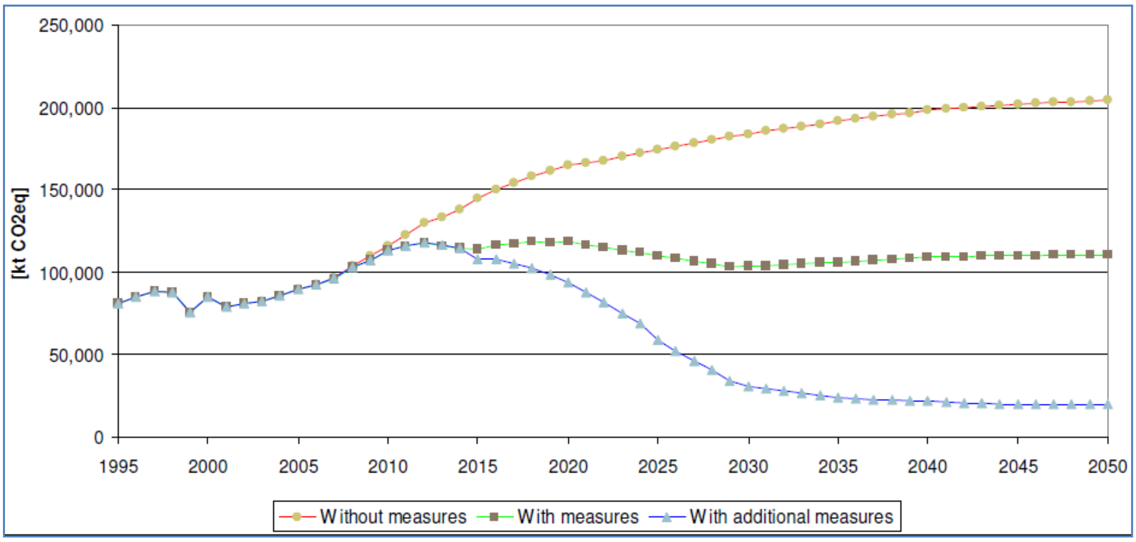


Figure 2-8. Predicted EU27 F Gas carbon emissions to 2050 for 3 scenarios

[Source: EEA (2011)]

2.5 Historical studies into refrigerant leakage

Refrigerant contained inside the system circuit poses no threat to the environment, but it is difficult to make systems completely leak tight. Bostock (2007) defined a leak tight system as one that can operate within its normal operating parameters for its useful life without requiring additional refrigerant to be added (i.e. it does not leak enough refrigerant – typically less than 10% of its original charge - to affect system performance).

Table 2-4 summarises the results of four separate studies for the UK, and indicates that the highest leakage rates tend to occur in the retail (supermarket) sector. This is partly due to the bespoke nature of these systems but also to long runs of sometimes difficult to access pipes that are necessary to connect the numerous fixtures (cabinets and cold stores) to the distributed system used in many retail applications.

Table 2-4. Reported Annual Refrigerant Leakage Rates for the UK

Sector/ equipment	Reported annual leakage rates (% of charge per annum)			
	Johnson (1998)	*March (1999)*	*Haydock et al (2003)*	*ETSU (1997)*
Domestic refrigeration	1%	1%	0.3 – 0.7%	2.5%
Retail refrigeration	9 – 23%			
· Integral cabinets		1%	3 – 5%	2.5%
· Split/condensing units		10 – 20%	8 – 15%	15%
· Centralised supermarket		10 – 25%	10 – 20%	8%
Air conditioning	12 – 20%			
· Unitary/split		10 – 20%	8 – 12%	
· Chillers	15 – 22%	3 – 10%	3 – 5%	4%
· Heat pumps		3 – 10%	3 – 5%	4%

[Source: MTPROG (2007)]

A number of authors have investigated leakage of the refrigerant charge from supermarkets from around the world over the last 20 years. The reported data have been reviewed and are shown graphically against time in Figure 2-9. Although there is a large degree of scatter, the data for the period 2000 to 2011 indicate a steady reduction in refrigerant leak rates, due to increasing awareness of the global warming impact of refrigerant emissions and additional measures taken to improve the handling and management of refrigerants and to reduce leaks. This chart is based on a range of data including that from specific store chains and national and international average figures.

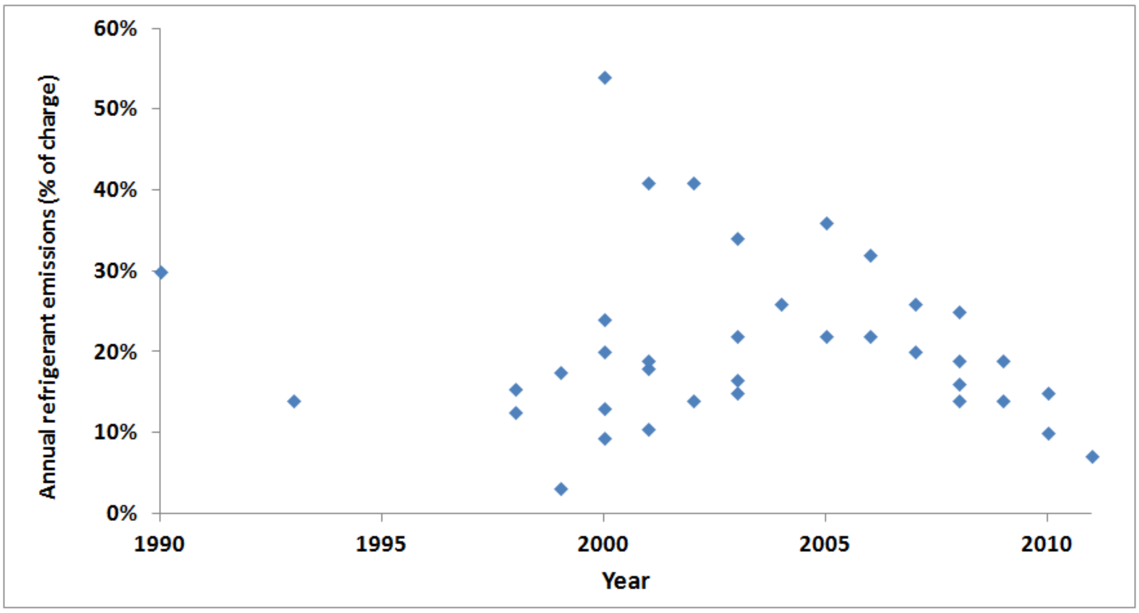


Figure 2-9. Reported refrigerant emissions against time for published data.

[Source: Updated from Cowan *et al* (2010)]

Leakage rates in the retail sector are among the highest of all RACHP system types. One UK supermarket reported an average 14% annualised leakage rate for 2008, but this figure reduces to around 6% for newer systems. Rhiemeier *et al*. (2009) reported consistent leakage rates for multi-compressor refrigeration systems of between 5% and 10% in Germany, 8% for supermarkets in the US. In the Netherlands, where they have had the STEK programme for a number of years, average emission rates of only 3% are reported, although the reliability of this data has been questioned (Anderson, 2005). In Germany, legislation (Bundesgesetzblatt, 2008) requires that the annual leakage rate for new systems containing more than 100kg of refrigerant must be less than 1%.

A number of authors have reported on the reasons why refrigeration systems continue to leak. ETSU in 1997, identified the six most common leaks following an extensive survey of professionals, as shown in Figure 2-10 (illustrative only). Bostock (2007), cited a study on supermarket refrigeration systems carried out in Germany which showed that:

- 96% of the total refrigerant loss was through field assembled joints.
- 15% (by number) were responsible for 85% (by weight) of the refrigerant loss
- 22% of all measurable leaks were from flared joints, and these were responsible for 50% of the refrigerant losses.

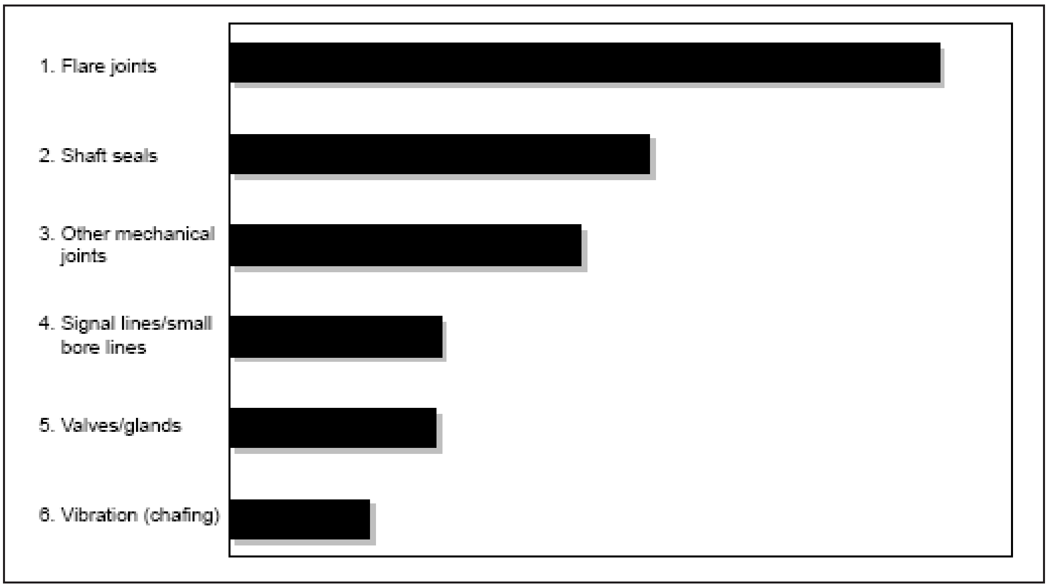


Figure 2-10. Illustration showing the six most common leaks identified by ETSU (1997)

However, these investigations provide limited information regarding where and why leakage occurs, which is essential knowledge if industry wants to be able to reduce refrigerant leaks.

2.6 The urban environment and the heat island effect

The urban heat island effect that exists in many large towns and cities is primarily due to the storage of solar energy in the urban fabric during the daytime and its release into the atmosphere at night. As urbanization increases, areas that were previously vegetated and contributed to cooling by a process of evaporation are replaced by engineered surfaces that are impervious and retain heat energy, releasing it into the atmosphere at night. In addition, higher population densities and numbers of high rise buildings, results in an increasing density of energy use for each unit of land area and more waste heat emitted into the atmosphere.

A study of the heat island effect in London (GLA, 2006) reported the increase in ambient temperature compared with rural areas during the summer of year 2000. Figure 2-11 indicates that the average midday temperature increase was around 1.25°C, but at night was 3°C and at times as high as 4.5°C. Figure 2-12 shows the temperature contours from mapping the relative night time temperatures across a 36 x 25 mile area of London, indicating a temperature increase of 6°C in central London compared with rural areas. Simulations performed for the same study suggest that the mean summer temperature in London could increase by as much as 1°C by 2020, 3°C by 2050 and 6°C by 2080, in addition to the urban heat island effect.

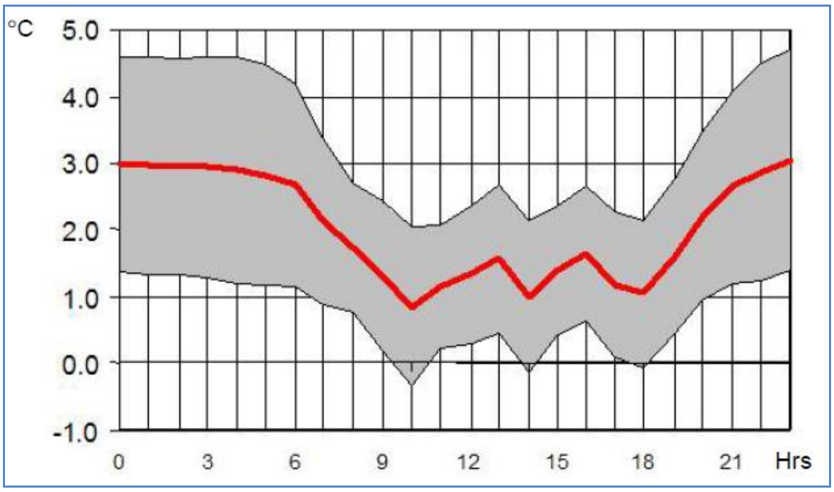


Figure 2-11. Variation in London UHI intensity (temperature increase) over 24 hours (summer 2000)

[Source: GLA, 2006]

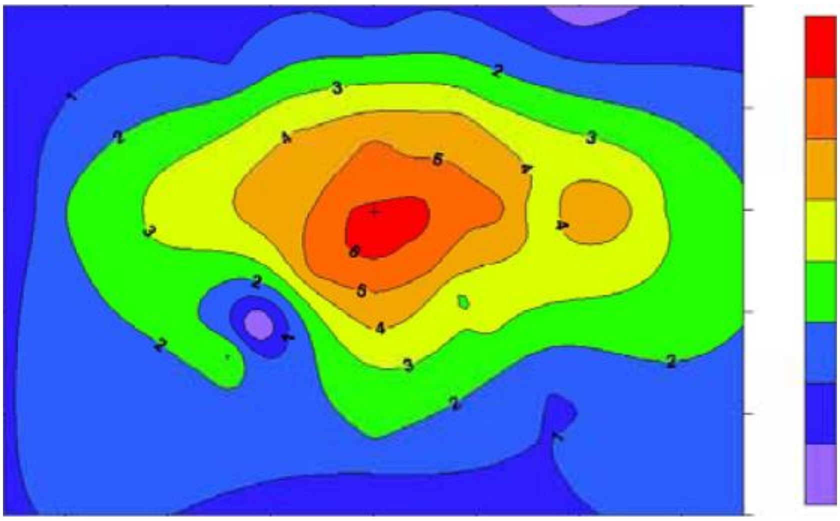


Figure 2-12. Temperature contours from mapping London night time temperatures (summer 2000)

[Source: GLA, 2006]

Several studies have proposed reducing the heat island effect by measures such as planting more trees and shrubs, increasing the albedo of paved surfaces and buildings and the evaporative cooling of large structures and surfaces. Santamouris (2012) reported that, for each 0.1 increase in albedo, the mean temperature decreases by 0.3°C and the peak temperature decreases by 0.9°C. Shahidan et al. (2012) reported a potential reduction in air temperature of 2.7°C for a combination of high tree canopy density and an albedo of 0.8, with a corresponding potential cooling reduction of 29% in building cooling energy loads. However, this example was for a city in Malaysia, with average annual temperature of 26.1°C, so the benefits in the London area could be rather more limited.

2.7 UK grid electricity generation, demand and carbon intensity

The RACHP sector is one of the largest users of grid electricity, so the method and efficiency of generation and distribution of electricity are key factors in assessing the indirect emissions from RACHP systems and the potential to reduce them. It is therefore useful to review some of the key statistics for UK electricity.

Table 2-5 indicates the net calorific value and carbon dioxide equivalent emissions associated with the use of different types of fuel. Grid electricity is generated from a mix of fuel types, including renewables, nuclear power, natural gas, oil and coal. The CO_2 emissions are high because of the overall energy conversion efficiency and transmission and distribution losses, making it one of the least environmentally friendly solutions for heating. However, recent developments in heat pump technology have resulted in systems that can achieve a coefficient of performance (COP) well in excess of 2.5, at which point heat pumps start to compete with traditional fossil based heating systems in terms of their net CO_2 equivalent emissions per kWh. For cooling, vapour compression refrigeration systems remain the most efficient type (with the exception of passive cooling systems), both in terms of energy efficiency and their carbon emissions.

Table 2-5. Calorific value and carbon emissions factors for a range of fuel types

Fuel Type	Net calorific value (kWh/kg)	CO_2 equivalent emissions ($kgCO_2e$/ kWh)
Grid electricity	N/A	0.41205
Natural gas	13.28	0.20444
LPG	12.77	0.23041
Fuel Oil	11.32	0.28492
Industrial coal	7.12	0.33931
Wood pellets	4.25	0

[Source: GOV.UK (2016)]

Figure 2-13 indicates the mix of primary energy and other sources used to generate grid electricity in the UK in 2012, together with the energy flow and electricity consumed by various sectors. It does not include locally generated electricity from combined heat and power (CHP) and other systems. The flow chart indicates a net energy conversion efficiency of 38%, with more than 567 TWh being lost through conversion (mainly waste heat), transmission and distribution losses.

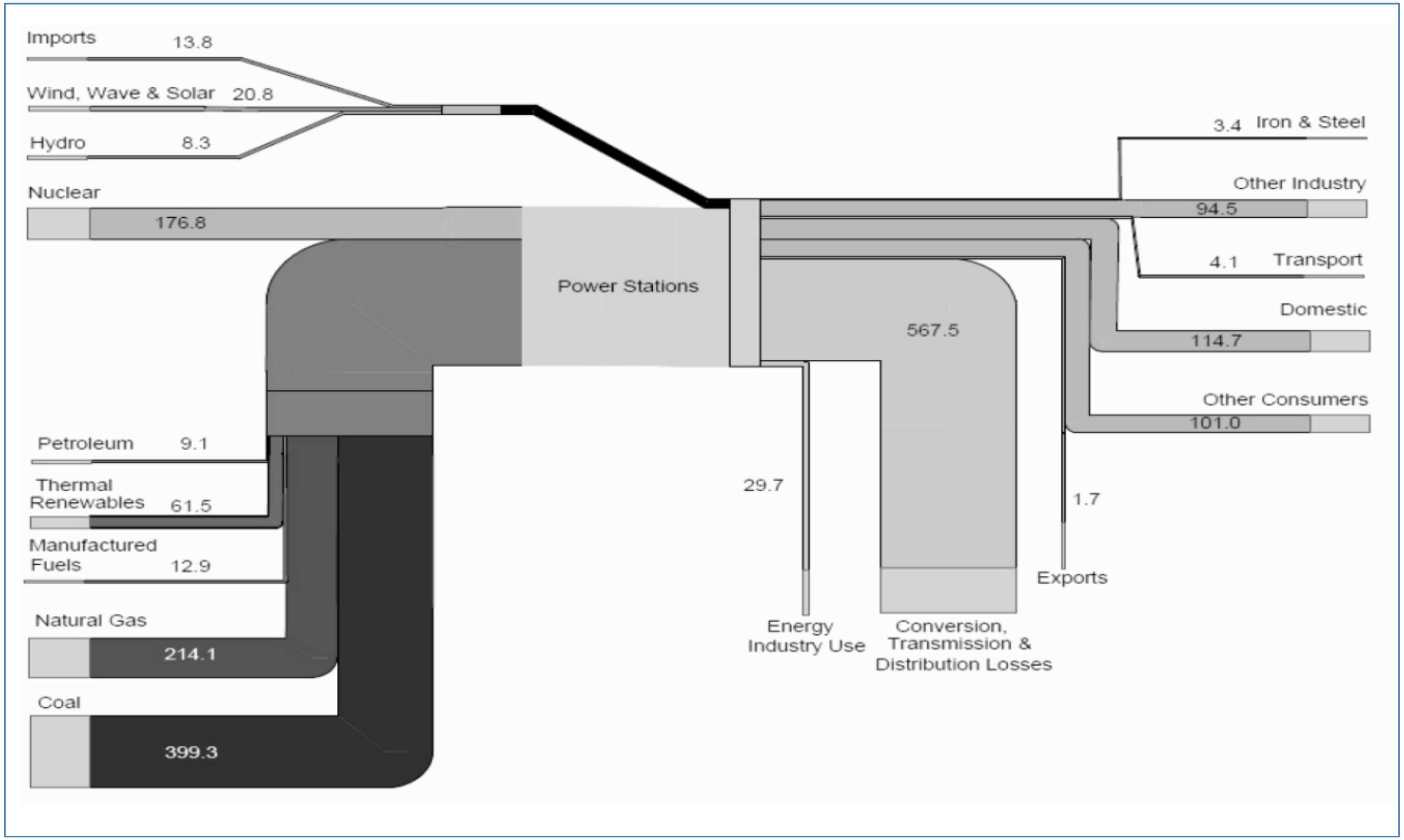


Figure 2-13. UK electricity flow chart 2012 (TWh)

[Source: Dukes (2013) Ch 5]

Figure 2-14 shows the breakdown of electricity demand by sector, indicating that the domestic sector was responsible for 30% of total demand, compared with 47% for the combined industrial and commercial sectors. The total demand includes losses and electricity use within the energy industry.

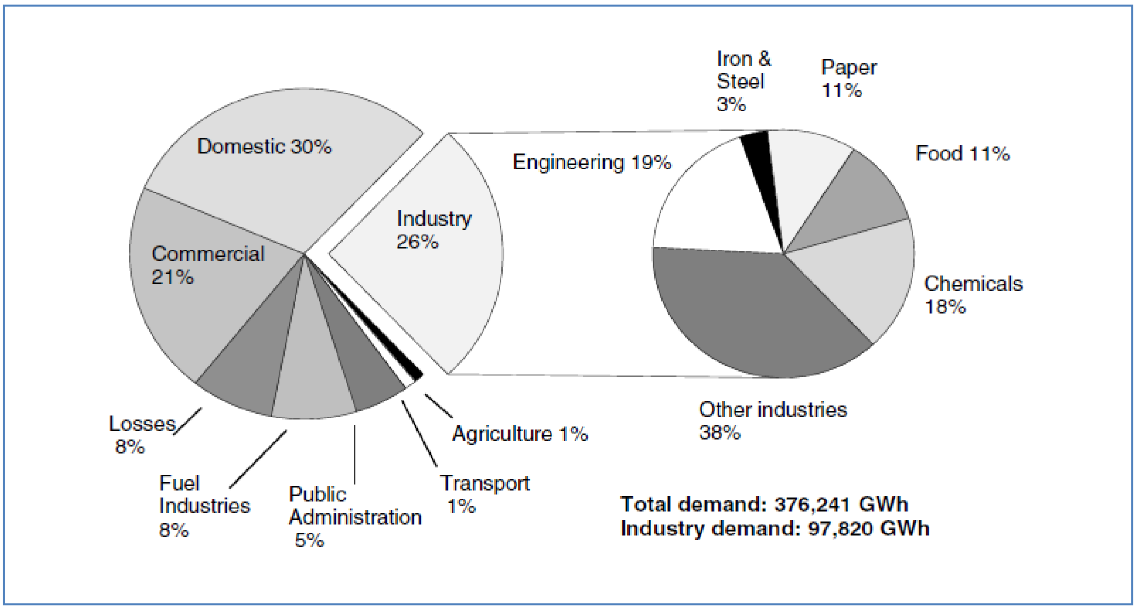


Figure 2-14. UK electricity demand by sector 2012

[Source: Dukes (2013) Chart 5.1]

A breakdown of UK electricity sales in 2011, by region is shown in **Table 2-6.**. This indicates that the Greater London area consumed almost 14% of all UK grid electricity, with total sales in the combined industrial and commercial sectors being approximately 2x the sales in the domestic sector.

Table 2-6. Breakdown of UK electricity sales in 2011 by region and sector

	Domestic sector sales (GWh)	Number of domestic customers (thousand) *(1)*	Industrial and commercial sector sales (GWh)	Number of I & C customers (thousand) *(1)*	All consumers sales (GWh)
Greater London	13,374	3,396	26,572	399	39,946
South East	16,361	3,712	22,660	330	39,021
North West	12,406	3,139	18,610	233	31,015
Scotland	11,150	2,747	15,508	212	26,658
East of England	11,193	2,547	14,954	214	26,147
West Midlands	9,747	2,371	14,862	193	24,609
South West	10,489	2,429	13,826	246	24,315
Yorkshire and the Humber	8,884	2,338	15,239	178	24,123
East Midlands	7,985	1,985	12,598	155	20,582
Wales	5,287	1,375	9,939	124	15,226
North East	4,209	1,195	7,472	80	11,681
Unallocated Consumption	236	66	2,801	23	3,037
Sales direct from high voltage lines *(2)*					4,237
Great Britain	111,321	27,301	175,040	2,386	286,361
Northern Ireland *(3)*					7,939
Total					298,537

(1) *Figures are the number of Meter Point Administration Numbers (MPANs); every metering point has this unique reference number.*
(2) *Based on estimate provided by Ofgem.*
(3) *Northern Ireland data are based on data for electricity distributed provided by Northern Ireland Electricity*

[Source: Dukes (2013) Table 5D]

2.8 UK energy demand and emissions – pathways to 2050

The 2050 Pathways Analysis report published by DECC (2010) identified a number of different trajectories and pathways for the UK to meet its carbon emissions reduction targets, as well as providing a calculator to allow independent assessment of the various options. The 'Alpha' pathway, summarized in Figure 2-15, assumes a balanced approach across all energy sectors, with a concerted effort to reduce overall energy demand (even so, electricity generation is forecast to more than double by 2050). The combined energy demand for heating and cooling is forecast to remain more or less unchanged. The pathway assumes an increasing dependence on nuclear power generation, renewable energy, carbon capture and storage and bio fuels, which together achieve the desired 80% reduction in CO_2 emissions.

The decarbonisation of the electricity grid is a key element of all of the pathways analysed in the report and will allow electrically powered vehicles and heat pump systems to achieve lower emissions than equivalent fossil fuel based vehicles and heating systems, while cooling systems, which depend mainly on electricity for their primary energy, should see a dramatic reduction in their energy related emissions. However, since more than 25% of current emissions from cooling systems are due to refrigerant leakage (direct emissions), even if total cooling energy demand did not increase by 2050, the RACHP sector could only achieve an 80% reduction in total emissions by also making significant reductions to direct emissions and increasing system efficiencies (or by reducing cooling energy demand through other measures). In practice, individual systems will need to achieve a reduction much greater than 80% to offset the increase in emissions due the growing use of RACHP systems over the next 30 – 40 years.

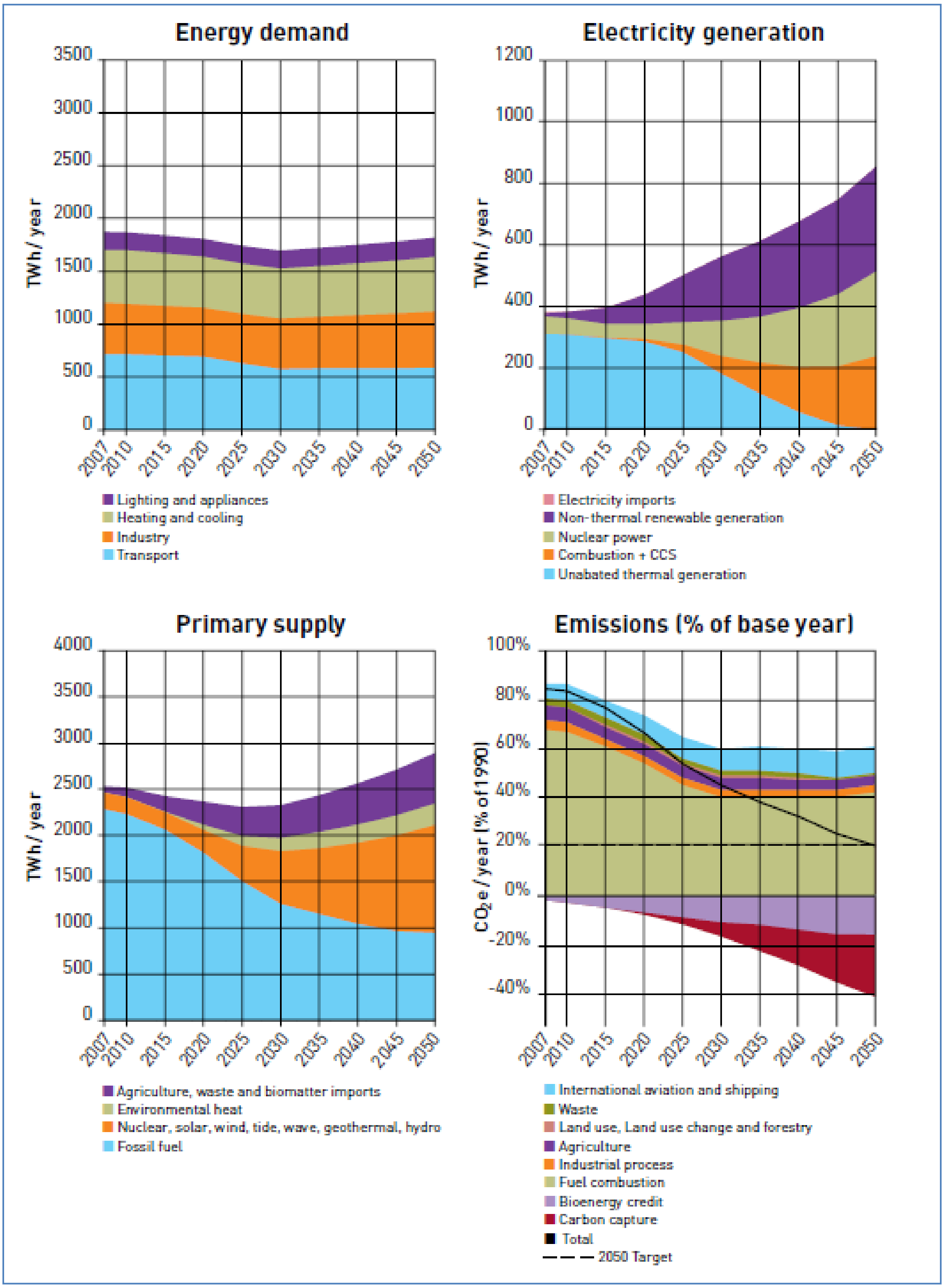


Figure 2-15. Pathway Alpha

[Source: DECC (2010)]

Figure 2-16 and Figure 2-17 indicate how domestic heating and cooling energy demand might change in the period up to 2050. There are 4 trajectories (level 1 to level 4), based on 4 different sets of assumptions. They are:

- Level 1. Average internal temperatures rise to 20°C by 2050 (from 17.5°C), the average heat loss coefficient drops by 23%, hot water demand increases by 50% and every house has air conditioning
- Level 2. Average internal temperatures increase to 18°C, the average heat loss coefficient drops by 31%, no change to hot water demand, 67% of houses have air conditioning
- Level 3. Average internal temperature drops to 17°C, the average heat loss coefficient drops by 41%, hot water demand is reduced by 25% and 33% of households have air conditioning
- Level 4. Average internal temperature drops to 16°C by 2050, the average heat loss coefficient drops by 51%, hot water demand reduces by 50% and there is no additional domestic air conditioning

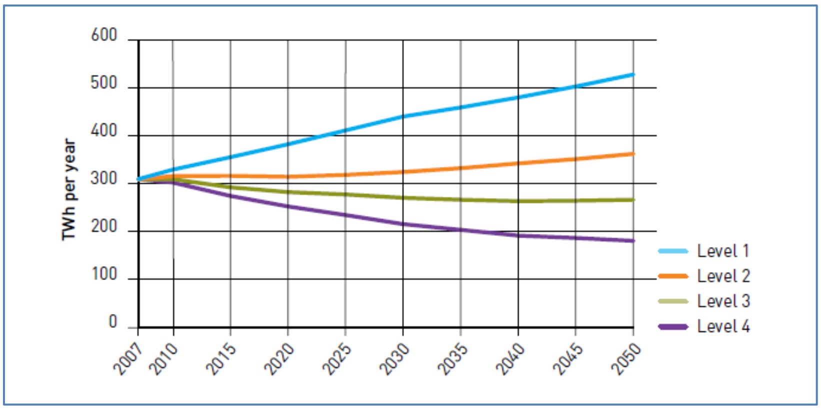


Figure 2-16. 2050 Pathway trajectories for domestic heating demand

[Source: DECC (2010)]

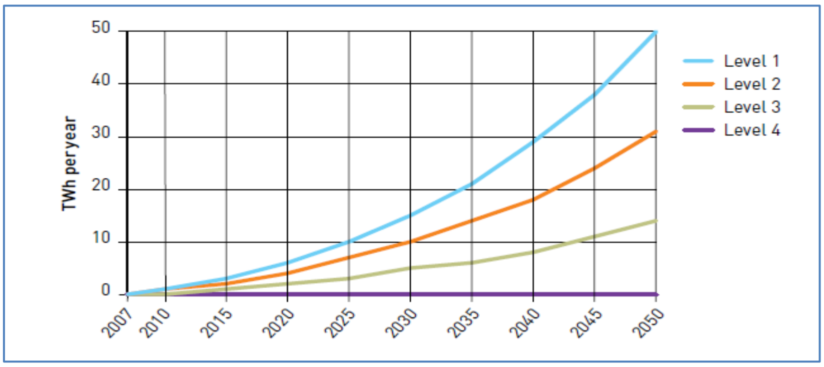


Figure 2-17. 2050 Pathway trajectories for domestic cooling demand

[Source: DECC (2010)]

The level 1 and level 4 scenarios represent extremes that are unlikely to be expereinced in practice, with a range somewhere between level 2 and level 3 being more likely. This would result in a heating demand of between 270 and 370 TWh annually (compared with around 300 TWh in 2007) and a cooling demand of between 13 and 31 TWh annually (from a base of almost nothing in 2007).

Figure 2-18 and Figure 2-19 indicate potential energy demand for non-domestic heating and cooling over the same period. Again there are 4 trajectories, with the following assumptions:

- Level 1. Little change in space heating demand, with building regulations similar to 2006, no change in hot water demand, all non-domestic floorspace assumed to be air conditioned
- Level 2. Space heating demand drops by 20% due to improved build standards, hot water demand per building drops by 10%, 100% of office and retail floorspace and 50% of other non-domestic floorspace assumed to be air conditioned (overall 40%), with a 20% improvement in energy efficiency of systems
- Level 3. 30% reduction in space heating due to refurbishment of existing stock, 20% reduction in hot water demand, total fraction of non-domestic floorspace air conditioned is unchanged (28%) and new builds reduce cooling demand by 50%
- Level 4. 40% reduction in space heating (90% for new build), 30% reduction in hot water demand, floorspace with air conditioning reduced by 50% (90% for new build) through passive design measures

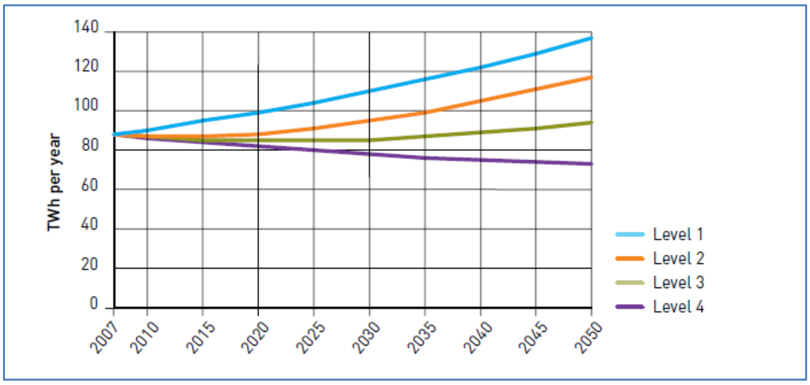


Figure 2-18. 2050 Pathway trajectories for non-domestic heating demand

[Source: DECC (2010)]

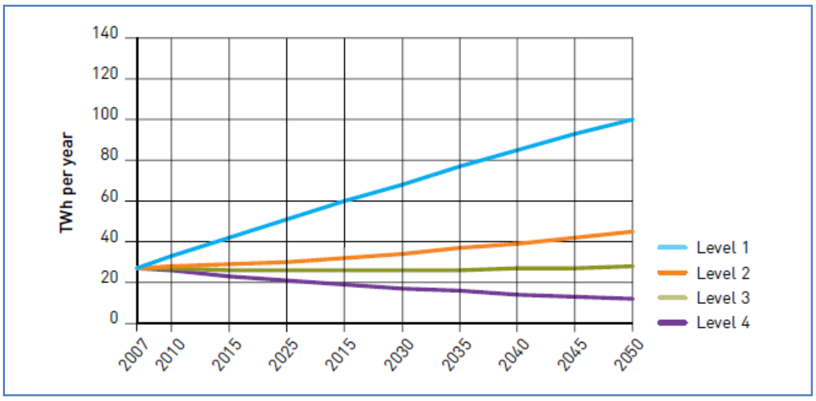


Figure 2-19. 2050 Pathway trajectories for non-domestic cooling demand

[Source: DECC (2010)]

Again, the level 1 and level 4 trajectories may represent unlikely extremes and a range between level 2 and level 3 is probably more likely. This would result in a heating demand of between 95 and 118 TWh (compared with about 88 TWh in 2007) and a cooling demand of between 30 and 45 TWh (compared with about 28 TWh in 2007). The projected increase in the heat demand between 2007 and 2050, from 88 TWh to 138 TWh, for the level 1 trajectory (minimal change from current scenario) appears to imply an increase in non-domestic floorspace of more than 50% by 2050.

2.9 Heating and cooling systems – evolution and environmental impact

2.9.1 Heating Systems

For hundreds of years burning fossil fuels such as wood and coal was the only viable method of comfort heating, as well as for cooking and industrial processes. The energy conversion efficiency of solid fuels is highly dependent on their moisture content, since energy will be wasted in boiling off any water that is absorbed in the material. Traditional open fires had very poor energy conversion efficiency, which improved to some 30-40% with the advent of inset open fires with refractory fire backs to radiate heat. Modern convector fires can achieve up to 60% efficiency, whilst back boilers and wood burning stoves can achieve over 75% efficiency, resulting in considerably lower carbon emissions as well as reduced fuel consumption for a given heat output. Maximum efficiency is achieved in condensing boiler designs with fan assisted flues.

Efficiencies estimated by the Solid Fuel Technology Institute (SOLIFTEC) for different solid fuel appliances are listed in Table 2-7. They claim that the actual efficiency is generally much lower than the CE declared efficiency due to heat wasted in boiling off water in the fuel and because the heat transfer efficiency is not taken into account in the official numbers. According to Soliftec (2016) this results in a negative number for the efficiency of an open fire with a large chimney opening. The environmental impact of these appliances could therefore be considerably higher in terms of their CO_2 equivalent emissions than indicated by the nominal carbon emissions factors for the relevant fuels.

Table 2-7. Typical efficiency for different solid fuel appliance configurations

Appliance installation	CE Declared Appliance Efficiency	Actual heating System Efficiency
Free-standing metal stove with all-masonry chimney wholly inside the building	75%	75%
Free-standing metal stove with external chimney	75%	60%
Free-standing metal stove with metal liner inside masonry chimney	75%	68%
Free-standing metal stove with metal liner inside masonry chimney, burning slightly damp wood	75%	31%
High-Efficiency Stove with external metal chimney	90%	66%
Open fire - basket grate in large opening	35%	-4%
Open fire, inset type with multi-pass back boiler, in internal masonry chimney	77%	76%
'Firefront'-type inset stove without all-round convection chamber	75%	35%
Inset stove with convection chamber	75%	68%
Central heating from standalone wood-fired 'batch' boiler in outhouse + thermal store	90%	73%
Central heating from wood-fired stove hearth boiler + internal masonry chimney	77%	77%

[Source: Soliftec (2016)]

The first commercial use of gas was for lighting in Britain towards the end of the 18th century, the gas being produced from coal. Towards the end of the 19th century, as electric lighting replaced gas lighting, the development of the Bunsen burner demonstrated that gas could be safely used for heating and cooking. In the 20th and 21st centuries, improved processing, supply pipeline and storage developments, together with exploitation of natural gas resources, has resulted in gas becoming the largest source of primary energy in the UK. As well as achieving high energy conversion efficiency - over 90% according to the International Gas Union (IGU, 2017) the carbon emissions are lower than for all other forms of primary energy apart from nuclear and renewable (Figure 2-20).

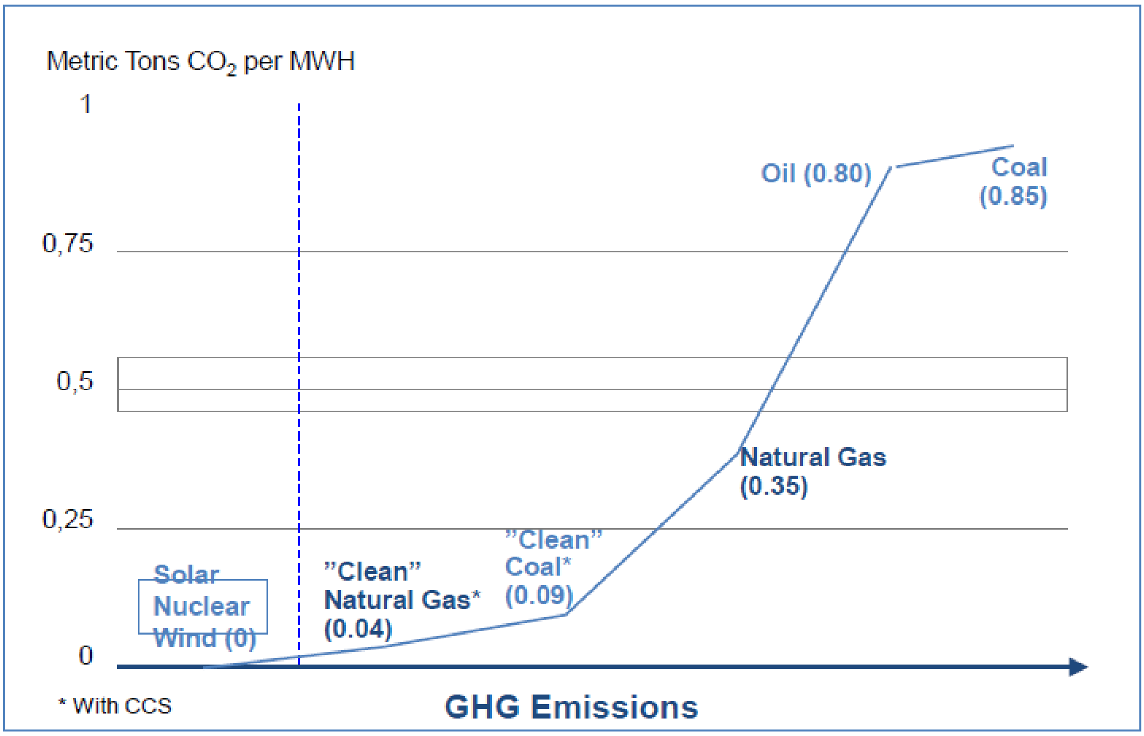


Figure 2-20. The environmental impact of natural gas compared with other fuel types

[Source: IGU (2015)]

Whilst electricity is potentially a clean and efficient form of heating from an end user perspective, the thermal conversion efficiency in UK power stations is only 36% for coal fired, rising to 48% for combined cycle gas turbine power stations. When transmission and distribution losses of over 7% are included the net thermal efficiency for grid electricity in the UK in 2012 was around 38%. However, according to the IGU (2017) combined heat and power generation can enable the utilisation of 80% of the energy content in natural gas.

Biofuels and biomass (including wood pellets) are deemed to have zero carbon emissions when the overall renewal cycle is considered. However, at the time they are burned to generate heat they do generate considerable levels of emissions (0.349 $kgCO_2e$/ kWh in the case of wood pellets – similar to coal), as well as environmentally damaging particulates.

2.9.2 Cooling systems

The basic concepts behind using evaporative cooling are said to have been understood for many centuries and used as a method of comfort cooling, especially in hot climates. It has been reported that practical mechanical vapour compression refrigeration machines were produced from the mid 1800s. However, it was not until 1902 that Willis Carrier invented the first modern air conditioning system in the USA (Carrier, 2017).

In cool temperate regions such as the UK, the demand for cooling had, until the second half of the 20th century increased only slowly and was mainly limited to applications such as food preparation and storage. However, with increasing demand for frozen foods and longer storage life for fresh foods, the refrigeration industry then experienced a rapid growth. At the same time, the increasing number of high rise buildings, many equipped with energy intensive IT equipment and built to new standards with high levels of insulation, resulted in a rapidly escalating demand for comfort cooling solutions such as air conditioning. According to Hitchin and Pout (2000), at the end of 1994 about 10% of UK commercial building floor area was air conditioned and under a business as usual scenario this could increase to as much as 40% of commercial floor space by 2020. In a minimal air conditioning scenario (removing air conditioning from some buildings on refurbishment and limiting its use in new buildings) this figure would be reduced to 23% for commercial offices (and pro rata for other building types). Figure 2-21 shows forward projections of UK annual electricity demand for the two scenarios.

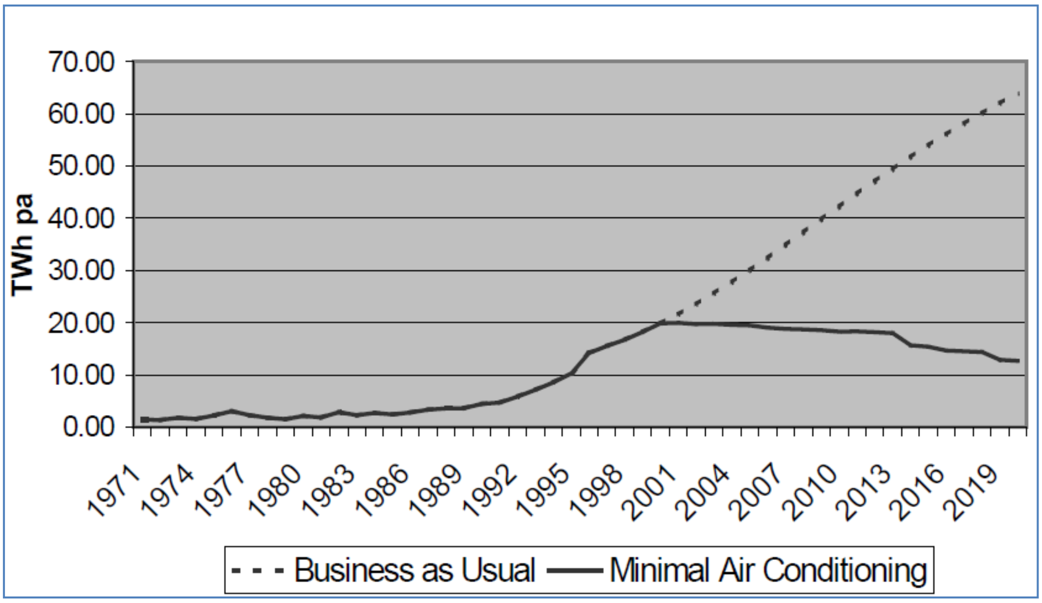


Figure 2-21. Growth in UK annual cooling electricity demand under two scenarios

[Source: Hitchin and Pout (2000)]

According to the UK DEFRA Market Transformation Programme evidence base (MTPROG, 2010) the estimated UK annual electricity consumption for air conditioning systems in 2010 was 18.3 TWh and was predicted to rise to nearly 25 TWh by 2020. This figure was reduced to 21.1 TWh under the 'Policy' scenario (Figure 2-22), based on changes to UK building regulations and EU policies, or 19.3 TWh using best available technology.

The performance and environmental impact of cooling systems are discussed in Chapter 4.

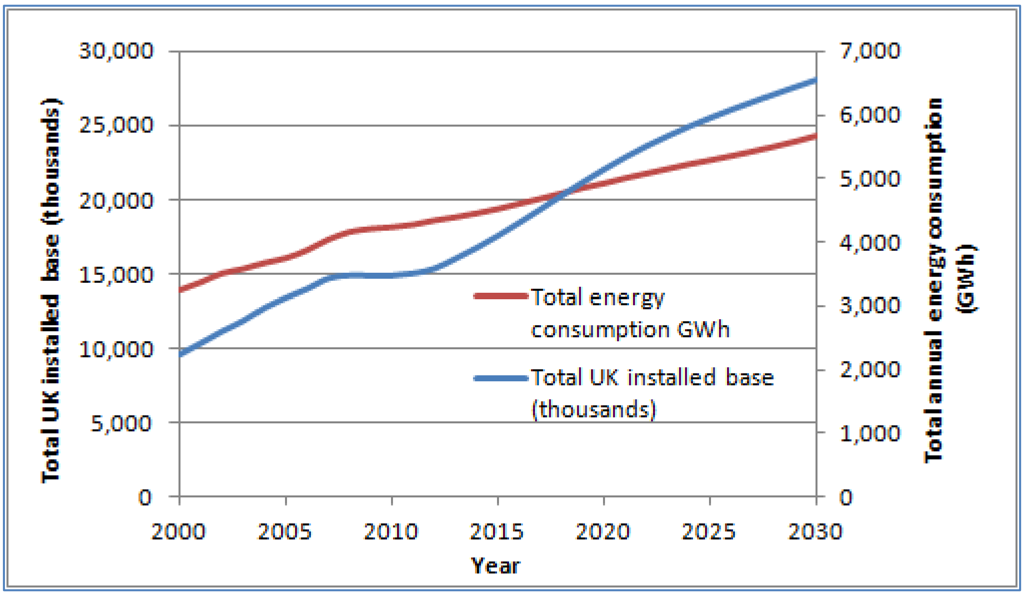


Figure 2-22 Forecast increase in UK air conditioning installations and energy consumption ('Policy' scenario)

[Adapted from MTPROG (2010)]

2.10 Demographics and trends – impact on energy demand and emissions

Globally there is an increasing trend for populations to migrate from rural areas to cities and urban areas. The introduction of more efficient farming methods reduces the demand for manpower in the agricultural and related sectors and encourages workers to seek new employment opportunities in industry, commerce and the service sector. London's population peaked at 8.6 million in 1939 but then fell to 6.7 million by 1988 as a result of decentralization policies and the building of new towns. However, since then it has risen again to an estimated 7.8 million in 2011 and is projected to rise to 8.82 million by 2031. Over the same period the number of people employed in greater London is forecast to increase from less than 4 million to nearly 5.5 million people (GLA, 2011a). The increase in employment numbers is not expected to be uniform and for example is projected to be 26.5% in Southwark but only 2.7% in Richmond.

London's infrastructure, including road and rail transport, utilities, commercial and industrial buildings, schools, hospitals, housing, other buildings and open spaces will all need to be developed and enhanced in order to cope with the increasing population. For example, it is estimated that the demand for office floorspace will increase by almost 4 million m^2 between 2011 and 2031. New building regulations, new technologies and changing work patterns will impact the energy density (energy demand per unit area) and the heating and cooling requirements for buildings. According to the London Plan's Map 5.1 (GLA, 2011a), in the centre of London the heat density (relative heat demand based on fuel use) currently exceeds 96 kWh/m^2 per year.

London is estimated to be responsible for approximately 8.4% of all UK greenhouse gas emissions (44.7 million tonnes), but also has some of the lowest domestic and transport CO_2 emissions at 2.26 tonnes and 1.38 tonnes per person per year respectively, due to the density of development and the high use of public transport. However, even though London's CO_2 emissions are projected to fall to 40 million tonnes by 2025 on a business as usual basis, climate change projections are for an increase in mean summer temperature of 2.7°C by the 2050s, with a 15% increase in mean winter rainfall and an 18% decrease in mean summer rainfall (GLA, 2011a).

Consequences of the demographic changes forecast for London are likely to include a higher density of population, housed in better insulated buildings that require less energy to heat. However, these buildings may also become more difficult to keep cool once the impact of global warming and climate change are taken into account.

2.11 Previous London studies – energy demand, cooling and emissions

Various studies have been undertaken to assess the current and future cooling demand for London, some within the context of the overall development strategy, others in response to the need to develop a strategy for climate change mitigation and future energy supply. The London Plan (GLA, 2011a) presented an overall strategic plan and within the section on climate change and mitigation the report set targets to reduce carbon emissions to 60% of 1990 levels by 2025, requiring all new buildings to be zero carbon by 2019 and promoting increased use of decentralised energy and heating and cooling networks. It also included a cooling hierarchy to be applied when making planning decisions and 'urban greening' objectives to mitigate climate change.

A report on Delivering London's Energy Future (GLA, 2011b) addressed the environmental issues in greater depth. However, apart from setting a target to increase the supply of decentralised energy (including CHP and Tri-generation systems and associated heating and cooling networks) to 25% of London's energy, there was no detail concerning cooling energy demand and delivery.

A study undertaken by URS for the City of London (URS, 2009) investigated the carbon footprint of the City. Figure 2-23 shows the breakdown of energy use reported from 106 responses to a survey of 1400 members of the Clean City Awards and indicates that air conditioning was responsible for 26%, with refrigeration responsible for a further 9%. On the other hand, heating and lighting combined were responsible for only 31% of total energy use, demonstrating that in an urban environment containing many office blocks the cooling energy demand is likely to equal or even exceed the heating energy demand.

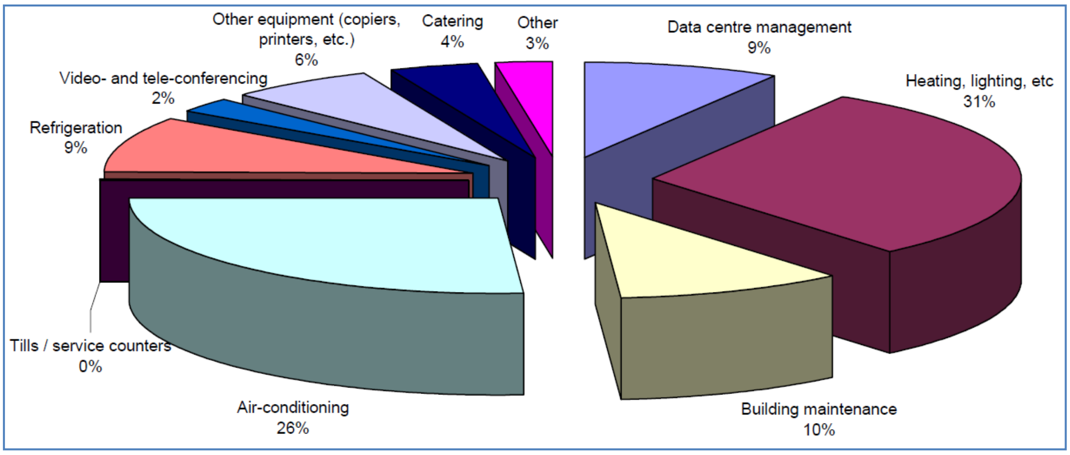


Figure 2-23. Reported energy use by activity in the City of London

[Source: URS (2009)]

Table 2-8 and Figure 2-24 show a breakdown of energy use and associated emissions by energy type, including the split between domestic and commercial energy use. Domestic energy consumption is small in comparison with commercial, since the City of London is dominated by commercial activity and the number of residential properties is small. Electricity use is reported to be responsible for more than 85% of total emissions in the City.

Table 2-8. Reported City of London carbon emissions

Emission source	Consumption per annum [kWh, litres-water]			CO_2 generated per annum	CO_2 generated per annum / capita & commuter	CO_2 generated per annum
	Domestic	Commercial	Total	tonnes of CO_2	tonnes of CO_2	%
Gas	36,330,689	907,956,684	944,287,373	194,523	0.56	11.7%
Electricity	24,591,119	2,632,511,028	2,657,102,147	1,426,917	4.13	85.5%
Green tariff electricity		85,309,144	85,309,144	45,813	0.13	2.7%
Onsite renewables				-	-	0.0%
CHP heat		4,829,850	4,829,850	909	0.00	0.1%
Petroleum (non transport)	174	11,436	11,610	3	0.00	0.0%
Clean water supply	482,566,500	21,417,433,500	21,900,000,000	6,373	0.02	0.4%
TOTAL				**1,668,165**	**4.84**	**100%**

Source: URS Analysis December 2008. Refer to Data Sources in Appendices.

[Source: URS (2009)]

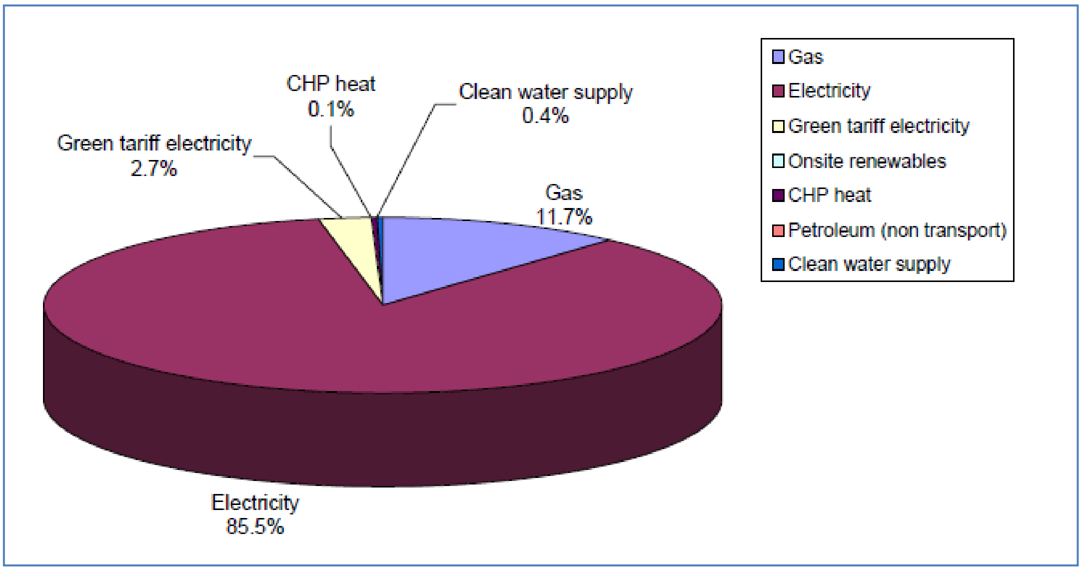


Figure 2-24. Reported breakdown of City of London emissions

[Source: URS (2009)]

A paper by Day *et al* (2009) estimated that under a business as usual scenario the total cooling demand for London would increase from 4.5TWh to 8.5TWh in the period 2004 to 2030, with corresponding increases in primary energy (electricity) demand and emissions from 1.6TWh to 3.1TWh and from 670k tonnes CO_2 to 1.3m tonnes CO_2 respectively. The methodology was based on estimating London's building stock, split by building type and floor area and calculating cooling degree day energy demand using CIBSE guidelines TM41 (CIBSE, 2006a). Eight generic cooling system types were used in the analysis and the split between system types was based on market data and market growth assumptions. The authors concluded that climate change could potentially add as much as 350k tonnes CO_2 emissions each year, but this would be offset by system efficiency improvements and reduced carbon intensity for grid electricity. However, it is important to note that this study did not take into account other potential improvements (for example using passive and free cooling techniques) that could lead to a reduction in cooling energy demand.

A Low Carbon Cooling Guide (Day *et al*, 2011) that was developed for the Greater London Authority provides a cooling hierarchy and methodology for determining the environmental impact rating of cooling systems and introduces the concept of a Greenhouse Gas Impact Rating (GGIR) for different system types, which is a measure of the indirect emissions associated with the primary (generally electrical) energy use and depends on system performance and efficiency. A second rating, the Greenhouse Gas Impact Factor (GGIF) also takes into account the direct emissions associated with refrigerant leakage. The authors of the

Low Carbon Cooling Guide developed an A to G rating for systems that corresponds to GGIR values between 0 and 2100 $kgCO_2$/yr.kW. The rating system allows for characterisation of passive and free cooling systems as well as mechanical cooling solutions. Figure 2-25 indicates the typical range of GGIF values for different cooling system types, including absorption, borehole and passive cooling systems.

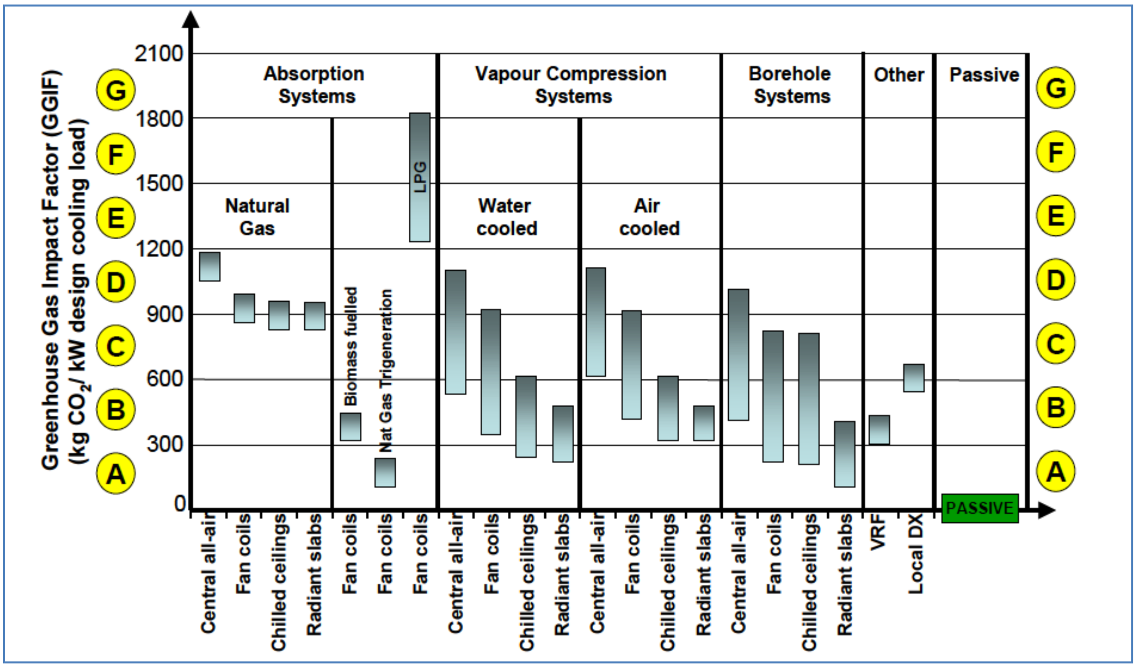


Figure 2-25. GGIF range for typical modern cooling systems

[Source: Day *et al* (2011)]

2.12 Benchmarks for heating and cooling energy demand

The EU Energy Performance of Buildings Directive or EPBD (EU, 2010), which was implemented in the UK via changes to Part L of the Building Regulations and the Energy Performance of Buildings Regulations (GOV.UK, 2012) encourages building owners and users to improve their energy efficiency. Energy Performance Certificates or EPCs (DCLG, 2014) indicate the potential performance of a building whilst Display Energy Certificates or DECs (DCLG, 2014) show the actual energy use.

Various benchmark data have been published by building industry professional and trade associations such as CIBSE and BSRIA. CIBSE Guide F (CIBSE, 2004) provides guidance and a methodology for both design and operation of buildings, together with benchmarks for energy use (generally expressed as kWh/m2 per year) according to building type, component type and end use. CIBSE Guide TM46 (CIBSE, 2008) provides additional benchmarking data and adds factors that can be used to adjust the benchmarks for variable weather data (using degree days) and occupancy that varies from the assumptions used for the benchmark values. The BSRIA benchmarking data (BSRIA, 2011) provides 'Rules of Thumb' for construction professionals.

2.13 Natural ventilation and passive methods of cooling

There are several potential approaches to mitigating the heat island effect and maintaining comfort levels in buildings, the most obvious being to increase the amount of cooling. However, although current RACHP technology is capable of delivering ever increasing amounts of cooling energy, this approach could in the long term be self defeating, since the extra waste heat emitted from cooling systems would add to the heat island effect and could increase cooling demand even further. Passive cooling techniques avoid generating additional heat energy, but since the characteristics of the urban heat island effect are for the temperature increase to be higher at night than in the middle of the day, the effectiveness of a 'night cooling' approach for buildings could be lower than in rural areas. Other potential technological solutions could include adaptation by modifying the building design and services and changing the way the building is used (operating parameters, occupancy profiles and occupant behaviour). Energy sharing and reuse via district energy networks are other possibilities.

CIBSE guide KS3 (CIBSE, 2005a) provides an overview of low energy cooling technologies and ranks them in terms of their energy saving potential, cost of implementation, capabilities and design and operating risk (Table 2-9). Reducing heat gains and increasing the use of natural, mixed mode and night ventilation are relatively straightforward to implement, along with free cooling. Ground cooling systems can achieve good energy savings but can be expensive to implement. Reductions in heat gains can be achieved through both changes to the building structure (shading, glazing, thermal insulation etc.) and better management of energy use within the building. The CIBSE guide is relatively simplistic, but it is difficult to find other authoritative sources of information that categorise and compare the merits of alternative cooling technologies.

Table 2-9. Comparative merits of different low carbon cooling solutions

Low cooling solution	Energy saving potential	Cost to implement	Ability to provide low chilled water temps.*	Ability to provide accurate control of space temps.	Design/ operating risk
Reduce heat gains	☺	☺	NA	NA	☺
Natural ventilation	☺	😐	NA	☹	😐
Mixed mode ventilation	☺	😐	NA	☹	😐
Night cooling	☺	😐	NA	😐	😐
Ground cooling air system	☺	☹	NA	😐	😐
Ground cooling water system	☺	☹	😐	😐	😐
Surface water cooling	☺	😐	😐	😐	😐
Free cooling in re-circulating air systems	😐	☺	NA	☺	☺
Free cooling in full fresh air systems	😐	☺	NA	☺	☺
Desiccant cooling	😐	😐	NA	☺	☺
Free cooling in systems with cooling towers or evaporative coolers	😐	☺	😐	☺	☺
Thermosyphon chillers	😐	☺	☺	☺	☺

☺ = good 😐 = average ☹ = poor NA = not applicable

* Inability to achieve low chilled water temperatures indicates that the solution is best suited for use with a delivery system which can utilise raised chilled water temperatures, such as those described in section 6.

[Source: CIBSE (2005a)]

2.14 Decentralised energy – district heating and cooling

An EU funded report by Euroheat and Power (Europa, 2006) claimed that a district cooling network could achieve efficiencies of as much as 5 to 10 times the efficiency of traditional mechanical cooling systems and suggested that such networks could provide 25% of European cooling demand by 2020. However, the quoted efficiency was based on extensive use of free cooling, heat storage and waste heat sources. District cooling networks are already used extensively in France, Sweden, Finland and Germany.

Another Euroheat publication (Euroheat, 2010) reported that the district cooling networks in Gothenburg and Stockholm were saving 144,000 tonnes of CO_2 (tCO_2) annually in 2010 and that expansion of these networks would increase the annual savings to 233,000 tCO_2 by 2020. The advantages of district cooling are highlighted in Figure 2-26, which compares the primary energy factor (which encompasses the whole cycle from conversion to delivery to the customer) for alternative cooling schemes and indicates that district cooling using industrial chillers is at least twice as efficient as using conventional chillers in buildings.

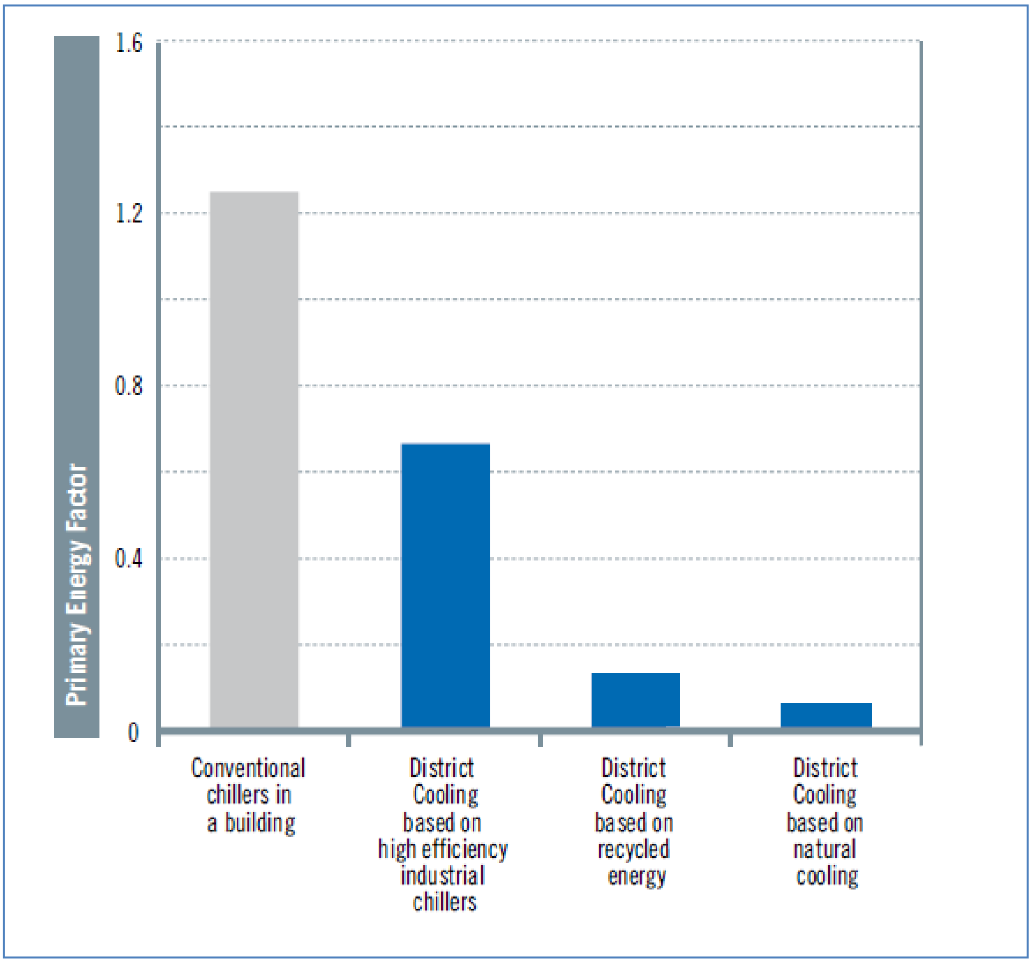


Figure 2-26. Comparison of the primary energy factor for alternative cooling schemes

[Source: Euroheat (2010)]

According to the UK Association for Decentralised Energy (ADE, 2012) there were some 200 district heating schemes in the UK in 2012 and 20% of these also provide district cooling.

A more recent EU funded project Stratego has identified opportunities for district heating and cooling in Europe, with specific focus on the countries of the five project partners: Czech Republic; Croatia; Italy; Romania; United Kingdom. A series of reports (Stratego, 2016) document the work and includes reports for each of the partner counties, as well as identifying the potential for district heating and cooling across the EU. A related project (Energy Plan, 2016) has developed a freeware software tool that can simulate the operation of national energy systems on an hourly basis and includes the electricity, heating, cooling, industry and transport sectors. Another EU funded project, that aims to create the scientific evidence to support the decarbonisation of the heating and cooling sector in Europe, is Heat Roadmap Europe (Heatroadmap, 2017).

Chapter 3. Proposition and research method

3.1 The problem

Refrigeration, air conditioning and heat pump (RACHP) systems currently account for nearly 20% of UK electricity use and over 7% of all UK greenhouse gas emissions. Under existing scenarios global warming and the trend towards urbanization will result in increases in both cooling demand and the associated emissions. The UK commitment to reducing greenhouse gas (GHG) emissions by 80% by 2050 requires new and innovative approaches to the cooling of buildings. For example, new low carbon methods of delivering cooling, such as distributed cooling networks might be developed and cooling loads reduced, through optimization of the building's design and operation. There is also potential to reduce emissions from RACHP systems through improvements in their performance and efficiency and by reducing refrigerant leakage.

3.2 Gaps in the knowledge

At the level of a single RACHP system that has been manufactured within the past 10 years, there is good understanding of the technology, design, operation and their typical environmental impact. However, there is also a large installed base of legacy systems, many dating back 20 to 30 years. Information about these systems and the total installed base of RACHP systems is much less well understood. There are significant uncertainties regarding the total number of systems in operation, their energy use and their environmental impact.

Governments have introduced a wide range of regulatory and fiscal measures to control and reduce refrigerant emissions, most notably the adoption of the Montreal and Kyoto Protocols and more recently the implementation of the EU F Gas regulations. Various studies have been undertaken to assess the effectiveness of these and other measures, but there remains a significant level of uncertainty. At national level, refrigerant inventories are estimated using a combination of a 'top down' and 'bottom up' approach, the results of the two methods being compared to establish the reliability of the data. The 'top down' approach is based on the reporting of refrigerant purchase, sales and use in systems, while the 'bottom up' approach uses market data for installed equipments and default assumptions regarding refrigerant types and charge size. Emissions from leakage of refrigerant can be estimated and reported by individual organisations from changes in their refrigerant inventory (Simplified Material

Balance Method) or by calculation, using their RACHP equipment inventories and default assumptions for the leakage rate during installation, operation and disposal of equipment (Screening Method). However, smaller organisations are not required to report such data and actual refrigerant leakage rates can vary significantly from the default values, depending on the type of equipment, manufacturing methods and the quality of maintenance.

The indirect emissions associated with electrical energy use are not well understood, because sub-metering is not generally employed (except for some large systems). Although equipment is available for monitoring the cooling performance and efficiency of systems, it is normally used for diagnostic purposes rather than for continuous monitoring. The actual performance and efficiency of a RACHP system may differ significantly from predicted values, depending on the installed configuration and environment, equipment settings and the load factor and duty cycle. Incorrect sizing of the cooling (or heating) capacity in a particular installation may result in poor efficiency, leading to high indirect emissions. If sub-metering is not installed, such inefficiencies may not be identified or resolved. Correct matching of the cooling or heating capacity of the system to its operating environment (for example to heat or cool a building) requires an accurate estimate of the thermal load.

Higher GWP HFC refrigerants are increasingly being replaced by lower GWP HFC refrigerants, newer refrigerants such as HFOs (hydrofluoroolefins) and natural refrigerants such as ammonia (NH_3) and carbon dioxide (CO_2). Whilst the use of such refrigerants can reduce direct emissions from refrigerant leakage, they may in some instances result in an increase in the total emissions due to higher indirect emissions from lower efficiency and increased electrical energy use. The calculation of the TEWI (Total Equivalent Warming Impact) of a RACHP system can be used to assess both indirect and direct emissions over its lifetime, providing a useful method of evaluating existing and new systems, proposed design changes and improvements. However, this tool does not appear to have been widely adopted within the industry.

In buildings, sub-metering of the electricity used by RACHP systems is rarely employed, so real data on the cooling energy used is hard to find. Energy Performance Certificates (EPCs) and Display Energy Certificates (DECs) indicate only the total energy demand of a building and do not distinguish between its heating, cooling and other energy use. It can therefore be difficult to quantify the level of cooling emissions and the potential for reducing them. Current estimates and projections for future cooling demand rely heavily on historical benchmarks developed by organizations such as CIBSE and ASHRAE over the past 20-30 years and market projections for RACHP system installations. However, evolving building standards and modern design trends (such as high levels of glazing), coupled with the increasing use of IT in businesses of all types, could mean that existing benchmarks are no longer appropriate and need to be updated.

In practice, the cooling and heating emissions from a building cannot be considered in isolation from each other, since cooling and heating energy demand are both dependent on the heat gains and losses for the building, that arise from many different sources. These include heat gains and losses associated with the fabric of the building, the heating, cooling and ventilation systems, occupancy levels, lighting, ICT equipment, and other power loads such as lifts, hot water, refrigeration and cooking. Changes in any of these areas can impact the building's heating and cooling energy demand, so a building that has been optimised for low cooling energy and emissions may not be good in terms of its heating energy demand and emissions (and vice versa) and the building's total energy use and emissions might even increase.

An improved understanding of building energy use and emissions, including a breakdown of the various contributions and the impact of changes to the building's design, fabric, operation and the external environment, could assist planners, architects, building services engineers and contractors to design build and maintain buildings that use less energy and have lower emissions.

3.3 Research aims

This research project was aimed at addressing some of the gaps in current knowledge by investigating and understanding the energy demand and carbon footprint of cooling in the urban environment. It aimed to provide answers to the following questions:

1. What is the current level of carbon emissions from RACHP systems and buildings?
2. What measures might be taken to reduce the carbon emissions from buildings?
3. How might the level of carbon emissions from RACHP systems and buildings vary in the future in response to global warming, changes to building design and construction techniques and other new developments?

3.4 Plan & novelty

The study was designed to undertake two complementary investigations:

1. Investigation of the environmental performance of installed RACHP systems by analysing data from site surveys of equipments, in order to better understand the mechanisms and causes of refrigerant leakage and to identify opportunities to reduce leaks. Also to assess the relative contributions to total emissions from refrigerant leakage and energy use, the potential for reducing them and the resulting impact on total emissions.
2. Investigation of the extent to which emissions from RACHP systems that are used to cool and heat buildings might be reduced through optimisation of a building's design features, construction materials and modes of operation, to reduce its cooling and heating energy demand.

By developing a better understanding of the sources and causes of refrigerant leakage, effective measures to cut leakage and reduce the direct emissions might be implemented in a relatively short time frame. Analysis of the relative emissions from refrigerant leakage and energy use could also help to clarify the potential for future emissions reductions.

Reductions in the indirect (energy related) emissions from RACHP systems could be achieved by reducing the cooling energy demand (smaller cooling loads), by increasing the efficiency of the systems with better technology, through decarbonising the electricity grid, or a combination of all three approaches.

A key element of this research study was to investigate the breakdown of the cooling energy demand in buildings as well as the cooling system's energy use and emissions. Current trends suggest that in the absence of a fundamental change of approach, cooling demand for buildings will continue to increase, resulting in higher energy use and the associated emissions. Identification of the underlying sources of cooling demand and their sensitivities to the building's design, construction and operating parameters could aid our understanding of cooling emissions and how to reduce them.

Where sub-metering is used in buildings its primary purpose is to identify the energy used by particular systems and sub-systems, but not how the various energy using systems and heat gain and loss mechanisms interact. Many different software tools exist for simulating energy performance and emissions, but those that rely on static or long term energy balance methods are incapable of analysing such interactions, whilst many dynamic simulations tools (for example EnergyPlus, IES-VE and TRNSYS), are relatively complex and may not be the most appropriate tool for the rapid assessment of alternative approaches aimed at reducing a building's energy use and emissions.

The novelty of this study includes the method employed to identify the individual contributions to the cooling energy demand and emissions of a building, through a new energy balance model and software tool that uses an out-of-balance analysis technique to predict the dynamic performance of the building. The relative simplicity of the approach allows for a rapid assessment of a building's thermal response and the heating and cooling demand and emissions, permitting the user to see immediately the impact of making changes to any of the parameters used in the simulation. It can provide a high level characterization of a building, helping the user to assess the options and potential solutions for reducing energy use and emissions.

The new tool might be used to: assess potential improvements to existing buildings; to provide an early indication of, and an opportunity to optimise, the energy and emissions performance of new buildings before detailed plans are prepared; or as a strategic planning tool, to assess potential impacts and responses to the effects of climate change and to changes in building standards and regulations.

3.5 Research methods

3.5.1 Reducing the emissions associated with RACHP systems

The following methods were employed to investigate and understand how emissions from RACHP systems might be reduced:

- Develop an understanding of current energy use and emissions from RACHP systems in the UK, using available data and reports.
- Compare the relative impact of refrigerant leakage (direct emissions) and energy use (indirect emissions) on the total emissions from RACHP systems.
- Analyse data from site surveys undertaken to investigate refrigerant leakage and from RACHP system maintenance logs, to establish leakage rates and key causes of leaks.
- Identify measures that could be undertaken to reduce refrigerant leakage and the impact of a reduced leak rate on the total emissions from a RACHP system.

- Investigate some alternative refrigerants and their suitability for use in heat pumps and air conditioning systems, including a comparison of their energy use and emissions.

These activities are described in Chapter 4.

3.5.2 Reducing the thermal energy load and RACHP emissions in buildings

The focus of this activity was to assess how cooling loads in buildings might be reduced, using the following methods:

- Establish some key principles and approaches for reducing a building's energy demand and emissions
- Establish the suitability of existing energy modelling software tools for evaluating RACHP and building emissions and the impact of building changes.
- Develop a generic energy balance model (and software tool if deemed necessary) for analysis of building energy demand and emissions.
- Obtain suitable building and weather data for use in the simulation model.
- Compare the model and new software tool against an existing industry standard software application, using a standard building design for the comparison.
- Compare simulation results using the new software tool with existing energy and emissions benchmarks and other sources of energy data.
- Evaluate the sensitivity of energy demand and emissions to changes in the building and operating parameters and the external environment (including the effects of climate change), in order to identify the key factors influencing building energy and emissions.

These activities are described in Chapters 5, 6 and 7. A discussion of the new tool and the results and conclusions from the simulations are presented in Chapter 8.

A significant amount of background work was undertaken obtain the relevant benchmark energy and emissions data and weather data. It included a review of building parameters from past and present Building Regulations, the download and analysis of statistical demographic and energy data for 3 London Boroughs and the download and reformatting of current and future weather data. Selected data from this background work are included in Chapters 5 and 6, while more detailed information is included in Appendices E, F, G and H.

Chapter 4. Analysis of the emissions associated with RACHP systems

There are three types of emissions associated with RACHP systems – Direct emissions, Indirect emissions and Embedded emissions. Direct emissions are those due to escape of greenhouse gases from equipments during commissioning, operation and maintenance and at end of life (decommissioning). Indirect emissions are those associated with generating and delivering the primary energy (usually grid electricity) used by the RACHP system, while Embedded emissions are those associated with the manufacture of the equipment (from extraction of raw materials to fabrication, delivery and installation), upgrades during its operating life and at end of life (disposal or recycling). In practice it is very difficult to assess embedded emissions as this requires detailed knowledge of the source and processing of the raw materials and the manufacturing processes. Most studies of RACHP emissions, including this investigation, therefore assess only Direct and Indirect emissions, either separately or in terms of their Total Equivalent Warming Impact (TEWI).

In this chapter, estimates of the total energy demand and emissions for all RACHP systems in the UK are presented, both as absolute values and as a percentage of total UK energy demand and emissions. The estimates were generated from recently available data and reports and the results provide a baseline for estimating the scope for reducing direct and indirect emissions in the future. The chapter also documents analysis of RACHP emissions through investigations that were either led by the author, or for which the author was a key contributor. The investigations included the analysis of data from site surveys and RACHP equipment maintenance and repair logs, to assess refrigerant leakage rates and identify key causes of refrigerant leakage.

An analysis of the impact of refrigerant leakage on TEWI is also presented, together with a review and TEWI assessment of some alternative refrigerants that could be used in heat pumps and air conditioning systems. A summary of results and conclusions is presented at the end of the chapter.

4.1 RACHP system efficiency and Coefficient of Performance

An ideal refrigeration system would be a reverse Carnot Cycle engine, with coefficient of performance

$$COP = \frac{T_L}{(T_H - T_L)}$$ **Equation 4-1**

Where T_L is the evaporator temperature and T_H is the temperature of the condenser (both measured in K or absolute temperature). So for an evaporator temperature of 278K (5°C) and condenser temperature of 308K (35°C) the theoretical COP is 9.3. The theoretical limits for COP, for condenser temperatures of 35°C, 45°C and 70°C, over a range of evaporator temperatures are shown in Figure 4-1.

However, these are limiting values and cannot be achieved in practice. The Carnot cycle assumes adiabatic compression and expansion of the refrigerant and isothermal transfer of heat between the evaporator and condenser and their surroundings, both of which are reversible processes. Practical refrigeration systems can never achieve the theoretical performance, because the transfer of heat between the evaporator and condenser and their surroundings requires a temperature difference and is an irreversible process. Likewise true adiabatic compression and expansion cannot be achieved as heat energy is added due to inefficiencies and friction in the compressor, whilst in the work done by the compressed refrigerant in expanding cannot be fully recovered.

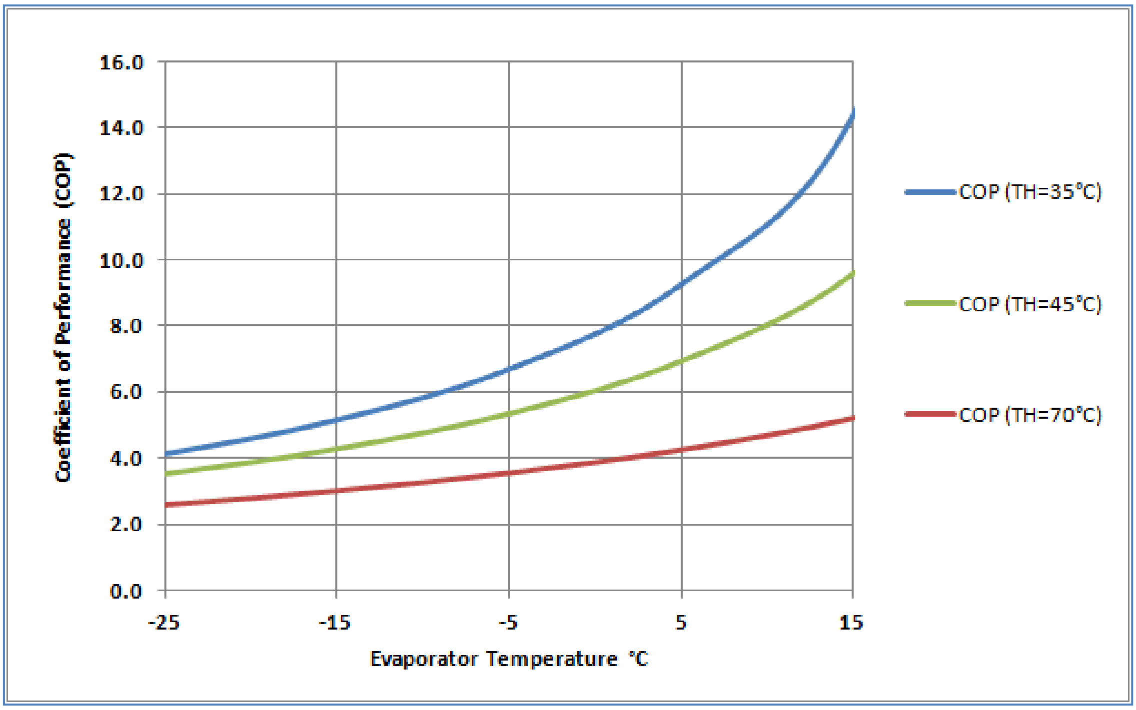


Figure 4-1. Theoretical performance limits for condenser temperatures of 35°C, 45°C and 70°C

Typical COP values can range from less than 1 to more than 3 for refrigeration and air conditioning systems and the COP of heat pumps is typically in the range 2 to 5. Factors influencing COP include:

- The heat transfer characteristics of the evaporator and compressor, the refrigerant flow rate and the refrigerant properties. These will determine the temperature difference between the refrigerant and the heated/ cooled surfaces - low values lead to higher COP.
- The efficiency of the heating/ cooling delivery system (forced air, chilled beam, air coil etc.) and auxiliary equipment such as pumps for secondary coolant flow or forced air flow.
- The temperature lift ΔT between the evaporator and condenser (reducing ΔT will increase the COP).
- The degree of superheating in the evaporator and sub-cooling in the condenser.
- The choice of air cooled or water/ secondary refrigerant cooled condensers and evaporators. Thermal stores and heat sources/ sinks can be used to improve efficiency (for example by using water/ secondary refrigerant cooled condensers or evaporators to sink/ extract low grade heat to/from the ground or aquifers), which reduces the variation in performance that is experienced with air cooled evaporators and condensers due to changes in external ambient temperature and humidity.

Figure 4-2 charts the typical COP for a range of refrigerants used in an air conditioning system with an evaporator temperature of 7°C and a condenser temperature of 45°C. The COP is in the range 4 to 4.35, compared with a theoretical limit of about 7.4 (Figure 4-1).

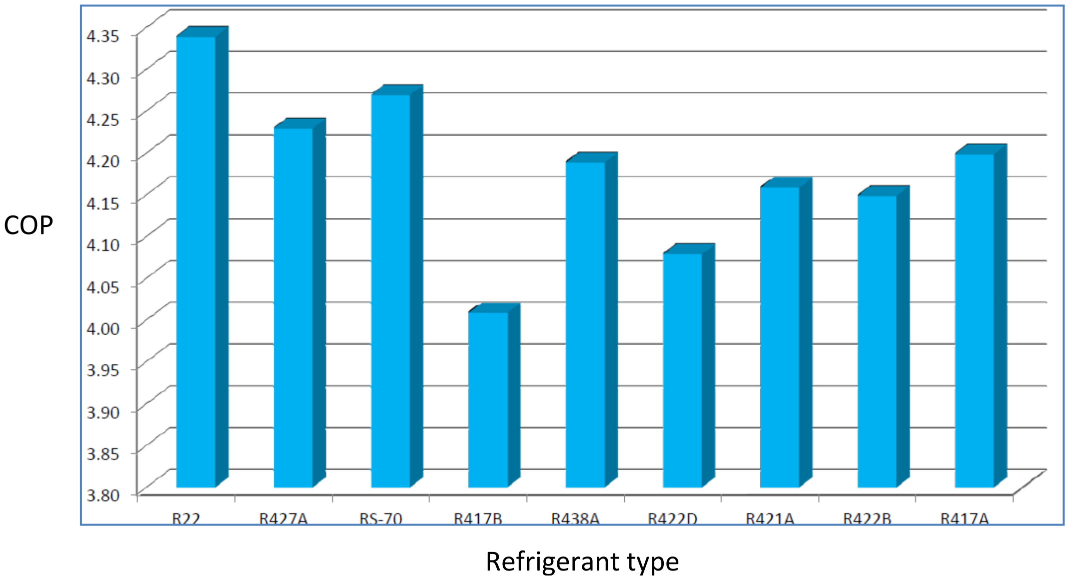


Figure 4-2. Typical COP for some refrigerants used in air conditioning systems (T_L = 7°C, T_H =45°C)

[Source: Refsols (2012)]

4.2 UK energy use and emissions from RACHP systems

A range of data sources has been used by the author to estimate the total UK energy demand and emissions for RACHP systems. Although there is significant uncertainty in some of the data, overall it is believed to provide a reasonable baseline from which to assess the potential for future energy and emissions reductions.

Total UK GHG emissions in 2012 were reported to be 575.3 $MtCO_2e$ (GOV.UK, 2015). The breakdown is shown in Figure 4-3 and indicates that 2% of the total was associated with HFC emissions due to refrigerant leakage from RACHP equipment. There may also be some GHG emissions from leakage of the HCFC refrigerant remaining in legacy RACHP systems. However, even though users of such equipments are required under EU law to maintain records of refrigerant additions and removals (EC. 2009), there is no formal mechanism in place to report this (within the EU). In any event, since 1 January 2015 it has been illegal to use HCFCs to service RACHP equipments and only HFC and low GWP alternative refrigerants are permitted, so the amount of HCFC refrigerant remaining in systems and the potential for HCFC emissions are likely to be small.

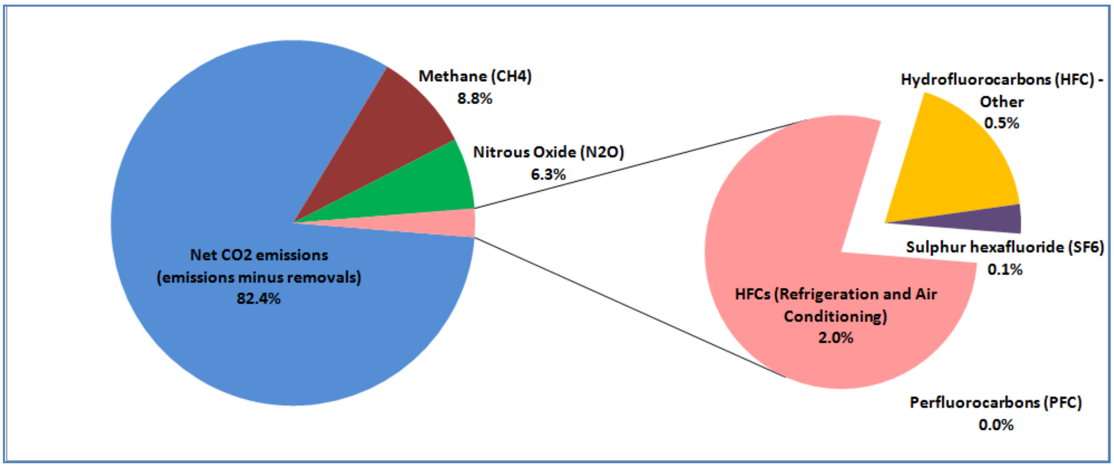


Figure 4-3 . Breakdown of UK Greenhouse Gas emissions in 2012

[Adapted from: GOV.UK (2015)]

The consequence of the transition from the use of HCFC to HFC refrigerants in the RACHP sector is indicated in Figure 4-4, which shows a steady increase in HFC emissions every year from 1990 to 2010. The RACHP sector is now the dominant source of HFC emissions in the UK, the other contributions being mainly from foams, fire fighting, solvents, electronics and research and sporting goods.

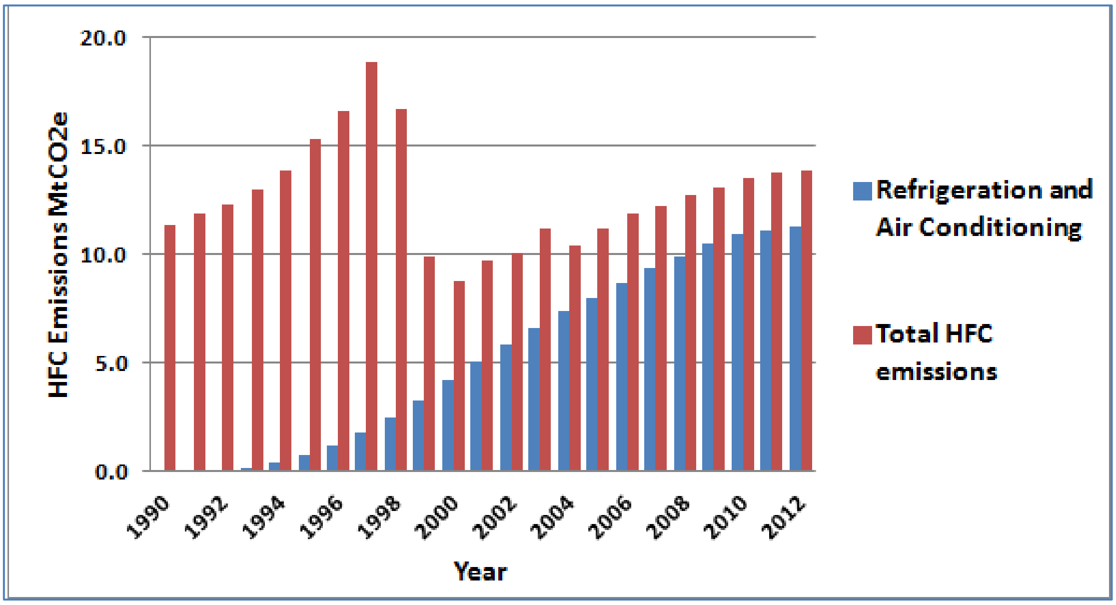


Figure 4-4. Growth in RACHP HFC emissions between 1990 and 2012

[Adapted from: GOV.UK (2015)]

In addition to the direct emissions from refrigerant leakage, indirect emissions associated with grid electricity use by the RACHP sector are estimated to account for up to 5.4% of all UK GHG emissions. There is some uncertainty in this figure, which relies heavily on market intelligence data for the RACHP sector, compiled under the UK Market Transformation Programme (MTPROG, 2010), covering the UK stock of commercial refrigeration, domestic refrigeration and air conditioning equipments. The uncertainty is primarily associated with Commercial refrigeration, where the data changed considerably between 2006 and 2010, in particular for package chillers. Also, between these dates the Commercial equipment category groupings were also changed, making it more difficult to compare like for like. For these estimates the 2010 data have been used (the corresponding figure for indirect emissions as a percentage of all UK emissions would have been 4.2% using 2006 data), as being the most recent available (and also the data reported by the UK into the EU under the Ecodesign Directive). Further detail is included in Appendix A. There is some additional uncertainty associated with using 2010 market intelligence data together with data from 2012 for UK electricity use (Dukes, 2013), however the market intelligence data indicates only small year on year changes in both equipment numbers and energy consumption, which have minimal effect on the results.

Figure 4-5 shows the breakdown of UK grid electricity consumption by the three main RACHP sub-sectors: Commercial Refrigeration, Domestic Refrigeration and Air Conditioning (which includes Heat Pumps). The chart indicates that stationary cooling systems consume nearly 20% of all UK grid electricity (62.6 TWh).

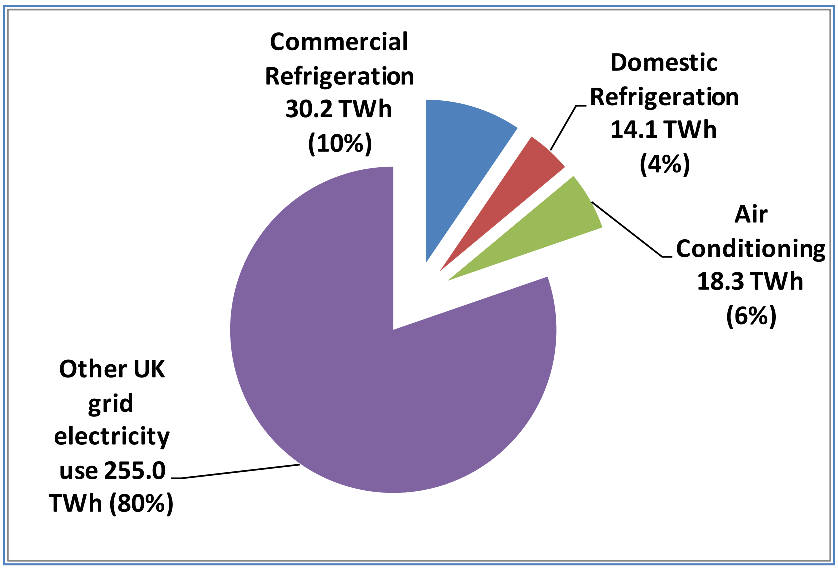


Figure 4-5. Estimated consumption of UK grid electricity by cooling systems in 2012

[Source data: Dukes (2013); MTPROG (2010)]

Table 4-1 summarises the estimated energy demand and emissions for UK stationary cooling systems in 2012. The emissions data indicate that the RACHP sector is responsible for up to 7.4% of all UK emissions, of which more than 25% is due to refrigerant leakage (direct emissions). If the 2006 market intelligence data had been used in this calculation the corresponding figure for direct emissions would have been nearly 32% of all UK RACHP emissions.

Table 4-1. Estimated energy demand and emissions for UK stationary cooling systems in 2012

Emissions Type	Emissions Source	Annual Grid Electricity Consumption TWh	Annual Grid Electricity as % of Total UK Consumption	Annual GHG Emissions $MtCO_2e$	GHG Emissions as % of Total UK GHG Emissions
Indirect	Commercial refrigeration	30.2	9.5%	15.0	2.61%
	Domestic refrigeration	14.1	4.4%	7.0	1.22%
	Air conditioning	18.3	5.8%	9.1	1.58%
Indirect	**RACHP sector**	**62.6**	**19.7%**	**31.1**	**5.40%**
Direct	**RACHP sector (HFC refrigerant leakage)**			**11.3**	**1.96%**
Direct + Indirect	**Total UK RACHP sector emissions**			**42.4**	**7.37%**

[Source data: Dukes (2013); MTPROG (2010); GOV.UK (2015)]

The data for RACHP direct emissions are broadly corroborated in the UK National Inventory Report submitted to UNFCCC in 2016 (Ricardo-AEA, 2016). The model used was revised in 2015 and Figure 4-6 shows the results from both the old and new model (the spike in the new model is attributed to a peak in retrofit activity for R22 refrigerant). The chart shows emissions of about 13 $MtCO_2e$ in 2012, compared with 11.3 $MtCO_2e$ in Table 4-1. The Ricardo-AEA model input assumptions are listed in Table A-2 in Appendix A, referenced by RACHP sector, the installed equipment base, equipment lifetime, refrigerant type(s) and typical refrigerant charge and leakage rate.

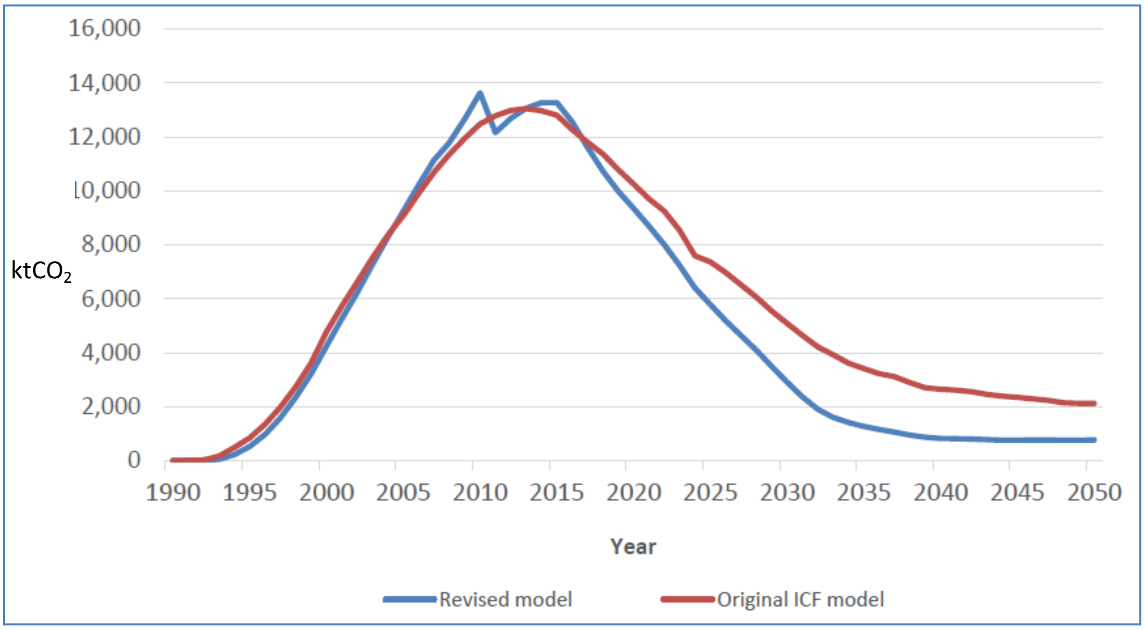


Figure 4-6 UK RACHP GHG emissions estimates (from UK National Inventory submission to UNFCCC in 2016)

[Source: Ricardo-AEA (2016)]

4.3 The environmental and financial impact of refrigerant leakage

Improving the environmental sustainability of a RACHP system requires a full understanding of both refrigerant emissions and the indirect emissions associated with its energy use. One measure of the environmental impact of RACHP systems, used by Sand *et al* (1997) to characterize the energy and global warming impact of HFC refrigerants and emerging technologies, is TEWI or total equivalent warming impact, which is an estimate of the total emissions from a system over its lifetime. The relative importance of direct refrigerant emissions, compared with the indirect emissions, can be assessed by performing a TEWI calculation.

TEWI = (GWP x L x n) + (GWP x m [1-R] + (n x E x CF) **Equation 4-2**

where:

GWP = refrigerant global warming potential [CO_2 equivalent]

L = refrigerant leakage rate per year [kg]

n = system operating time [years]

m = refrigerant charge [kg]

R = recycling factor (fraction of charge lost during end of life refrigerant recovery)

E = energy consumption per year [kWh]

CF = CO_2 equivalent emissions [kg CO_2(e) per kWh] (the value depends on the fuel mix used to generate grid electricity; the UK figure for 2012 was 0.460 kgCO_2(e) per kWh)

The description of an approach developed by the author for using a TEWI calculation to assess the relative importance between indirect and direct emissions for any system follows, with a worked example. It is based on calculating the TEWI for a range of refrigerant leakage rates and plotting the emissions against annual leak rate.

The table and charts in Appendix B show example TEWI calculations for high (HT) and low (LT) temperature supermarket refrigeration systems with the commonly used HFC refrigerant R404A (GWP = 3,922), for different annual leak rates. The results indicate that, for an annual leak rate of 5%, the direct emissions increase the TEWI for the HT system by nearly 60%, also that the lifetime TEWI may increase by as much as 5% for every 1% increase in the leak rate (a 'multiplier' effect). Figure 4-7 shows the lifetime emissions (in tonnes of CO_2 equivalent), for the direct and indirect emissions and for the total emissions (TEWI). The calculations assume that that lost refrigerant is regularly replaced, so that leakage of refrigerant does not deplete the refrigerant buffer sufficiently to reduce the system efficiency and that the indirect emissions associated with grid electricity use remain constant Figure 4-8 demonstrates that, for both high and low temperature system types, refrigerant leakage can more than double the TEWI. In this example, when the leak rate exceeds 9% for a HT system, or 14% for a LT system, the direct emissions become greater than the indirect emissions.

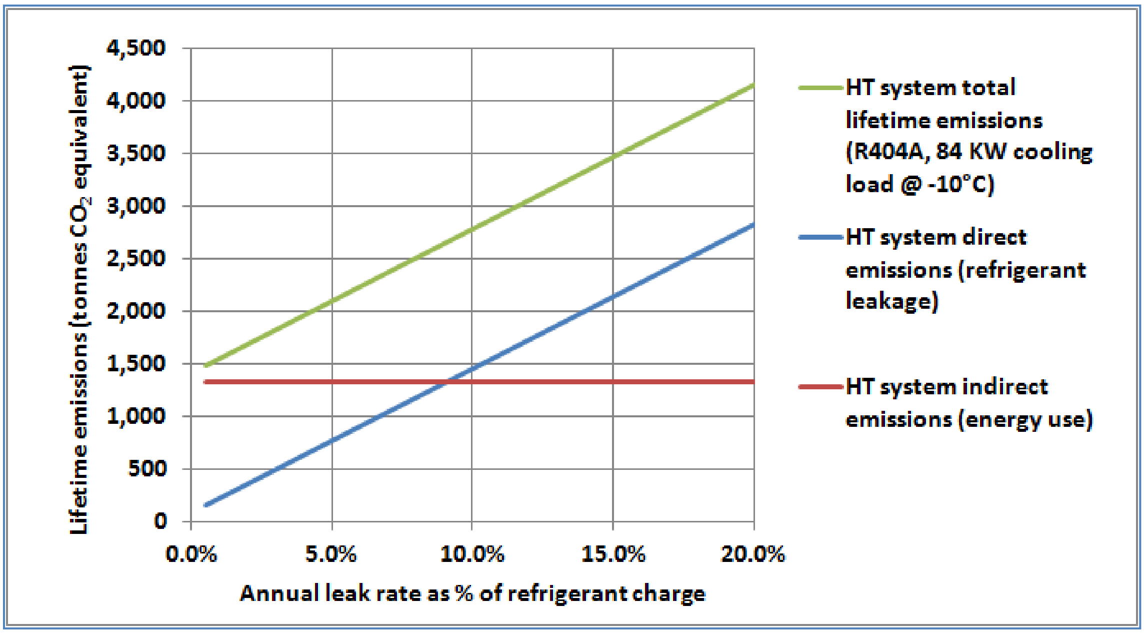


Figure 4-7. Impact of refrigerant leak rate on TEWI for a HT supermarket system using R404A refrigerant

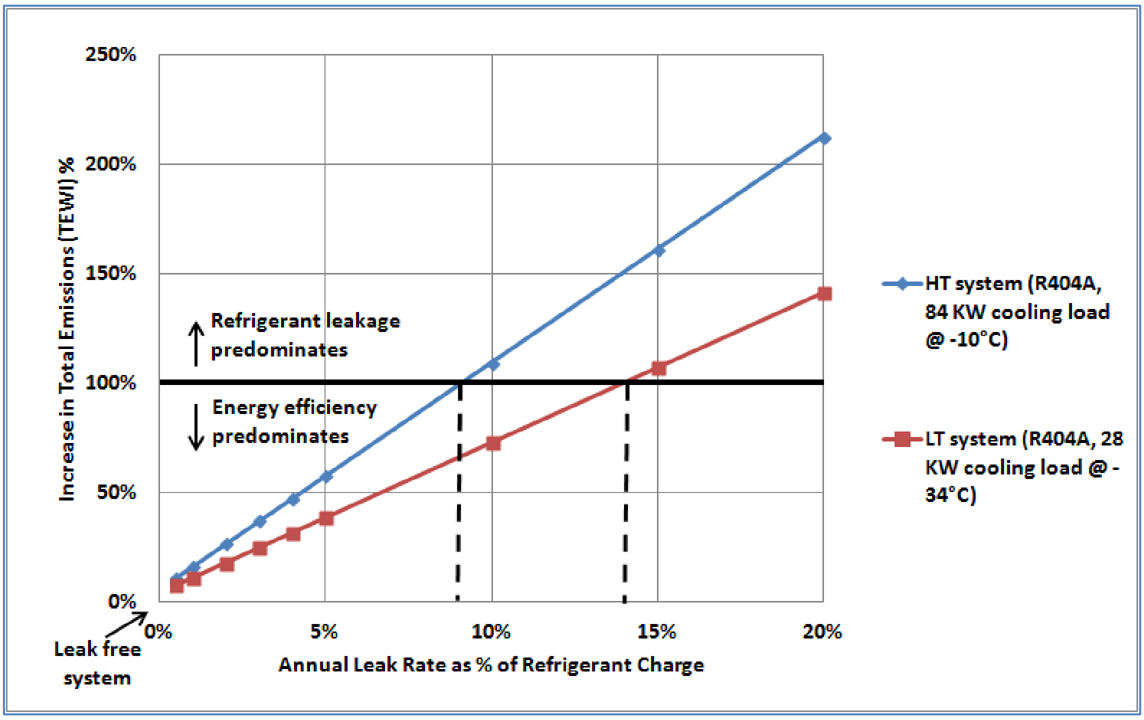


Figure 4-8. The relative impact of refrigerant leakage and energy related emissions on TEWI

The 'multiplier' effect demonstrates the value in focusing on leakage reduction and improved refrigerant containment for existing systems containing high GWP refrigerants. In contrast, a 1% increase in system efficiency (or a 1% reduction in the CO_2 emissions factor for grid electricity) would reduce the system TEWI by 1% at best.

For this example, replacing the R404A refrigerant with refrigerant R407A (a drop-in replacement with GWP = 2107) would result in direct emissions for the HT system being less than 25% of total emissions for an annual leak rate of 5% and the direct emissions would not exceed the indirect emissions until the annual leak rates exceeded 17.5% (HT system) and 27% (LT system). The corresponding 'multiplier' effect on the lifetime TEWI would be smaller (about a 3% reduction for every 1% drop in the leak rate) but still significant. However, if the refrigerant GWP is lowered to around 500 or less, the benefits of the 'multiplier' effect are lost altogether, the TEWI dropping by less than 1% for every 1% reduction in the leak rate.

In addition to the environmental impact of refrigerant leakage there can also be a significant financial impact if the leak is not identified and repaired quickly. Figure 4-9 illustrates this graphically. When the leak starts, the only cost is for repairs. However, over time the cost of replacing the refrigerant increases steadily and when the buffer of refrigerant in the system becomes depleted the system efficiency will drop, resulting in increased energy costs. Eventually the system becomes unable to support the cooling demand and fails to maintain temperature, resulting in consequential costs such as damage to perishable stock. When the system finally breaks down the repair and consequential costs to the business may escalate rapidly.

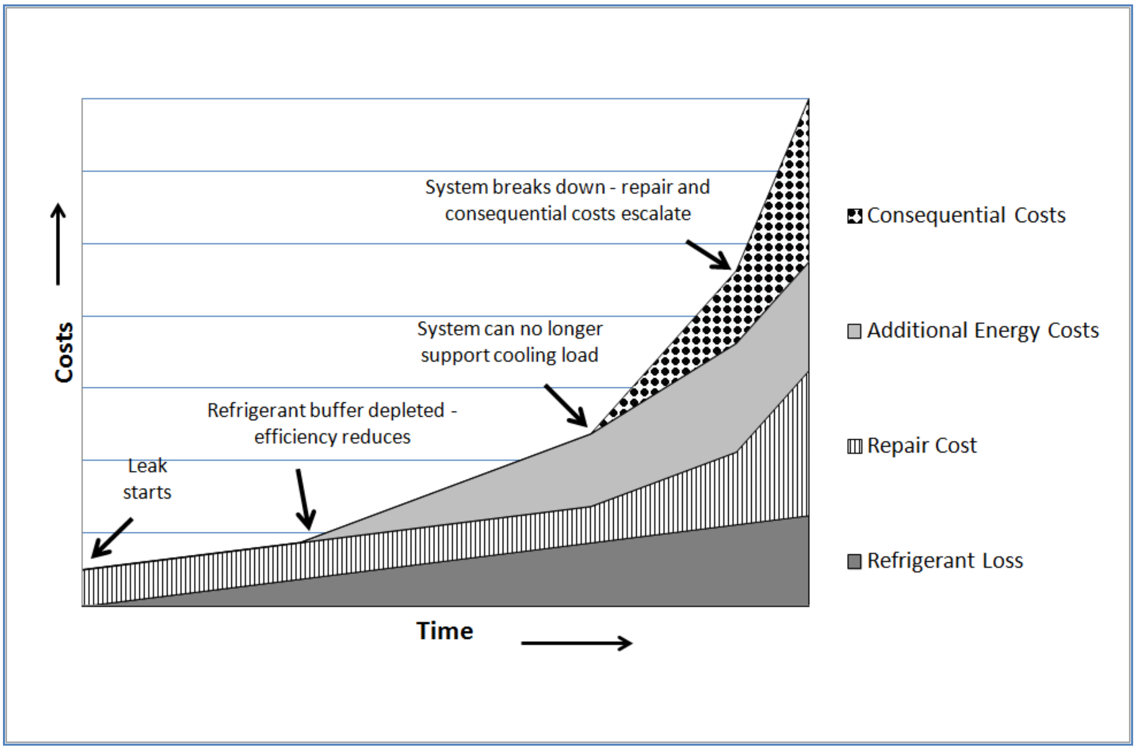


Figure 4-9. Illustration of the increasing cost of refrigerant leakage over time

These costs, with the exception of the cost of replacing lost refrigerant, may be difficult to quantify, as they vary from system to system and with the rate of loss of refrigerant. In particular, the loss of efficiency due to depletion of the refrigerant buffer is system dependent and there is little published information on how the efficiency varies with refrigerant charge level. However, a test undertaken on a reversible, water-to-water ground source heat pump (GSHP) in the K2 building at London South Bank University (for which the author acted in an advisory capacity), demonstrated that reducing the refrigerant charge below 90% of the nominal charge could significantly reduce the relative COP in both heating and cooling mode. Figure 4-10 charts the results for the LSBU system in heating mode, along with the results from three other studies. Whilst these results are based on a small number of data points, they all demonstrate a significant loss of efficiency when refrigerant is lost, resulting in increased emissions from grid energy use and a consequent increase in energy costs.

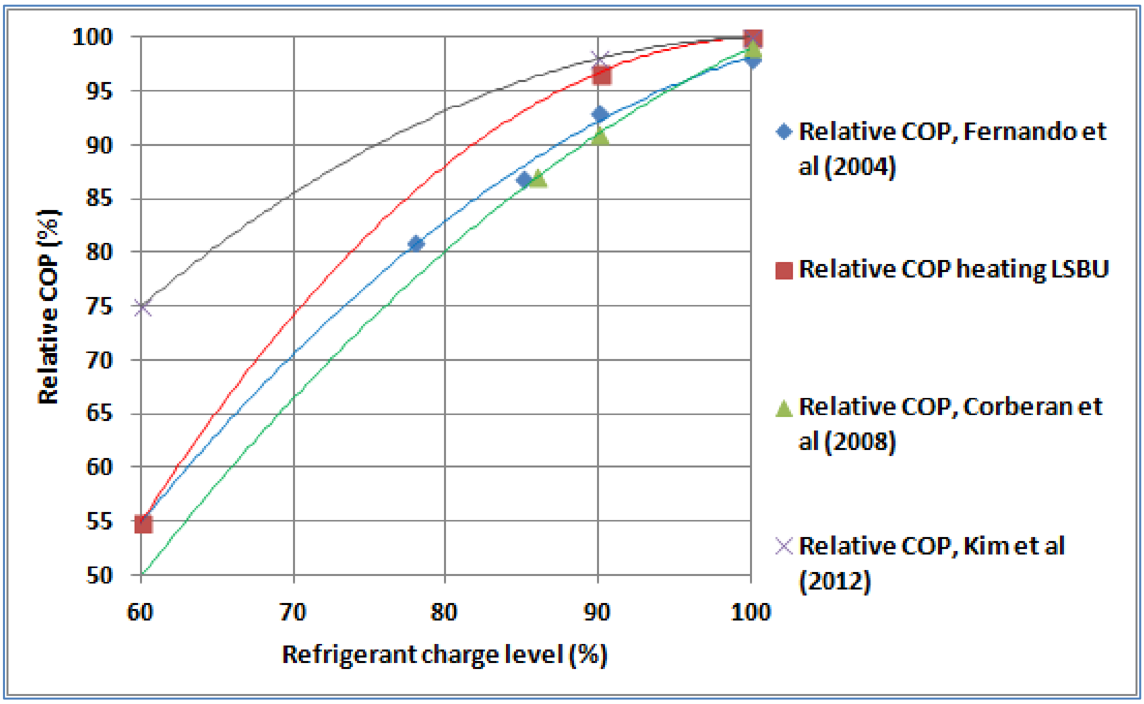


Figure 4-10. LSBU relative COP vs refrigerant charge test results compared with results from other studies

[Source: Revesz (2013) unpublished work]

4.4 Analysis of refrigerant leakage rates and the causes of leakage

In May 2006 the European Parliament adopted Regulation (EC) No 842/2006 (EC, 2006) on 'certain fluorinated greenhouse gases' (more generally described as 'The F Gas Regulations'). The Regulation included a requirement for operators of RACHP equipments to undertake regular checks of the leakage of F Gas from these systems and to maintain records on the type and quantities of F Gases installed, added and recovered during service and maintenance activities, thereby establishing a formal reporting mechanism that aids the collection and analysis of data.

4.4.1 Analysis of refrigerant leakage data - REAL Zero

One of the first such studies was a project titled 'REAL Zero' (Refrigerant Emissions and Leakage – Zero), led by the UK's Institute of Refrigeration and carried out in partnership between industry and academia. The author was the project manager and responsible for collating and analysing the data collected from site surveys.

The investigation included surveys of 81 systems on 26 sites, using a methodology developed specifically for the project. The site survey format included:

- A detailed visual inspection of the system to check for general condition, operational status, cleanliness, corrosion, evidence of poor design, installation or maintenance practices and visual indications of refrigerant leakage (e.g. oil stains) and potential leakage points
- Using available F Gas and service records to calculate the CO_2 equivalent emissions and the cost of the refrigerant added to the system during maintenance activities
- A consultation with site staff to obtain feedback on system reliability, historical problems and trends
- A detailed leak check, using a portable electronic leak detector, covering all accessible parts of the system, including components, pipe work, joints and auxiliary components such as pressure switches and pressure relief valve vent lines

The information was captured on site survey record sheets and used to prepare detailed survey reports for site owners that included a financial and environmental impact statement, a recommended leak reduction strategy and specific actions that should be undertaken to address the issues identified by the survey.

The surveys covered several different types of RACHP system including Large Retail (supermarket), Building Air Conditioning, Cold Storage, Industrial Processing and Small Retail. They revealed a varied implementation of the F Gas logs. The refrigerant records that were available covered periods of typically 12–18 months and the total CO_2 equivalent direct refrigerant emissions from the 56 systems for which records were available were over 20,000 tonnes, at an estimated replacement refrigerant cost of £115,000. The results are summarised in Table 4-2..

Table 4-2. Summary of results from REAL Zero site surveys

Parameter	Data Value
No. of sites analysed	26
No. of these sites with useful leakage data	23
Total number of refrigeration packs	81
Total number of pack leakage records	56
Average period covered by records (months)	13
Total Refrigerant Usage over Period Recorded (kg)	7,908
Total Refrigerant Cost Over Period Recorded (£)	114,593
Potential Cost Savings for 25% reduction (£)	28,648
Total CO_2 equivalent emissions (tCO_2e)	20,439
Potential CO_2e savings for 25% reduction (tCO_2e)	5,110
Number of Leaks Detected at Site Survey	96

Figure 4-11 shows the annualised refrigerant use for 51 of these systems as a percentage of the system charge and indicates that in a few instances the total system charge was lost on more than one occasion.

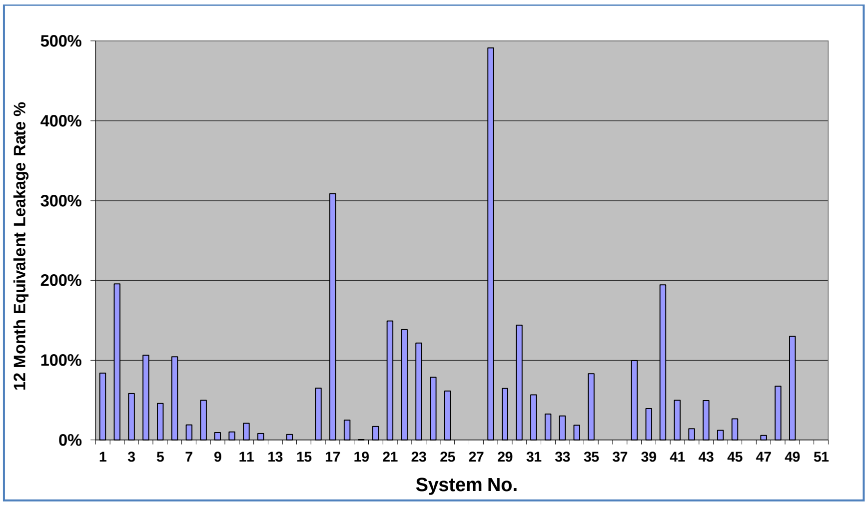


Figure 4-11. 12 month equivalent refrigerant use for 51 systems (from REAL Zero project)

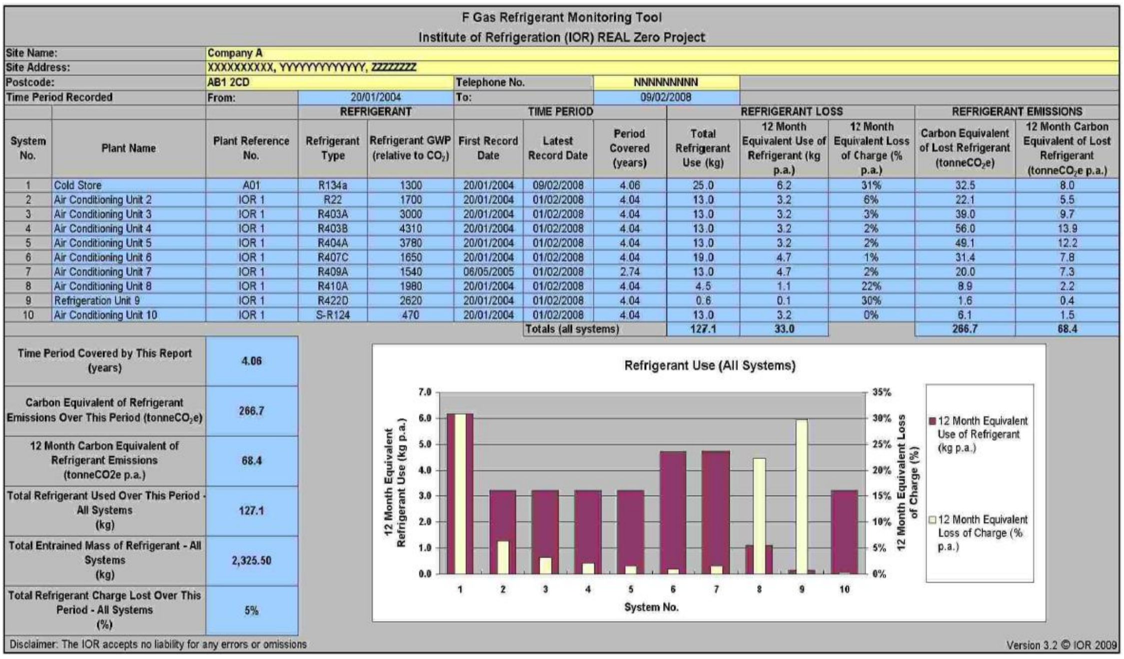
There was a significant variation between different types of site, but the sample was too small and the data too variable in quality to be able to provide a statistically significant graph on refrigerant leakage by sector. Energy consumption records were not available for the systems surveyed, but calculations performed using the reported cooling capacities, together with conservative assumptions for the COP and duty cycle, indicated that the direct emissions due to refrigerant leakage were of a similar magnitude to (and in some instances greater than) the indirect emissions for many systems. This confirmed the important role that reducing refrigerant leakage can play in improving the sustainability of large scale refrigeration systems.

96 refrigerant leaks were detected using calibrated leak detectors during the site surveys, the severity varying between 'minor' and 'severe' (the leak detectors were capable of detecting leakage rates of as little as 5g per annum). Many systems were found to be short of refrigerant at the time of the inspection and potential leakage points such as Schrader and service valves were not always capped. In many instances the approach to service and maintenance appeared to be reactive (responding to faults that had already occurred) rather than proactive and there was often no evidence of regular leak testing being performed. Another issue was that many leak detectors used by equipment maintainers had not been verified or calibrated on a regular basis, resulting in the possibility of incorrect operation when performing leak tests.

The information obtained from the system site surveys was used to develop a set of REAL Zero support materials and tools, including:

- Guidance notes and advice for service and maintenance engineers, design engineers, service companies and equipment owners on topics such as common leak points, good practice in leak testing, new system design, maintenance contracts and legal responsibilities under the F Gas Regulations
- Software tools to keep track of and value the carbon case for refrigerant management
- A methodology and tools for undertaking site surveys and developing leakage reduction strategies and
- A training and on-line assessment scheme, aimed at developing specialist skills in refrigerant management and leakage reduction techniques

Two software tools developed as part of the REAL Zero project were an Excel Workbook for F Gas logging and management reporting of refrigerant use and associated carbon emissions and a carbon and financial impact calculator that could be used to help develop a business case for measures to reduce refrigerant leakage. The F-Gas and ODS Regulations require that equipment owners keep a record of leak checks and service and maintenance activity related to refrigerant use. The keeping of such records is essential to developing a clear understanding of the potential to reduce refrigerant use in individual systems or sites. The data should be analysed on a regular basis and the Excel Workbook helps by holding the records for each system on separate tabs and generating a summary report for all of the systems for use in management reporting and review.



F Gas Refrigerant Monitoring Tool
Institute of Refrigeration (IOR) REAL Zero Project

Site Name:	Company A		
Site Address:	XXXXXXXXXX, YYYYYYYYYYYY, ZZZZZZZZ		
Postcode:	AB1 2CD	Telephone No.	NNNNNNNNN
Time Period Recorded	From: 20/01/2004	To:	09/02/2008

			REFRIGERANT		TIME PERIOD			REFRIGERANT LOSS			REFRIGERANT EMISSIONS	
System No.	Plant Name	Plant Reference No.	Refrigerant Type	Refrigerant GWP (relative to CO_2)	First Record Date	Latest Record Date	Period Covered (years)	Total Refrigerant Use (kg)	12 Month Equivalent Use of Refrigerant (kg p.a.)	12 Month Equivalent Loss of Charge (% p.a.)	Carbon Equivalent of Lost Refrigerant (tonneCO_2e)	12 Month Carbon Equivalent of Lost Refrigerant (tonneCO_2e p.a.)
1	Cold Store	A01	R134a	1300	20/01/2004	09/02/2008	4.06	25.0	6.2	31%	32.5	8.0
2	Air Conditioning Unit 2	IOR 1	R22	1700	20/01/2004	01/02/2008	4.04	13.0	3.2	6%	22.1	5.5
3	Air Conditioning Unit 3	IOR 1	R403A	3000	20/01/2004	01/02/2008	4.04	13.0	3.2	3%	39.0	9.7
4	Air Conditioning Unit 4	IOR 1	R403B	4310	20/01/2004	01/02/2008	4.04	13.0	3.2	2%	56.0	13.9
5	Air Conditioning Unit 5	IOR 1	R404A	3780	20/01/2004	01/02/2008	4.04	13.0	3.2	2%	49.1	12.2
6	Air Conditioning Unit 6	IOR 1	R407C	1650	20/01/2004	01/02/2008	4.04	19.0	4.7	1%	31.4	7.8
7	Air Conditioning Unit 7	IOR 1	R409A	1540	06/05/2005	01/02/2008	2.74	13.0	4.7	2%	20.0	7.3
8	Air Conditioning Unit 8	IOR 1	R410A	1980	20/01/2004	01/02/2008	4.04	4.5	1.1	22%	8.9	2.2
9	Refrigeration Unit 9	IOR 1	R422D	2620	20/01/2004	01/02/2008	4.04	0.6	0.1	30%	1.6	0.4
10	Air Conditioning Unit 10	IOR 1	S-R124	470	20/01/2004	01/02/2008	4.04	13.0	3.2	0%	6.1	1.5
						Totals (all systems)		127.1	33.0		266.7	68.4

Time Period Covered by This Report (years)	4.06
Carbon Equivalent of Refrigerant Emissions Over This Period (tonneCO_2e)	266.7
12 Month Carbon Equivalent of Refrigerant Emissions (tonneCO2e p.a.)	68.4
Total Refrigerant Used Over This Period - All Systems (kg)	127.1
Total Entrained Mass of Refrigerant - All Systems (kg)	2,325.50
Total Refrigerant Charge Lost Over This Period - All Systems (%)	5%

Figure 4-12. F Gas logging and management reporting tool – multi-system site summary report

The cost of the lost refrigerant generally represents a small proportion of the total running cost, even though the resulting environmental impact is high, but the actual costs of replacing refrigerant will normally be significantly higher due to service engineer site visit cost, as well as any consequential costs due to system downtime. The carbon emissions and cost calculator (Figure 4-13) uses refrigerant GWP, cost and labour charge defaults to estimate the environmental and financial impact of refrigerant leakage, from historical records of refrigerant additions.

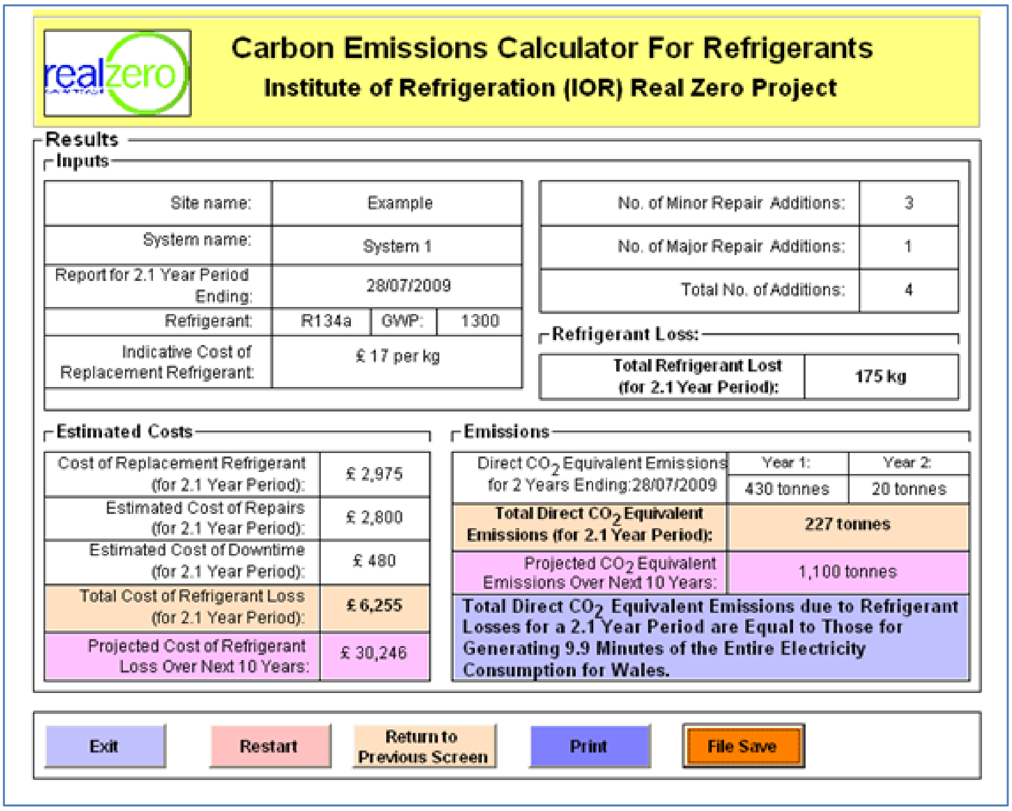


Figure 4-13 Carbon emissions and financial cost calculator

All the materials and tools were made available as free downloads from a dedicated website at www.realzero.org.uk. They have since been revised as part of the REAL Skills Europe project and updated versions are available from the REAL Skills Europe project website. The REAL Skills Europe project is described in Appendix D.

As a 12 month follow up to the REAL Zero site surveys and analysis, further data were obtained from 26 of the 81 systems and used to estimate the potential impact of the REAL Zero project if implemented more widely. For these systems, a net reduction in refrigerant leakage of 4,905 kg refrigerant was reported for 2009/2010 compared with 2008/2009. This represented a direct saving of 7,979 tonnes of carbon dioxide equivalent (tCO_2e), a reduction of more than 43% compared with the previous 12 month period.

The leakage rates across their entire refrigeration estate for two supermarkets that have adopted REAL Zero principles are shown in Figure 4-14. Their annual leak rates have continued to reduce and are now significantly below 10%. New systems employing best practice in design, build and operation can achieve annual leak rates of 1%.

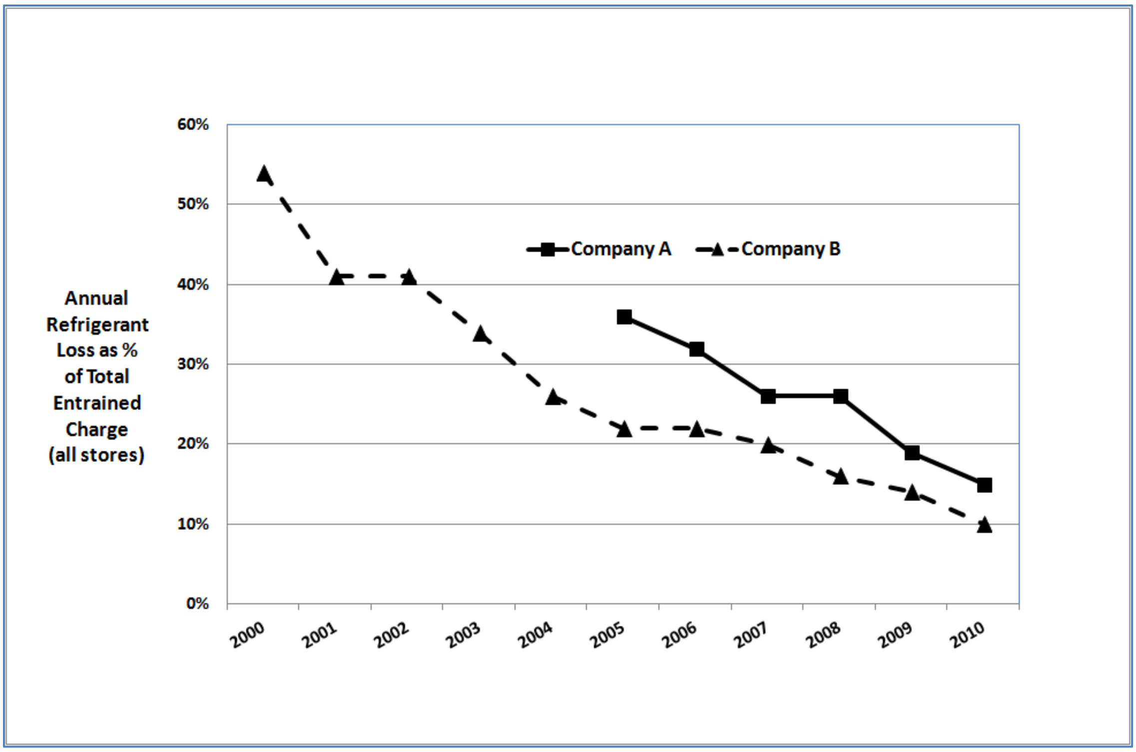


Figure 4-14. UK supermarket refrigerant leak rate improvement for two companies: 2000 to 2010

4.4.2 Investigation into refrigerant leakage and emissions from heat pumps

In 2013 an investigation was carried out into refrigerant emissions from heat pump systems, an area that had previously not been well researched or documented. It was part of a 'Refrigerants in Heat Pumps Review' project undertaken by LSBU and the consultancy Eunomia for DECC. More than 80 organisations and individuals that were suppliers, operators, maintainers, or professional bodies associated with heat pump systems, were contacted. Access to their log books or refrigerant records was requested, in order to analyse and classify refrigerant use and leakage, by system type, size and refrigerant type.

82 companies were asked to provide F Gas log data to support the study. These included site owners, end users, government departments, consultants, manufacturers, distributors,

installers, contractors, trade associations, technicians/ engineers, and training bodies. 46 indicated a willingness to participate, however data were provided by only 6 companies. Data were received for 528 unique systems, although data in the format required by the F Gas Regulations were received for only 219 of these systems. For the other systems, only summary data were received (as a listing of refrigerant added to the systems, by year). It was noted that none of the F Gas logs were fully compliant with the requirements of the F Gas Regulations, despite these requirements having being in place since July 2007.

Where an explicit serial number was not listed, a sequence number was allocated and combined with the site name to provide a unique system ID. Data from both the summary spreadsheets and the F Gas logs were entered into a Logbook Review spreadsheet, then sorted by the system unique ID and year. Data were entered only for systems that could be verified (by checking their part/ model number against manufacturer data sheets) to be heat pumps (or heating and cooling systems).

Entries were included for the systems on which a leak test had been performed but no leak found. It was assumed that if a system had tested leak free, it had been leak free over a 12 month period (i.e. 0% leakage over 12 months). Leak test records and results were available only for the systems with F Gas logs, but summary records that stated nil refrigerant addition in a given calendar year were also assumed to indicate a leak-free system in that year. Where there was more than one row of data for a given system in a single calendar year, the data from the rows were merged (and any refrigerant additions summed) to provide a single line entry for that year.

The resulting Logbook Review spreadsheet listed 528 unique systems, with 840 line entries (or 'system years') indicating on average 1.6 records per system. Many system records contained just a single entry – this implies either that log books were not being properly maintained or that the required regular testing under the F Gas Regulations was not being performed. However, for some systems there was evidence that a new record was being created during each site visit, rather than an existing log being updated.

A summary of the analysis is shown in Table 4-3 and

Table 4-4. These indicate that the majority of records related to equipment between 1 and 3 years old, with records covering at least 2 years for only 219 systems and records covering 3 years for only 93 of the 528 systems. The averaged annualised leak rate was 2.67% for all 840 system records (3 years of data), or 4.02% for the 528 systems based on just the one year data.

Table 4-3 indicates that for the 1 year data 86% of the systems were leak free, however more than 4% of the systems had lost at least 75% of their refrigerant charge (a catastrophic failure). The level of confidence in the data received from the responding companies was low, so the results should be interpreted as a qualitative rather than quantitative indication of the levels of refrigerant leakage and emissions from heat pump systems (and air conditioning systems).

Table 4-3 Breakdown of heat pump systems by equipment age and number of years of data available for analysis

Equipment Age	1 Year data	2 Year Data	3 Year Data
Age 0-1 year	251	0	0
Age 1-2 year	46	174	0
Age 2-3 year	55	32	50
Age 3-4 year	28	8	32
Age 4-5 year	27	4	7
Age 5-6 year	15	0	4
Age 6-7 year	21	1	0
Age 7-8 year	0	0	0
Unknown	85	0	0
Total	**528**	**219**	**93**

Table 4-4. Refrigerant leakage rate analysis for 840 heat pump systems

Number of systems	Total system charge of all systems (kg)	Total refrigerant recharged for all systems (kg)	Average annualised leakage rate (%)	Number of systems by % of system charge lost								
				No leakage	0-5%	5-10%	10-15%	15-20%	20-25%	25-50%	50-75%	>75%
528	8550.44	344.12	4.02%	454	3	7	4	8	6	14	9	23
219	4539.67	58.28	1.28%	215	0	0	0	0	0	0	1	3
93	1981.84	0.00	0.00%	93	0	0	0	0	0	0	0	0
840	**15071.95**	**402.40**	**2.67%**	**762**	**3**	**7**	**4**	**8**	**6**	**14**	**10**	**26**

The main conclusions from the heat pump study were that quality of the data received was poor and none of the records fully met the requirements of the F Gas Regulations. Although the data were used to calculate global leakage rates across all systems and over the years 2009 to 2013, it was recommended that they should be used with caution in the benchmarking of refrigerant leakage rates for heat pumps. A larger and more reliable set of F Gas data would be required in order to achieve a high level of confidence.

4.4.3 A structured approach to the analysis of RACHP system logs

The REAL Zero and other projects undertaken for the IOR and LSBU demonstrated the difficulty in obtaining good quality data on refrigerant leakage from the owners, operators and maintainers of RACHP systems. Although the F Gas Regulations specified requirements for the type of data to be logged, they did not specify a format and there was no system in place for monitoring logs. In consequence, most organizations adopted their own solution and in many instances the data were recorded within an incident log rather than as standalone data. At the same time, compliance with the F Gas requirements was generally poor and many companies were reluctant to share their refrigerant leakage data with researchers, for fear of being identified as having poor environmental credentials.

The unstructured nature of such data as were made available indicated that a methodology was required for documenting and analyzing the refrigerant use and leakage data received from different sources. A new structured approach for refrigerant use analysis was therefore developed by the author and an MSc student at LSBU (Francis, 2010).

The concept behind the structured methodology was to devise a categorization approach that could be used to reformat the available data for incidents, faults and refrigerant additions into a structure that could be used with a spreadsheet to analyse the incident in terms of the fault type, category and location (down to component level), the cause of the fault (where identifiable), the steps taken to rectify the fault and the amount and type of any refrigerant added or replaced. This would involve first generating a generic schematic diagram, partitioning it between the key sections (compressor, condenser, evaporator etc.) and identifying the main components within each section. A spreadsheet would include fields and sub-menu listings corresponding to the location and components, together with fields for recording equipment type, serial number, date of incident, repair time etc.

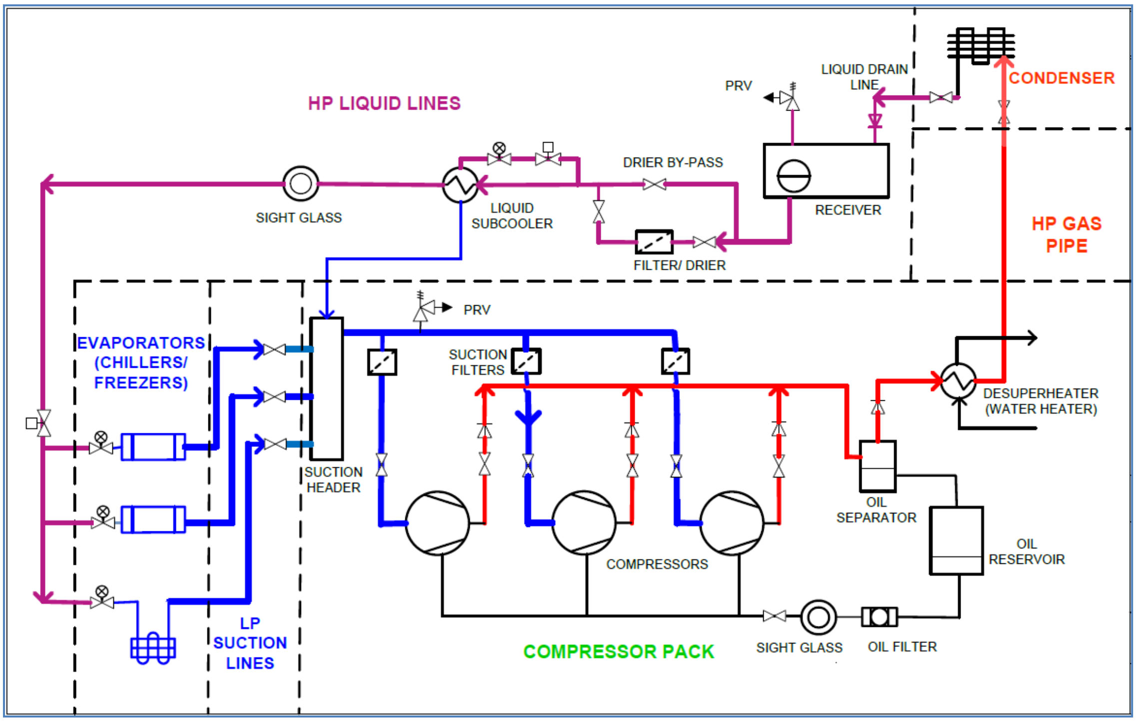


Figure 4-15 Generic schematic diagram for RACHP system structured fault reporting and analysis

The schematic that was generated for this purpose is shown in Figure 4-15. It is based on a typical distributed RACHP system, which for a retail application would typically comprise a roof mounted multi-compressor pack, with an integral or remote condenser and remotely located evaporators, connected by long pipe runs. However, the schematic is sufficiently generic that it can be used for analysis of the majority of DX (direct expansion) system types.

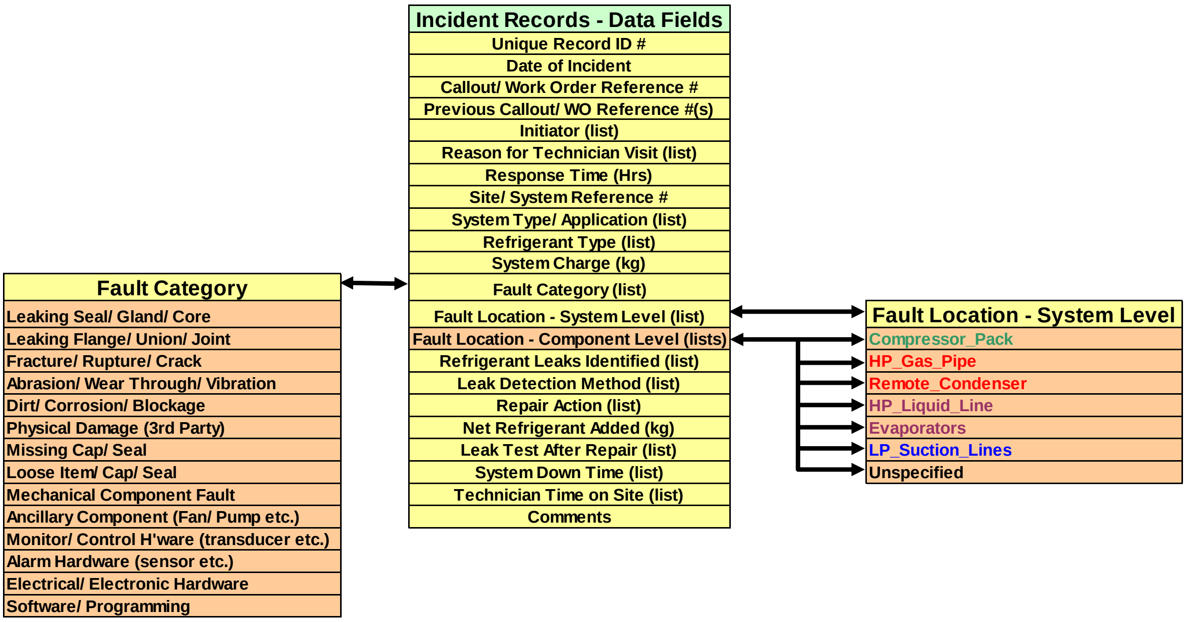


Figure 4-16 Data fields used for spreadsheet recording and analysis of RACHP system incident reports

Figure 4-16 details the key fields used for recording and analyzing data (for ease of interpretation the component-level and other sub-menu lists are not shown). The spreadsheet has 26 data fields, which include previous (related) incidents, call out initiator, response time, leak detection method, number of leaks detected and repair actions and times, as well as the fault location, type and refrigerant additions. It does not require all fields to be completed, simply whatever information is available and it allows data to be consolidated and compared from multiple sources. It is however, time consuming to use, as the unstructured data normally has to be entered into the spreadsheet manually. The minimum input data for obtaining meaningful output from the analysis are:

- Refrigerant Type
- Fault Category
- Fault Location- System Level AND/OR –Component Level
- Net Refrigerant Added

1464 'events', split between two companies (678 for Company A and 786 for Company B), were analysed using this methodology. Most of the data was provided in the form of incident reports, taken either from the company's work order records or produced as a summary report of refrigerant use across multiple sites.

After the 'events' data had been reformatted by entering it into the spreadsheet, the analysis indicated a high degree of correlation between the two companies, even though the formats they used for the fault reporting were completely different. After removing the 'fault not stated/ not known' category there was a striking similarity in the incidence of identifiable fault categories for the two companies, as shown in Figure 4-17. Mechanical failures in pipework, joints, seals or components were the most common cause of failure, leading to refrigerant loss and a consequent loss of cooling performance.

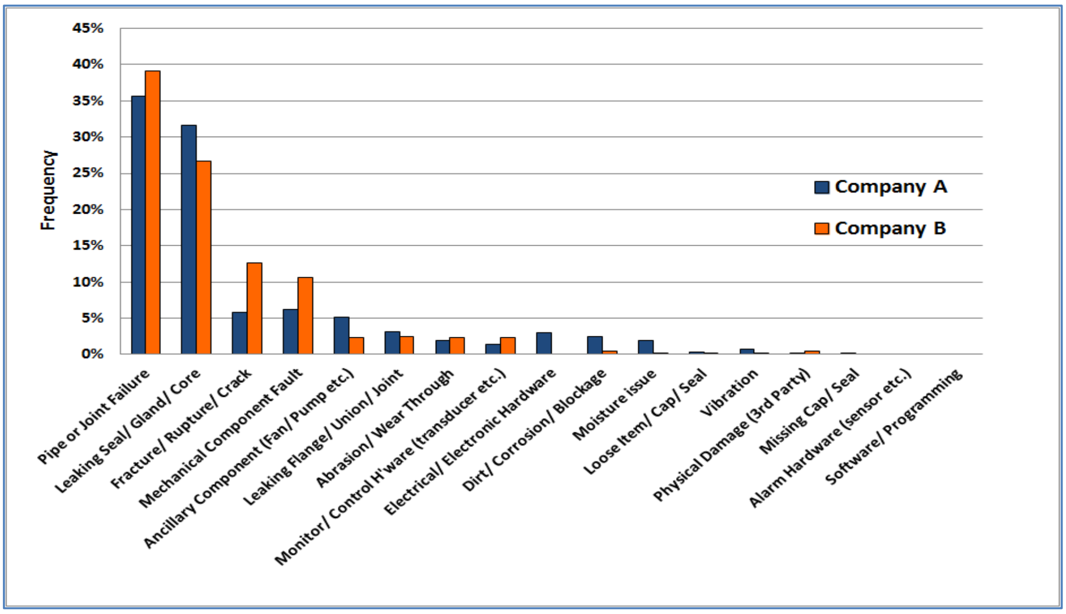


Figure 4-17 RACHP system fault breakdown by fault category for two companies

The breakdown of the primary location for the faults is shown in Figure 4-18 – this demonstrates that the majority of faults occur in the high pressure areas in the refrigeration system.

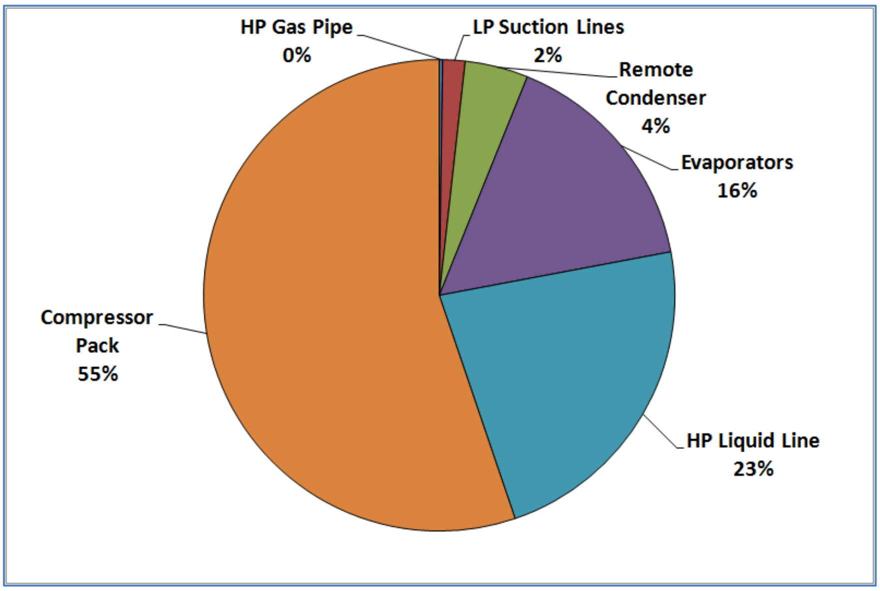


Figure 4-18. RACHP system fault primary location

For many of the incidents it was possible to analyse the fault down to component level and to correlate the amount of refrigerant lost with the particular component type. Figure 4-19 shows the breakdown for the RACHP compressor pack section of the system (for both companies), indicating that the highest percentage of faults occurred in the compressor body, followed by rotalock valves and the suction pipe work. However, the greatest loss of refrigerant (38 kg on average) was associated with PRV (pressure relief valve failures), although such failures accounted for only slightly more than 2% of all compressor pack faults.

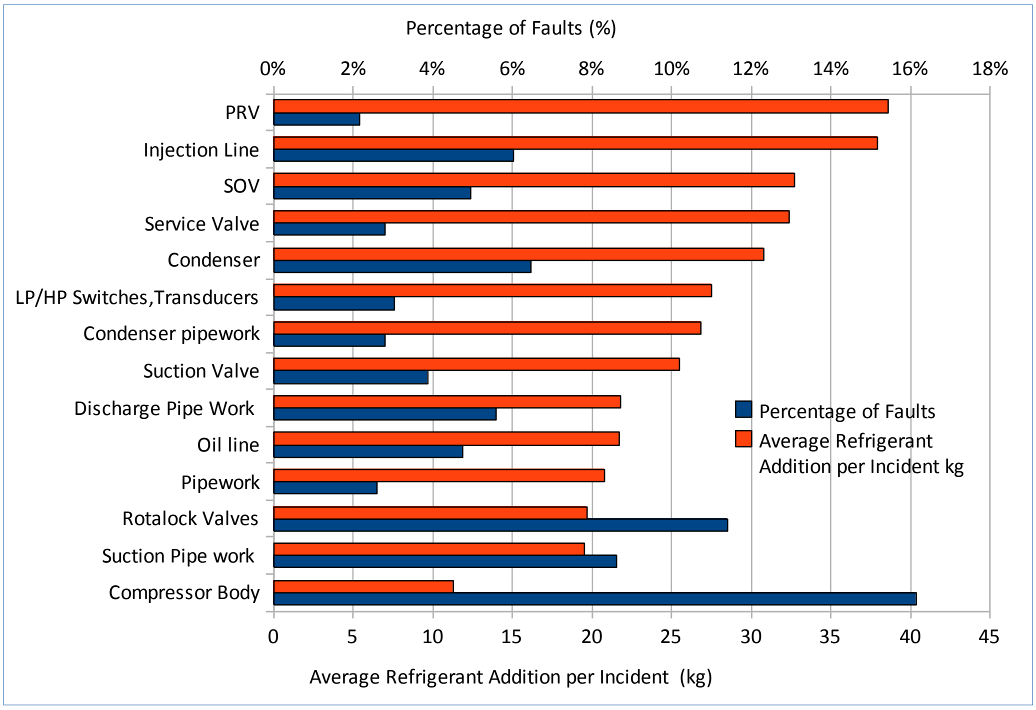


Figure 4-19. Compressor pack fault types by component and amount of refrigerant leaked

The refrigerant reported for over 80% of the incidents analysed was R404A, which is a relatively high GWP refrigerant (GWP 3922), used extensively in the retail sector. Other refrigerants included R22 (4.5%) and R134a (3.5%). The average amount of refrigerant added per incident was about 24.5kg. Further additions or recharge of R22 (HFC) refrigerant in systems was banned from 2015, so most systems have been retrofitted with an alternative refrigerant or replaced with new equipment.

The results presented here demonstrate the power of a structured approach to fault analysis in identifying key issues and the root causes of the faults associated with refrigerant leakage and emissions in RACHP systems. Even though the data in individual incident reports and logs is frequently incomplete, the analysis of a large number of reports across a range of systems can be used to highlight fundamental problems and the system components with high leakage potential. More analyses of this type could help the industry to identify the key areas and causes of leakage, which in turn could influence and modify practices in design, installation, commissioning and service and maintenance.

4.4.4 Refrigerant leakage – the key causes

The direct emissions associated with refrigerant leakage can occur during many stages throughout the life of RACHP equipment: system manufacture, operation, servicing and repair, decommissioning and disposal. The studies and projects described in this chapter have helped to identify the root causes and specific leak prone areas and components and were used to develop technical guidance and training, to assist equipment designers, installers, operators and maintainers in reducing refrigerant leaks and emissions. The data collected showed that some systems lost more than their total refrigerant charge in less than 12 months, while a focus on leakage reduction and the adoption of best practice refrigerant containment principles has been shown to reduce leakage by over 40% across a number of systems,

Eliminating leaks from refrigeration systems can be challenging, particularly since systems are often constructed with copper pipes using brazed or silver soldering and in these joints there are potential flaws such as minute cracks. These ‘flaws’ may be too small to detect even with the best leak detection instruments but given time, vibration, temperature and environmental stress, these ‘flaws’ become larger, detectable leaks. A particular challenge for the retail sector is that many current systems are single loop DX (direct expansion), employing long pipe runs, with joints that have been mostly fabricated on site rather than in a controlled factory environment. Some systems also contain many hundreds of kilograms of refrigerant charge, so the environmental impact of major leak from a single system containing a high GWP refrigerant such as R404A could be several tonnes of CO_2 equivalent, in terms of global warming.

The evidence from the studies shows that the key factors that influence refrigerant leakage are mechanical stress caused by vibration, temperature differentials or pressure. Most leakage occurs due to some form of mechanical failure or movement, which may be triggered by vibration (for example from the compressor) or stresses due to rapid temperature and pressure changes. Contributory factors may include wear and tear, poor maintenance and corrosion. Corrosion, wear and tear and poor maintenance can all result in greater susceptibility to failure. Accidental damage may be a lower risk but when it does occur the amount of refrigerant lost can be very high.

4.5 Alternative refrigerants and the environmental performance of heat pumps

Many of the refrigerants still in use have high global warming potential, so the environmental impact due to loss of refrigerant can be very high, as discussed earlier. Whilst the adoption of best practice in the design, build and operation of equipment can minimise leakage, it is difficult to eliminate leaks altogether, so there is increasing focus on alternative refrigerants that have much lower GWP, such as ammonia (R717), hydrocarbons such as propane (R290), carbon dioxide (R744) and the new class of refrigerant blends based on hydrofluoroolefins (HFOs). However, there are many potential issues in using such refrigerants: ammonia is highly toxic and attacks copper, so cannot be used in systems with copper pipe work; hydrocarbons are highly flammable; carbon dioxide refrigerant requires much higher operating pressures which increases the leakage potential end enhances the risk of mechanical failure, presenting a significant safety hazard. The issues around HFO refrigerants depend on the specific blend - some are mildly flammable and all tend to be very expensive.

The suitability of such refrigerants for use in specific applications also depends on their thermophysical properties, which determine the required operating parameters and settings for the cooling system. This can be a particular problem when seeking a replacement refrigerant for an existing cooling system, with limited scope for making major adjustments to the operating parameters. Table C-1 (Appendix C) summarises the thermophysical properties, environmental and safety issues of different refrigerants that are either used or have the potential to be used for heat pump applications. The boiling point (BP), critical temperature

(CT), freezing point (FP), critical pressure (CP), vapour pressures (VP) at different temperatures, vapour density (VD) and chemical stability state are given from the refrigerant material safety data sheets provided by refrigerant manufacturers and suppliers.

Refrigerants that are currently used in heat pumps include R134a and HFC blends R407C, R404A and R410A, for water heating and space heating. R290 has properties similar to those of R22 (HCFC and no longer permitted), apart from its flammability. Until 2004 almost half of the heat pumps sold in the EU used R290 but the use has declined due to the introduction of the Pressure Equipment Directive (PED) and low availability of R290 compressors. R744 heat pump water heaters were introduced to the market in Japan in 2001. R717 is used mainly for large capacity systems, since there are no compressors small enough for domestic heat pumps and copper cannot used with R717. Refrigerants with the potential for future use in air to water systems include R32 and R1234yf. Both R32 and R1234yf are mildly flammable whilst R1234yf has similar thermophysical properties to R134a. For water heating and space heating heat pumps currently using R22, R410A or R407C, significant design changes would be required to optimise them for operation with R1234yf. A recent new low GWP refrigerant with similar in thermophysical properties to R1234yf is R1234ze.

A comparison of the environmental impact of these alternative refrigerants in an air to water heat pump configuration was undertaken. The heat pump performance was calculated using Coolpack, a software tool developed by IPU and the Department of Mechanical Engineering at the Technical University of Denmark (IPU, 2012). COOLPACK is a collection of simulation models for refrigeration systems that includes cycle analysis, dimensioning of main components, energy analysis and optimization. The key assumptions were:

- Heat output from the condenser = 10 kW
- Condensing temperature (Tc) = 70°C and 45°C (2 separate calculations)
- Evaporating temperature (Te) = 2°C
- Compressor isentropic efficiency = 75%
- Suction superheat = 10 K
- Sub-cooling = 5 K

For the R744 system at 70°C condensing temperature (transcritical operation), a discharge pressure (Pc) of 85 bar was assumed, with a gas cooler output temperature of 40°C. Due to thermodynamic properties of R744, the performance at 45°C condensing temperature could not be calculated.

R32, R1234yf and R1234ze refrigerants were not available in COOLPACK, so their system performance was calculated using Pressure-Enthalpy charts, with the same assumptions. Using the Coolpack results the annual energy consumption, annualized refrigerant loss (assumed 6% for all refrigerant types) and their individual and combined environmental impact were then calculated in a spreadsheet to assess the TEWI over a 16 year life for each refrigerant type, at condensing temperatures of 45°C and 70°C. The spreadsheet also included a calculation of the energy and refrigerant replacement costs. A summary of the results is shown in Table 4-5, while the spreadsheet is included as Figure D1 (Appendix D). The results are also shown in graphic form in Figure 4-20.

Table 4-5. Heat Pump TEWI, COPs, energy consumption and annual leakage for different refrigerants

Refrigerant name	Calculated COP		Annual Energy consumption kWh		System charge kg	Annual leakage amount kg	TEWI $kgCO_2(e)$	
	70°C	45°C	70°C	45°C			70°C	45°C
R22	3.02	4.94	13,328	8,148	3	0.18	110,313	69,548
R134a	3.00	4.99	13,417	8,066	4	0.24	111,302	69,196
R404A	2.45	4.60	16,429	8,750	3	0.18	141,050	80,624
R407C	2.77	4.80	14,531	8,385	3	0.18	119,671	71,311
R410A	2.60	4.69	15,481	8,582	3	0.18	128,089	73,800
R290	2.94	4.93	13,690	8,164	1.5	0.09	107,741	64,253
R600a	3.10	5.07	12,984	7,939	1.5	0.09	102,180	62,479
R717	3.22	5.01	12,500	8,034	1	0.06	98,368	63,223
R32	2.82	4.70	14,273	8,564	2	0.18	114,346	69,418
R744	2.41	N/A	16,701	N/A	1.5	0.09	131,431	N/A
R1234yf	2.70	5.32	14,907	7,566	4	0.24	117,329	59,555
R1234ze	2.20	5.05	18,295	7,970	4	0.24	143,999	62,746

In cooling (air conditioning) applications the more relevant TEWI results would be for the 45°C condensing temperature scenario (evaporating temperature 2°C). These suggest that R134a refrigerant would achieve a lower TEWI than R404A, R407C and R410A. Although refrigerants R290, R600a and R717 could achieve lower TEWI, their potential safety hazards could limit their usefulness. The HFO refrigerants could achieve a significantly lower TEWI with a 45°C condensing temperature, but are not believed to be readily available or commercially viable at this time.

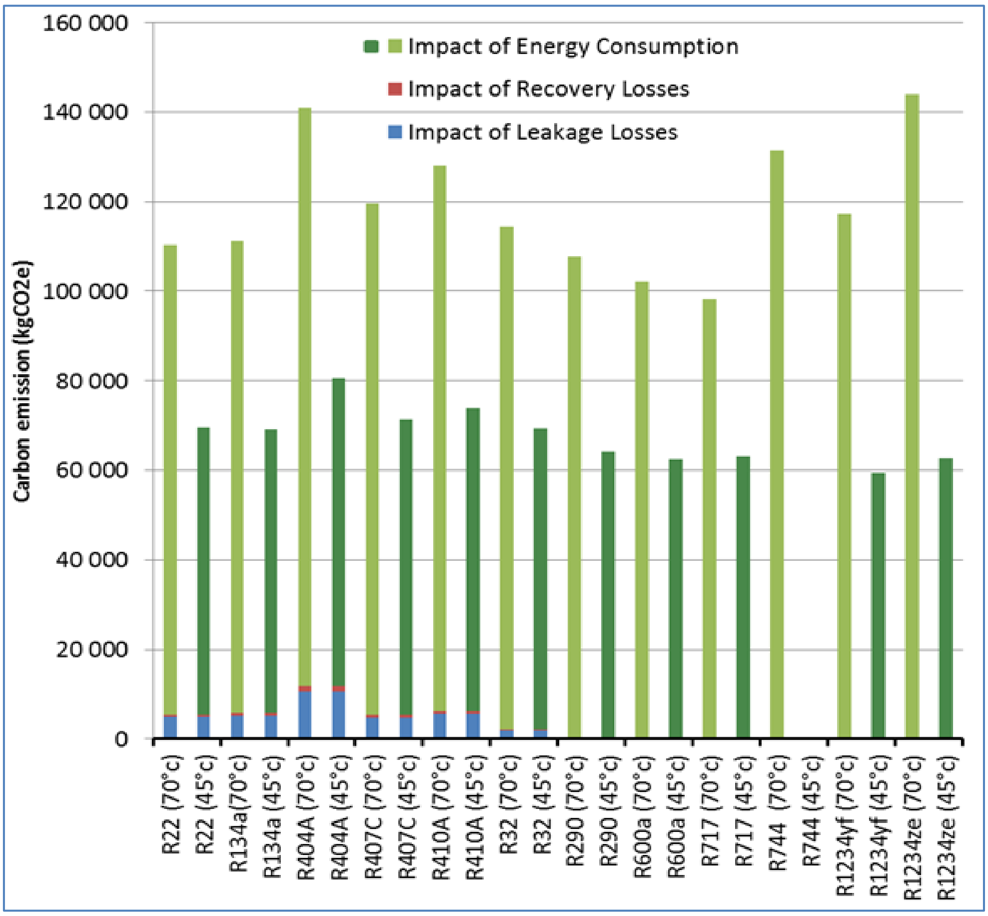


Figure 4-20. Heat Pump TEWI calculations for different refrigerants over 15 year life

For a 70°C condensing temperature (heating/ hot water scenario) the systems using R290, R600a and R717 were the best, whereas, systems using R404A, R744 and R1234ze were the worst (the worst performing system producing 46% more carbon than the best). The impact of refrigerant leakage on total carbon emissions was relatively small in all cases particularly for those refrigerants with a GWP below 2500. However, the energy related emissions vary significantly and do not necessarily correlate with the refrigerant GWP, for example lower GWP refrigerants such as R32 and R1234yf have only average life cycle carbon performance, due to their lower efficiency.

For the best performing systems (R290, R600a and R717), there are reported concerns about the availability of components which consequently limit their immediate future application. For instance R717 can only be used with open type compressors (and cannot be used with copper, zinc or their alloys), whilst there are reported to be few compressors available for use with R290 and R600a. Of the existing HFC refrigerants R404A does not perform well. R134a systems perform the best, followed by R410A and R407C. Whilst hydrocarbon, R32 and R1234yf refrigerants may have potential for use in heat pumps in the future they do not currently appear to offer an attractive and commercially available alternative to current HFC refrigerants. The 2014 assessment of the UNEP refrigeration, air conditioning and heat pumps technical options committee (RTOC) provides a more in depth review of the suitability of refrigerants for use in air to water heat pump systems (UNEP, 2015).

4.6 Reducing total emissions from RACHP systems

This chapter has focused mainly on direct (refrigerant leakage) emissions from RACHP systems, which, according to the author's investigations, accounted for over 25% of all RACHP system emissions and almost 2% of total UK GHG emissions in 2012. As described earlier in this chapter, the 'multiplier' effect (the impact of refrigerant leak rate on the overall system TEWI) can be as large as 5x for high GWP refrigerants such as R404A, which is still in common use (especially in the retail sector), but the multiplier drops to 1x or less when refrigerants with a GWP of 500 or lower are used, at which level refrigerant leak rates of less than 10% would have only a small impact on the overall TEWI. The results suggest that for RACHP systems using high GWP refrigerants, an emissions reduction strategy should initially focus on reducing refrigerant leaks, switching to a focus on the indirect (energy related) emissions once the direct emissions have been reduced to a level where their impact on the overall TEWI is small (10-15%). This would typically equate to an annual refrigerant leak rate of about 2% for systems using R404A refrigerant, or about 4% with refrigerant R134a (GWP = 1430).

A reduction in RACHP indirect emissions could be achieved in a number of different ways, including:

- Reducing the overall cooling (and heating) demand
- Increasing the efficiency (COP) of RACHP systems
- Recovery and re-use of waste heat
- Greening of the electricity grid (reducing the carbon emissions factor per kWh generated, by the use of 'cleaner' fuels and renewable energy technologies)
- On-site renewable energy generation

Unlike direct emissions, there is no multiplier effect for any of these approaches, so a 1% reduction in indirect emissions would reduce the overall TEWI by no more than 1% (the actual figure depending on the level of direct emissions).

Significant work is already being undertaken by other researchers and organisations into increasing the performance and efficiency of RACHP systems and reducing carbon emissions from the electricity grid, so these have not been investigated. Instead, the focus of the second part of this research project has been to investigate ways to reduce the cooling (and heating) energy demands and total emissions from buildings.

4.6.1 Reducing cooling energy demand

The 'Pathways to 2050' report (previously mentioned in the literature review) was based on a detailed study and assessment of likely future energy demand and production. It included a number of projections based on alternative scenarios (trajectories) and provides a good starting point for investigating future cooling energy demand.

Summing the 2050 Pathway domestic and non-domestic heating and cooling energy projections for the level 2 to level 3 trajectories leads to the predictions shown in Table 4-6 for total heating and cooling energy demand.

Table 4-6. 2050 Pathway projections for domestic and non-domestic heating and cooling energy demand (level 2-3 trajectories)

	Energy Demand 2007 Domestic + Non-Domestic (TWh)	Energy Demand 2050 (Domestic + Non-Domestic) TWh	Projected Increase 2007 to 2050 (range)
Heating Energy	300 + 88 = 388	(270 to 330) + (95 to 118) = (365 to 448)	-6% to +15.5%
Cooling Energy	0 + 28 = 28	(13 to 31) + (30 – 45) = (43 to 76)	+54% to +270%
Total Heating and Cooling Energy	416	408 to 524	-2% to +26%

[Adapted from: DECC (2010)]

The broad conclusions are that the change in heating energy demand between 2007 and 2050 will be relatively small. However, cooling energy demand might increase by anywhere between 50% and 270% according to the mid-range (level 2 & 3 trajectories), which emphasises the importance of reducing the energy demand and associated emissions from buildings incorporating RACHP systems.

4.7 RACHP emissions – summary of results and conclusions

This chapter has described investigations undertaken by the author into the levels, sources and causes of emissions from RACHP systems. It identified that, in 2012, RACHP systems in the UK used 19.7% of all grid electricity and were responsible for 7.4% of all UK emissions (direct emissions from refrigerant leakage being responsible for 1.98% of all UK emissions and an increasing trend). Key outcomes of the investigations were:

- The TEWI analysis identified that refrigerant annual leak rates of just 8% could double the lifetime TEWI for systems using a high GWP refrigerant such as R404A and that the 'multiplier' effect (a 5% increase in TEWI for every 1% increase in leak rate) implies that leak reduction should be the primary focus for reducing the total systems emissions (at least until the leak rate is reduced to around 2%). Below a leak rate of 2% it may be more effective to switch the focus to reducing the direct emissions from energy use. As the refrigerant GWP is lowered, the 'multiplier' effect also reduced, until for GWP values of around 500 it drops to less than 1x, at which point reducing either direct or indirect emissions by 1% would have a similar impact on the overall TEWI.
- The REAL Zero investigation, which analysed site survey data for a range of system types and sizes, found that many systems were leaking more than the total system refrigerant charge over a 12 month period. The guidance and training have helped owners and maintainers of RACHP systems using high GWP refrigerants such as R404A (largely in the industrial and retail sector) to reduce their annual refrigerant loss to less than 10% of the system charge. A follow up study concluded that in the 12 months following the site surveys, the average reduction in refrigerant emissions was 43% for the 26 systems that were rechecked.
- The project to develop a structured approach to the analysis of fault reports and system logs has provided useful data that aids understanding of the sources and causes of refrigerant leaks, as well as the identifying the typical amount of refrigerant lost, according to the type of leak and its location in the RACHP system.
- The project to analyse heat pump system logs concluded that typical refrigerant leak rates for heat pumps and air conditioning systems are less than 3%, so that even when using refrigerant R410A (the most common refrigerant reported in the study, with a GWP = 2088), the direct emissions would be small relative to the indirect emissions.
- An investigation into alternative refrigerants for use in heat pump (and air conditioning) applications concluded that, for the assumed refrigerant annual leak rate of 6%, the impact of leakage on the overall TEWI was small for all of the refrigerants considered, apart from R404A. For R134a (GWP = 1430), which is frequently used in heat pumps, the direct emissions from a 6% annual leak rate would contribute less than 7% of the overall TEWI, so for a 3% leak rate the contribution to the TEWI would be below 4%. Although low GWP alternative refrigerants, including R290, R600a, R717

and R744, could achieve a lower TEWI, there are potential safety hazards associated with their use. Provided that high GWP refrigerants such as R404A are not used, the environmental impact of refrigerant leakage is likely to be small in most heat pump and air conditioning applications.

- Of the options for reducing the indirect emissions from RACHP systems, increasing RACHP system efficiency (and COP) and ‘greening’ the electricity grid are major standalone topics and were considered to be outside the scope of this study, which has investigated only how to cooling energy demand in buildings might be reduced. The ‘Pathways to 2050’ report implies that cooling energy demand might increase by somewhere between 54% and 270% by 2050 (considering the level 2 and level 3 scenarios). This highlights the importance of reducing the energy demand and associated emissions from buildings incorporating RACHP systems.
- Chapters 5, 6 and 7 describe the investigation into reducing energy demand and emissions from buildings.

Chapter 5. Modeling energy demand and carbon emissions in buildings

This chapter discusses some key principles and approaches to reducing the energy demand and emissions from buildings and provides a brief overview of energy modeling methods and existing software tools. It then describes the reasoning behind the decision to develop a new model and software tool, the energy balance model and equations and the practical implementation of the model in an Excel workbook. Some existing models did not appear to offer all of the features considered essential and in particular they did not include analysis of the environmental impact of refrigerant leakage from RACHP systems or facilitate speedy optimization of designs.

5.1 Principles for reducing building energy demand and emissions

Whilst Life Cycle Analysis (LCA) is sometimes used to estimate and compare the total energy and emissions from buildings over their lifetime, this study has considered only the energy and emissions during the operational phase of the building. It has addressed all thermal energy sources, sinks and heat transfer within the building (including heating and cooling, ventilation and air conditioning, lighting and electrical power etc.). Cooling demand cannot usefully be considered in isolation and can only be accurately assessed by taking into account all sources of heat generation and removal, both within the building and between the building and its external environment.

Cooling and heating energy demand are generally not independent of each other, since a change that reduces the heating load (for example increasing the insulation in a building in order to reduce heat losses) could increase the cooling load in the summer due to an increased risk of overheating. Conversely, reducing internal heat gains in a building (for example, by moving to more efficient lighting and IT equipment) will reduce the cooling load in summer but increase the heating load in winter. If the key objective is to reduce the total emissions from a building, it is necessary to assess both the cooling and heating energy demands and to sum the emissions associated with both, to determine whether a planned change will actually reduce the total emissions. All of the internal heat gains associated with human occupancy, lighting, ICT and other power loads must also be included in the calculation, since they can all impact the net heating and cooling loads.

In any cooling or heating application, the primary energy input and associated emissions might be reduced by:

1. Increasing the efficiency (or COP) of the cooling or heating system
2. Reducing the thermal load through other improvements (such as changes to a building's design features or operating parameters)
3. A combination of both of these measures

The indirect emissions could also be reduced through the use of greener (lower carbon) energy sources, which could be cleaner fossil fuels or electricity from renewable sources. There may also be scope to lower the direct emissions by reducing the refrigerant leakage in RACHP systems and by using lower GWP refrigerants, as discussed in Chapter 4.

Opportunities to reduce the thermal loads for RACHP systems depend on the application, the system installation and the operating environment. In recent years significant efforts have been made in supermarkets to reduce their energy use through measures that include adding doors and lids to freezer and refrigeration cabinets, replacing filament lamps with low energy LEDs, improving the insulation and efficiency of equipments and better temperature control (which may permit higher storage temperatures for some products). At the same time, improvements in compressor design, alternative refrigerants and optimisation of setup parameters have helped to increase the COP of these systems.

Measures to reduce the carbon emissions associated with the cooling and heating of buildings (whether using RACHP or other technology) might include:

- Reducing the thermal loads associated with the building fabric, through more efficient building design. Modern Building Regulations play a key role here, although they have until recently tended to focus more on heating energy than cooling.
- Modifying the thermal mass of a building, either by increasing it to reduce the sensitivity of the internal environment to a rapidly changing external environment, or alternatively by reducing it to achieve a faster thermal response, for more precise control of the internal environment.
- Storing thermal energy (within the building or a separate store) for later release.
- Reducing the internal heat gains (and losses) associated with the heating, cooling and ventilation systems, occupancy levels, lighting, ICT equipment, and other power loads such as lifts, hot water, refrigeration and cooking.
- Changes to the building management system (BMS) and operational parameters (e.g. the use of pre-heating and cooling, temperature set points etc.).

- Recovering and re-using energy that might otherwise be discarded from the heating and cooling systems and exhausted into the external environment.
- Making use of ‘free’ cooling, night time cooling and natural energy sources and heatsinks (e.g. ground, rivers and acquifers).
- The adoption of modern low carbon cooling technologies (e.g. low GWP refrigerants and high efficiency compressors).
- The use of low carbon electricity (from the national grid or decentralized local power generation) and renewable energy generated onsite.
- In cities, reducing the impact of the heat island effect through measures such as increasing vegetation and evaporative cooling, as well as by increasing the albedo (solar reflectivity) of the urban environment to reduce the absorption of solar energy

5.1.1 Building design and comfort levels

Factors that influence the heating and cooling energy demand and emissions from buildings include:

- The building design, orientation and construction materials
- Glazing, solar gains and shading
- Density of occupation and occupancy profile
- Ventilation, heating, cooling and hot water systems and controls
- Internal heat gains (people, lighting, IT, small power, catering, machinery etc.)
- External environment (daily and seasonal weather), comfort levels and set points

There may be further opportunities to reduce carbon emissions through passive cooling methods and the inclusion of renewable energy technologies, also to make improvements over the life of the building, particularly during renovation or refurbishment.

Opportunities may also exist to reduce heating and cooling energy demand and emissions through adaptive control of temperature set points (adjusting the set points according to the external environment). Figure 5-1 indicates that for any given outdoor air temperature there is a wide range of indoor temperatures that are considered acceptable by the majority of building users, the 90% acceptability window being more than 5°C wide. Set points could therefore be adaptively moved towards these limits as the external environment changes.

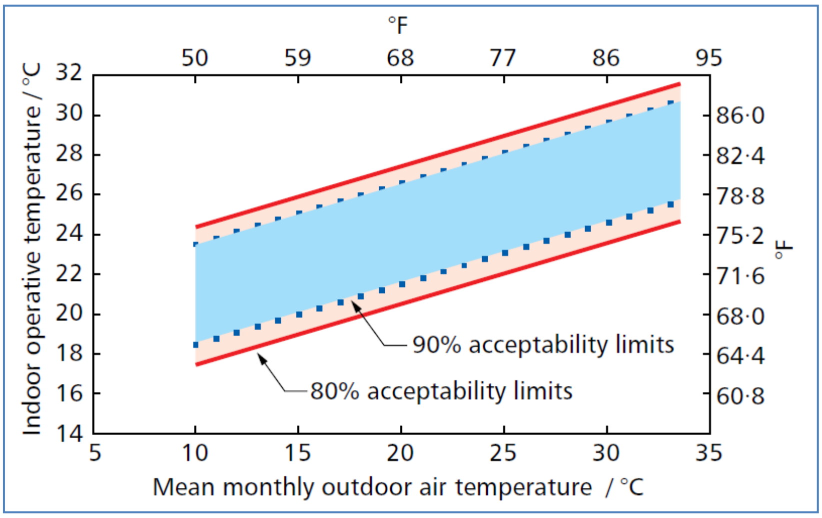


Figure 5-1. Acceptable operative temperature ranges for naturally conditioned spaces

[Source: CIBSE (2013)]

Whilst the principles behind reducing energy demand and emissions are straightforward, the relative merits of alternative design approaches and other measures can only be assessed accurately through the use of building simulation and energy analysis software tools.

5.2 Energy modelling methods and software tools

Current approaches to modelling energy demand include:

1. For urban and rural districts and neighbourhoods :
    a. Analysing historical energy demand patterns, demographic projections and emerging technologies to predict future energy needs.
    b. Aggregation using demographic data for building types and numbers and building energy benchmarks.
2. For individual buildings:
    a. Static models based on heating and cooling degree days and building heat loss coefficients for individual buildings.
    b. Cyclic models that take into account the building admittance and assume the external conditions vary in a predictable manner over each 24 hour period.
    c. Transient models, where the weather, state of the building and its components are time varying and non-cyclic, allowing the transient behaviour and recovery (from shut-down for example) to be predicted. Transient models are generally more complex and typically employ energy and mass flow balance techniques and CFD (Computational Fluid Dynamics) analysis tools.

The results from modelling individual buildings can also be extrapolated across urban areas using demographic data for building types and numbers.

Software tools for the transient thermal analysis of individual buildings typically use CFD models and 24hour x 365 day weather data (normally TRY or Test Reference Year data), resulting in the need for a large amount of input data, with relatively long computing times and large output data files. Whilst this approach can work well for an individual building where the design parameters have already been set, it can present significant challenges when trying to optimise the building design or when analysing multiple buildings. Optimisation requires multiple simulations, varying one or more parameters at a time and post processing of the data to search for optimum values is a significant burden.

A key aim of this study was to identify a way of analysing the thermal and environmental performance quickly and with sufficient accuracy to allow different design concepts and building parameters to be quickly assessed and an optimum approach identified prior to undertaking detailed design work. Static and cyclic models were considered unsuited to this requirement, since it would be important to include simulation of the thermal energy storage and dynamic thermal response associated with the thermal capacity of the building. However, since it would be impractical to undertake a comprehensive review of all the available software tools, the results of other studies of building simulation software were relied on.

Kalema et al. (2008) compared the results of 6 building energy simulation packages using the ISO 13790: 2008 methodology (CEN, 2008) and concluded that the ISO method was suitable for estimating annual energy demand for buildings in Nordic climates, also that single zone modelling was acceptable for energy analysis purposes. Crawley *et al.* (2008) compared the capabilities of several different simulation programmes (including IES-VE which has been used in this work) and concluded there is no common language to describe the capabilities of different tools. Attia (2011) compared 10 tools and found the user input/output interfaces to be complex, providing too much information, making interpretation difficult. Also, few provide good support for carbon emissions evaluation, or simulation of passive or innovative design strategies.

A review by Trcka and Hensen (2010) concluded that the real performance of buildings usually deviates from the performance predicted by a significant margin and that 'the initial modelling complexity should be the lowest possible complexity that satisfies the simulation objectives in terms of performance indicators'. They identified 3 sources of errors:

1. Abstraction error – due to an incomplete model of the physical system
2. Input data error – due to uncertainties in the parameters used in the simulation
3. Numerical errors - associated with the discretization (step size used in the simulation)

The modelling uncertainty is described as a modelling bias, which decreases with increasing complexity of the model. However, at the same time the predictive uncertainty (output error) will increase in line with the number of parameters in the model, so Trcka and Hensen suggested that there is a trade off between simplicity and complexity at which the summed errors reach a minimum. This is indicated in Figure 5-2 which indicates that summed errors may reach a minimum at relatively low levels of model complexity.

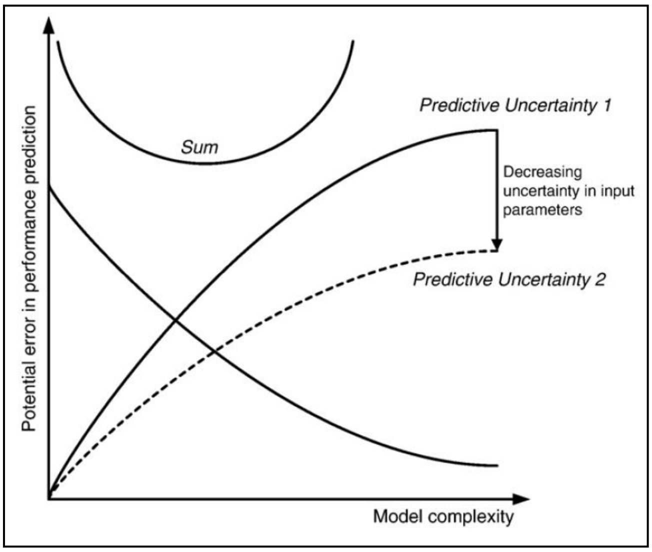


Figure 5-2 Model uncertainty vs complexity

[Source: Trcka and Hensen (2010)]

It was decided to adopt this 'lowest modelling complexity' approach, developing a generic model that would have the potential to be extended to analyse clusters of buildings as well as single building structures.

5.3 New generic energy balance and emissions model

The new model and Excel based software tool were developed to address some of the perceived limitations of existing tools in relation to understanding and optimizing building energy demand and emissions. The key aims of developing the model were to provide a high level planning tool that:

- is simple and easy to use, with the data describing the building, occupancy and environment limited to only that which is necessary to achieve acceptable simulation results and accuracy (in accordance with the Trcka and Hensen approach)

- provides easy to interpret output data and graphing, with rapid visualization of the impact of changes
- can simulate passive and low carbon cooling measures
- calculates the direct emissions from RACHP equipment as well as the energy related carbon emissions from the building
- will assist users to establish optimal high level solutions for building design and operation

The methodology broadly follows the guidance in ISO 13790: 2008 (CEN, 2008) using a dynamic heat balance approach, with simulation at hourly intervals. In order to characterise building transient behaviour and the effects of shut-down and start-up following weekends and holidays, the simulations are run over 72 hour periods. The model simulates the performance of the heating and cooling plant in terms of primary energy demand, distribution and delivery equipment losses and energy related and refrigerant loss emissions.

Because few buildings use sub-metering for the heating and cooling plant (or for other energy use), the availability of real data is very limited, so it was decided to validate the model against a well established and proven building simulation tool (IES, 2014).

5.3.1 Quasi-dynamic energy balance model

A schematic diagram of the quasi-dynamic energy balance model, which indicates the various thermal energy flows within a building, is shown in Figure 5-3. The model uses simple algorithms and a reduced weather data set in order to provide rapid results that can be viewed in near real time. At hourly intervals the heat gains and losses associated with the building fabric, solar gains, ventilation and internal gains are summed in order to calculate the energy required from the heating or cooling plant to balance the energy flows and sustain the required environment inside the building. However, unlike static models, which assume a steady state energy balance and cannot simulate out of balance conditions or the effects of the thermal mass of the building, the quasi-dynamic model also calculates an error function (based on deviation from the temperature set points) and uses this to predict the required output from the heating and cooling plant over the next one hour period, in order to achieve thermal balance by the end of that period. This feature permits analysis of the transient behaviour of the building, allowing the thermal profile to be simulated when the system is recovering from an out of balance condition (for example when the building has been unoccupied and the heating and cooling plant switched off for long periods). It avoids the complexities of a full dynamic or CFD simulation model, whilst offering similar capabilities, albeit at reduced resolution (due to the increased time interval between updates: 1 hour vs typically 10 minute intervals for many dynamic software tools). A consequence of the reduced temporal resolution is some undershoot and overshoot in the temperature profile predicted by the model. However, this effect would be smoothed in a real life building, since heating and cooling plant and control systems generally have a much shorter response time than the one hour interval used in the simulation.

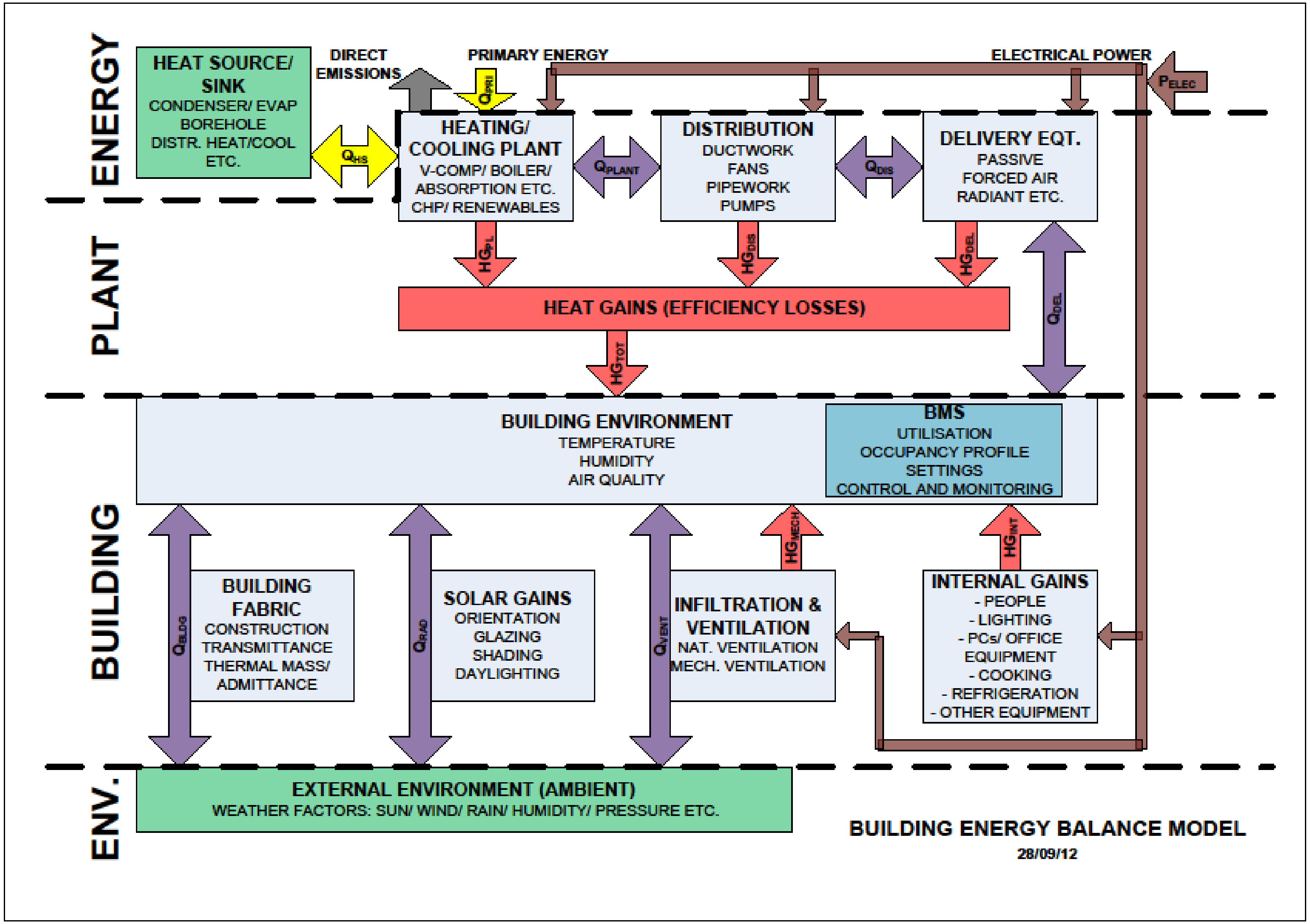


Figure 5-3. Energy balance model for building thermal analysis

5.3.2 Energy balance equations

Energy balance (steady state)

The heating (or cooling) required from the HVAC delivery system to maintain balance is:

$Q_{del} = -(Q_c + Q_r + Q_{ve} + Q_{me} + Q_{gn} + Q_{ls})$ **Equation 5-1**

where:

Q_{del} = heat delivered (or extracted) by the HVAC system

Q_c = heat flow through the building fabric

Q_r = radiative heat flow due to solar gain

Q_{ve} = heat flow due to infiltration and natural or mechanical ventilation

Q_{me} = heat gain associated with natural and mechanical ventilation (actuators and fan power)

Q_{gn} = heat flow due to internal heat gains (people, lighting, equipment etc.)

Q_{ls} = heat gains due to efficiency losses in the HVAC plant, distribution and delivery equipment

Out of balance thermal response (unsteady or transient state)

In practice a true steady state is never achieved. In the quasi-dynamic model, building energy balance and temperature calculations are performed at hourly intervals and the temperature error at the end of each hour is used to set the heating (or cooling) level for the next hour. The rate of change of temperature in a one hour period may be approximated as

$\Delta\theta = (\theta_t - \theta_{(t-1)}) = Q_u/C$ [°C/h] **Equation 5-2**

where:

θ_t = building internal temperature at time t [°C]

$\theta_{(t-1)}$ = building temperature at time (t-1) [°C]

Q_u = average net heat flow due to energy unbalance between time (t-1) and time t [kW]

C = effective heat capacity of the conditioned space [kWh/K]

The additional heating or cooling necessary to correct the temperature deviation from the desired set point between time t and time (t+1) (the following hour) may be approximated as

$\Delta Q_{del} = -Q_u = (\theta_{(t-1)} - \theta_t)*C$ [kW] **Equation 5-3**

In both the model and in real systems, the maximum heating or cooling capacity of the plant and the modulation control will determine the amount of heating or cooling that can actually be delivered in any one hour period.

Energy demand and emissions

The model can estimate the primary energy demand and the carbon emissions from the building. The HVAC system is modelled as 3 separate elements: the plant, a distribution system (ductwork, fans, pipework, pumps etc.) and delivery equipment (fan coil, radiator etc.). The energy balance equation for the HVAC system is

$$Q_{del} + Q_{ls} = -(Q_{pr} + Q_{hs} + Q_e) \quad \textbf{Equation 5-4}$$

where:

Q_{pr} = primary energy input (gas, oil or electricity)

Q_{hs} = heat transfer between any external heat source or heat sink (condenser, evaporator etc.)

Q_e = heat emitted directly from the plant to the external environment (e.g. flue gases)

Q_{ls} = the sum of the losses from the heating (cooling) plant and the distribution and delivery equipment (auxiliary electrical energy used to drive fans etc. is accounted for in this loss term)

The overall coefficient of performance of the HVAC system during any time period is

$$COP = Q_{del}/Q_{pr} \quad \textbf{Equation 5-5}$$

The greenhouse gas emissions associated with both primary and secondary energy use are calculated as CO_2 equivalents using published conversion factors for each fuel type. For RACHP systems there may be additional emissions due to leakage of the refrigerant contained within the system. These are predicted by estimating the amount of refrigerant charge in the system and using the refrigerant GWP and typical leakage rate to calculate the CO_2 equivalent emissions as

$$EM_{RACHP} = L_{em}*m*GWP/1000 \quad [tCO_2(e) \text{ per annum}] \quad \textbf{Equation 5-6}$$

where:

EM_{RACHP} = direct emissions from the RACHP system

m = standard refrigerant charge in the RACHP system [kg]

GWP = global warming potential for the specific refrigerant type [expressed as CO_2 equivalent]

L_{em} = refrigerant leakage rate per year [% of the refrigerant charge]

5.4 Implementation of the new model

The model has been implemented as a macro enabled Excel workbook, with linked sheets, which provides a flexible design environment and permits new and enhanced functionality to be included as the model is developed. The use of multiple windows and a results dashboard allows the impact of changes to input parameters to be quickly assessed and viewed in near real time. Output data can be visualised using the charts embedded in each sheet. By simultaneously viewing multiple windows it is possible to see immediately the impact of making changes to any of the input parameters.

The simulations are performed and results plotted over a 72 hour period; the start temperature is assumed to be mid-way between the external temperature and the desired (set point) temperature. The data for the first 24 hours can be used to demonstrate the recovery from a weekend shutdown, for example, while the day 2 and 3 data indicate the performance when the building is occupied on a daily basis.

The default external temperature profile is the mean hourly air temperature from CIBSE Guide A, Table 2.34 (CIBSE, 2006b), but the user can specify other weather data. The CIBSE Guide A 97.5 percentile irradiance data (Table 2.30) is used to calculate the solar gain of the building. Building design parameters and operational data (occupancy profile, ventilation rate, heating and cooling temperature set points, pre-heat and cooling periods etc.) are input by the user and are typically based on Building Regulations and CIBSE and other benchmarks. The heating and cooling plant type and efficiency, together with distribution and delivery losses, are modelled to estimate primary energy demand and the associated carbon emissions, together with the direct emissions due to leakage of refrigerant from RACHP systems.

5.4.1 Worksheets

The multiple worksheets are:

- Reference Data (defaults and user data inputs)
- Dashboard (results overview – can be reconfigured to suit user requirements)
- Temperature Profile (table and charts of the calculated temperature profile over 72 hour periods for each month)
- Sensitivity Analysis (configurable by the user according to the specific application –

results can be copied and pasted to this sheet for graphing etc.)

- Climate Change Sensitivity (for the recording and analysis of simulation results using different weather files in order to assess the impact of climate change. Configurable by the user)
- Building Power and Emissions (heating/ hot water, cooling specific and electrical energy plus direct and indirect emissions)
- Total Building Heat Energy Load (the hourly heat energy balance, the required heating and cooling plant outputs and the rate of change of temperature in each 1 hour period)
- Ventilation – Air Con Load (the hourly heat energy load due to natural or forced ventilation of the building, including night cooling, plus the electrical load for ventilation fans)
- Building Fabric Heat Load (the hourly heat load due to conduction through walls, windows, floors, roofs and doors and air infiltration)
- Solar Gain_CIBSE_A_T2.30 (summation of hourly solar gain on N,S,E,W facing facades and roof, averaged for each month using a 'cloud transmittance' factor)
- Internal Heat Gains – Simple (the estimated heat gains due to people, lighting and equipment based on occupancy profile and CIBSE benchmarks. Includes sensible heat gains only, from people, lighting and equipment. Default values can be changed by the user)
- Hot Water Load (the hourly hot water energy load, estimated from occupancy profile using CIBSE benchmarks. It is not used in the heat energy balance calculation but is included in the total energy and emissions calculation. Default consumption rates and water temperatures can be changed by the user)

Most of the user data input fields are contained in the 'Reference Data' sheet (the input cells are highlighted yellow). Some of the inputs require the user to type in values while others have a pull-down list and use lookup tables. Cells that are highlighted blue indicate data input fields that are not currently active, while grey cells indicate fixed data or values carried across from other sheets. At present there is no protection for any cells or worksheets so the user must take care to avoid overwriting any formulae (it is recommended that the workbook is saved with a new file name when undertaking analysis or making any changes to worksheets).

The building data input fields allow multiple areas to be specified in the horizontal plane, to allow for more complex shapes than simple rectangular buildings. However, there is currently no provision for zoning - all floors in the building are assumed to be of equal height and shape and to have similar operational parameters (temperature set points, occupancy and internal gain profiles etc.).

Output data are not directly highlighted in each worksheet, but charts are embedded in each sheet and in the Dashboard. The associated data cells can be highlighted by clicking on the chart area or selecting 'source data' from the menus. Other data that are not charted can be located using row and column labels and table headers.

5.4.2 Model assumptions, limitations and constraints

In order to simplify the analysis, the constraints and assumptions include:

- Non-rectangular building shapes can be simulated by defining the structure in terms of multiple rectangular cells (although they are termed 'zones' within the Excel tool there are no internal walls or separate climate zones).
- All floors in the building are assumed to be of equal height and a single climate zone is assumed for the whole building.
- The alignment options for the building's main axis are restricted to N-S or E-W only for the solar gain calculations. Also the solar gain calculation will currently work only for zone 1.
- An empirically derived cloud factor (transmittance) is used in the solar gain calculation to account for weather variations, to generate an average value for each month. However, for overheating assessments the transmittance can be set to 100% by the user and the simulation performed with a peak temperature dataset.
- Latent heat is not included in the simulation - only sensible heat gains and losses are accounted for.
- Hot water used within the building is assumed not to contribute to the internal heat gains, since it will be flushed out of the building. The model does not currently include any provision for hot water heat recovery.
- The quasi-dynamic model assumes that heat flows are constant during each one hour calculation period.

5.4.3 User data inputs and default values

Most of the user data input cells are in the 'Reference Data' worksheet and highlighted in yellow. The physical parameters for the building and weather files are key data inputs and their derivation (and reformatting for the weather files) are described in sections 5.5 and 5.6

of this chapter. The following tables show the key user input data fields and the default values (which are based on a modern six storey air conditioned office block).

Table 5-1. Building construction data

Parameter	Input Value	Units
U Wall (Uwa)	0.35	W/m^2K
U Floor (Uf)	0.25	W/m^2K
U Roof (Ur)	0.25	W/m^2K
U Window (Uwi)	2.2	W/m^2K
U Door (Ud)	2.7	W/m^2K
Air Infiltration Rate N	0.25	ac/hr
Cp Wall	44	$kJ/m^2/K$
Cp Ground Floor	38	$kJ/m^2/K$
Cp Roof	70	$kJ/m^2/K$
Cp Internal Floor	67.5	$kJ/m^2/K$

Table 5-2. Building design

Parameter	Input Value	Units
Orientation - Building length L Facing	N-S	N/A (list)
Length L	60	m
External Walls No. Nl (along length)	2	-
Width W	30	m
External Walls No. Nw (along width)	2	-
No of floors	6	-
Roof Height H	24	m
Window Area Wip (as % of wall area)	40%	% (list)
Glazing Transmittance T	0.54	-
Maintenance Factor M	92.0%	%
Reflectance R	0.5	-
Vertical Angle Subtended by Sky	80	deg
Standard Lighting Load	12	W/m^2
Standard Lighting Level Slux	500	Lux
Daylit Coverage Distance from Window Xm	6	m
Cloud Factor (Transmittance)	50%	% (list)
Door Area Ad	4	m^2

'list' = pull down list of values

Cells highlighted blue are not currently active

Cloud Factor is currently fixed value for each month (no seasonal variation)

There can be multiple values for L, Nl, W and Nw as several zones (or similar buildings can be specified)

Table 5-3. Heating and cooling plant

Parameter	Input Value	Units
Max Heating Capacity kW	1000	kW
Heating Set Point °C	19	°C
Include Space Heating in Calc?	Y	Y/N
Max Cooling Capacity kW	800	kW
Cooling Set Point °C	21	°C
Include Space Cooling in Calc?	Y	Y/N
Base temperature tb	Not used	ºC
HVAC Heat Recovery? (Y/N)	N	Y/N
HVAC Heat Recovery Efficiency %	70%	% (list)
Allow Night Cooling?	N	Y/N
Pre-heat/ cooling period hrs	2	(list)
Heating/ cooling early stop period hrs	2	(list)
Heating Fuel Type	Natural gas	(list)
Heating Fuel CO_2 kg/kWh	0.20421	(lookup table)
Heating Plant COP	0.9	(list)
Heating/ HW Dist/Del Losses (Heat Gains) %	5%	(list)
Cooling Fuel Type	Grid electricity	(list)
Cooling Fuel CO_2 kg/kWh	0.44548	(lookup table)
Cooling Plant COP	2.25	(list)
Cooling Dist/Del Losses (Heat Gains) %	5%	(list)
Refrigerant Type	R410A	(list)
Refrigerant GWP(CO_2=1)	1720	(lookup table)
Specific Charge (kg/kW)	0.2	(list)
Annual Leakage Rate %	5%	(list)

'list' = pull down list of values

"lookup table" = data entered automatically based on selected value from pull down list

Base temperature (tb) is not used in the 72 hour quasi-dynamic calculations

Table 5-4. Carbon factors for alternative fuel types

Heating Fuel Type	Carbon Factor CO_2 kg/kWh
Custom (specify)	0.5
Fuel Oil	0.28594
Grid electricity	0.44548
Industrial coal	0.32893
LPG	0.22991
Natural gas	0.20421
Wood pellets	0

The user can change the carbon factors or specify a different fuel. Values for heating are copied automatically to the cooling lookup table

Table 5-5. Lookup tables for heating and cooling system modulation

VLOOKUP Table (Heating Modulation)	
Temp Error degC	Modulation 1= max output
0	0
0.5	0.2
1	0.4
1.5	0.6
2	0.8
2.5	1

VLOOKUP Table (Cooling Modulation)	
Temp Error degC	Modulation 1= max output
0	0
0.5	0.2
1	0.4
1.5	0.6
2	0.8
2.5	1

The simulation determines the modulation level for the heating and cooling system according to the temperature error from the set point value. Values can be changed by the user.

Table 5-6. Heating and cooling months

Heating & Cooling Months	Month											
Set By Facilities Mgr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating On (1)/ Off (0)	1	1	1	1	1	0	0	0	1	1	1	1
Cooling On (1)/ Off (0)	0	1	1	1	1	1	1	1	1	1	1	0
Night Cooling Months	0	0	0	0	0	1	1	1	1	0	0	0

Enabling both heating and cooling in a given month may increase total energy demand and emissions due to contention between the heating and cooling systems.

Night cooling is not operative unless the “Allow night cooling?” flag is set to “Y”

Table 5-7. Building occupancy profile and cooling demand

Hour Ending	Heating/ Cooling (On =1)	Occupancy (0-100%)	Night Cooling Profile	Occupancy Start-Finish Times
1	0	0%	1	N/A
2	0	0%	1	N/A
3	0	0%	1	N/A
4	0	0%	1	N/A
5	1	0%	0	N/A
6	1	0%	0	N/A
7	1	50%	0	7
8	1	50%	0	8
9	1	100%	0	9
10	1	100%	0	10
11	1	100%	0	11
12	1	100%	0	12
13	1	100%	0	13
14	1	100%	0	14
15	1	100%	0	15
16	1	100%	0	16
17	1	100%	0	17
18	0	50%	0	18
19	0	50%	0	19
20	0	0%	1	N/A
21	0	0%	1	N/A
22	0	0%	1	N/A
23	0	0%	1	N/A
24	0	0%	1	N/A
'On' Time	13		9	
				7
				19

The values in the grey cells are calculated and set automatically during the simulation

Table 5-8. Occupation density, ventilation and pre-heating/ cooling

Parameter	Input Value	Units
Density of Occupation m^2/person	12	m^2 (list)
Ventilation L.sec-1/person	12.5	L/s (list)

'list' = pull down list of values – these are based on CIBSE Guide A benchmarks (Table 4.1 and Table 6.1)

Table 5-9. Hot water (default values – sheet: "Hot Water Load")

Parameter	Input Value	Units
Hot Water Demand/ Service	10	l/day/person
Catering Hot Water Demand	0	l/day/person
% of Staff using Catering	50%	
Water Inlet Temperature	10	ºC
HW Delivery Temperature	65	ºC

Default values are based on CIBSE Guide B Table B4.8 [Source: CIBSE (2005b)]

Table 5-10. Internal gains (lookup table - sheet: "Internal Heat Gains – Simple")

Density of Occupation m^2/person	Sensible Heat Gain W/m^2			Latent Heat Gain W/m^2	
	People	Lighting	Equipment	People	Other
4	20	12	25	15	0
8	10	12	20	7.5	0
12	6.7	12	15	5	0
16	5	12	12	4	0
20	4	12	10	3	0

Default values are based on CIBSE benchmarks (Guide A Table 6.1)

Table 5-11. Temperature data (Dry Bulb °C)

Hour Ending	Jan (29)	Feb (26)	Mar (29)	Apr (28)	May (29)	Jun (21)	Jul (4)	Aug (4)	Sep (4)	Oct (4)	Nov (4)	Dec (4)
1	3.3	7.6	8.6	10.2	8.7	15.3	16.6	16.8	13.7	12.7	7.3	4.6
2	3.1	7.5	8.4	9.7	8.4	14.8	16.0	16.4	13.4	12.5	7.3	4.5
3	3.0	7.2	8.2	9.6	8.2	14.5	15.5	16.1	13.3	12.3	7.3	4.3
4	3.0	7.2	8.0	9.3	8.0	13.9	15.2	15.8	13.1	12.2	7.2	4.3
5	2.9	7.1	7.8	9.0	7.7	13.5	14.9	15.5	12.9	12.0	7.1	4.4
6	2.8	7.1	7.7	8.8	7.6	13.5	14.8	15.4	12.7	11.7	6.9	4.5
7	2.8	7.0	7.7	8.9	8.1	13.9	15.2	15.5	12.6	11.5	6.7	4.5
8	2.8	7.3	8.1	9.4	9.1	14.7	15.8	16.0	12.9	11.5	6.8	4.5
9	3.1	7.7	8.9	10.1	10.1	16.1	16.7	16.9	13.5	12.0	7.1	4.7
10	3.6	8.3	9.7	11.1	10.9	17.0	17.7	17.9	14.5	12.9	7.7	4.9
11	4.1	8.9	10.7	12.0	11.6	18.0	18.5	18.7	15.5	13.7	8.3	5.4
12	4.6	9.3	11.6	12.7	12.2	18.9	19.4	19.4	16.1	14.4	8.9	5.8
13	4.9	9.7	12.4	13.5	12.3	19.6	20.3	19.9	16.6	14.9	9.3	6.1
14	5.1	9.8	13.0	13.9	12.6	20.1	20.9	20.4	17.1	15.1	9.4	6.1
15	5.0	9.8	13.1	14.2	12.8	20.6	21.1	20.9	17.3	15.3	9.4	6.1
16	4.8	9.5	12.9	14.3	12.8	20.7	21.3	21.0	17.5	15.3	9.1	5.7
17	4.4	9.1	12.5	14.1	12.7	20.6	21.3	20.9	17.3	15.0	8.8	5.5

18	4.2	8.8	11.8	13.8	12.5	20.2	20.9	20.6	16.9	14.5	8.5	5.3
19	4.1	8.6	11.2	13.5	12.2	19.9	20.7	20.2	16.4	14.2	8.3	5.1
20	3.9	8.4	10.6	12.7	11.6	19.1	20.2	19.6	15.7	13.9	8.0	4.9
21	3.9	8.3	10.1	11.9	10.9	18.4	19.4	19.0	15.2	13.6	7.7	4.8
22	3.8	8.2	9.7	11.5	10.4	17.4	18.6	18.3	14.8	13.3	7.6	4.6
23	3.7	8.1	9.3	10.9	9.9	16.7	17.9	17.6	14.3	13.0	7.5	4.5
24	3.5	8.0	9.0	10.5	9.4	16.1	17.2	17.1	14.0	12.7	7.4	4.5

Default values are derived from file 'Hrow9697.fwt'.

5.4.4 Outputs available from the model

The results of calculations can be viewed on the individual worksheets, which tabulate data over 72 hour periods (24 hours for Internal Gains, Solar Gain and Hot Water, since they are not affected by cold start/ warm up). Most worksheets include one or more embedded charts, graphing results. These charts can also be copied to the "Dashboard" worksheet and arranged to provide multiple output data within a single window. To view the impact of making changes to any input parameter two windows should be viewed simultaneously, side by side, one showing the relevant data input cells, the other the output (either the "Dashboard" or other worksheet, depending on the parameters to be viewed.

Building temperature profile (sheet: "Temperature Profile")

This is available in tabular and chart form with hourly data over a 72 hour period (from 'cold' start i.e. after a period of non-use) for each month. Charts are available for the entire 72 hour period and over 24 hours for days 1-3.

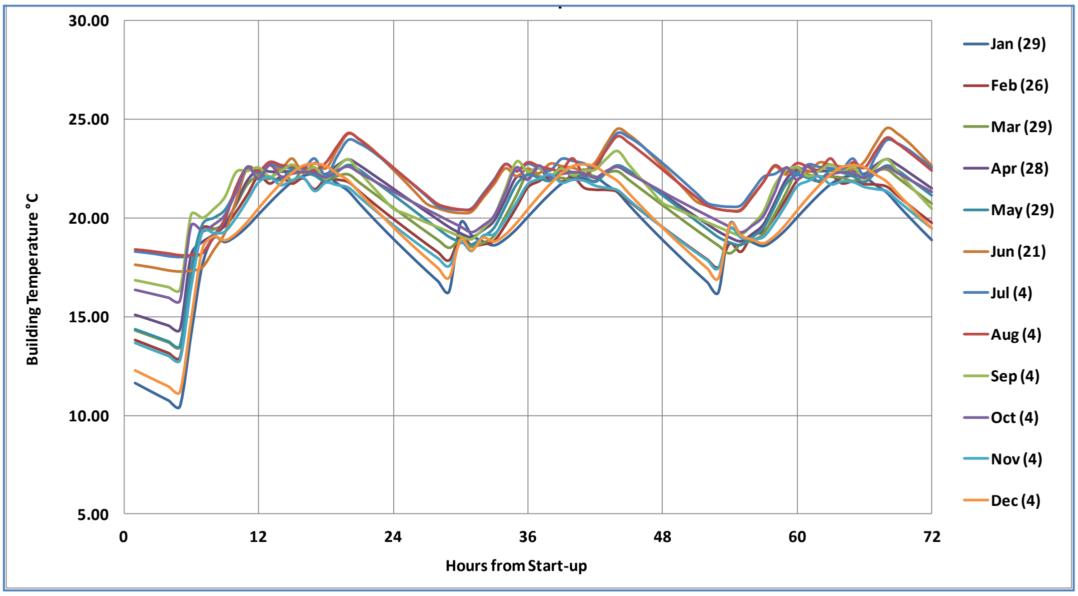


Figure 5-4. Building temperature profile – 72 Hour (3 day) period from start up

A typical 72 hour temperature profile is shown in Figure 5-4 and a typical 24 hour response for day 3 (48 – 72 hours from start up) is shown in Figure 5-5.

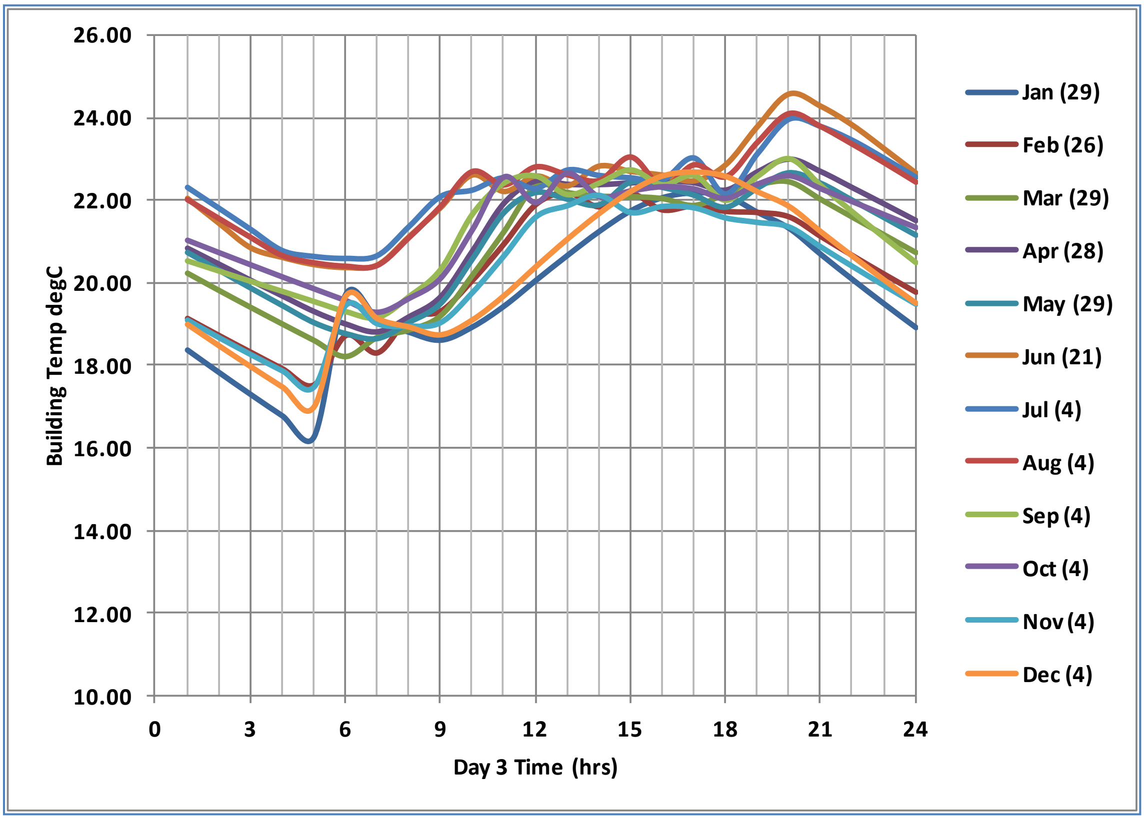


Figure 5-5. Building temperature profile – day 3

Building net thermal energy load (sheet: "Total Building Heat Energy Load")

The building's net thermal energy load (energy balance excluding the heating or cooling plant output) during each 1 hour period is calculated from the heat energy balance model:

Building Heat Energy Load = (Building Fabric Heat Load) + (Ventilation-Air Con Load) – (Solar Gain) – (Internal Heat Gains) **Equation 5-7**

The energy load, which represents the heating or cooling energy demand, is available in tabular form with hourly data over a 72 hour period (from 'cold' start i.e. after a period of non-use) for each month. It is also charted for day 3 of the 72 hour period. A typical energy load profile is shown in Figure 5-6. Positive values (black axis labels) indicate heating demand, while negative values (red axis labels) indicate cooling demand.

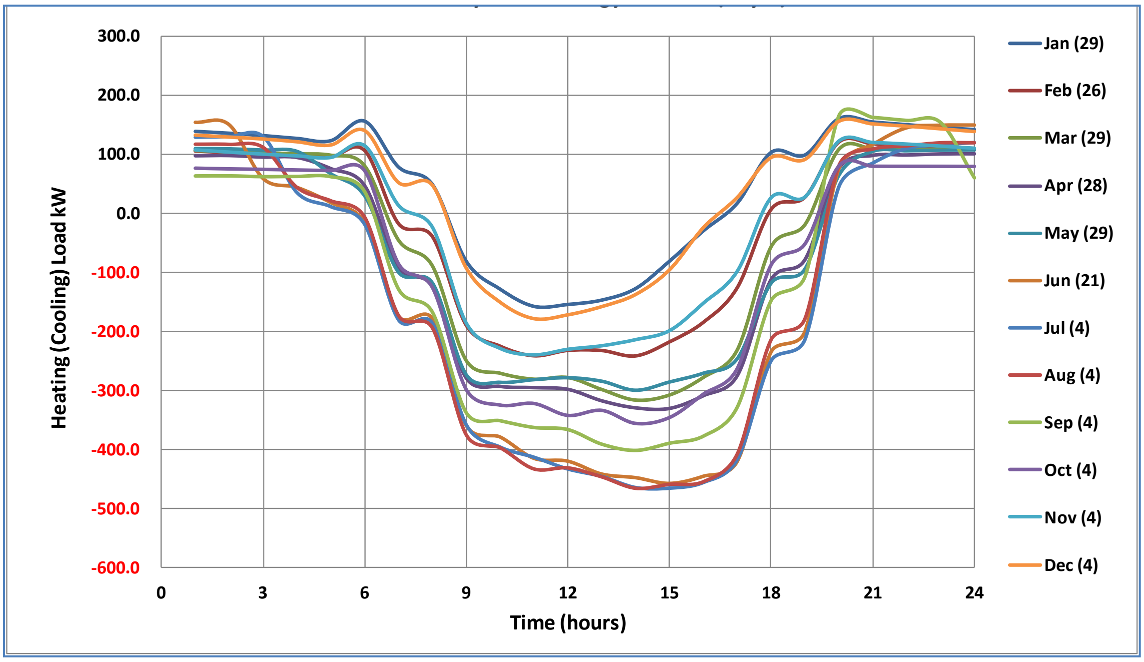


Figure 5-6. Building heating and cooling energy Load – Day 3

The heating and cooling plant outputs are also available in tabular form with hourly data over a 72 hour period (from 'cold' start i.e. after a period of non-use) for each month, together with the change in building temperature over each 1 hour period. The typical day 3 heating and cooling plant load profiles for January and July respectively are also charted (Figure 5-7 and Figure 5-8). Figure 5-9 and Figure 5-10 show the total space heating and cooling energy demand in each calendar month – they indicate that during the months February to May and September to November there is both heating and cooling energy demand. On some days both heating and cooling may be required (heating in the morning, following overnight cooling of the building and cooling in the afternoon, to offset the internal gains).

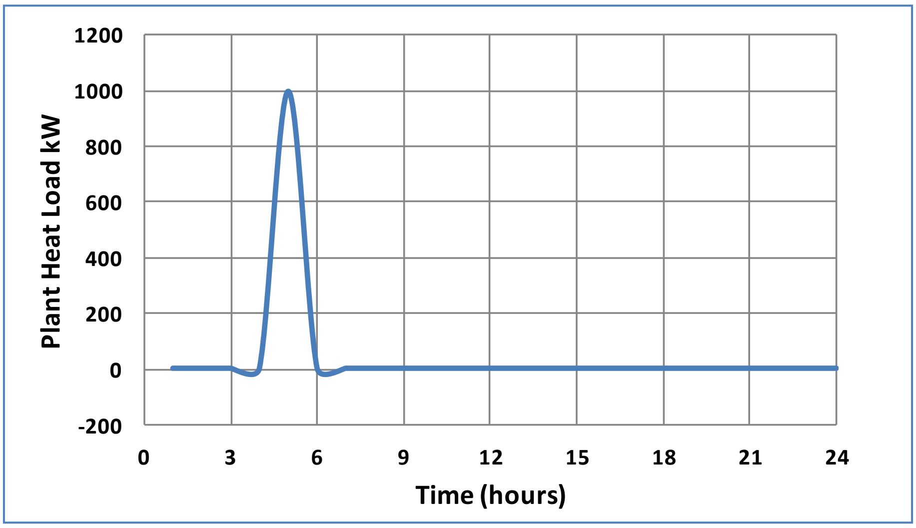


Figure 5-7. Heating plant daily load – January (day 3)

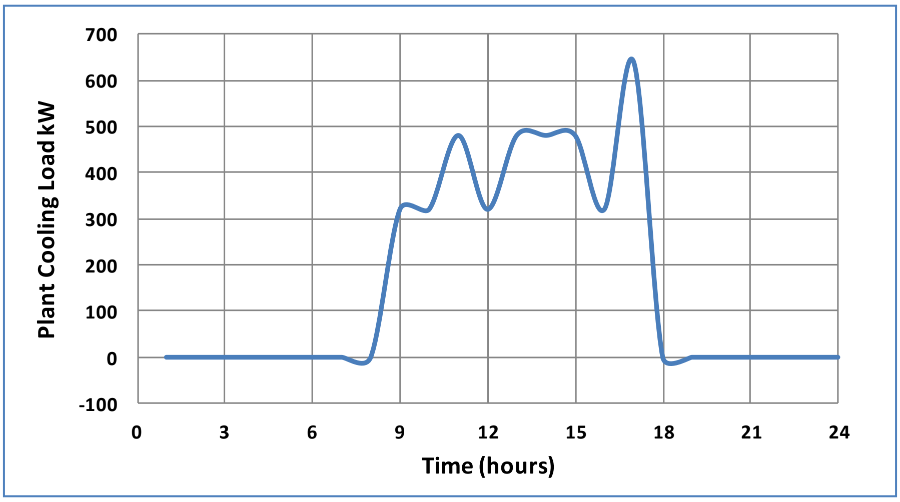


Figure 5-8. Cooling plant daily load – July (day 3)

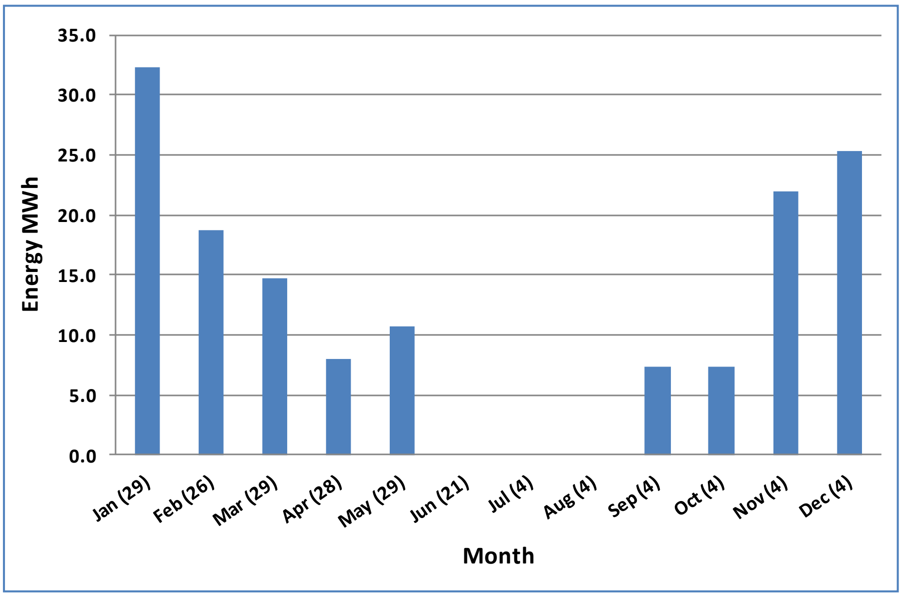


Figure 5-9. Monthly space heating energy demand

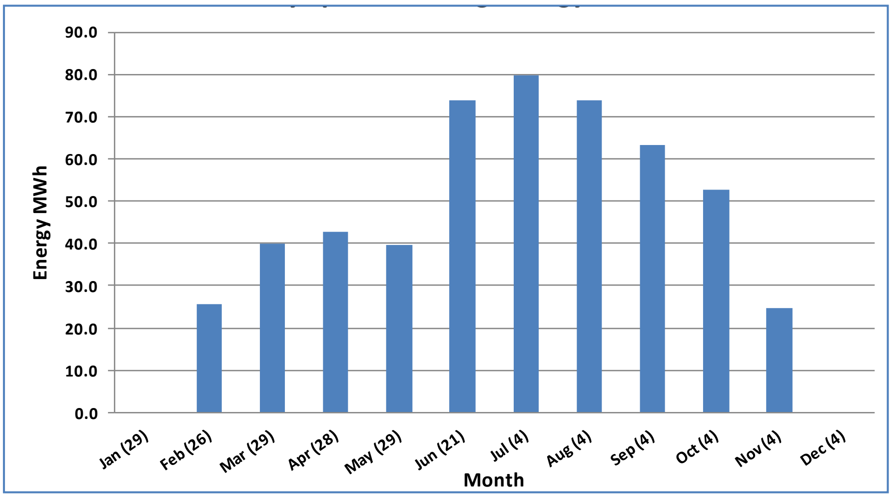


Figure 5-10. Monthly space cooling energy demand

Ventilation and air conditioning thermal load (sheet: "Ventilation – Air Con Load")

This sheet calculates the heat losses (or gains) associated with natural ventilation or air conditioning air flow, based on the specified ventilation rate per person. It is calculated over a 72 hour period (from 'cold' start i.e. after a period of non-use) for each month, using the building temperature profile. The calculation is based on the volume of air entering the building (specified by density of occupation and ventilation rate per person) and the difference between the external and internal temperatures. A heat recovery option (specified in terms of efficiency) can be selected to reduce the ventilation heat losses (the heating or cooling load). The results are available in both tabular and chart form. A typical chart is shown in Figure 5-11.

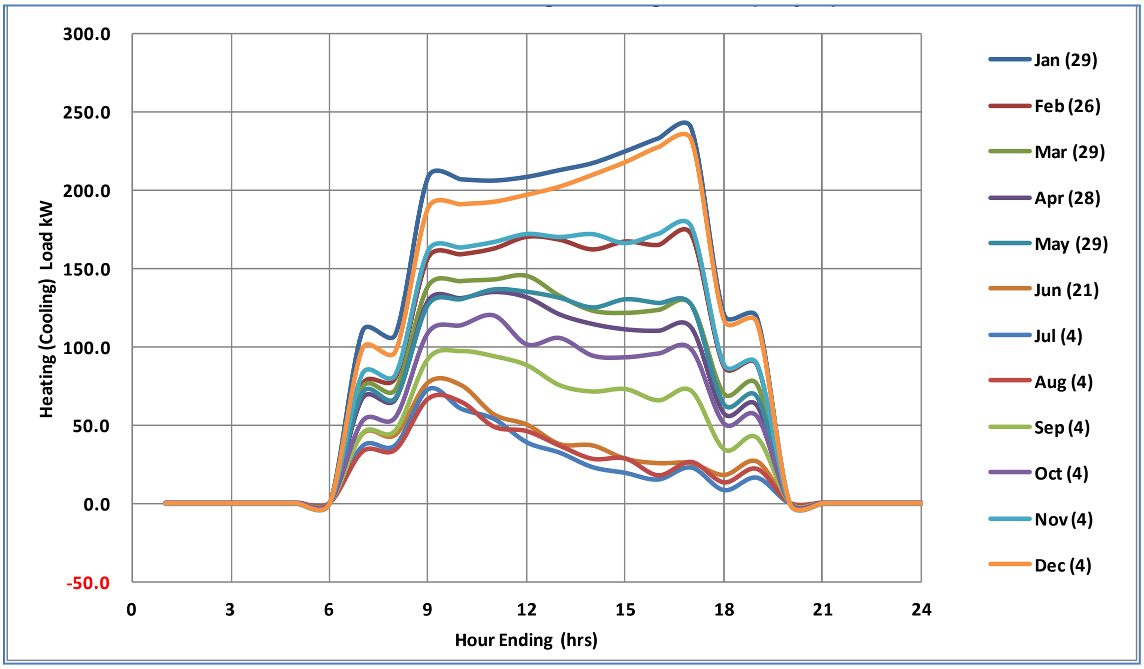


Figure 5-11. Ventilation and air conditioning load (day 3)

This sheet also calculates the night cooling ventilation heat load if the night cooling option is enabled. Again the load is calculated over a 72 hour period. The inbuilt algorithm permits night cooling only during the hours when the building is normally unoccupied and the heating and cooling systems are switched off, so the night cooling ventilation load is always zero when the building is occupied. Night cooling assumes the same ventilation rate (and electrical fan power) as when the building is occupied during the day. A typical day 3 chart is shown in Figure 5-12.

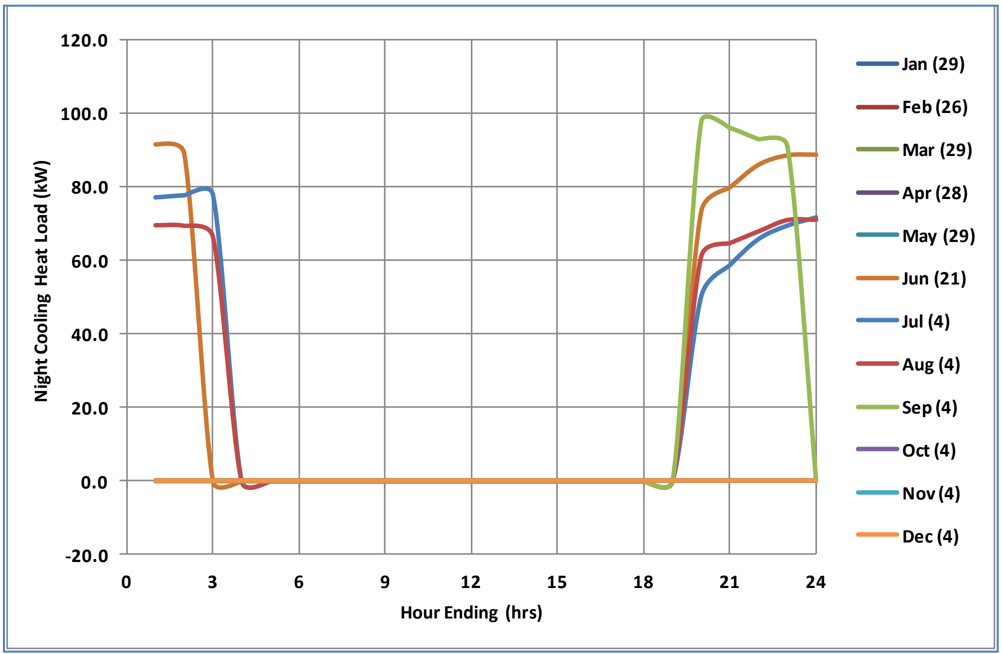


Figure 5-12. Night cooling ventilation heat load (night cooling enabled)

Building structure heat load (sheet: 'Building Fabric Heat Load')

This sheet calculates the heat losses (or gains) associated with the fabric and construction of the building and includes losses (or gains) due to thermal transmittance through the walls, ground floor and roof of the building and air infiltration. The losses are calculation using the actual building temperature at one hour intervals (dynamic load). The results are shown in both tabular and in chart form (for day 3). The chart is shown in Figure 5-13.

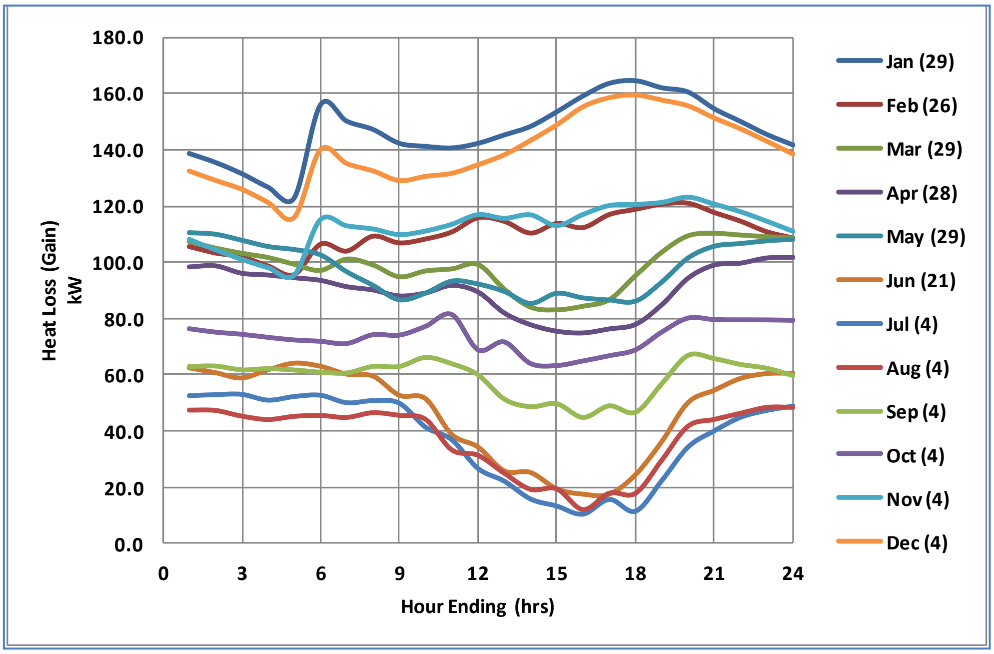


Figure 5-13. Building fabric heat loss (day 3)

Building solar gain (sheet: 'Solar_Gain_CIBSE_A_T2.30')

This sheet calculates the seasonal hourly solar radiation entering the building through each wall and sums the values to estimate the total solar gain in each 1 hour period. The results are tabulated and charted (Figure 5-14). The calculation should be considered an approximation, for the reasons described in the following paragraphs. However, it does provide results that are comparable with IES for simple rectangular shapes.

Solar gain for the building is calculated using CIBSE 97.5 percentile irradiance data, the glazing transmittance factor for the windows and a 'cloud transmittance' factor to convert from 97.5 percentile to average daily data for each month. To simplify the calculation it is assumed that the 4 sides of the building are aligned precisely North, South, East and West, with the user specifying whether the longest walls are aligned North-South or East-West, It is also assumed that the glazing (as a percentage of the wall area) is the same for all 4 walls. The solar gains are calculated for each vertical face then summed to generate a value for the whole building. The model does not currently include a calculation for solar gain due to roof glazing but this could easily be added.

The error in the calculation for the solar gain due to the alignment approximation is relatively small. The maximum angular error compared with an actual building's alignment is 45° and the solar gain error for any single face would be partly offset by a complementary error (of the opposite sign) for the adjacent face of the building. To illustrate this, changing the orientation of the default office building (60x30m) from N-S to E-W results in a difference in solar gain of less than 20% over any single month and less than 10% for the whole building over a 12 month period.

There is currently no provision for external shading, but this can be approximated by adjusting the glazing transmittance to simulate the effect. Although the cloud transmittance factor is assumed to be constant every month, in practice there will be a seasonal variation.

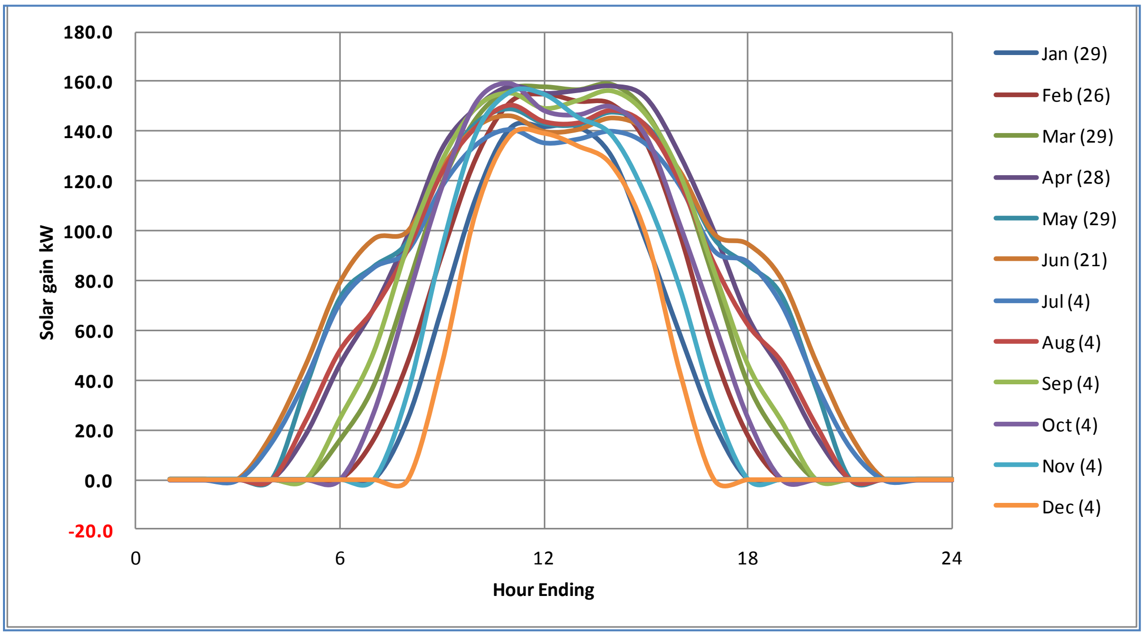


Figure 5-14. Building solar gain

Building internal heat gains (sheet: 'Internal Heat Gains – Simple')

This sheet calculates the internal heat gains for the building, based on occupancy profile, density of occupation and CIBSE benchmarks (CIBSE Benchmarks for office buildings - Guide A Table 6.1). The sources of heat gain are people (sensible and latent heat), lighting and equipment (computers etc.). There is currently no separate provision for cooking or heavy equipment loads, but these can be included by amending the lookup tables used in the calculation. The calculation is for sensible heat gains only - latent heat gains are summed but not included in the overall building energy balance calculation.

The daily internal heat gain is tabulated and charted (Figure 5-15). Monthly internal heat gains are aggregated using the typical number of working days in each month.

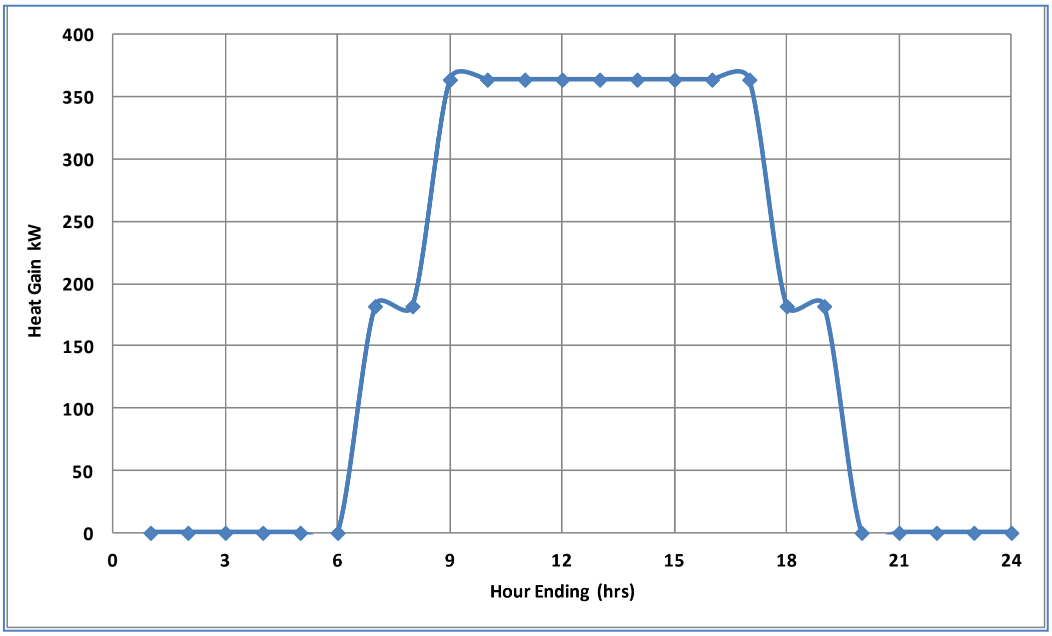


Figure 5-15. Building internal heat gains

Hot water (sheet: 'Hot Water Load')

This calculation uses CIBSE benchmarks for hot water demand and inlet and outlet temperatures, together with the occupancy of the building during each 1 hour period. It assumes a steady demand profile (per person) through the working day. The hot water energy load is not included in the thermal energy balance calculation for the building as it is assumed that the heat is not retained in the building but lost through the drainage system (however, it is included in the total energy demand and emissions calculations). Modifications to the worksheet could be made to allow for a percentage of the heat energy to be retained in the building (grey water heat recovery), also for the demand profile to be adjusted for peaks due to mealtimes and catering.

The hourly energy load is calculated and charted (Figure 5-16). The monthly energy demand is aggregated, using the typical number of working days in each month.

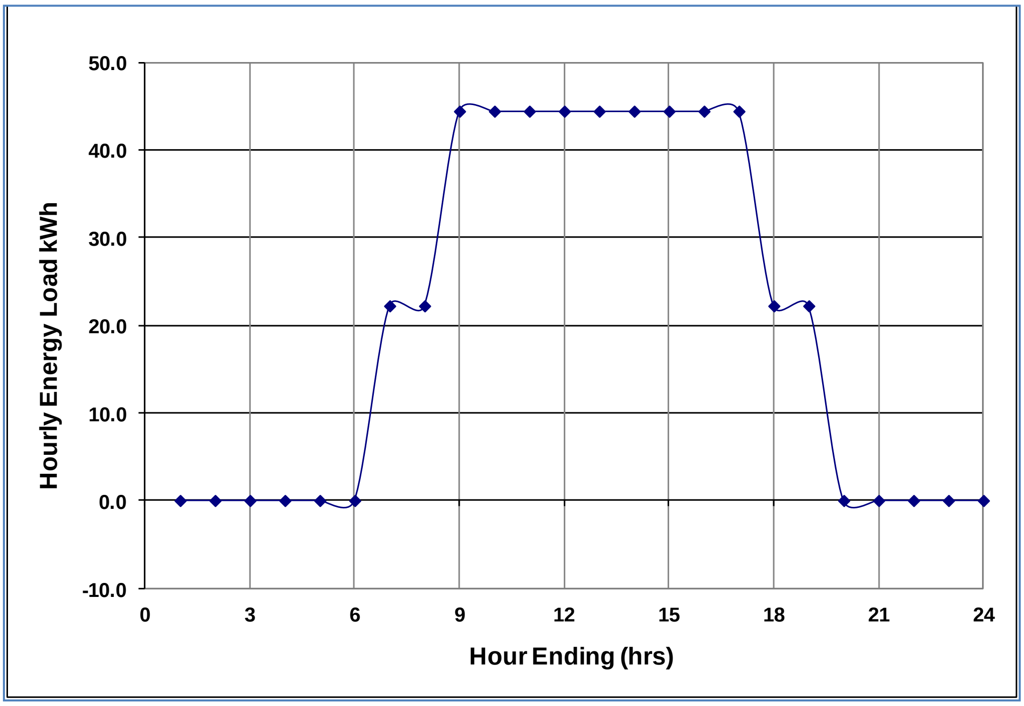


Figure 5-16. 24 Hour hot water energy Load

5.5 Building data sources - Building Regulations and energy benchmarks

The sources used for the building parameters used as data inputs for the new Excel tools are described in the following sub-sections. Most parameters have been taken from current and historical Building Regulations, the documented physical properties of the materials used in construction of buildings, or energy benchmark data. The Excel workbook includes default values that can be changed by the user, either from a pull-down list or by direct entry of the data into the relevant cells (highlighted in yellow).

For the past 40 years UK Building Regulations have set mandatory requirements for the thermal parameters of both domestic and non-domestic buildings and for the majority of buildings, unless of unusual design or built to a higher standard, these parameters are suitable for use in the analysis of energy demand and emissions. There have been many changes to the UK Building Regulations since their inception, so it is important to know which version applied at the time of construction. Table E-1 and Table E-2 in Appendix E summarise the evolution of the Regulations for non-domestic buildings and dwellings, including the year and key parameters for each version.

The thermal parameters for buildings that were constructed prior to the introduction of the UK Building Regulations can usually be derived from information available in a range of technical guides from organisations such as the Chartered Institute of Building Services Guide A (CIBSE, 2006b), provided that the method of construction and materials are known.

Energy benchmarks, which are produced by a variety of organisations, complement the Building Regulations, by providing reference values for supplementary energy use (such as lighting, ICT, small power, hot water, cooking and other building services) which can be used to construct and analyse a more complete model of a building's energy use than for the building fabric alone. Benchmarks have also been published for whole buildings of different types, allowing comparison and cross checking of the results from different energy modelling tools.

5.5.1 Building Regulations

Prior to 1976 there were no regulations pertaining to energy standards in buildings. UK Statutory Instrument (SI) 1976 No 1676 Part F (Thermal Insulation) and Schedule 11 introduced a requirement for the maximum U values of walls, floors, roofs and windows of dwellings, as well as specifying the required thickness for their construction (according to the material types used). The U values that were specified were 1.0 for walls (or 1.8 average including windows), 1.0 for floors and 0.6 for roofs. The requirements at that time did not extend to non domestic buildings.

In 1985 Statutory Instrument 1985 No 1065 Part L (Conservation of Fuel and Power) introduced new requirements for both dwellings and non-domestic buildings. In the case of dwellings the U values for walls and floors were reduced from 1.0 to 0.6 and for roofs from 0.6 to 0.35. For non-domestic buildings, the corresponding maximum U values for walls, floors and roofs were all 0.6 for shops and offices and 0.7 for industrial buildings. The SI also introduced requirements for heating system controls and insulation of hot water systems, pipes and warm air ducts. Building Regulations (NBS, 2014) are currently defined as Approved Documents Part L (ADL) and since 2002 they have been divided between ADL 1 (dwellings) and ADL 2 (non-domestic buildings). Since 2006 they have been further subdivided between new (A) and existing (B) buildings. New parameters such as air permeability for the building structure, mechanical ventilation requirements, Target CO_2 Emissions Rate (TER) and Dwelling Emissions Rate (DER), heat recovery and efficiency ratios for the heating and cooling systems, have also been introduced, together with a range of assessment procedures.

The evolution of Building Regulations for new dwellings and key parameters for each version are documented in Appendix F (Table F1 for non-domestic buildings and Table F2 for dwellings). The tables also include typical U values for buildings constructed using solid brick walls, as was common practice in the 19th and early 20th century. The most recent Building Regulations (2013) specify 2 sets of requirements - 'notional' and 'limiting' fabric parameters. If the building is designed and constructed in accordance with the 'notional fabric parameters' it should comfortably meet the TER (and DER) requirements, whereas a design that meets only the 'limiting fabric parameters' would not achieve compliance unless additional energy saving measures were employed. Since the introduction of Building Regulations typical U values for new buildings have reduced by a factor of as much as 10 times.

Table 5-12 shows the parameters used in this study for the comparative assessment of the energy performance and emissions of dwellings of different age and construction, using the new model.

Table 5-12. Building Regulations thermal design parameters for dwellings of different ages

Building Regulation/ Date	U Value			
	Pre-War/ Solid Walls	1976	2006	2013
Reference Document(s)	CIBSE Guide A Section 3	SI 1976/1676 Part F & Schedule 11	AD L1A (2006)	AD L1A (2013) Notional Dwelling Specs
External Wall	2.09 (220mm brick, 13mm plaster)	1	0.35	0.18
Roof	2.3 (no insulation), 0.71 (50mm insulation)	0.6	0.25	0.13
Floor	2.26 (vinyl, 50 mm screed, 150mm concrete), 1.37 (vinyl, 19mm timber, 100mm joists)	1	0.25	0.13
Windows	4.8 (single glazing, wood frame)	5.7 single 2.8 double glazed	2.2	1.4
Doors Opaque	2.7 (44mm solid wood)			1
Doors Semi Glazed				1.2
Windows as % of external walls		17% (for U = 5.7)		
Windows as % of total floor areas		-	Not specified	25%
Air Permeability			10m3/(h.m2) at 50 Pa (recomendation)	5m3/(h.m2) at 50 Pa
Mechanical Ventilation Specific Fan Power			2.0 W/l/sec (balanced) 0.8 W/l/sec (unbal)	
Mechanical Ventilation Heat Recovery Efficiency			66%	
Target CO_2 Emissions Rate (TER) Dwelling CO_2 Emissions Rate (DER)			TER = SAP2005 - 20% DER <=TER	

Table 5-13 lists the equivalent parameters for non-domestic buildings.

Table 5-13. Building Regulations thermal design parameters for non-domestic buildings of different ages

Building Regulation/ Date	U Value			
	Pre-War/ Solid Walls	1985	2006	2013
Reference Document(s)	CIBSE Guide A Section 3	SI 1985/1065 Part L	AD L2A (2006)	AD L2A (2013) Notional Building Parameters
External Wall	2.09 (220mm brick, 13mm plaster)	0.6 net (residential/ shop/ office) 0.7 net (industrial)	0.35	0.26
Roof	2.3 (no insulation), 0.71 (50mm insulation)	0.6 net (residential/ shop/ office) 0.7 net (industrial)	0.25	0.18
Floor	2.26 (vinyl, 50 mm screed, 150mm concrete), 1.37 (vinyl, 19mm timber, 100mm joists)	0.6 net (residential/ shop/ office) 0.7 net (industrial)	0.25	0.22
Windows	4.8 (single glazing, wood frame)	5.7 (for glazing as below)	2.2	1.6
Doors Opaque	2.7 (44mm solid wood)		2.2	1
Doors Semi Glazed			2.2	1.2
Air Permeability			10m3/(h.m2) at 50 Pa (recomendation)	5m3/(h.m2) at 50 Pa
Carbon Performance Rating Air Conditioning			10.3 kgC/m2/yr	
Carbon Performance Rating Mechanical Ventilation			6.5 kgC/m2/yr	
Whole Office CPR Nat Ventilated			7.1 kgC/m2/yr	
Whole Office CPR Mech Ventilated			10 kgC/m2/yr	
Whole Office CPR Air Conditioned			18.5 kgC/m2/yr	
Mechanical Ventilation Specific Fan Power				1.8 W/l/s
Mechanical Ventilation Heat Recovery Efficiency				70%
Target CO_2 Emissions Rate (TER) Building CO_2 Emissions Rate (BER)			TER = SBEM (2005) BER <= TER	
Cooling SSEER				2.7 (mixed mode) 3.6 (Air Con)

5.5.2 Energy benchmarks

At system and component level, many energy benchmarks are available – these are estimates based on the power consumption of the individual systems and components, together with an assumed utilisation factor (or operating hours per annum) and can be used directly in energy modelling.

Reference benchmarks for other parameters such as ventilation rate, internal heat gains and supplementary energy use (including lighting, ICT, small power, hot water, cooking and other building services) are usually based on the building's occupancy density and use. In this study most of the reference data used was obtained from CIBSE Guide A (CIBSE, 2006b), but is also available from other sources, including CIBSE Guide B (CIBSE, 2005b) and Guide F (CIBSE, 2004), various Carbon Trust publications and the BSRIA 'Rule of Thumb' guide (BSRIA, 2011).

Overall building energy benchmarks can be helpful in predicting the overall performance of new and existing buildings, but the available data tends to be rather limited, especially in relation to cooling parameters. In many instances the data are restricted to annualised electricity and fossil fuel energy use, normalised to a unit floor area (kWh/m^2 per year). Sub-metering is not widely employed, so cooling energy benchmarks are very generally not identified separately.

One of the most comprehensive sources of energy benchmarks is CIBSE Guide F (CIBSE, 2004). Chapter 20 of this guide details all of the known energy and component benchmarks (from all sources) at the time of publication. It includes both 'typical' and 'good practice' figures for fossil fuel and electricity consumption, for multiple building types, split by major categories such as: Catering; Entertainment; Education ('higher' and 'schools'); Hospitals; Hotels; Industrial; Local Authority; Ministry of Defence; Offices; Primary Health Care; Public Buildings; Residential and Nursing Homes; Retail; Sports and Recreation. These are further split by specific building function (e.g. for Public Buildings: Churches; Courts; Libraries; Museums; Prisons etc.). Additional tables provide more detailed system and component benchmarks for specific building types, although many are based on data from a relatively small sample (<50). Table 5-14. shows the breakdown for a 'standard' air conditioned office (Type 3), which is typical of many offices built in the past 20-30 years. Both 'Good Practice' and 'Typical' data are given, indicating that the energy demand in 'Good Practice' buildings is around 50% of that for 'Typical' buildings. It should be noted that the cooling energy is reported in terms of the electrical energy required to drive the cooling system (primary energy input), so to estimate the thermal cooling energy delivered the electrical energy should be multiplied by the COP of the cooling system.

Table 5-14. Office Type 3 ('standard' air conditioned) breakdown of system and building energy benchmarks

System	Delivered Energy (kWh/m^2 per year)	
	Good Practice	Typical
Gas/oil heating and hot water	97	178
Catering gas	0	0
Cooling	14	31
Fans, pumps and controls	30	60
Humidification	8	18
Lighting	27	54
Office equipment	23	31
Catering electricity	5	6
Other electricity	7	8
Computer room	14	18
Total gas or oil	97	178
Total electricity	128	226

[Source: CIBSE (2004) Table 20.9]

CIBSE Technical Memorandum TM46 (CIBSE, 2008) was produced to provide a set of overall building energy benchmarks that are compatible with the requirements of the EU Energy Performance of Buildings Directive (EPBD), which was implemented in the UK via changes to Part L of the Building Regulations in 2006 and through the Energy Performance of Buildings (Certificates and Inspections) (England and Wales) Regulations 2007 (as amended) and the Energy Performance of Buildings (Certificates and Inspections) Regulations (Northern Ireland). These introduced requirements for energy certification of buildings and inspection of air conditioning systems. The Department for Communities and Local Government (DCLG) developed an operational ratings procedure for Display Energy Certificates and CIBSE proposed benchmarks that were based on Chapter 20 of CIBSE Guide F. These were subsequently amended following consultation to produce the 29 benchmark categories and building types listed in TM46 Table 1. TM46 also includes factors that can be used to adjust the benchmarks for variable weather data (using degree days) and different occupancy profiles. A comparison of TM46 and CIBSE Guide F benchmarks for some equivalent building types is shown in Table F1 (Appendix F).

Some additional benchmarks have been extracted from the BSRIA Rule of Thumb guidelines for building services and are also listed in Table F1 (Appendix F). They identify the heating and cooling loads separately for some building types (in W/m^2) and additional columns have been included, with estimates for the annual heating and cooling energy demand (kWh/m^2 per annum), based on specific assumptions regarding annual operating hours for the heating and cooling systems. The cooling energy demand figures cannot be directly compared with those listed in Guide F (which reports cooling energy in terms of the electricity used rather than thermal energy and takes into account the cooling system COP).

5.6 Sources of weather data and future weather data

For simplicity, the energy and emissions simulation model developed for this study uses 'typical day' 24 hour dataset for each month rather than a full 24 hour dataset for each day in the month. One of the objectives was to achieve near 'real time' modelling and this approach reduces the computation time by as much as 30 times, due to the smaller dataset (with only a minor impact on the accuracy of the results if the 'typical day' datasets are generated by averaging all of the data in the full datasets, as described below).

Dry bulb temperatures are used, together with solar radiation data and an empirically derived cloud cover factor. Wind, rain and humidity data were excluded, again in the interests of simplicity and processing speed. The temperature and solar gain data are therefore 24 row (hour) x 12 column (month) matrices. The weather dataset was initially derived from CIBSE Guide A table 2.30 (97.5 percentile irradiance) and table 2.34 (air and air-sol temperatures for the London area).

During assessment of the new Excel simulation model against an equivalent building using IES-VE software, some of the differences were found to be associated with the different weather data sets used. IES-VE uses a more comprehensive dataset of .fwt and .epw files, derived from TRY data, whilst the one used in the Excel tool was the Heathrow file ‘Hrow9697.fwt’. A reduced dataset for the ‘Hrow9697.fwt’ file was therefore generated by averaging the hourly values over all the days in each calendar month to produce a 24 x 12 matrix that would be compatible with the new simulation model. When this weather dataset was used the correlation between the IES-VE simulation and the simulation using the new model improved significantly. Figure 5-17 shows a comparison between the two weather datasets, indicating that the average temperatures over a month differed by up to 5°C.

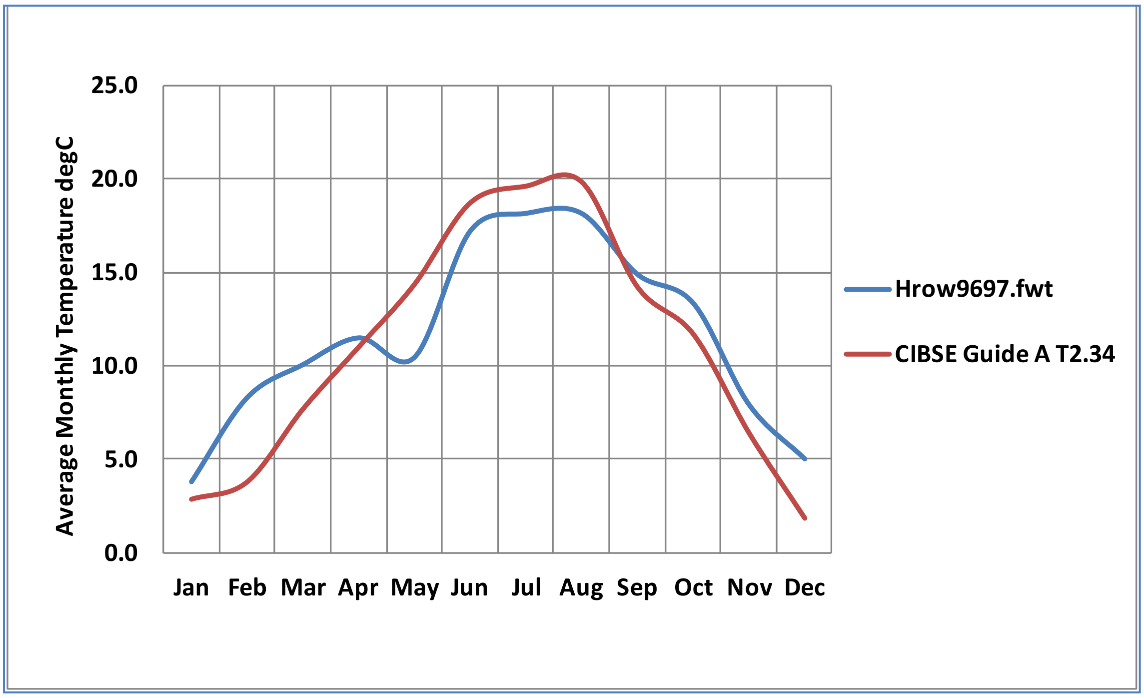


Figure 5-17. Comparison of temperature data derived from CIBSE Guide A Table 2.34 and IES-VE Hrow9697.fwt file

Having validated the new simulation model using the ‘Hrow9697.fwt’ data, the sourcing of additional weather data files, including future weather data for modelling the impact of climate change, was researched. The outputs of the Prometheus project undertaken by Exeter University Centre for Energy and the Environment (Exeter, 2013) include not only data for inner and outer London (represented by Islington and Heathrow), but also future weather data for the years 2030, 2050 and 2080. The Prometheus files were created using the outputs of the UKCP09 weather generator, which uses the 2009 climate change scenario predictions and a gridded set of baseline data from the period 1961 to 1990.

Weather data files were downloaded for London Heathrow and London Islington, covering the years 2030, 2050 and 2080. The 50th percentile (a1b) scenarios were selected, together with 'control' files based on historical data. Both TRY and DSY files were downloaded. The files (in .epw format) were opened in Excel and post processed by averaging the hourly values over every day in each calendar month to generate the required 24 x 12 matrices for simulation. Together with the CIBSE and Hrow9697 weather files a total of 14 averaged temperature files were then available for use in the simulation model.

Figure 5-18 shows the resulting average monthly temperature for the 14 data sets, indicating a difference between datasets of around 5°C for most months, the peak value in July/ August being (as expected) for the 2080_Islington_DSY dataset.

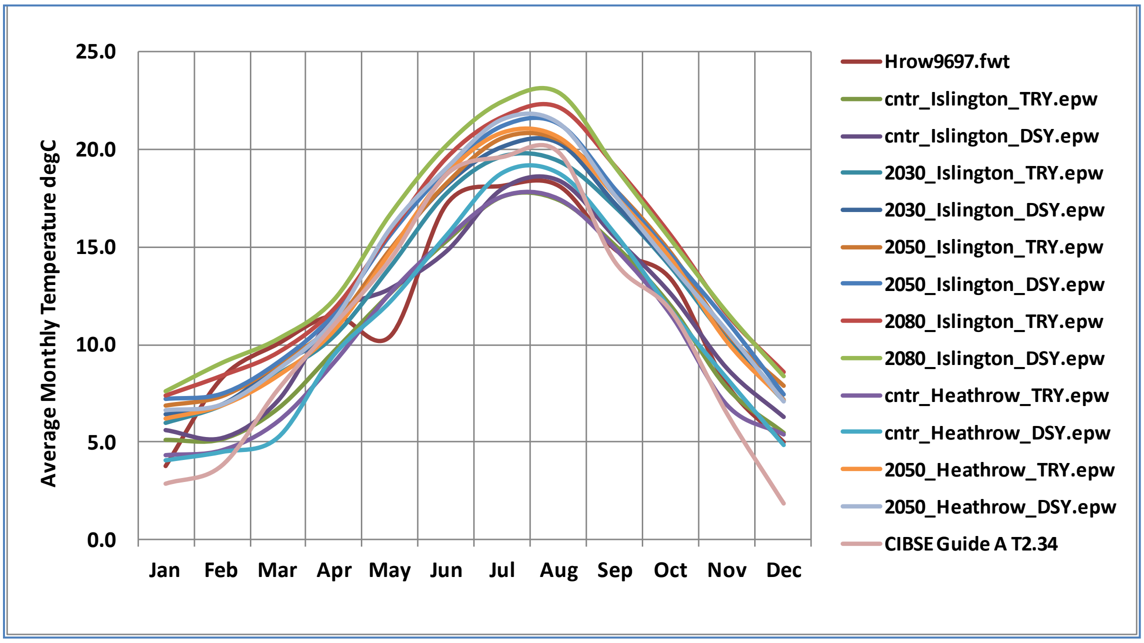


Figure 5-18. Average monthly temperature for the 14 datasets generated for simulation

However, since the averaging process smoothes out the peak temperatures, a further set of 13 files were generated by extracting the peak temperatures in each one hour period for every calendar month (this was not possible for the CIBSE data as it was already a reduced dataset). The peak temperatures were also averaged over 24 hour periods and are shown in Figure 5-19. Comparison with Figure 5-18 indicates that peak temperatures are typically 7 to 8°C higher.

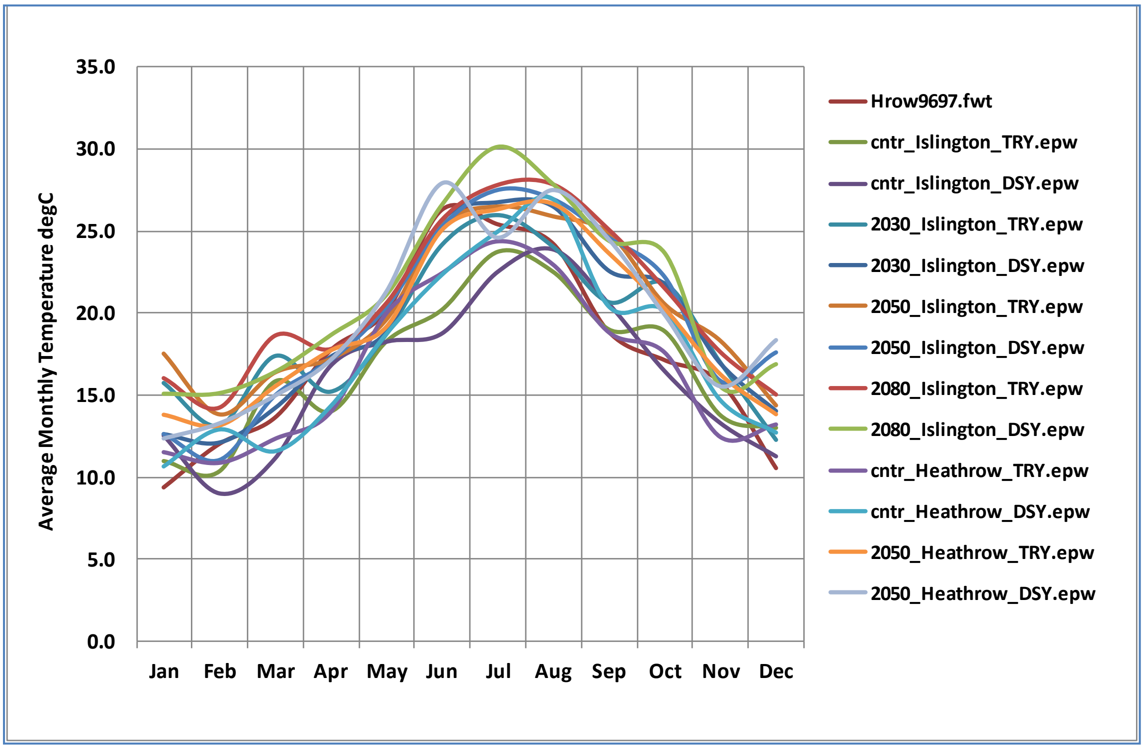


Figure 5-19. Daily average of the peak hourly temperatures (13 datasets)

A more detailed example of the difference between these datasets is given in Figure 5-20 and Figure 5-21, which plot the 24 hour temperature data in the month of July, for average and peak monthly temperatures respectively. The peak temperatures are typically between 4°C and 8°C higher than the average temperature over the 24 hour periods, for the range of scenarios.

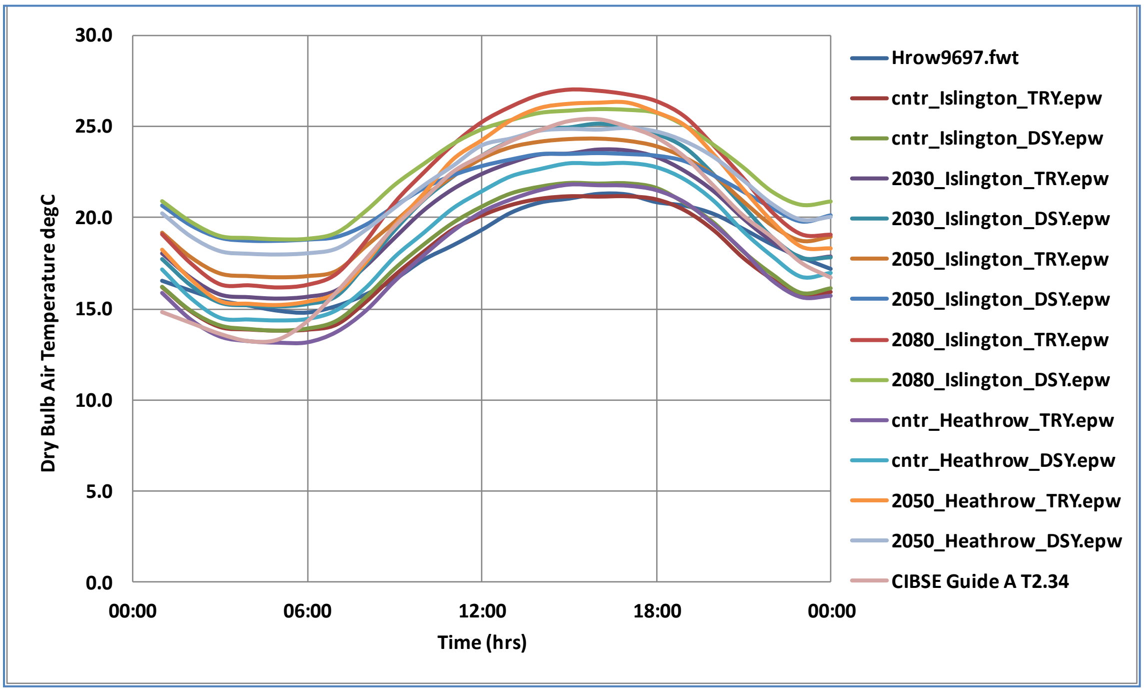


Figure 5-20. Average hourly temperature for the month of July (14 datasets)

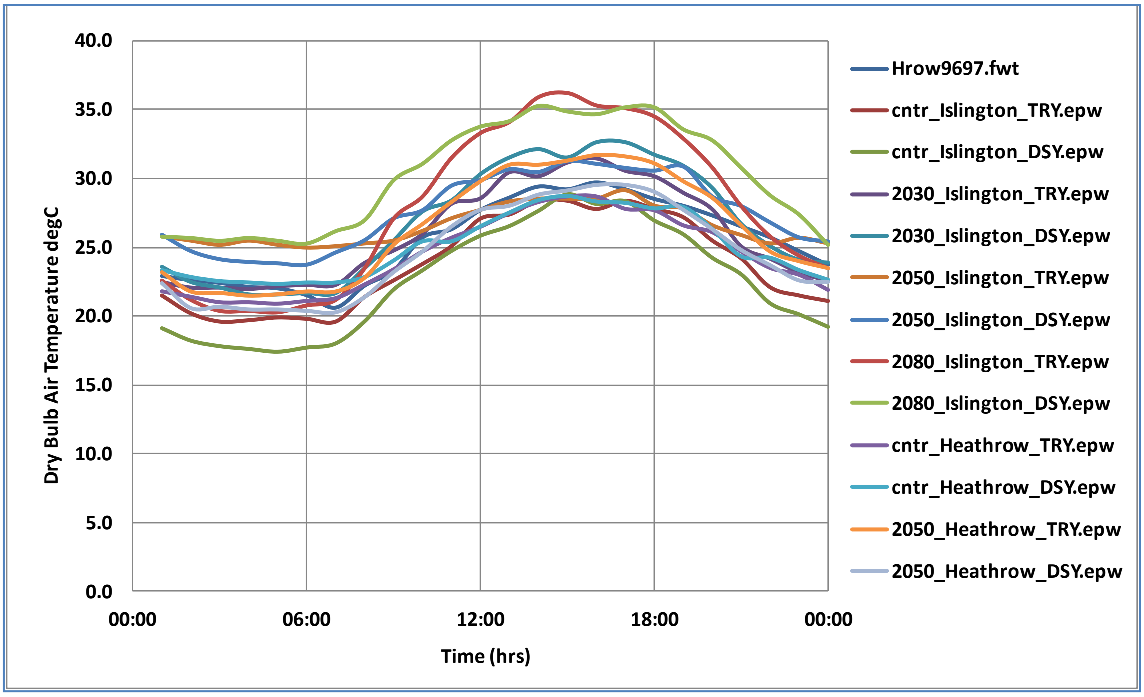


Figure 5-21. Peak hourly temperature for the month of July (13 datasets)

The 14 datasets with averaged hourly data can be used directly in the simulation model to estimate the typical energy demand and emissions for average weather conditions, while the 13 datasets with peak hourly data can be used to simulate extreme hot weather conditions, when the risk of overheating is greatest.

A summary description of the types of weather data normally used in simulation is included in Appendix G, together with tables generated from the Prometheus downloads and post-processing, The tables list the average daily temperature, average peak hourly temperature and the minimum and maximum temperature for each month, providing a summary indication of the differences in the data due to the alternative methods of post processing the downloads.

The complete temperature datasets are available in an Excel file (PROMETHEUS_London_Weather_Data_Files_Rev5_161129).

Chapter 6. Excel tool simulation results and comparisons

This chapter describes the results of simulations for a typical office building and dwelling and their comparison with benchmarks and energy and emissions data derived from other sources.

Owing to the difficulty in accessing real energy and emissions data for buildings, the results for the office building were also compared with an equivalent simulation using an industry standard software package, IES-VE (IES, 2014).

The relevant IES and Excel files are:

Office_6ST_1800FA_RECT_121029 (IES project folder)
Building_Energy_Model_130205_Hrow9697_Weather_File (Excel office building file)
IES-Excel_comparison_60x30m_office_130614_Rev170130 (Excel results comparison file)
Building_Energy_Model_House__150916_Climate_170122 (Detached welling file)

Initial simulation results indicated some significant differences between the IES and Excel results. However, these simulations used different weather data, so an exercise was undertaken to download the weather file used by IES and post-process it to the required format for the Excel simulation. Running the simulation with this new weather data produced much closer results between the IES and Excel simulation.

The benchmarks and other data sources used for the other comparisons are described in Chapter 5 (section 5.5), Appendix F and Appendix H.

6.1 Office building description

The building used for cross checking the Excel model was a 6 storey office building 60m x 30m in plan, located in London suburbs and constructed to the 2006 UK Building Regulations (ODPM, 2006), with the major axis aligned East-West. The windows on all sides were 40% of the wall area and the low emissivity double glazing had a transmittance of 0.54 and a U value of 2.2 W/m^{2}K. An occupation density of 12m^2/ person was assumed and a ventilation rate of 12.5 l/sec per person. The building was assumed to be occupied between the hours of 7 a.m. and 6 p.m. Monday to Friday, with the heating and cooling set points at 19°C and 21°C respectively. It was assumed that the building was heated using a 1 MW gas boiler with 90% efficiency and cooled using an 800 kW air-cooled vapour compression chiller with R410A refrigerant and a system EER (Energy Efficiency Ratio) of 2.25. Both heating and cooling plant were capable of being modulated in 20% increments of their peak output power (the output level at any time was set automatically according to an inbuilt algorithm and look-up table). The pre-heating and pre-cooling periods could be selected in 1 hour increments by the user.

The building is described in the Excel model by its dimensions, whereas in IES-VE it is represented by a 3D sketch (Figure 6-1). The design and operating parameters were set to be the same for both simulations, using benchmark values for internal gains from people, lighting and small power.

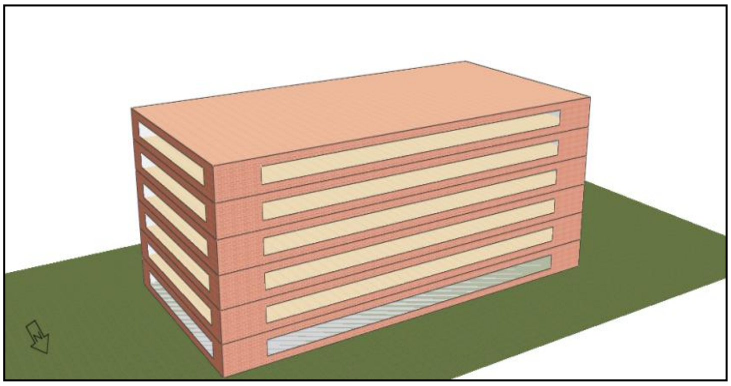


Figure 6-1. IES-VE 3D representation of the office building used for cross checking simulation results

6.2 Excel results for the office building

The following Figures show some of the results of the simulation (see also Section 5.4.4 which describes the outputs available from the tool. Figure 6-2 indicates the transient behaviour of the building and how the internal temperature varies over a 72 hours from a cold start. For clarity only 3 months are shown (January, April and July), which are fairly representative of the variation between the different seasons through the year. The simulation starts at 12 midnight and during the first 24 hours demonstrates the performance from a cold start. The full 12 month data is available in the Excel project file included on the project data disk.

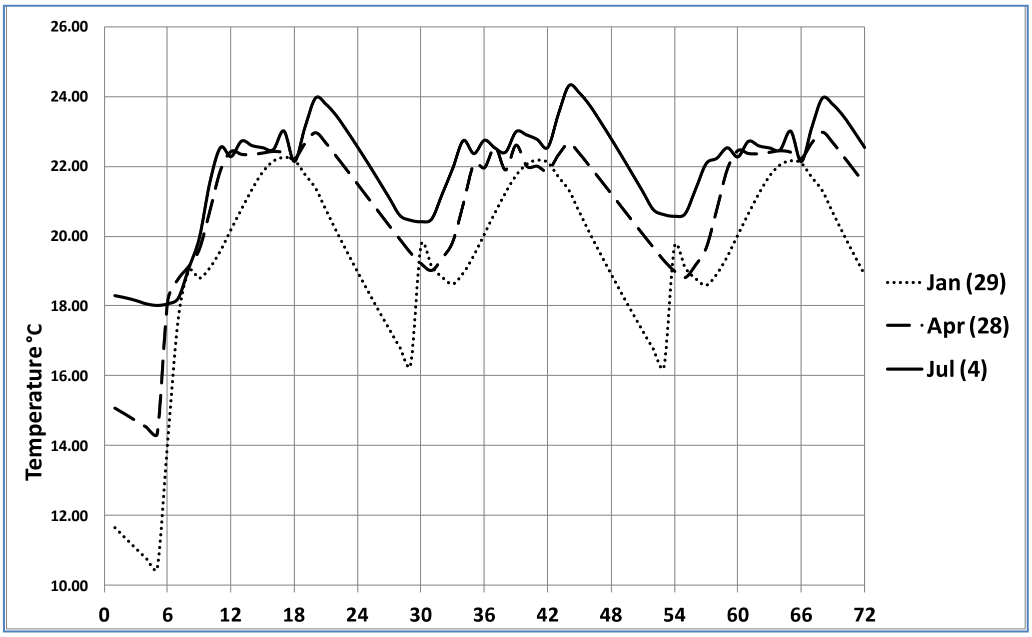


Figure 6-2. Simulation of the building temperature profile over 72 hours from cold start

Figure 6-3 shows the temperature profile for day 2, with the occupancy period highlighted The heating and cooling systems maintain the temperature within a window of approximately 19°C to 23°C when the building is occupied and the pattern of temperature variation over the course of the day indicates that heating is required only during the morning, as internal and solar gains tend to be sufficient to maintain the building internal temperature once the set point has been reached (even in winter). In summer the building temperature continues to rise after the occupants have left and the cooling is switched off. Night cooling is enabled in this example, which helps to reduce the early morning cooling load.

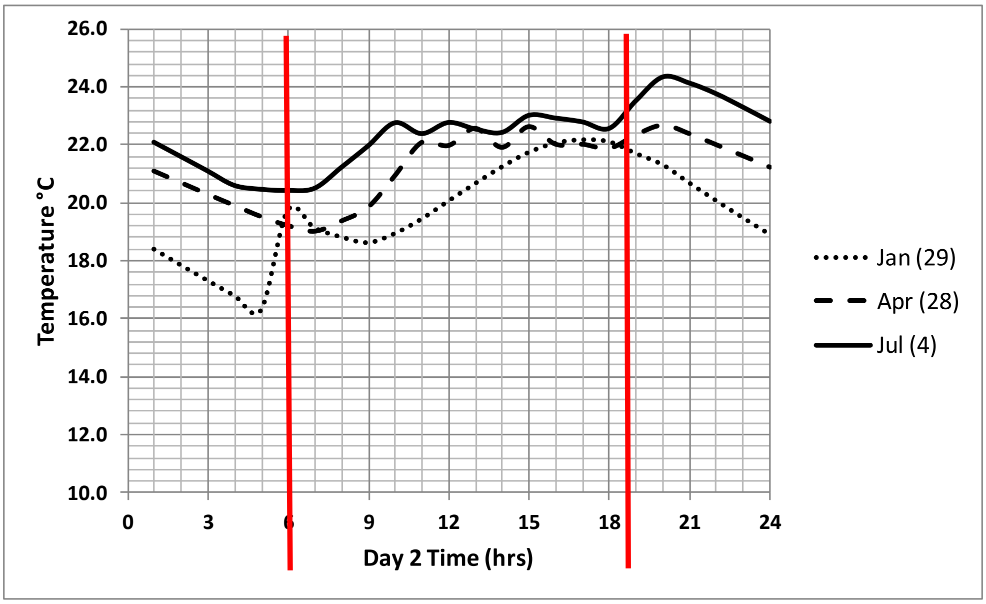


Figure 6-3. Simulation of the building temperature profile during day 2 occupancy period

Typical heating and cooling loads for day 3 are shown in Figure 6-4 and Figure 6-6. These indicate that whilst heating is required only in the early morning hours (because the building is effectively self heating), in the summer cooling is required throughout the day to avoid overheating.

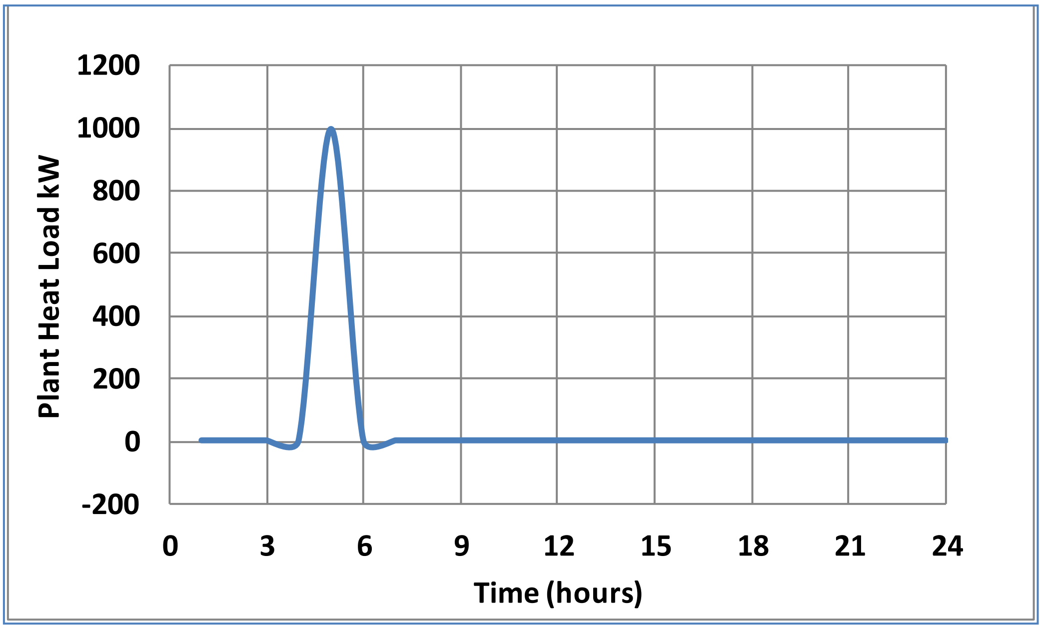


Figure 6-4. Office building day 3 heating plant load (January)

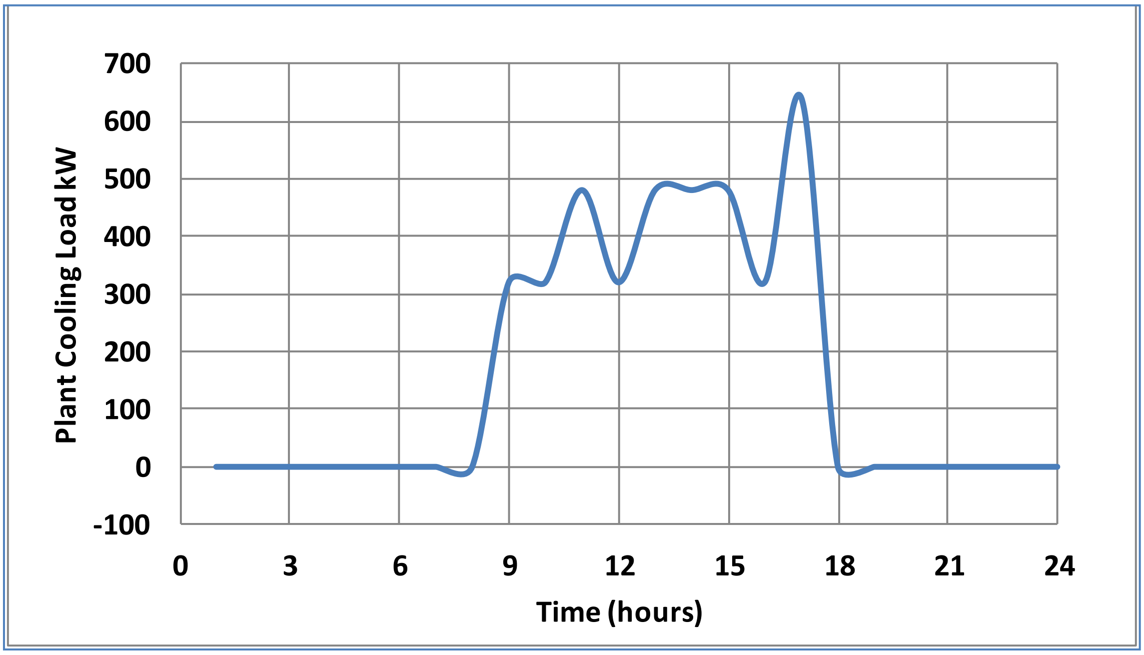


Figure 6-5. Office building day 3 cooling plant load (July)

A snapshot view of the results dashboard is shown in Figure 6-6. The dashboard can be configured to suit the user's preference by copying and pasting charts from any of the worksheets.

The dynamic energy balance chart for day 3 (see Figure 6-6 and Figure 5-6) shows the heating or cooling energy that is needed in order to maintain the net energy balance for the building at any point in time. It implies that for most of the time that the building is occupied (07:00-19:00 hrs) the heat gains are higher than the thermal losses, even in mid-winter, so the building normally requires cooling. This suggests that for modern buildings of this type, consideration should be given to shifting the emphasis on energy conservation and emissions reduction from heating to cooling, especially when taking future global warming into account.

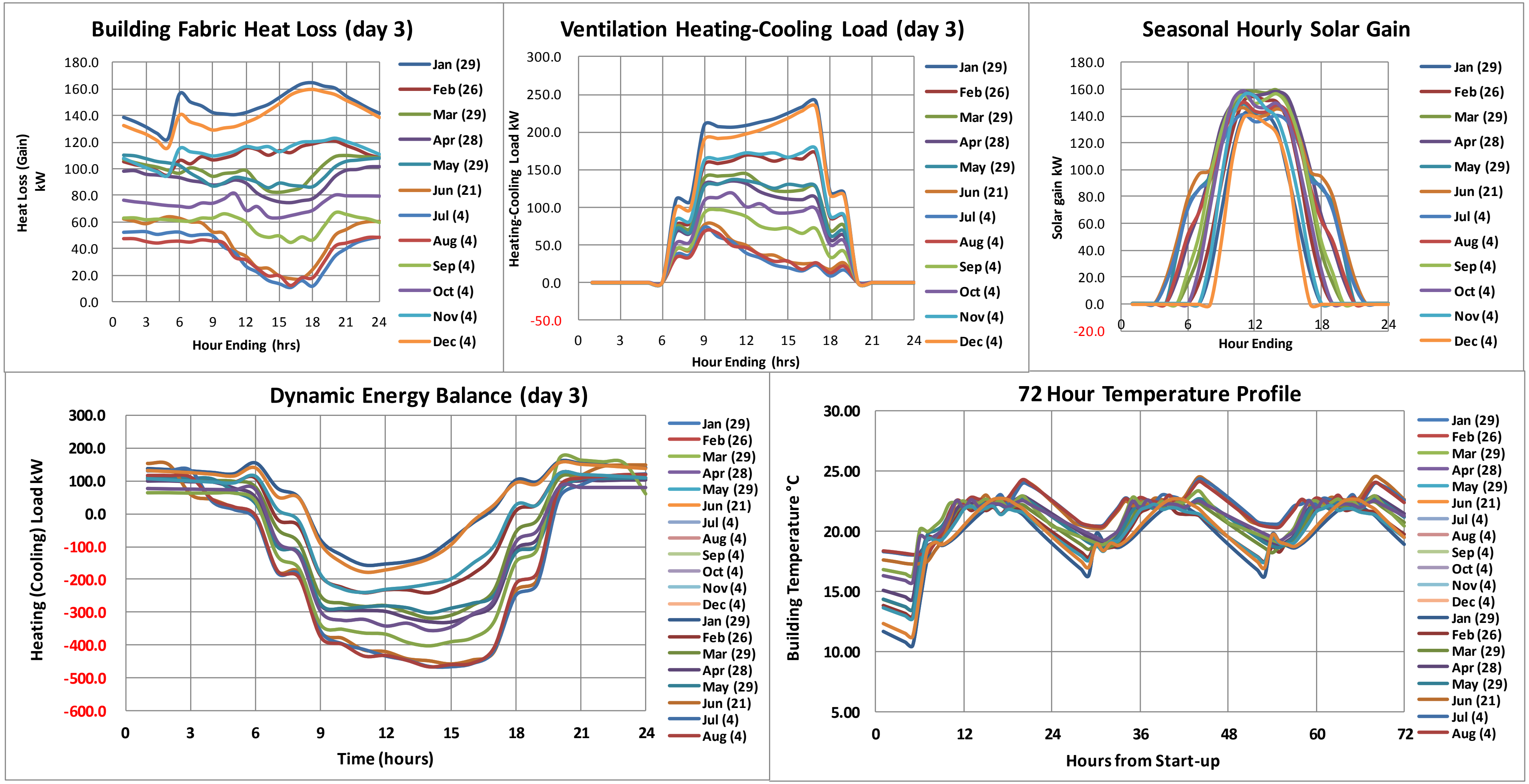


Figure 6-6. Results dashboard for office building simulation (configurable – other charts can be copied and pasted into this sheet)

Table 6-1. Annual heating and cooling energy and emissions for the office building

	Delivered Heating/ Cooling Energy MWh/yr	Delivered Heating/ Cooling Energy MWh/m^2/yr	Prime Energy MWh/ yr	Prime Energy kW/m^2/yr	Annual Emissions kgCO_2(e)	Annual Emissions kgCO_2(e)/m^2
Cooling	516	48	241	22	107,283	9.9
Refrigerant Loss					13,760	1.3
Heating + HW	146 + 125	14	286	26	58,388	5.4
Electricity (other)			970	90	432,020	40.0
Total			1,497	139	611,450	57

Table 6-1 summarises the annual delivered energy and emissions for the office building. It indicates that the delivered cooling energy is nearly 4x the heating energy. Taking the COP of the air conditioning system into account (including distribution and delivery losses) the prime energy demand for cooling is 241 MWh/m^2/yr, or an energy density of 22 kWh/m^2/yr. For heating and hot water, also taking into account the efficiency and distribution losses the prime energy demand is 286 MWh/m^2/yr, or an energy density of 26 kWh/m^2/yr. However, the cooling emissions are higher than those for heating and hot water, because of the higher carbon factor for electricity compared with gas fuel. In practice, both heating and cooling emissions combined are only 56% of the emissions associated with other electricity use (lighting, IT, small electrical and auxiliary fans, pumps etc.).

Figure 6-7 plots the building emissions for each month and confirms that the emissions associated with electrical energy use within the building predominate, followed by the energy related cooling emissions (indirect emissions from the energy used to power the cooling plant). In comparison, the emissions associated with the heating and hot water plant are relatively small, while the emissions due to refrigerant leakage make the smallest contribution to overall emissions in this instance (based on an annual refrigerant leakage rate of 5% of the refrigerant charge).

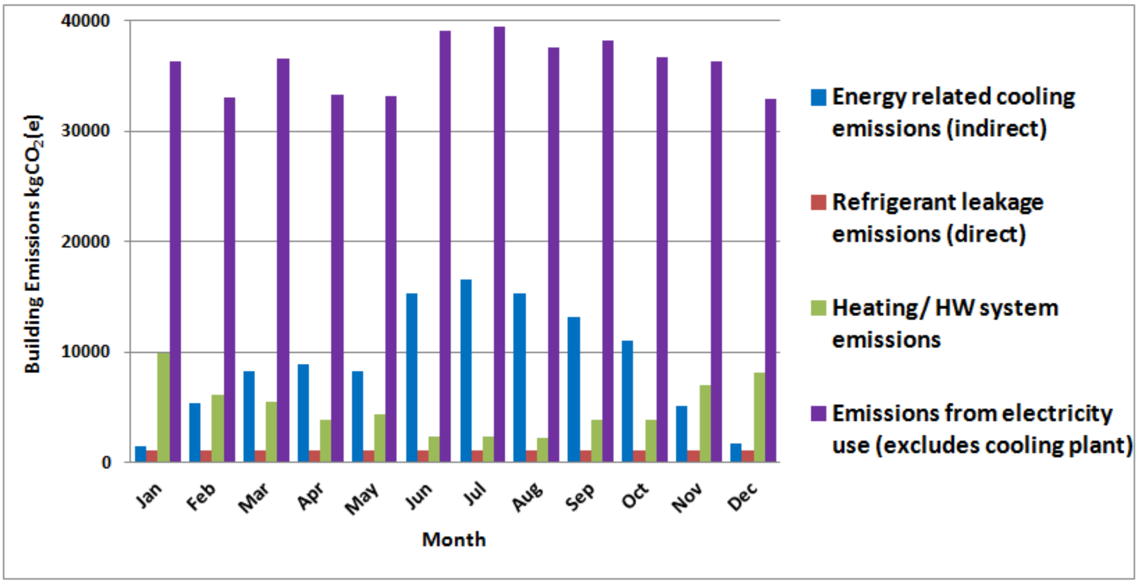


Figure 6-7. Office building breakdown of monthly emissions from all sources

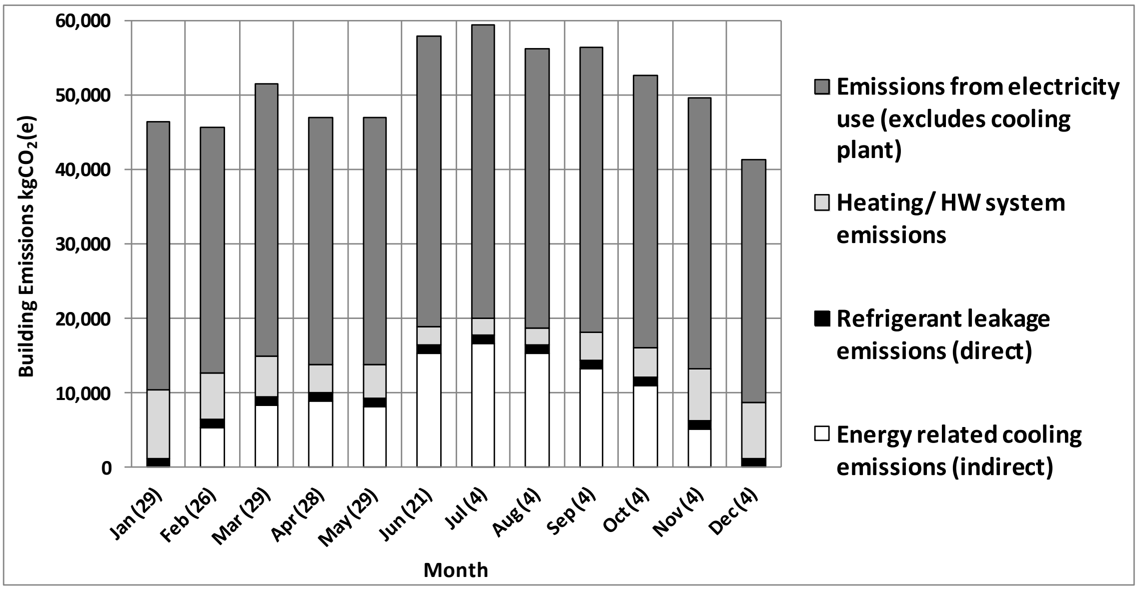


Figure 6-8. Office building total monthly emissions from all sources

A stacked column chart analysis (Figure 6-8) confirms that the peak monthly emissions associated with cooling energy are less than 30% of the total. Direct emissions from refrigerant leakage are less than 2% of total emissions. For this particular building, reducing the electricity use (for example through the use of more efficient lighting and IT systems) could be the most effective way to reduce emissions, since it would at the same time reduce the internal heat gains and consequent cooling load and emissions. There might also be opportunities to reduce emissions still further using a more efficient cooling system.

6.3 Comparison of the Excel office building results with IES-VE

The overall building heating and cooling loads and the heat loads associated with the building fabric, ventilation system, solar gain and internal gains were compared with IES simulations.

Figure 6-9 shows the monthly heating plant load for the IES and Excel simulations. Whislt the values for the months of December and January are in fair agreement, for other months the IES model predicts much lower heating plant loads than the Excel model. The annual heating plant load is predicted to be 87 MWh for the Excel model compared with 64 MWh for IES. The IES results are somewhat surprising for the winter months of November, February and March, in relation to the external temperature profile.

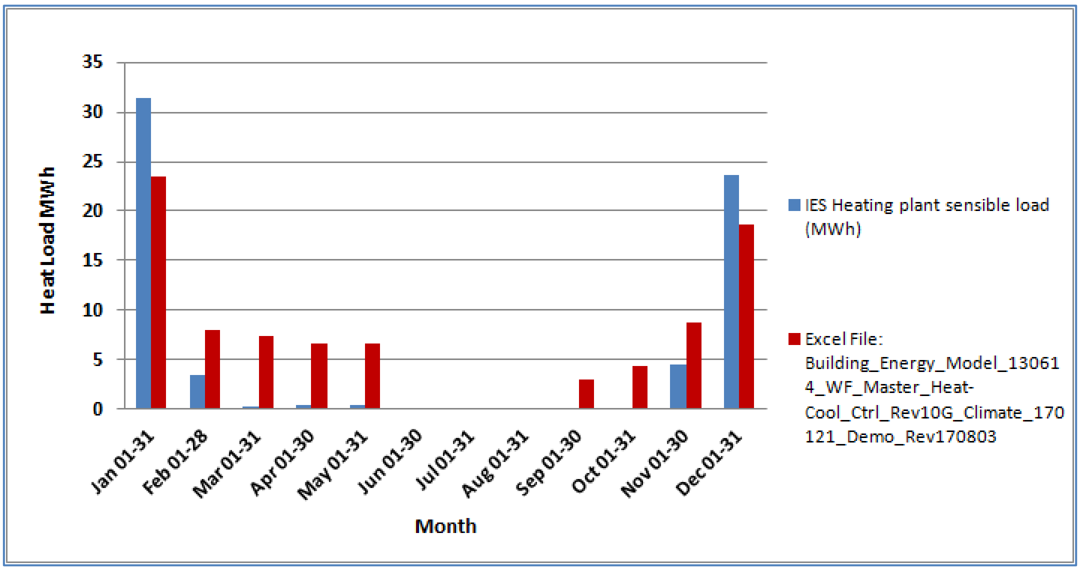


Figure 6-9. Monthly net heating plant load for IES and Excel simulations

Figure 6-10 charts the overall cooling load profile for the building for the IES and Excel models, indicating reasonable agreement in summer but less good in winter. On an annual basis the Excel simulation predicts a cooling plant load of 512 MWh compared with 437 MWh for IES.

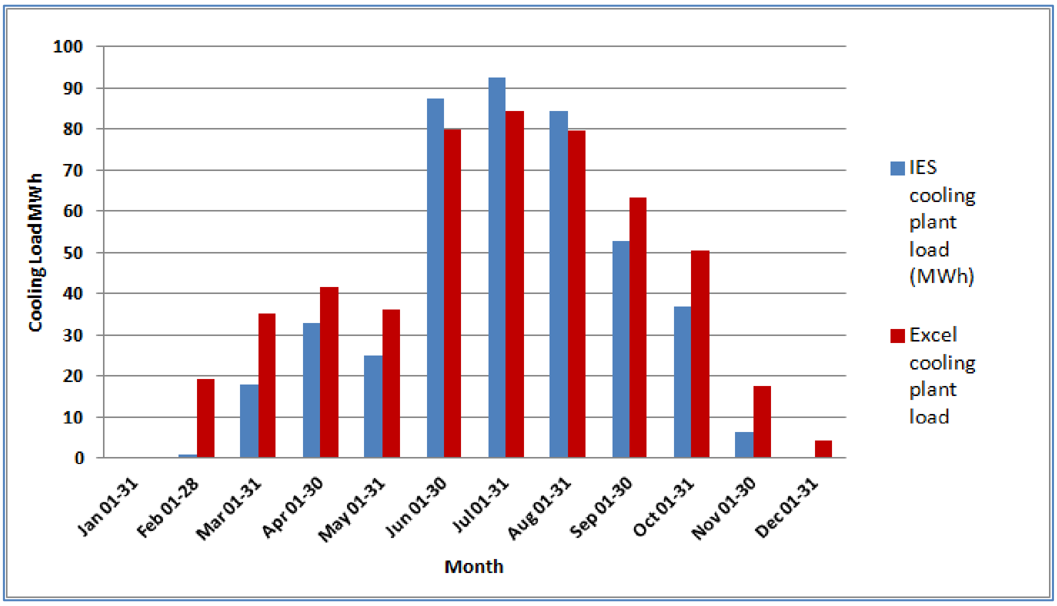


Figure 6-10. Monthly net cooling load for IES and Excel simulations

Examination of the building fabric heat load profile and ventilation heat load charts (Figure 6-11 and Figure 6-12) indicates that the Excel simulation predicts higher heat losses than IES in winter and slightly lower losses in summer. However, averaged over the year the net heat load profiles for the building fabric and ventilation heat losses are quite similar for the Excel and IES simulations.

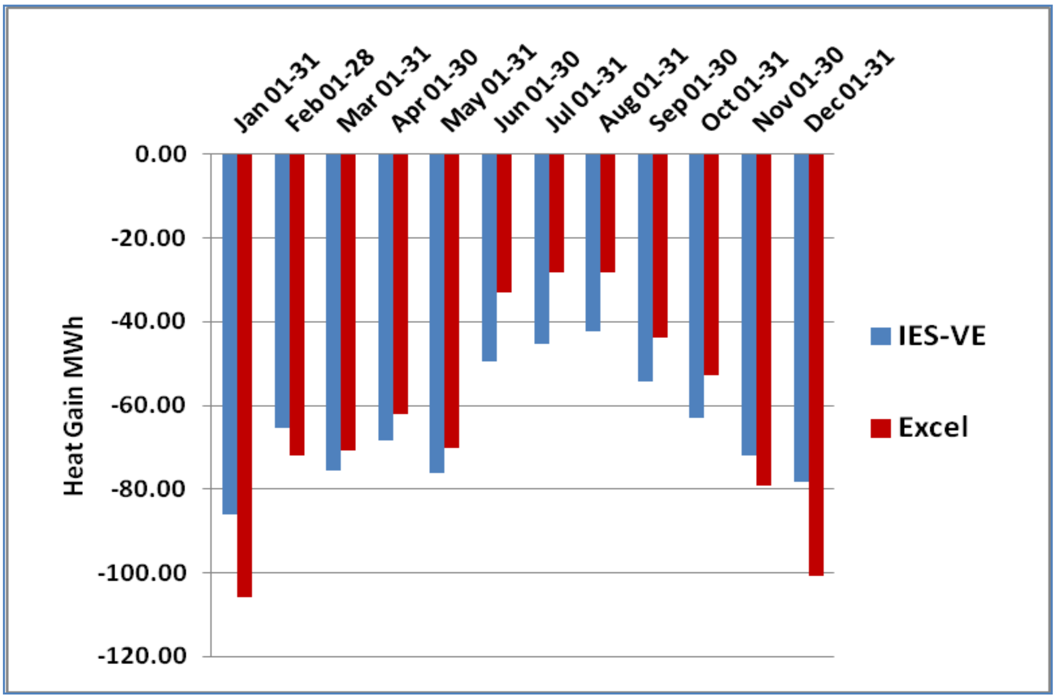


Figure 6-11. Monthly net building fabric heat load for IES and Excel simulations

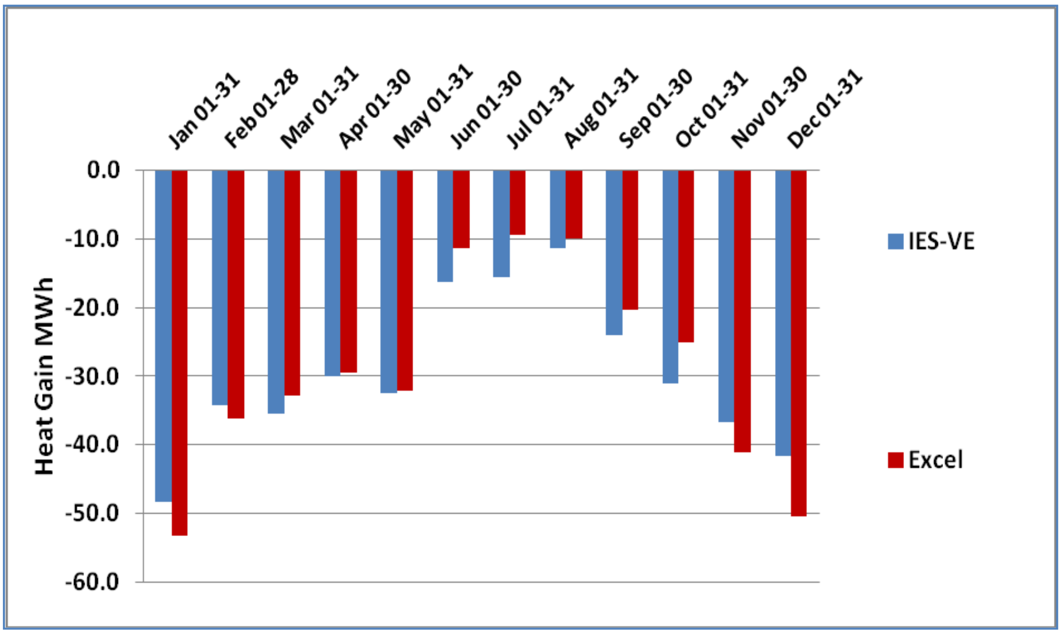


Figure 6-12. Monthly ventilation heat load for IES and Excel simulations

A more detailed analysis of the monthly heating and cooling plant loads suggests a possible reason for the discrepancy between the Excel and IES results. Figure 6-13 shows the net thermal load for the heating and cooling plant load for each month (by subtracting the cooling plant load from the heating plant load in each month). This demonstrates a much closer agreement between the Excel and IES results, typically within 5 MWh in any month. A possible explantion follows below.

In any month there can be both heating and cooling demand (for example a need to heat the building in the morning following an overnight fall in temperature, followed by a need to cool it later in the day because internal gains exceed the heat losses from the building fabric and ventilation). For several months, particularly in spring and autumn, the Excel results indicate both heating and cooling loads, whereas for IES the load is predominantly either heating or cooling, with almost no heating and cooling occurring simultaneously within the same month.

Examination of the Excel simulation hourly heat loads confirms that over the course of a day both heating and cooling can occur (but not at the same time), with a heating load between the hours of 5 a.m. and 8 a.m. and a cooling load that could start as early as 9 a.m. in summer (or as late as 3 p.m. in winter) and ending at 5 p.m. Therefore, for many months of the year it is it likely that there will be both heating and cooling loads.

The IES simulations on the other hand appear to show only heating or cooling (but not both) on any given day. In January the heat load typically peaks at just over 50% of the plant capacity for the first hour, then falls exponentially to about 15% of capacity by the end of the day. In July the cooling plant load is typically quite steady over the whole day at about 70% of capacity, which seems unusual, since the cooling load would be expected to increase during the course of a day as the external temperature rises and due to the warming effect of the solar gain.

Since the net (heating-cooling) loads are similar for both Excel and IES (as are the individual heat loads for fabric losses, ventilation etc.) it is likely that these differences are associated with the algorithms used for setting the operating parameters for the heating and cooling plant over the course of a day. The Excel model relies on using the temperature error at the end of the preceding hour to estimate the output required from the heating (or cooling) plant over the next hour to bring the building back into balance (the thermal capacity of the building os also used within this calculation). The algorithm used within the IES model has not been investigated.

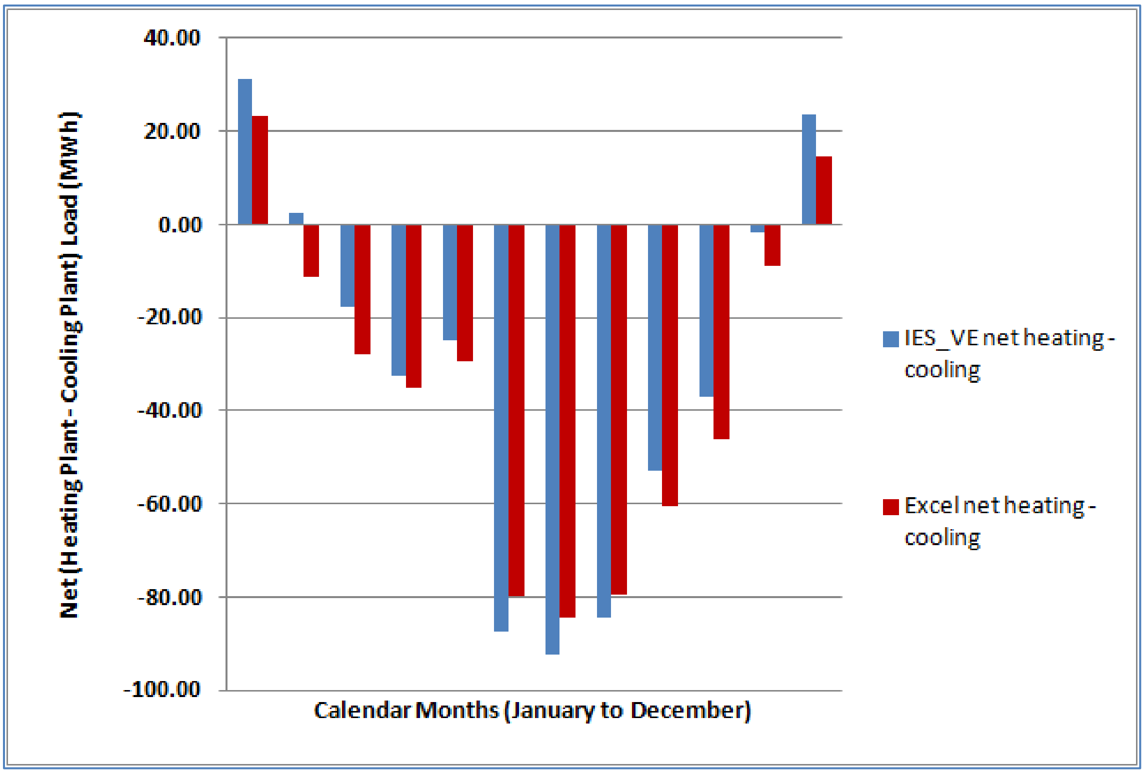


Figure 6-13. Net monthly (heating-cooling) plant load for IES and Excel simulations

The daily heat gains from the IES simulation for natural ventilation and infiltration are shown in Figure 6-14. Comparison with the equivalent Excel model results for day 3 (Figure 6-6) confirms that the shape of the daily profiles is very similar (the plots are of opposite sense because the IES plot is for heat gain whereas the Excel model plot is for heat load).

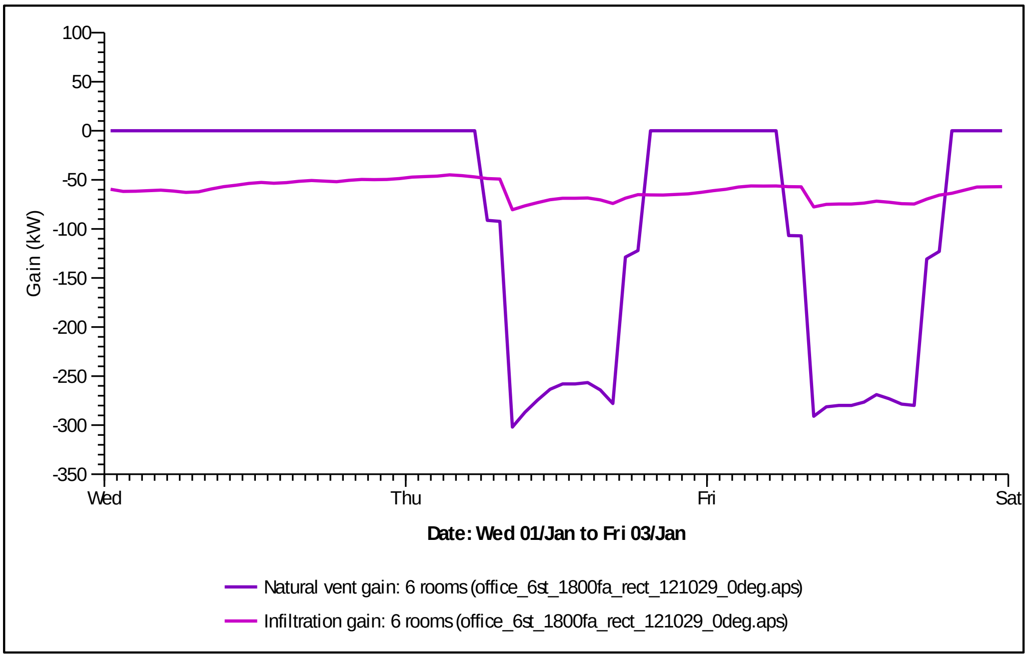


Figure 6-14. IES results plot showing the natural ventilation and infiltration heat gains over 2 days in January

The peak (cloud free) solar gain profiles (Figure 6-15) match well for the IES and Excel simulations. However, since the Excel model uses a more limited weather data set, the daily average illuminance and solar gain in each month are estimated using a 'cloud transmittance' factor which has been derived empirically and is the same value for every calendar month. Refinements to the model, to incorporate a seasonal cloud cover factor would be expected to improve the correlation of monthly gains and the overall heat load for the building.

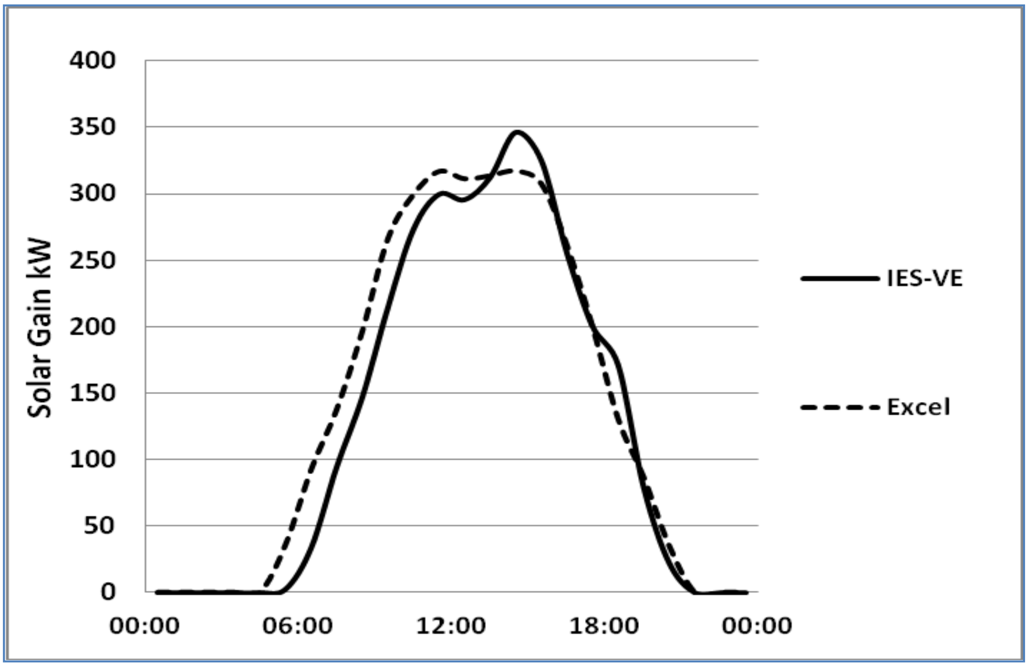


Figure 6-15. 24 hour peak solar gain (28 April) for IES and Excel simulations

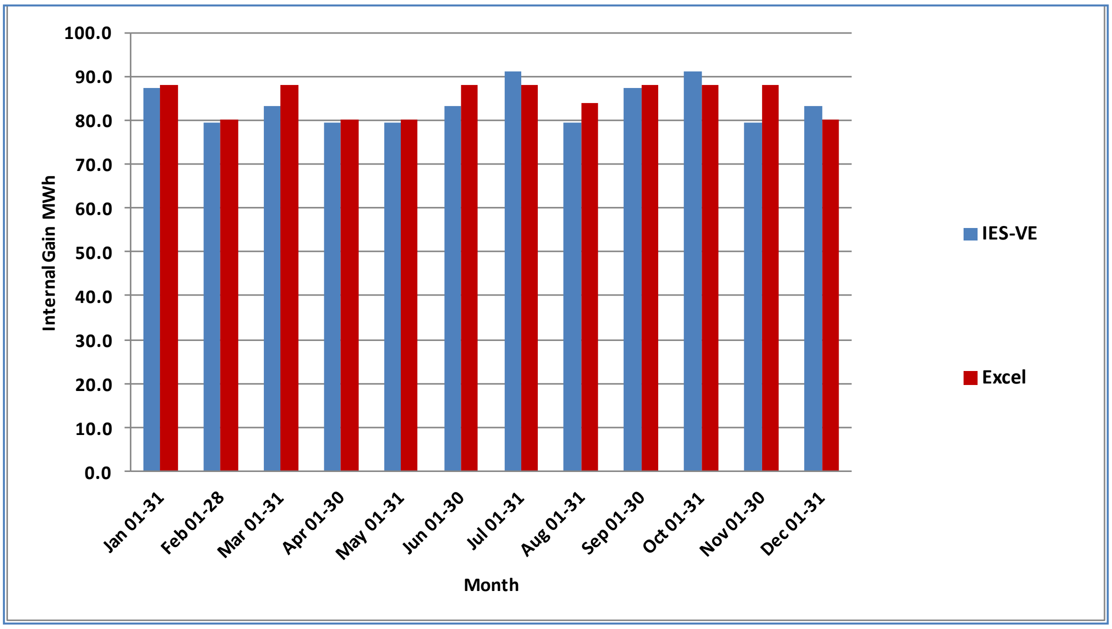


Figure 6-16. Internal heat gains according to the IES and Excel model simulation results

The internal heat gain chart (Figure 6-16) demonstrates good correlation between IES and the Excel model and provide support for the Excel model algorithms. The minor differences are probably due to the way that the Excel model calculates the number of working days in each month (pro-rata according to the total number of days in each calendar month, rounded to the nearest integer number).

6.4 Comparison of the Excel results with other energy and emissions data

An exercise was undertaken to compare the results obtained from the Excel model simulations with benchmark data and energy and emissions data derived from other sources. Since it was difficult to locate energy and emissions data for actual buildings (for reasons discussed earlier), other sources that were investigated included lodgements of DEC data (for non-domestic buildings) and EPC certificates (for dwellings). Data derived from London Heat Map reports and published by the UK Office of National Statistics (ONS) were also analysed. The statistical data downloaded from the ONS website (ONS, 2014) were used to estimate energy densities in three London Boroughs and for the whole of the Greater London area. Further details are provided in Chapter 5.5, Appendix G and Appendix I.

6.4.1 Office building comparisons

The prime energy density and emissions for the reference office building were compared with values taken from CIBSE TM46 (category 1 benchmark, Table 1). Table 6-2 shows the energy demand split between cooling, heating/ hot water and other electricity for the Excel model outputs. However, this level of detail is not available from the TM46 benchmarks, which show only the total fossil fuel and electricity energy densities.

Table 6-2. Comparison of Excel model prime energy demand with CIBSE TM46 benchmarks

Energy Type	Excel Model		CIBSE Benchmark TM46 (2008)
	Prime Energy MWh/ yr	Prime Energy kW/m^2/yr	Prime Energy kW/m^2/yr
Cooling	241	22	
Heating + HW	286	26	120
Electricity (other)	970	90	95
Total	1,497	139	215

Although the electricity energy density is similar for the Excel model and TM46 benchmark (or slightly higher for the Excel model if the electrical energy for cooling is included), the heating and hot water energy densities are very different. Comparison with an ‘Office Type 3’ benchmark taken from CIBSE Guide F (Appendix F Table F-2), which lists both ‘typical’ and ‘good practice’ values, similarly indicates reasonable correlation with the ‘good practice’ electricity energy density (and also similar order of magnitude for the cooling energy demand). However, there is still a major discrepancy for fossil fuel energy density which is unexplained, although the CIBSE building standards used could be lower than for the Excel model (2006 Building Regulations), also the solar gain may be larger for the Excel model due to the relatively large window area (40% of the wall area).

The emissions densities (Table 6-3) show similar discrepancies for fossil fuel emissions, but better correlation for emissions from electricity use.

Table 6-3. Comparison of Excel model annual emissions with CIBSE TM46 benchmarks

Emissions Source	Excel Model		CIBSE Benchmark TM46 (2008)
	Annual Emissions $kgCO_2(e)$	Annual Emissions $kgCO_2(e)/m^2$	Annual Emissions $kgCO_2(e)/m^2$
Cooling	107,283	9.9	
Refrigerant Loss	13,760	1.3	
Heating + HW	58,388	5.4	22.8
Electricity (other)	432,020	40.0	52.3
Total	611,450	56.6	75.1

Another source of data for comparison is the heat map reports produced by London Boroughs under the London Heat Map initiative (London.gov, 2016). Table 6-4 lists the results of data downloads for 3 London Boroughs and these again indicate much higher heating energy densities than the Excel model predicts. However, it should be noted that there were only 6 valid data samples for Southwark, also that some of the energy data incorporated in the Heat Map reports was estimated from benchmarks rather than actual energy use. The Heat Map reports include only heat energy and not electricity use.

Table 6-4. Heating energy densities for 3 London boroughs calculated from heat map report data

London Borough	Fuel consumption from all assets excluding CHP MWh/yr	Fuel consumption from CHP MWh/yr	Gross internal Floor Area m^2	Heating Energy $kWh/m^2/yr$	Number of valid data samples
City of London	1,973	148	23,003	113	134
Southwark	588	0	8,002	195	6
Sutton	675	0	4,272	182	232

[Adapted from: London.gov (2016)]

A third source of energy data was the Display Energy Certificate lodgements that public buildings with a useful area of more than 500m^2 are required to produce and display showing the actual energy use over 12 month periods. For buildings larger than 1000m^2 the DEC must be revalidated each year. Table 6-5 lists the energy and emissions data for City of London, Southwark and Sutton. Although these data show some degree of correlation with the TM46 benchmarks and Heat Map data, there are still significant discrepancies (by a factor of as much as 2:1 for the City of London).

Table 6-5. Energy densities and emissions for public buildings in 3 London boroughs (based on DEC lodgements)

London Borough	Number of Lodgements	Average Floor Area per Building (m^2)	Annual Energy Use ($kWh/m^2/year$) Heating	Annual Energy Use ($kWh/m^2/year$) Electricity	CO_2 Emissions ($kg/m^2/year$) Heating	CO_2 Emissions ($kg/m^2/year$) Electricity
City of London	285	11,106	203	172	32.0	91.3
Southwark	759	7,566	170	129	37.2	83.9
Sutton	587	3,411	175	90	35.9	61.8

It is difficult to draw any meaningful conclusions from the comparison of the Excel model results with other data. One interpretation might be that the Excel model simulations are flawed, however it should be remembered that when compared with simulations from IES-VE the results there was reasonable correlation (in fact IES-VE predicted even lower heating and hot water energy use than the Excel model). An alternative interpretation could be that the range and type of buildings included in the benchmark data and other assessments is so varied that it is not a fair comparison.

6.4.2 Dwelling comparisons

The dwelling example used for comparison with data from other sources is a 4 bed detached house, with a total floor area of 104m^2, constructed to 2006 Building Regulations. It is heated using natural gas, with a boiler rated at 10 kW, with a heating control set point of 19°C. A 3D representation is shown in Figure 6-17.

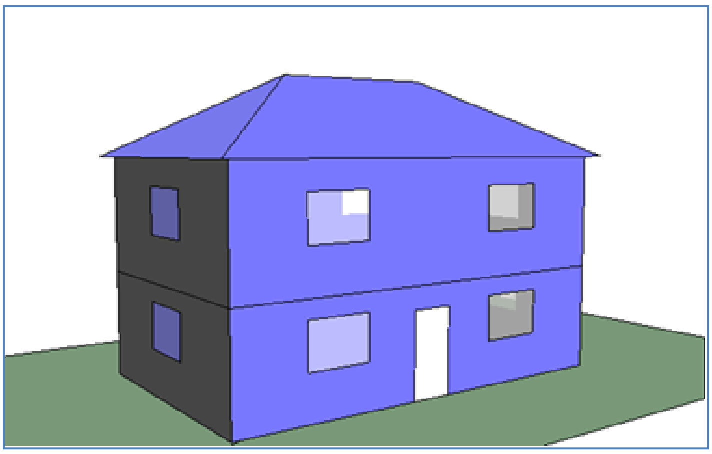


Figure 6-17. 4 bedroom detached house used for dwelling analysis (IES-VE 3D representation)

A summary of the dwelling's energy use and emissions, as predicted by the Excel model are shown in Table 6-6 (for this simulation it was assumed that the building did not have either mechanical ventilation or air conditioning).

Table 6-6. 4 bed detached house energy and emissions summary (no mechanical ventilation or air conditioning)

Energy/ Emissions Type	Energy		Emissions	
	Annual MWh	kWh/m^2	Annual $tCO_2(e)$	Annual kg $CO_2(e)$/ m^2
Building Thermal Heat Load	2.8	27.2		
Building Heating/ HW Energy	5.4	52.5	1.11	10.7
Building Electrical Energy (non-cooling)	2.3	22.1	1.02	9.9
Cooling Electrical Energy (air conditioning)	0.0	0.0	0.0	0.0
Direct Emissions (refrigerant leakage)			0.0	0.0
Total Dwelling Energy and Emissions	7.7	74.6	2.13	20.6

Table 6-7 and Table 6-8 provide comparison data from two other sources. Calculations for several dwelling types using the BRE BREDEM-12 model were undertaken as part of a previous MSc project (Cowan, 2008). These indicate an energy density some 50% higher for the detached house, although some of this may be accounted for by the inclusion of energy for cooking in the BREDEM model (this was not included in the Excel model analysis). However, the EPC (Energy Performance Certificate) lodgement data, which covers all lodgements in the UK up to the end of 2014, shows closer agreement.

Table 6-7. Dwelling energy consumption calculated using BREDEM-12 model (Part L 2006)

Dwelling Type	Dwelling Floor Area m^2	Total Annual Heat Energy kWh	Total Annual Electrical Energy kWh	Total Annual Energy Consumption kWh	Annual Energy Energy Density kWh/m^2
Flat	60.9	5,177	2,790	7,967	130.8
End-terrace	78.8	6,630	3,340	9,969	126.5
Det-bungalow	67.3	6,566	2,974	9,540	141.8
Semi-house	88.8	7,394	3,692	11,087	124.9
Det-house	104	8,903	4,292	13,195	126.9

[Source: Cowan (2008) after Anderson *et al* (2002)]

Table 6-8. Dwelling energy densities and emissions from Energy Performance Certificate lodgements

Property Type	Average Floor Area (m^2)	Average Energy Density Per Dwelling (kWh/ m^2)	Average CO_2 Equivalent Emissions Per Dwelling (tCO_2e)	Average CO_2 Equivalent Emissions Density (kg CO_2e/m^2)
Bungalow	85.2	120	1.7	19.95
Flat	65.1	111	1.2	18.43
House	111.1	94	1.8	16.20
Maisonette	89.2	111	1.6	17.94
All Properties	93.2	**101**	**1.6**	**17.17**

[Source: DCLG (2014)]

A further comparison is based on analysing downloads of statistical data from the Office of National Statistics (ONS, 2014). It was necessary to average the data across all dwelling types because although the statistical data provides total numbers and floor area for each dwelling type, the energy data is aggregated across all dwellings in each area. Data were downloaded and analysed for 3 London Boroughs and for the whole of Greater London. The results are shown in Table 6-9 and indicate much higher energy densities than for the other data sources. However, this data covers all housing stock in the London area and will include buildings constructed in accordance with much earlier building standards (or constructed before Building Regulations were introduced), whereas the other data are based on much newer housing stock constructed to more recent building standards.

Table 6-9. Average energy densities for dwellings calculated from ONS statistical data downloads

London Region	Greater London	Southwark	Sutton	City of London
Average m^2/ Dwelling	74.8	71.7	78.9	68.8
Average Energy Densities kWh/ m^2/ yr				
Electricity (Standard)	38.3	30.6	36.5	45.9
Electricity (Economy 7)	9.4	7.2	14.4	12.4
Gas	150.1	91.8	155.9	76.6
Total	**197.8**	**129.6**	**206.8**	**135.0**

Note: Energy densities have been calculated from ONS total floor area and energy consumption statistics

As with the commercial office building analysis, it is difficult to draw meaningful conclusions from this exercise, although the discrepancies are somewhat smaller. Again, there could be a wide variation in the type and age of the buildings used to derive the datasets. One particularly striking observation is the wide variation between the borough of Sutton and the boroughs of Southwark and the City of London. However, Southwark and City of London have a relatively small housing stock as they are primarily commercial areas, also the housing stock in these areas is more likely to be flats and apartments rather than individual houses.

Chapter 7. Sensitivity analysis - factors influencing building energy and emissions

This chapter describes the results of simulations to investigate the sensitivity of energy and emissions to changes in building design and operation and future climate change. Two sets of simulations were undertaken: the first was to assess the impact of changing various design and operational parameters for the building; the second was to predict the impact of climate change by repeating the simulations with different weather files. The investigations were carried out for both the office building and dwelling examples.

The Excel simulation files used were:

- Building_Energy_Model_130614_WF_Master_Heat-Cool_Ctrl_Rev10G_Climate_170121
- Building_Energy_Model_House__150916_Climate_170122

As well as summarising the results in new worksheets these files also incorporate the additional weather matrices used for the climate impact simulations

7.1 The sensitivity of energy and emissions to building design and operation

The sensitivity of the energy and emissions for the two reference buildings (office and detached house) to changes in the design, fabrication and operation of the building, were investigated using the Excel tool. For each assessment a single parameter was changed at a time. Key results are reported below.

7.1.1 Office building

The following examples are based on the 6 storey office building described in Chapter 6.

In the first example, the impact of reducing the lighting heat gain from 12 W/m^2 to 8 W/m^2 (corresponding to replacing fluorescent lights with LEDs) was assessed. Figure 7-1 demonstrates a reduction of more than 11% for the total building emissions. The energy related cooling emissions reduce by over 14% as a result of the reduced cooling load, although in absolute terms the emissions reduction for non-cooling electricity use is more significant (55,000 kgCO_2(e) vs 15,300 kgCO_2(e) for cooling emissions). The small increase in heating emissions is due to the reduced contribution from the lighting system to heating the building in winter months.

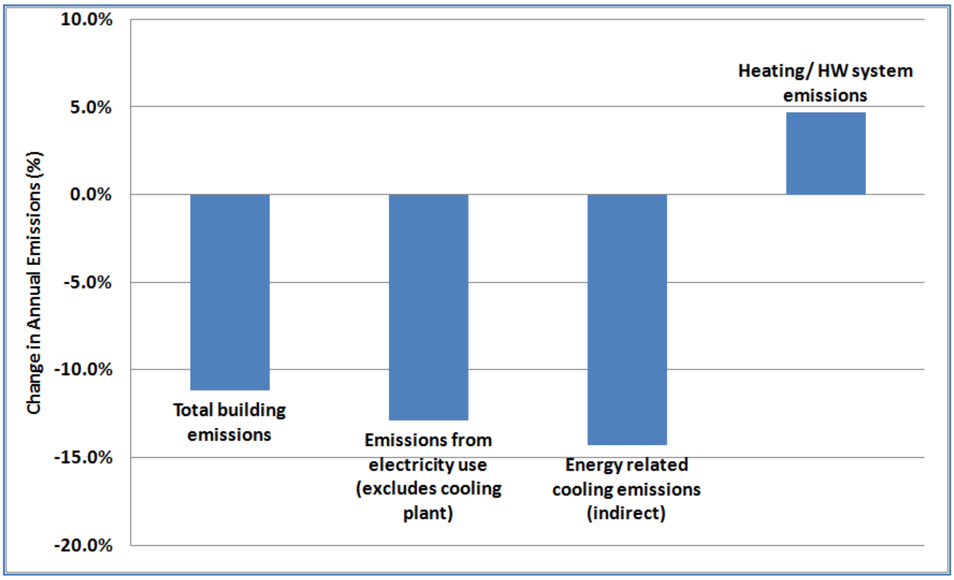


Figure 7-1. Percentage change in annual emissions due to replacing fluorescent lighting with LEDs

The sensitivity of the building's solar gain and emissions to the glazing design can be assessed by characterizing the emissions for different glazed surface areas. Figure 7-2 charts how the emissions would vary as the glazed area is varied between 20% and 80% of the total wall surface area. It shows that if the glazed area is reduced from 40% to 20% of the total wall area, the cooling energy related emissions reduce by almost 20% and the building's total emissions by almost 5%. Reducing the solar transmittance factor (by appropriate selection of the glazing materials) could achieve a similar improvement. On the other hand, if the glazed area were increased from 40% to 80% (as in many modern office buildings) the energy related cooling emissions would increase by over 40%.

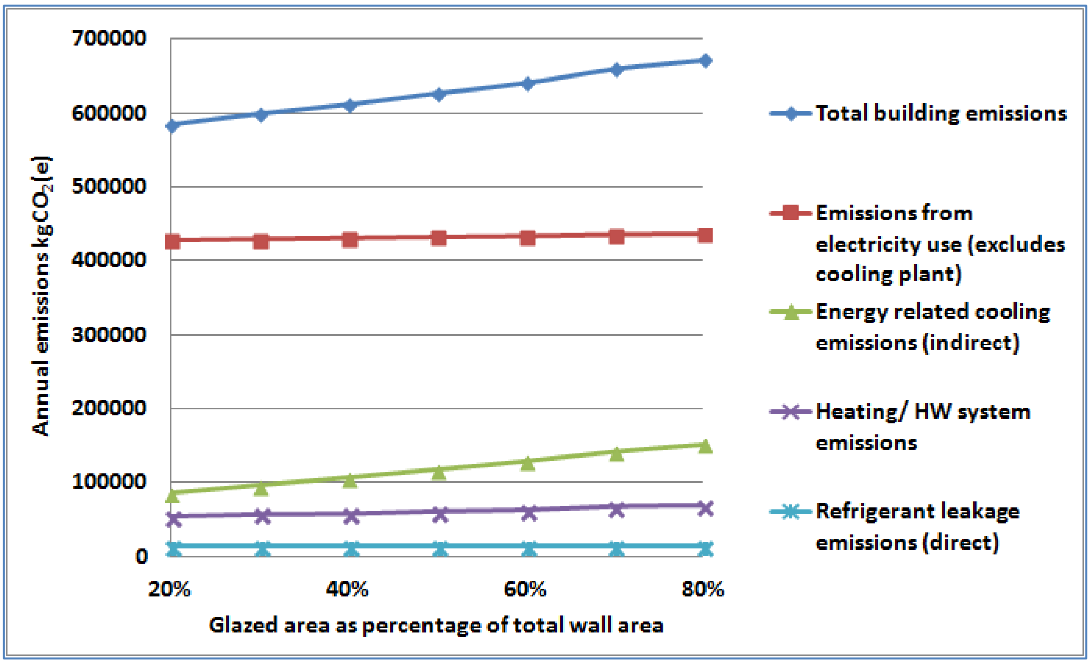


Figure 7-2. Sensitivity of building emissions to glazed surface area

The impact of increasing the cooling temperature set point can also be demonstrated. Figure 7-3 shows that an increase from 21°C to 23°C reduces the cooling emissions by 25% and the overall building emissions by nearly 6%. A similar reduction could be achieved by improving the EER of the cooling plant from 2.25 to 3.5.

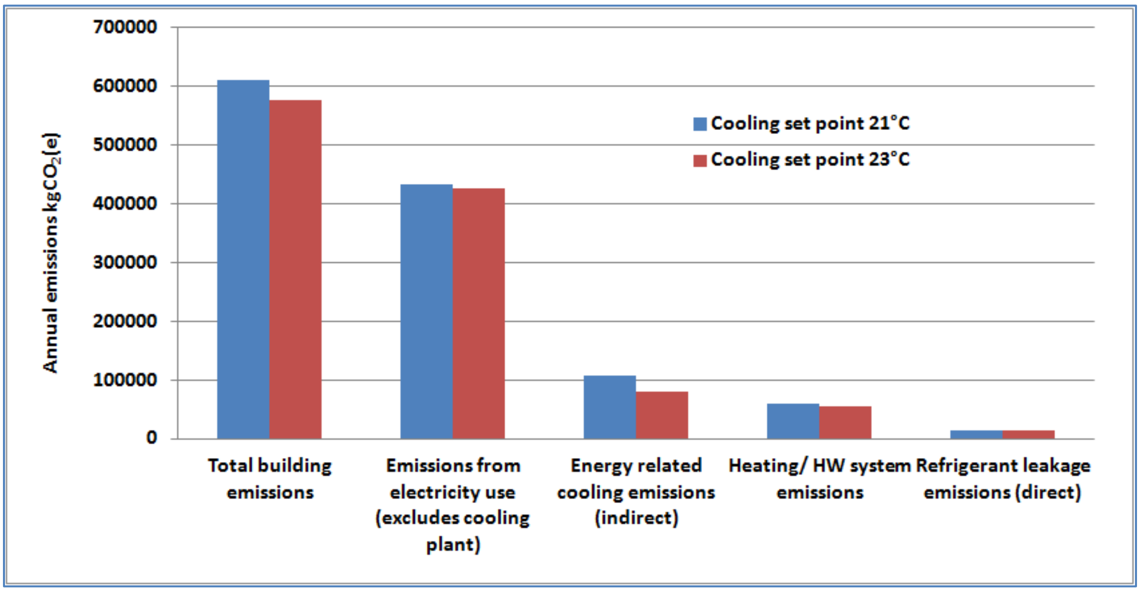


Figure 7-3. Impact of increasing the cooling temperature set point on cooling emissions

The impact of changing the cooling set point on the building temperature can be seen in Figure 7-4 and Figure 7-5. During the normal working day (08:00 – 18:00 hrs) the peak temperature in the summer increases from 23°C to 25°C. However, the temperature at all times remains well within the 'comfort temperature' window shown in Figure 5-1 and the total emissions reduce by 5.9%. Reducing the set point temperature for the heating controls could potentially also help to reduce emissions (a reduction from 19°C to 18°C reduces total emissions by 1.8%).

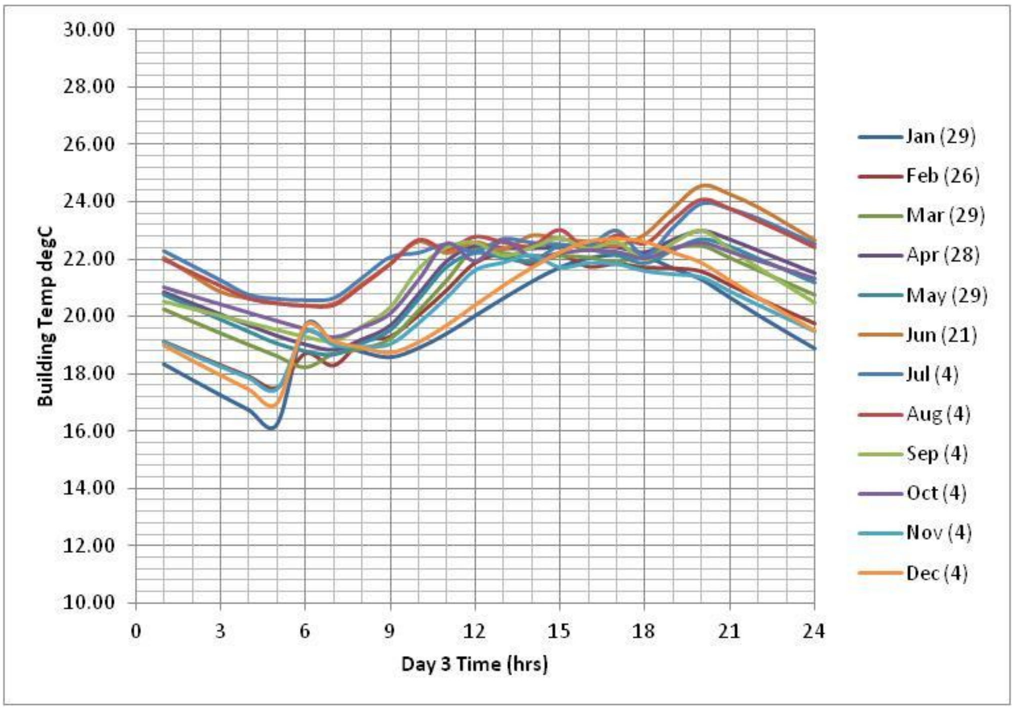


Figure 7-4. Office building day 3 temperature profile with cooling set point at 21°C

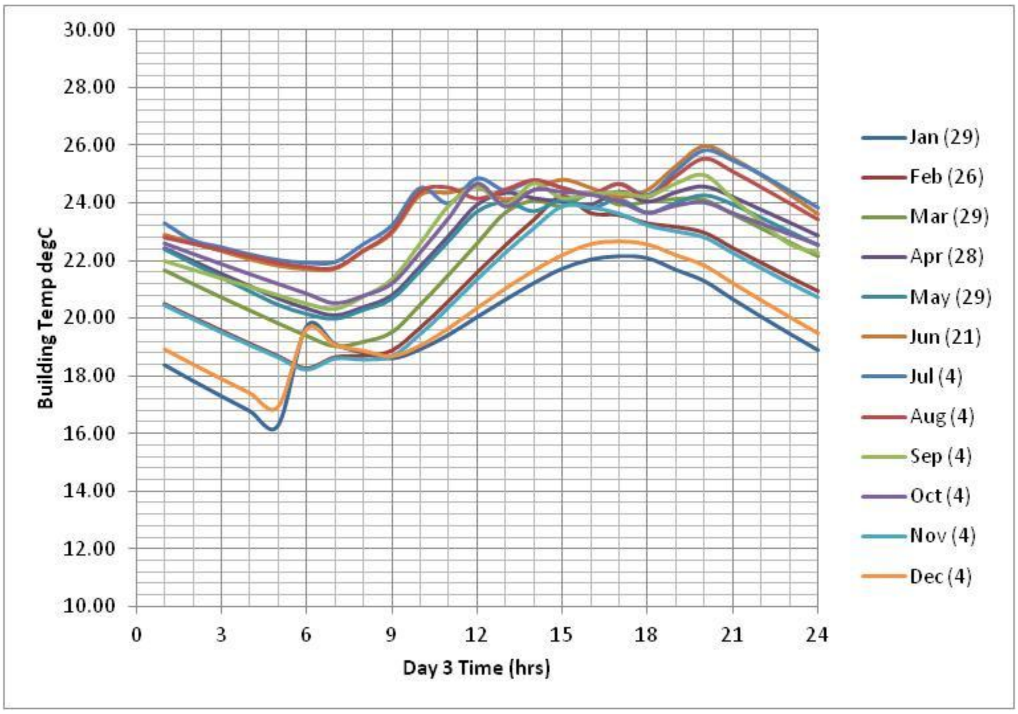


Figure 7-5. Office building day 3 temperature profile with cooling set point at 21°C

Other parameters that could be changed include for example:

- Modifying the thermal capacity of the internal structure of the building. The simulations indicate that increasing the thermal capacity of the internal floors from 67.5 kJ/m^2K to 135 kJ/m^2K reduces total emissions by 2.1%, as well as smoothing the temperature variations. Conversely, halving the thermal capacity of the internal floors increases emissions by 2.3% (and increase the temperature variation).
- Increasing the EER of the cooling plant from 2.25 to 3 will reduce emissions by 4.4%. A further increase to 4.5 would decrease emissions by a total of 8.7%.
- Modifying the U values for the building structure. There is a trade off between reduced heating energy demand and increased cooling energy demand as U vales are decreased through better insulation. However, the net impact on total emissions may be small. For this building if the U values are changed from 2006 Building Regulations to typical pre-war values (see Table F1 in Appendix F), the annual cooling energy use decreases from 23 kWh/m^2 to 12.9 kWh/m^2, but the heating and hot water energy use increases from 27 kWh/m^2 to 53kWh/m^2, while total emissions barely change (from 57.1 to 57.8 $kgCO_2(e)/m^2$).
- Varying the ventilation rates (this may impact air quality in the building and the ventilation fan energy consumption and associated emissions will also change).
- Modifying the heating and cooling plant peak capacity and modulation profile.
- Changing the losses in the distribution and delivery systems.
- Using alternative fuels.
- Changing the hot water temperature and reducing demand through water saving measures.

7.1.2 Dwelling (detached house)

The sensitivity analysis is based on changing the ventilation approach or adding a small air conditioning system to maintain comfort levels. The three ventilation and cooling scenarios are:

A. No mechanical ventilation or cooling. The default air infiltration rate is 0.25 ach (air changes per hour) and additional ventilation can only be provided by opening windows.

B. Mechanical ventilation system, with 1.3 air changes per hour (includes a balanced heat recovery system which is 70% efficient). The specific fan power is assumed to be 2W/l/sec.

C. A small (2 kW) air conditioning unit is used to maintain comfort temperature levels in the summer and prevent overheating. The COP of the cooling plant is assumed to be 2.25 and the cooling set point temperature is 21°C.

Figure 7-6 shows the 3 day (72 hour) temperature profile for scenario A (no mechanical ventilation or cooling). This indicates that during the months of July and August there is a tendency for the building to overheat, the temperature increasing to as much as 28°C over the 3 day period, so the comfort level will be poor. Re-running the simulation using a weather data file generated from peak (rather than average) hourly temperatures in each month suggested that the dwelling's internal temperature might occasionally exceed 30°C between the months of May and September, with a peak of 37°C in mid-summer.

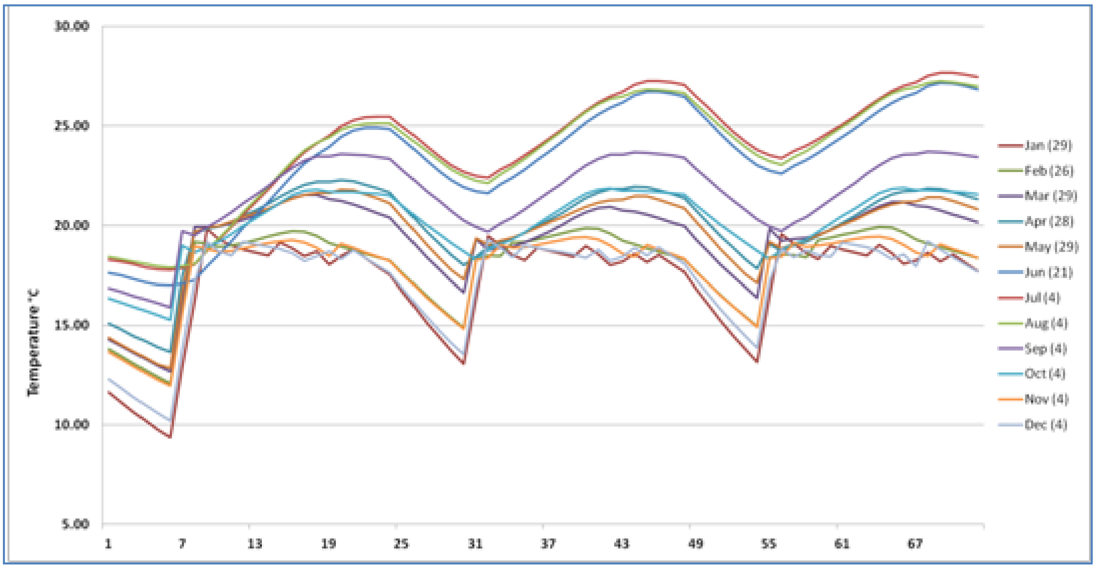


Figure 7-6. Scenario A (no mechanical ventilation or cooling) – building temperature profile over 72 hour period

For scenario B (mechanical ventilation) the improvement is small, with the temperature still reaching 27°C (Figure 7-7). Even at an air change rate of 1.3 ach (which is equivalent to 20 l/sec per occupant, assuming an occupancy of 5 people), the cooling effect of the forced ventilation air flow is minimal.

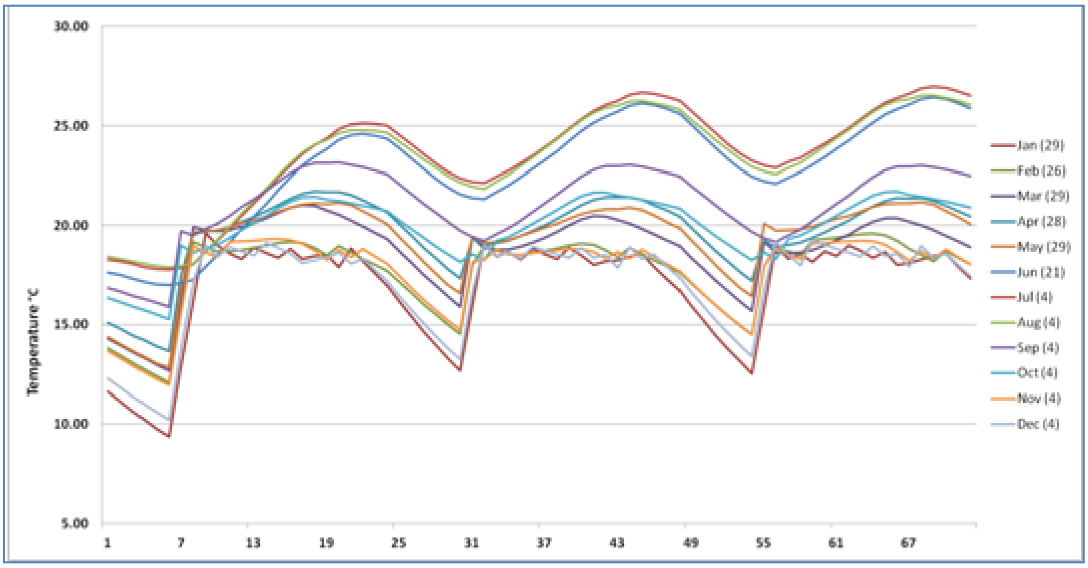


Figure 7-7. Scenario B (mechanical ventilation) – building temperature profile over 72 hour period

However, if a small air conditioner is used to assist cooling, the results are striking (Figure 7-8). The temperature peaks at 23°C, ensuring that comfort levels are maintained. The additional emissions associated with this cooling are small relative to the other emissions from the building (Figure 7-9). Even using the weather data file generated from peak hourly temperatures in each month, the Excel simulation indicated that the building's peak internal temperature would be less than 27°C, while the total building emissions would increase by less than 5% when compared with results from the average temperature weather file.

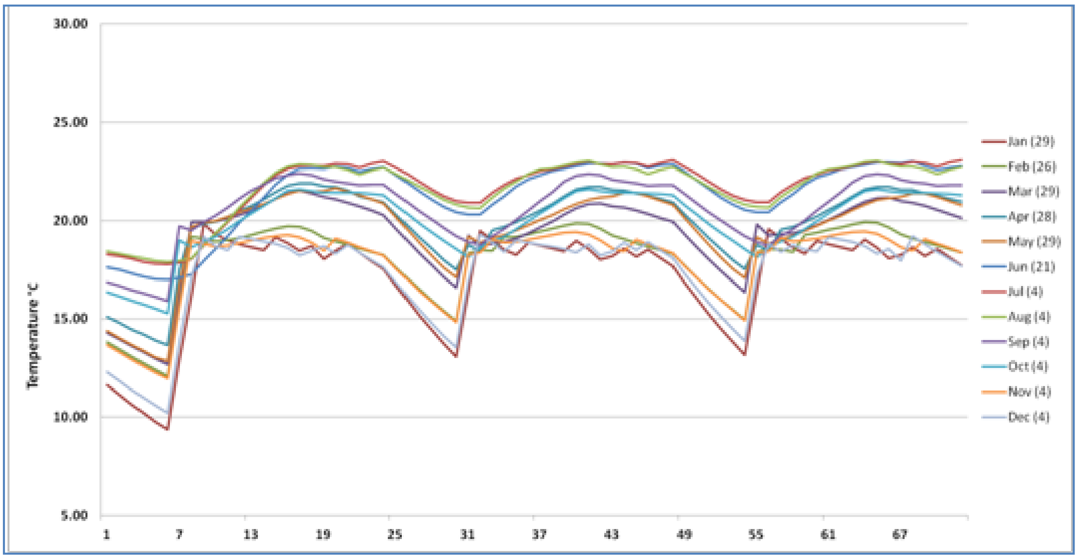


Figure 7-8. Scenario C (air- conditioning) – building temperature profile over 72 hour period

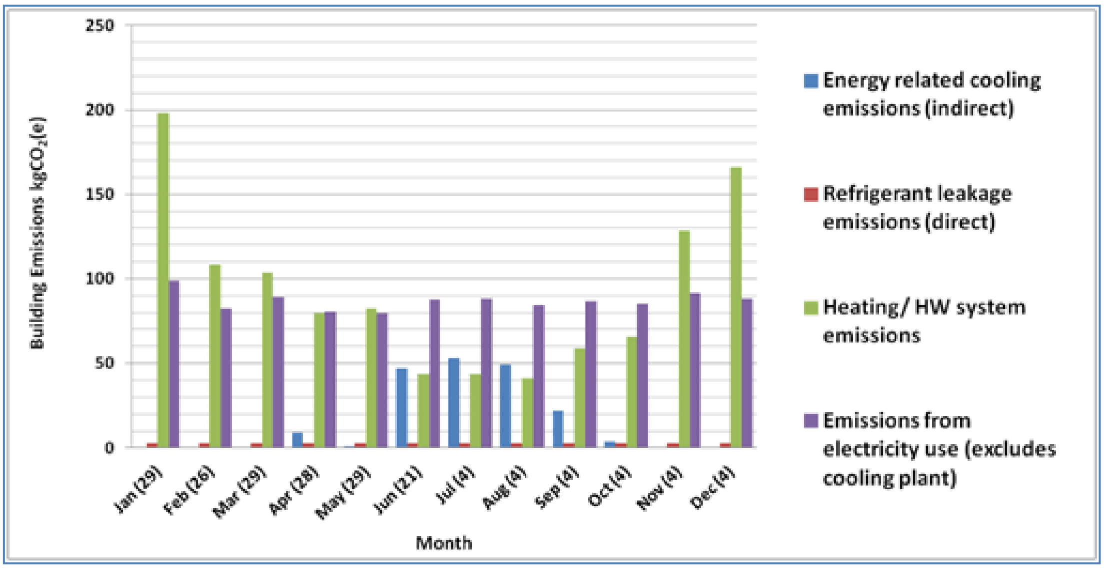


Figure 7-9. Breakdown of building emissions for scenario C, indicating that the impact of air conditioning is small

Even more striking is the comparison between the 3 scenarios for total building emissions (Figure 7-10). Whilst scenario A achieves the lowest emissions (at the expense of comfort), scenario C (air conditioning) achieves lower emissions than scenario B, as well as a significantly improved level of comfort. This suggests that mechanical ventilation (which is required to meet current Building Regulations) may not be the most appropriate way to control the building environment in dwellings.

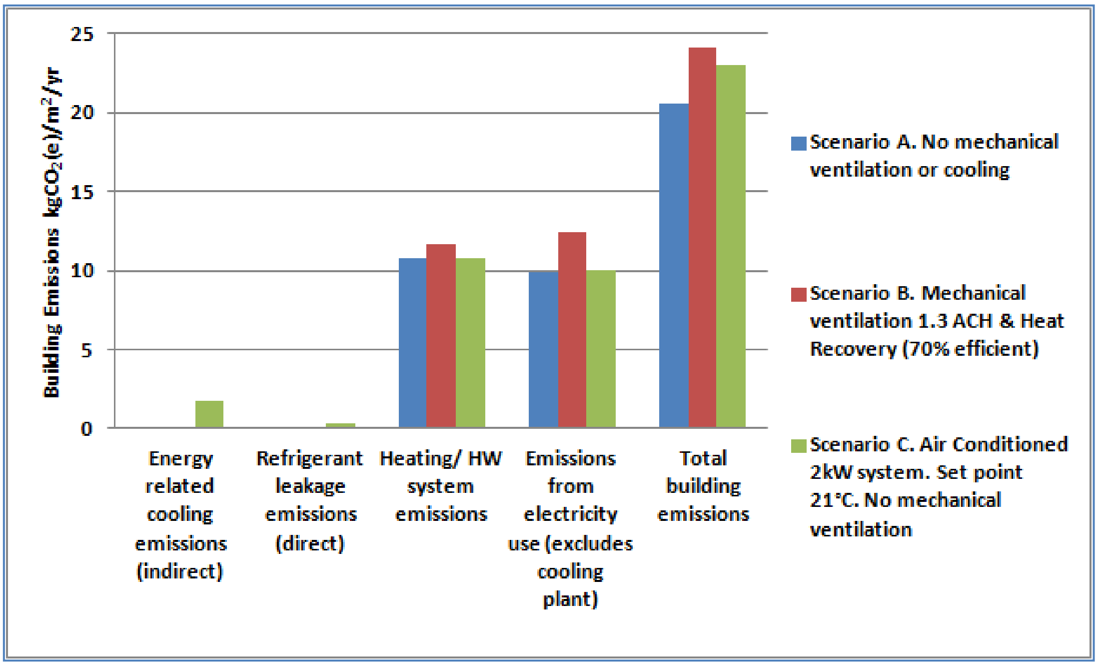


Figure 7-10. Comparison of total building emissions for scenarios A, B and C

The overheating potential for a house built to the standard of the 2006 Building Regulations becomes even more pronounced if the glazed area is increased above the 10% of total wall area assumed in the model. Conversely, dwellings constructed to older building standards (with lower U values) have a reduced risk of overheating, but use significantly more heating energy: if the simulation for scenario A is re-run with the dwelling constructed to pre-war building standards the annual heating and hot water energy use more than trebles from 5.1 MWh to 16.5 MWh and the total building emissions more than double, from 19.9 $kgCO_2(e)/m^2$ to 44.7 $kgCO_2(e)/m^2$. The highest internal temperature reached during the summer would be 23°C according to the simulation.

7.2 The sensitivity of energy and emissions to climate change

The sensitivity of the energy and emissions to climate change were investigated for the office and detached house using 4 different weather files, derived from downloads of future weather data (described in Chapter 5.6 and Appendix H). The files were based on central London weather files for Islington, covering the period present day to 2080. The files were:

Islington ctrl TRY (current)
Islington 2030 TRY
Islington 2050 TRY
Islington 2080 TRY

TRY (Test Reference Year) files were used. A quick assessment was also undertaken using an Islington 2080 DSY (Design Summer Year) file.

7.2.1 Office building

The building parameters used were the same as for the simulation described in Chapter 6 – only the weather files were changed and all other parameters remained unchanged.

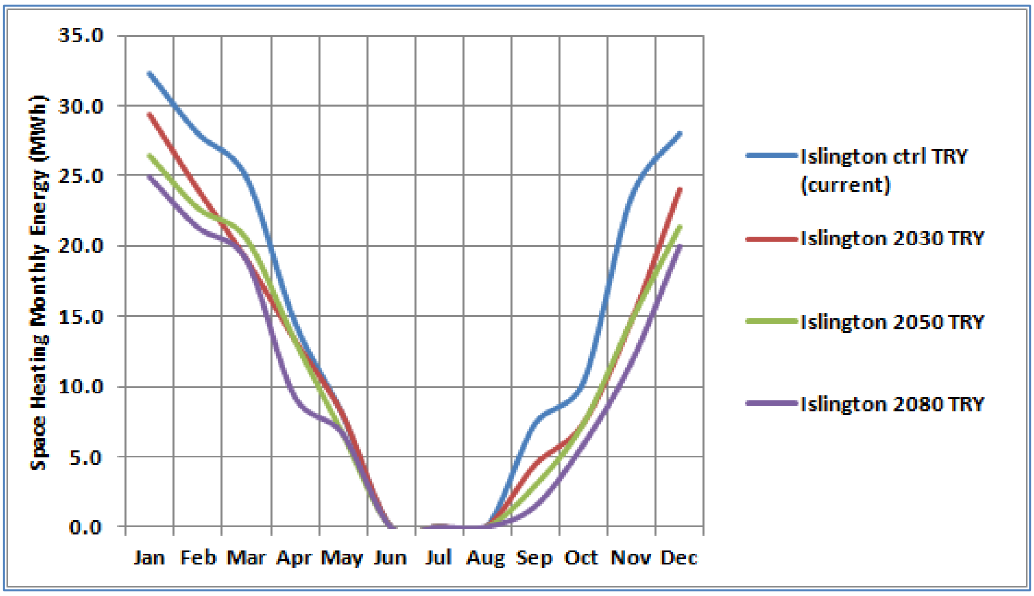


Figure 7-11. Office building monthly space heating energy for alternative climate scenarios

The monthly space heating energy demand for the alternative climate scenarios is shown in Figure 7-11. The annual space heating energy demands are shown in Figure 7-12. As expected, the impact of the warmer climates is to reduce the space heating demand (a reduction of 32% by 2080).

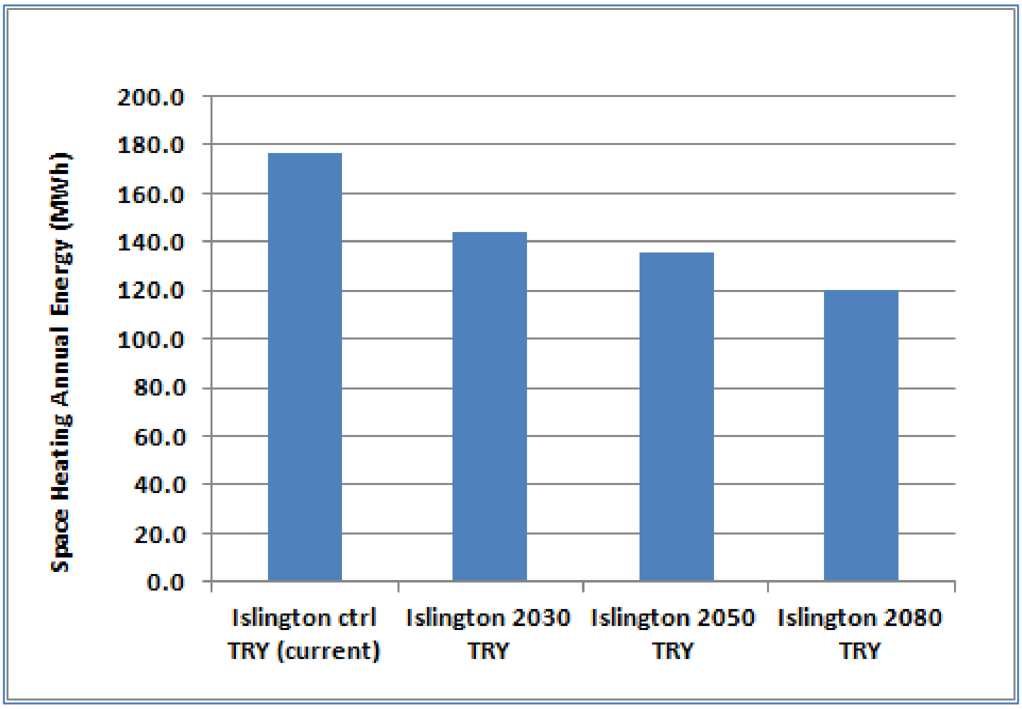


Figure 7-12. Office building annual space heating energy for alternative climate scenarios

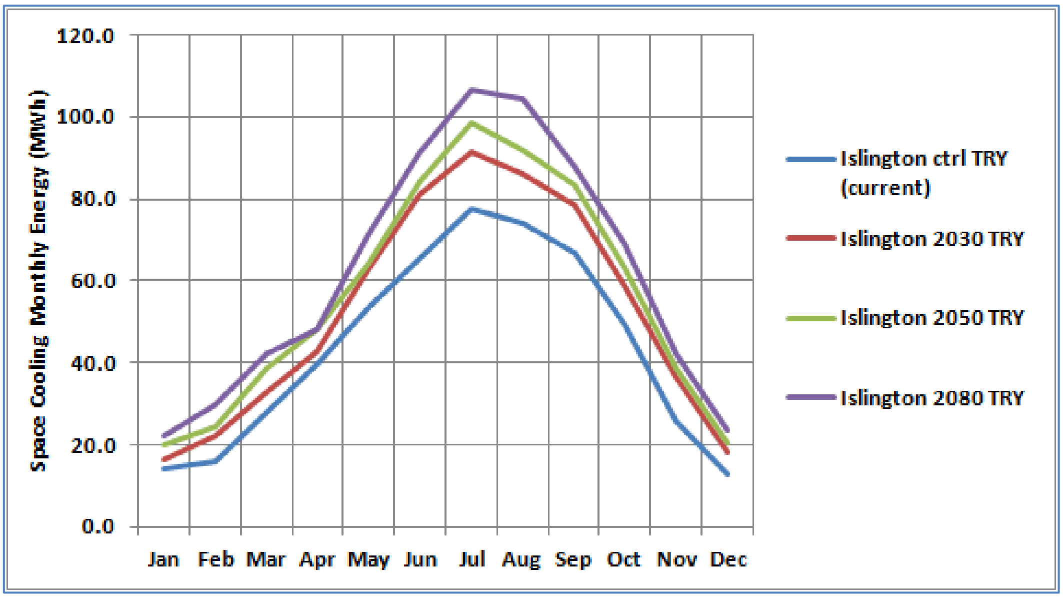


Figure 7-13. Office building monthly space cooling energy demand for alternative climate scenarios

The monthly space cooling energy demand is shown in Figure 7-13 and the annual totals in Figure 7-14. In the summer months the cooling demand increase by around 45% in 2080, when compared with the current weather scenario and on an annual basis the increase is over 41%. Even for the 2030 weather scenario the annual cooling demand increases by 20%.

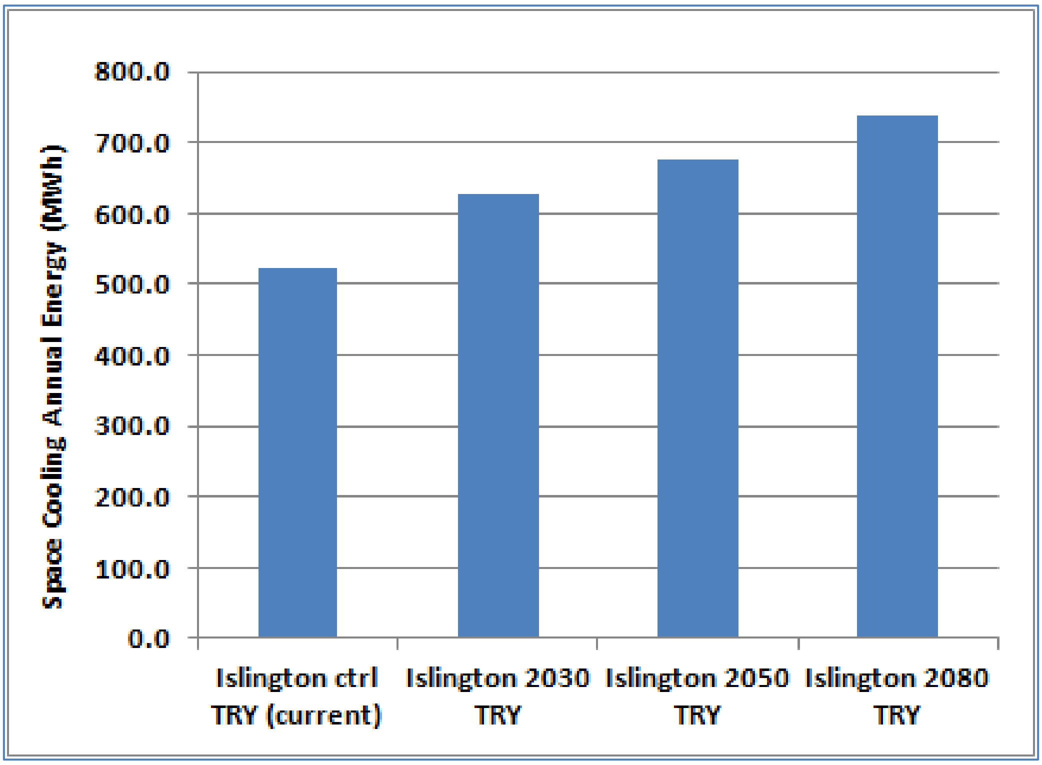


Figure 7-14. Office building annual space cooling energy demand for alternative climate scenarios

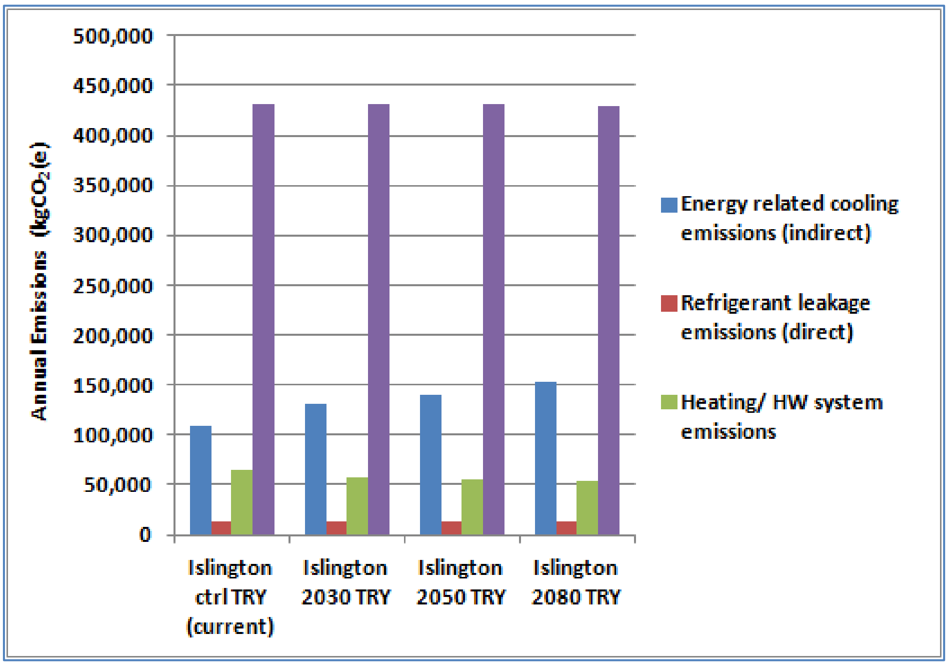


Figure 7-15. Office building emissions for alternative climate scenarios

A breakdown of the office building annual emissions is shown in Figure 7-15. The largest element continues to be the emissions from non-cooling electricity use. Although the cooling energy emissions increase by 45%, they represent less than 25% of the total building emissions. The heating emissions show a small decrease. Figure 7-16 indicates that the total annual emissions increase from 619,000 kgCO_2(e) (current) to 649,000 kgCO_2(e) in 2080, an increase of just 5%.

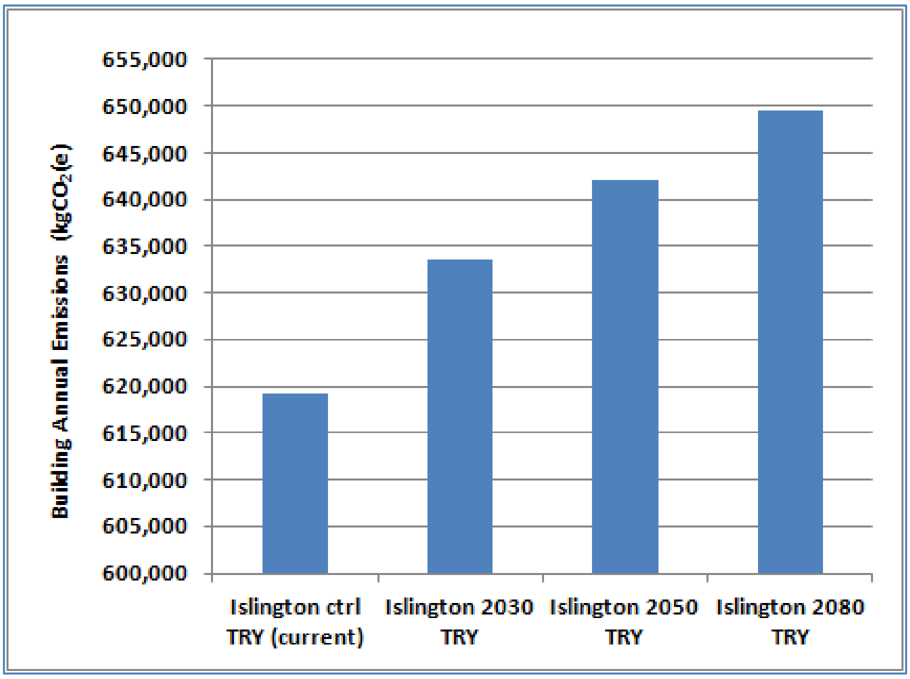


Figure 7-16. Office building total emissions for alternative climate change scenarios

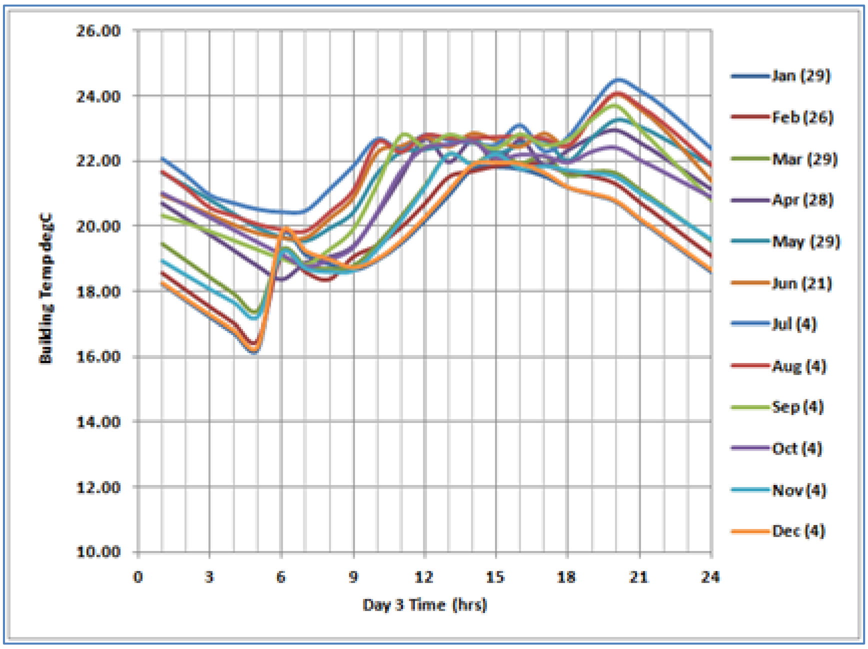


Figure 7-17. Office building day 3 temperature for 'Islington ctrl DSY' (current) weather file

Examination of the day 3 temperature profile for the current weather file (Figure 7-17) and the 2080 weather file (Figure 7-18) confirms that the higher temperatures have minimal impact on the building's internal environment and that the heating and cooling systems are easily able to adapt to the changing climate.

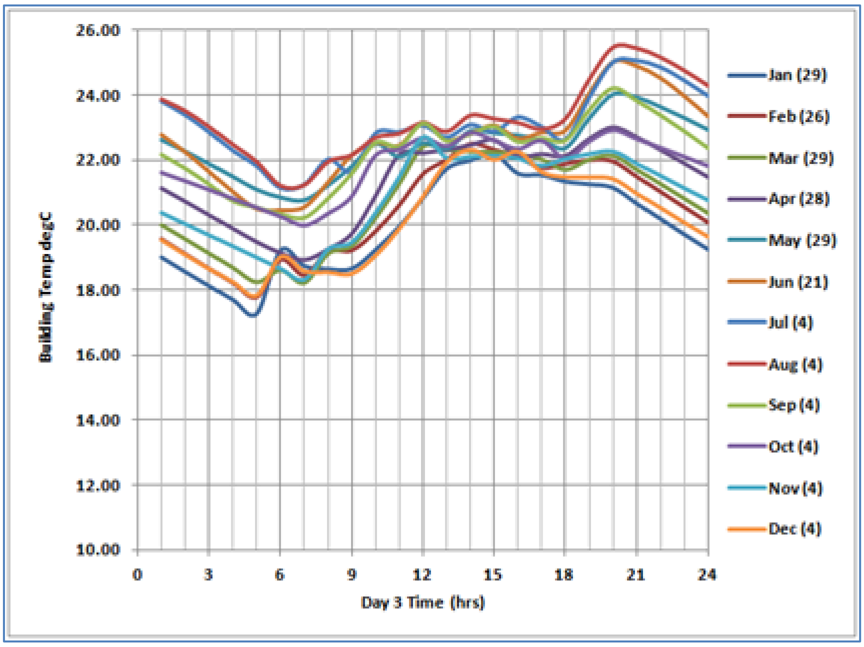


Figure 7-18. Office building day 3 temperature for 'Islington 2080 TRY' weather file

Also of interest is that even in 2080 there is still some benefit to the internal environment from the use of night cooling. Figure 7-19 shows the building's temperature profile in 2080 with night cooling disabled and indicates that at 5 a.m. the temperature is still 24°C, compared with 22°C with night cooling enabled (Figure 7-18). However, even without night cooling the air conditioning system is capable of bringing the temperature down rapidly between 5 a.m and 6 a.m. so the internal environment is not compromised. The total energy and emissions for the two conditions are very similar, since the additional cooling energy demand is offset by a reduction in the energy used by the night cooling ventilation fans.

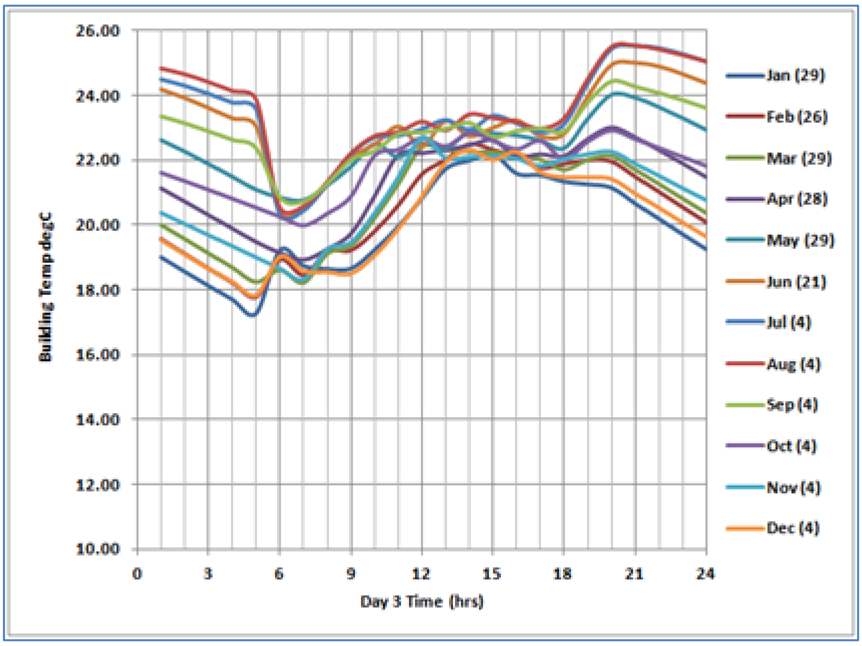


Figure 7-19. Office building day 3 temperature for 'Islington 2080 TRY' weather file – night cooling switched off

7.2.2 Dwelling (detached house)

The detached house energy and emissions sensitivity to climate change was investigated for the same 3 ventilation and cooling scenarios as before. For each of the 3 scenarios, A, B and C, the simulation was run using the 4 weather data files in turn and the results are summarized below.

Scenario A (no mechanical ventilation or air conditioning

The earlier results for this scenario (using current weather files) indicated the lowest building emissions but a poor internal environment with a tendency to overheat in the summer. This issue would be likely to escalate as a result of increasing temperatures from climate change.

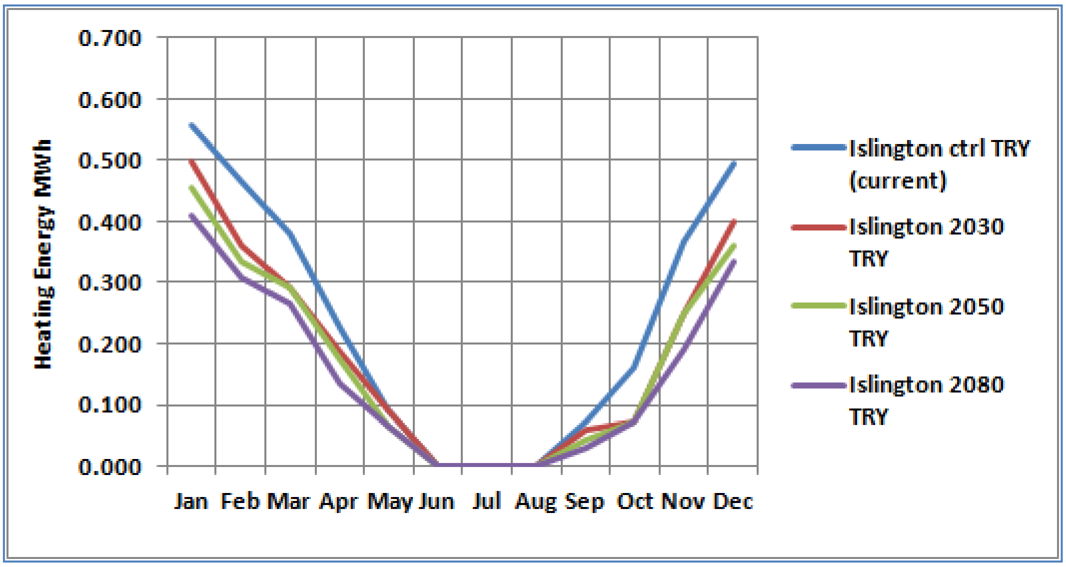


Figure 7-20. Detached house (Scenario A) monthly heating energy demand using different weather files

The monthly heating energy demand is shown in Figure 7-20 and shows a reduction of about 25% from present day to 2080 in the winter months. The corresponding reduction in total emissions on an annual basis is 11.3% (Figure 7-21).

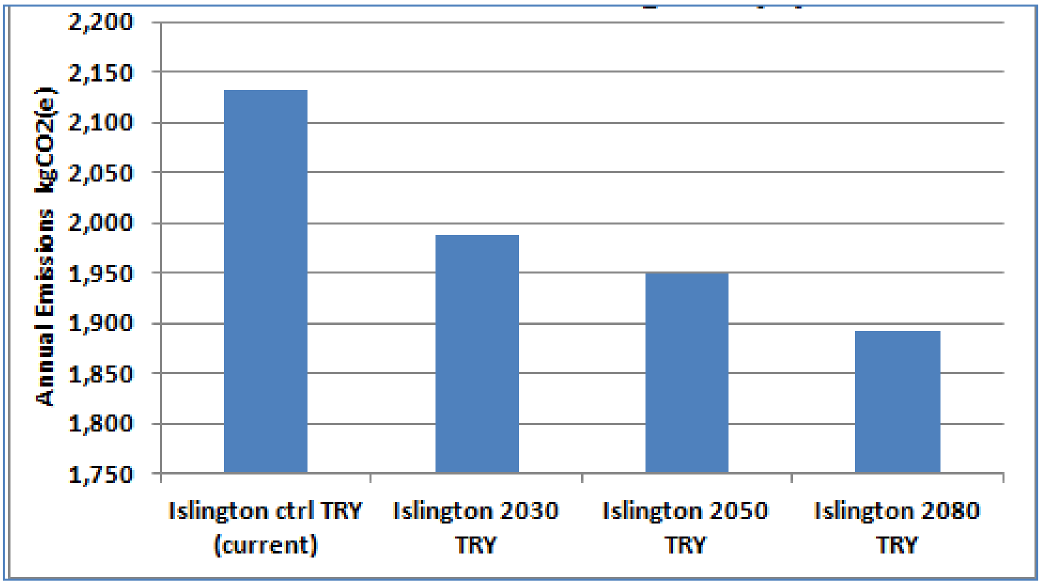


Figure 7-21. Detached house (Scenario A) total annual emissions using different weather files

However, without mechanical ventilation or air conditioning the building's internal environment becomes increasingly uncomfortable over time, as indicated in Figure 7-22, which plots the internal temperature in 2080. This suggests that in the summer the internal temperature could peak at 32°C (compared with 28°C for present day climate – refer to Figure 7-6).

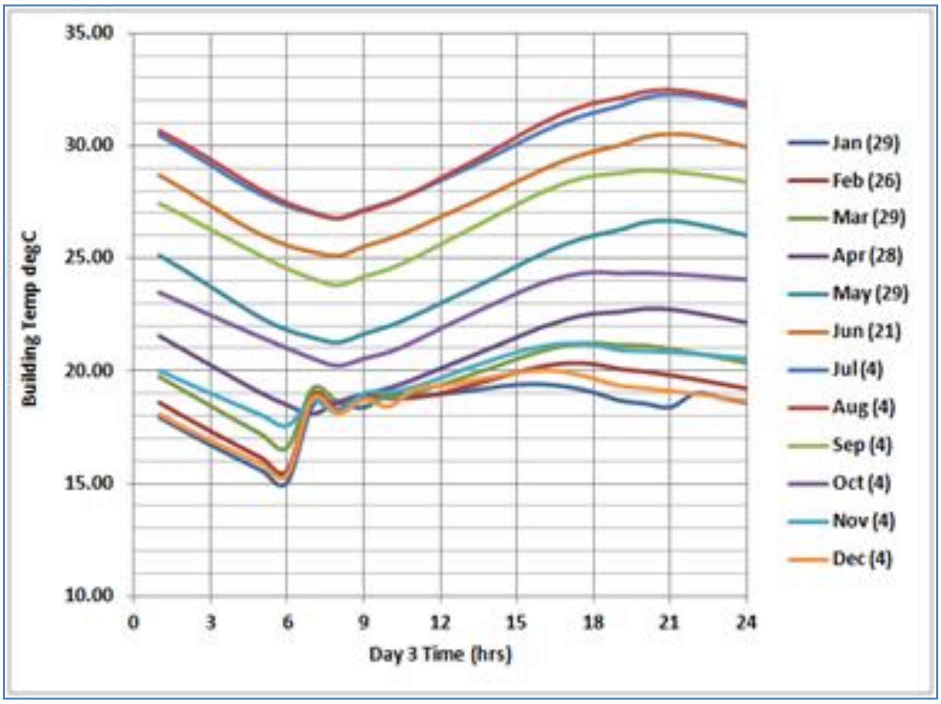


Figure 7-22. Detached house (Scenario A) day 3 temperature profiles using the 2080 weather file

Scenario B – Mechanical ventilation (1.3 ACH) plus heat recovery (70% efficient)

The earlier assessment of scenario B indicated that the addition of mechanical ventilation provided only a minor improvement in the internal environment and comfort levels compared with scenario A, also that due to the fan power total emissions were slightly higher than scenario C.

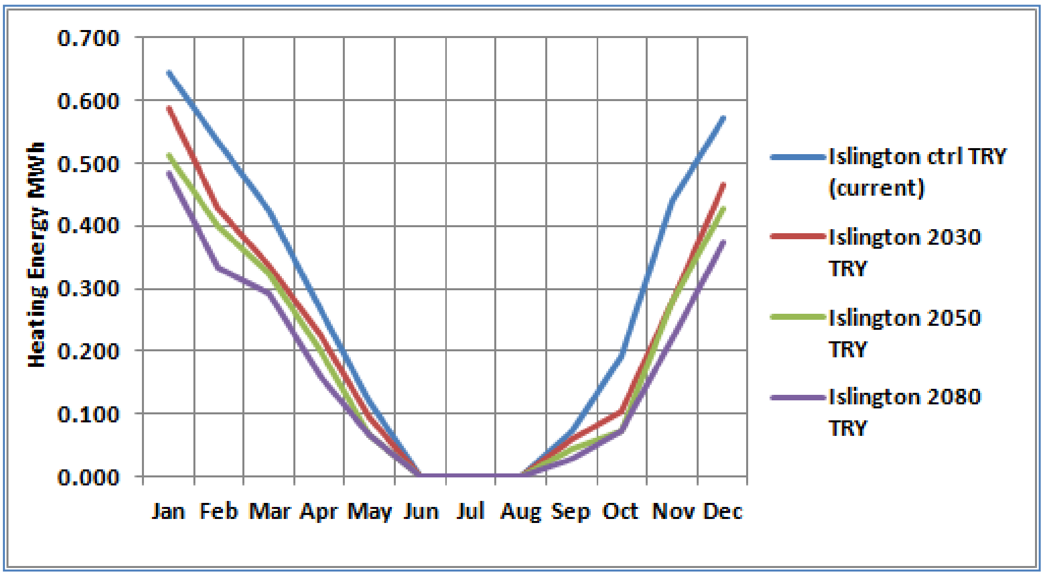


Figure 7-23. Detached house (Scenario B) monthly heating energy demand using different weather files

The monthly heating energy demand for scenario B (Figure 7-23) is similar to Scenario A, indicating a reduction of around 25% in the winter months. The corresponding reduction in total emissions between present day and 2080 is 12.1% (Figure 7-24). However, even with the mechanical ventilation the building remains prone to overheating, with a predicted peak summer temperature of 29°C in 2030 and 32°C. Adding night cooling might reduce these temperatures by around 1°C but in order to maintain a reasonable level of comfort in the summer it would be necessary to increase the ventilation rate to around 8 ACH. This in turn would significantly increase the electricity consumption and building emissions due to the much higher energy load from the fans.

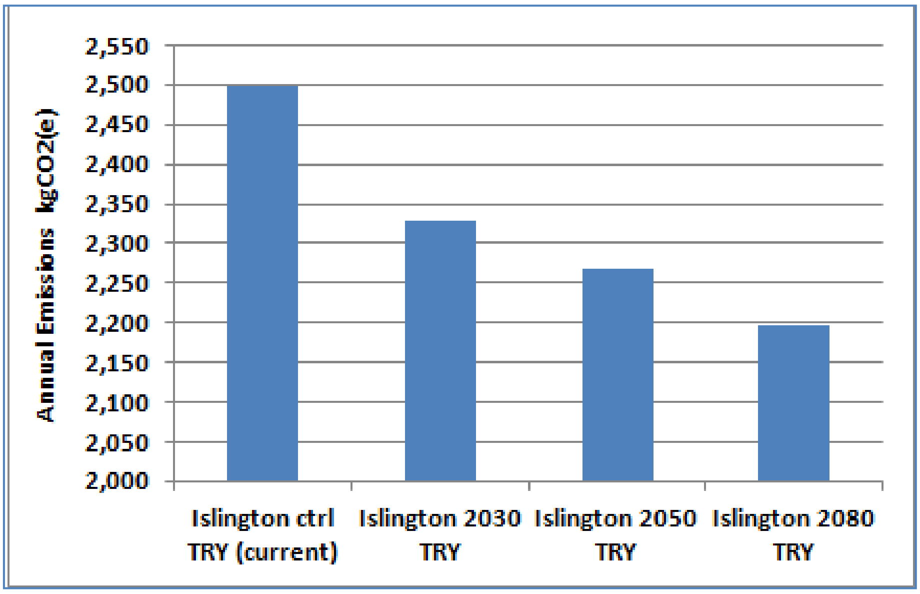


Figure 7-24. Detached house (Scenario B) total annual emissions using different weather files

Scenario C – 2 kW air conditioning, no additional mechanical ventilation

The previous assessment of scenario C indicated that adding air conditioning would ensure a good internal environment year round, with slightly lower emissions than for Scenario B. The monthly heating energy demand for the 4 climate scenarios is shown in Figure 7-25. The resulting annual heating energy demand in 2080 compared with present day is reduced by 37%.

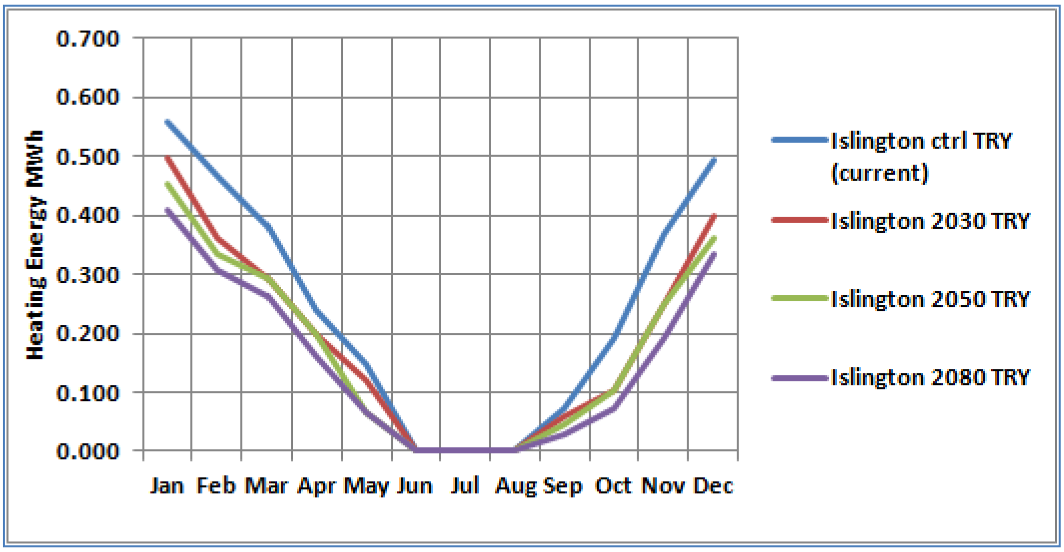


Figure 7-25. Detached house (Scenario C) monthly heating energy demand using different weather files

In contrast the monthly and annual cooling energy demands show significant increases (Figure 7-26). The annual cooling energy demand increases by 52% in 2030 and by 108% in 2080.

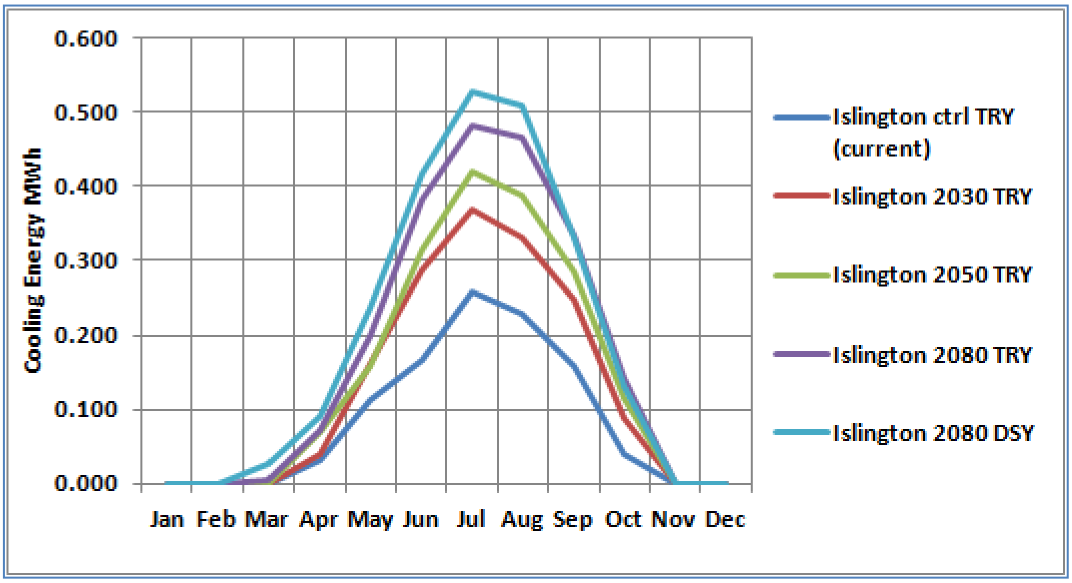


Figure 7-26. Detached house (Scenario C) monthly cooling energy demand using different weather files

The corresponding emissions breakdown for 2080 is shown in Figure 7-27. This indicates that in the summer months the cooling energy emissions are of similar magnitude to the emissions from other energy use.

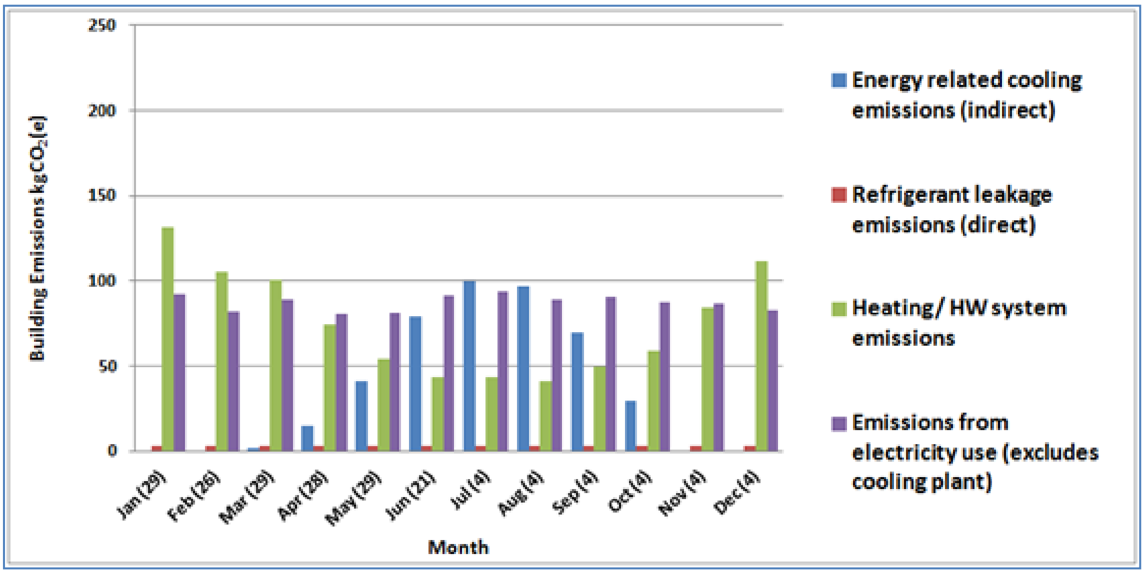


Figure 7-27. Detached house (Scenario C) breakdown of building emissions for 'Islington 2080 TRY' weather file

The total building emissions for scenario C with the 4 weather files are shown in Figure 7-28. However, these changes are very small, at -1.2% in 2030 and -0.5% compared with present day in 2080. While it may appear surprising that an increase in cooling energy demand results in an overall decrease in emissions, the cooling emissions are more than offset by a decrease in the heating energy emissions.

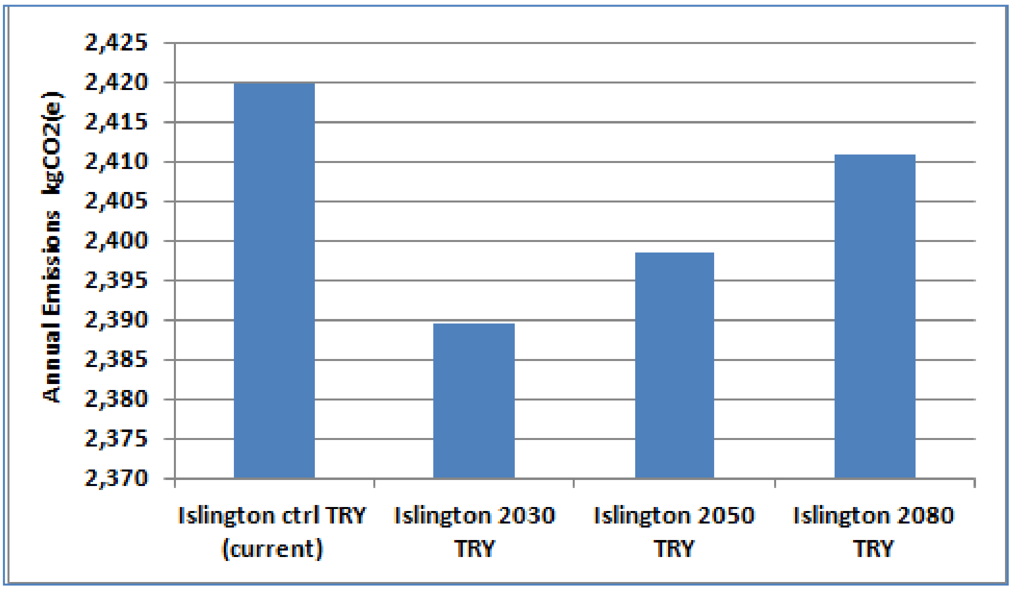


Figure 7-28. Detached house (Scenario C) annual building emissions using different weather files

In contrast with Scenarios A and B, scenario C demonstrates that the building environment is maintained to a good level of comfort with all of the weather files. Figure 7-29 confirms that there is little change in the day 3 profile between the present day and 2080 and that scenario C offers a much greater level of comfort than either of the other scenarios.

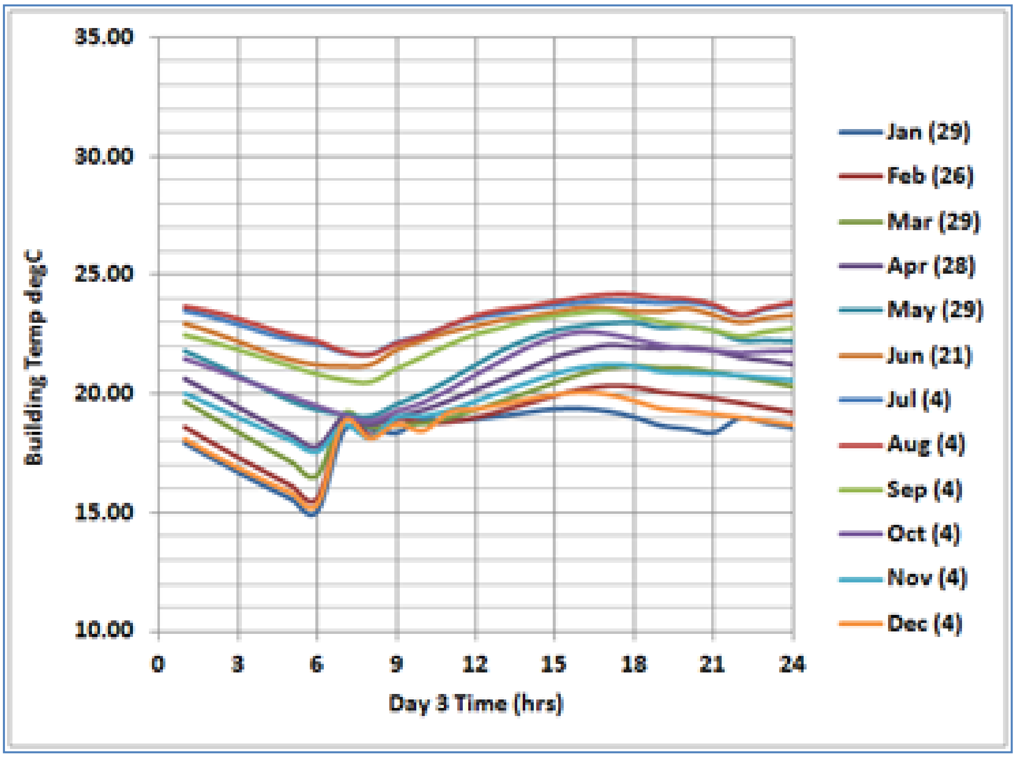


Figure 7-29. Detached house (Scenario C) building temperature using Islington 2080 TRY weather file

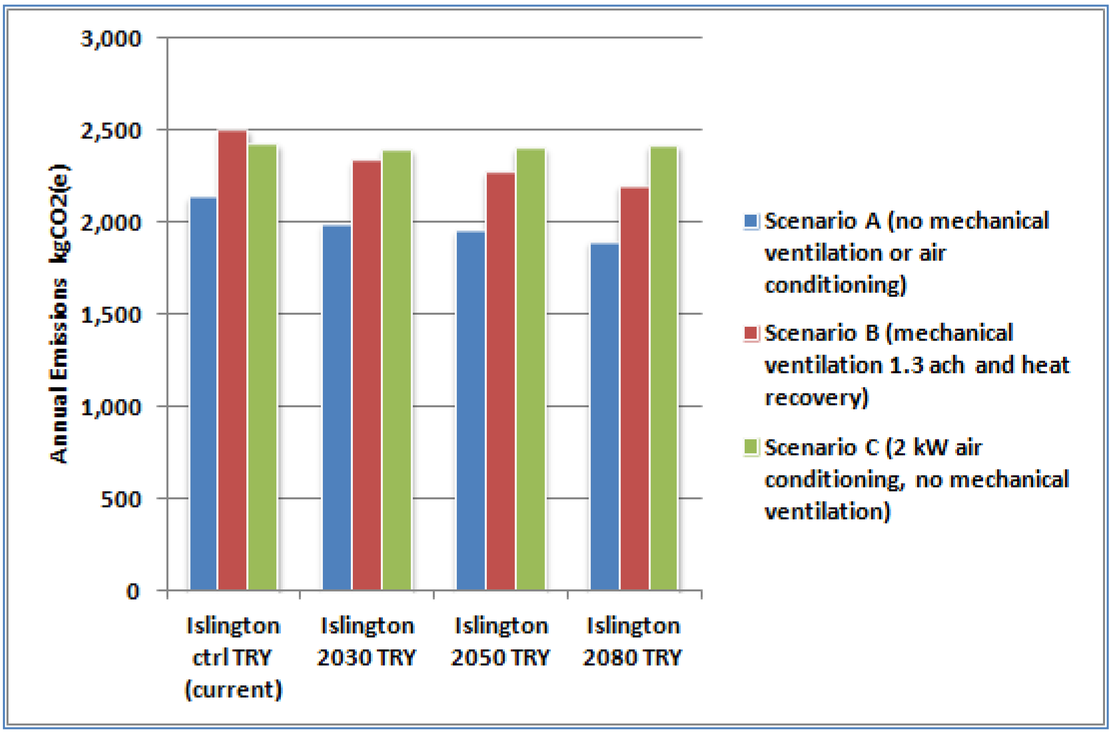


Figure 7-30. Detached house comparison of annual emissions for scenarios A, B and C using different weather files

Figure 7-30 compares that total building emissions for the 3 detached house scenarios for the 4 weather files. While scenario C achieves lower emissions than scenario B using current weather data, from 2030 onwards it has slightly higher emissions. However, this comparison does not take into account the fact that for both scenarios A and B the house is prone to overheating, so scenario C appears to provide a near optimal solution for all of the climate scenarios that were investigated.

Chapter 8. Discussion – the Excel tool: results and conclusions

A discussion of the capabilities and limitations of the Excel tool is followed by a review of the simulation results and comparisons that were described in Chapter 6 and the results of the sensitivity analyses described in Chapter 7.

8.1 The new Excel tool – capabilities and ease of use

The Excel tool is the author's implementation of the quasi-dynamic energy balance model described in Chapter 5. It incorporates most of the intended functionality and has been used for the simulations described in Chapters 6 and 7. There is still significant potential for refinement, improvement and further development of the tool. Some key points and observations concerning the design and use of the tool are detailed below:

- Although the schematic diagram (Figure 5-3) shows an external heat source or heat sink (such as a borehole, aquifer, or connection to a district heating or cooling scheme), this has not yet been modelled in the Excel tool. However, it could be added without undue difficulty, or approximated by adjusting the COP of the heating (or cooling) plant.
- Two relatively straightforward improvements that could improve the accuracy of the analysis are:
    - The addition of an algorithm to vary the 'cloud factor' seasonally (higher in winter, lower in summer). The current approach uses the same fixed value for all calendar months.
    - The addition of a flag to disable heat recovery when the building is in cooling mode. Currently when heat recovery is enabled it continues to operate when in cooling mode, resulting in higher cooling loads due to the unwanted heating of fresh air entering the building. However, in heating mode it does operate correctly, allowing the potential benefits of heat recovery to be assessed.
- The tool does not offer a dedicated user interface (dashboard), but relies on the user navigating between the worksheet to input data and view results. However, this does result in a high degree of flexibility whereby a competent Excel user can freely select and chart data from any worksheet and copy it to the results dashboard or a new worksheet for further analysis. The addition of macros could simplify some of the user actions.

- The tool does provide rapid results and if two windows are displayed simultaneously (one for input data, the other for results) it is possible to visualise instantly the impact of any changes (the 'undo'/ 'redo' buttons allow the user to switch back and forwards which helps to highlight the impact). However, there are some caveats:
    - Most of the charts have auto-scaling for the vertical axis. Although this simplifies the charting of results and offers the flexibility to cope with a wide range of building types and values, it can mean that the scaling will change when an input parameter is changed, making the comparison difficult. In such circumstances it was found necessary to revert to fixed scaling for some analyses.
    - Prior to undertaking the impact analysis, the user may be uncertain of what to expect. The existing results dashboard (which is currently configured to display temperature, energy balance and energy flow) will provide some indication of the impact, but the user may need to edit the results dashboard or add a new worksheet and copy results and charts from other worksheets, in order to be able to fully visualise the impact.
    - Once the user has undertaken an initial assessment using the screen displays, they will need to copy and paste results (using the 'paste special'/ 'paste values and number formats' commands) to a 'sensitivity analysis' worksheet in order to record and analyse the impact of each change.
- For most impact assessments a single parameter is changed at a time. However, when assessing the impact of climate change it is necessary to replace the entire weather file (12 x 24 matrix). In order to simplify the procedure, the relevant weather file matrices have been added to the 'Reference Data' worksheet, so that the weather file matrix can be changed using just 'copy' and 'paste'.
- Since the cells in the worksheets are not currently protected the user must take care not to inadvertently overwrite any existing data or formulae. It is recommended that the user always makes a copy of the original file under a new filename before undertaking any simulations.

It was originally intended to extend the Excel tool to model entire clusters of buildings in urban environments, using a series of linked workbooks/ worksheets. The key parameters for a range of typical building types (office, school, retail etc.), sizes and constructions could be stored in a library sheet with lookup tables and used to build up the cluster model by selecting the relevant quantities of each type and size of building. Demographic data from the UK Office for National Statistics for numbers and types of dwellings and business buildings would be used to construct the cluster model, which could then be used to predict the impact of changing demographics and climate change (for example). However, lack of time precluded this activity, also the added value of such an exercise is not clear.

8.2 Comparison of Excel and IES-VE results

The Excel tool and IES-VE software are very different both in concept and implementation, with the IES-VE software incorporating a full CFD model. The Excel simulation uses a relatively simple dataset (for example the external temperature matrix has only 288 data points and does not incorporate other climate factors, compared with 8,760 temperature data points plus other climate factors for IES-VE). IES-VE uses 3D drawing tools to define the building, whereas the Excel tool defines the building shape by its footprint and height. The Excel model treats the interior of the building as a single climate zone, whereas IES-VE can simulate multiple zones within a building (for this comparison a single climate zone was modelled for both simulations).

Notwithstanding these differences, the results of the Excel and IES simulations demonstrate good agreement for the heat gains and heat flows associated with the fabric of the building, ventilation, solar gain and occupancy, at least on a monthly and annual basis. The main discrepancy between the Excel and IES simulations is associated with the heating and cooling plant loads, as discussed in Section 6.3 of Chapter 6. The variance appears to be related to the mode of operation for the heating and cooling plant, where the Excel algorithms permit both heating and cooling on the same day (but not at the same time) to maintain the internal environment of the building, while the IES data suggest that only heating or cooling (but not both) can occur on the same day.

The consequence is that the Excel model predicts higher annual energy demands for both heating and cooling than IES. However, when the Excel model results were compared with CIBSE TM46 benchmark and other data (in Section 6.4 of Chapter 6), it was found that the Excel simulation still predicts significantly lower energy use than the TM46 benchmark (and energy and emissions data from other sources).

Despite these discrepancies, the Excel tool results do provide some support for the premise that less complex models can achieve sensible results. Some studies have suggested that building energy simulation software often fails to accurately predict the actual performance of buildings, although such software continues to be used extensively. One reason for this could be the difficulty in accurately modelling occupancy profiles and the building management system – in real buildings they could be very different from the parameters assumed within a simulation.

The key objective for the new model and Excel implementation was to provide a high level planning tool that is capable of rapidly simulating the impact of changes to the design and operational parameters of buildings, in order to assess the sensitivities and scope for energy and emissions reductions. The results of the sensitivity analyses suggest that objective has to a large extent been met.

8.3 Comparison with building benchmarks and other energy and emissions data

The comparison of the Excel simulation results with building benchmarks and other energy and emissions data derived from other sources demonstrated significant discrepancies for both the office building and the detached dwelling. However, there are also significant discrepancies between different benchmarks, as well as between benchmarks and the energy and emissions data derived from other sources. These discrepancies appear to confirm the difficulty in establishing meaningful and rigorous benchmarks for whole building energy and emissions.

On the basis of these results it might be reasonable to question the usefulness of benchmarks and other energy and emissions data when assessing the energy performance and emissions of buildings. However, this study considered only two building types, also there will inevitably be wide variations in the design, construction and operation of individual buildings within each benchmark category.

It should be noted that most (if not all) all building simulation software makes use of benchmarks within their model. HVAC system parameters, ventilation rates and internal power and heat gains (for lighting, hot water, office equipment etc.) for example, are generally based on established benchmarks, which are built into the software. Benchmarks for individual equipments and components can be measured with relative ease and good accuracy and are therefore likely to be similar for most building energy software.

8.4 Energy and emissions sensitivity to building design and operating parameters

8.4.1 Office Building

The results of the Excel model analysis indicated that over 50% of the emissions from the office building were associated with non-cooling electricity use, primarily for lighting and office equipment. The internal heat gains (mainly from this electricity use) were a key factor in determining the amount of cooling (and heating) required by the building. Cooling emissions were the second largest source of emissions, being up to 30% of total emissions from the building in summer months. Emissions from heating and hot water were lower: even in mid-winter they were less than 20% of total emissions.

It was therefore evident that the most important factor in reducing building emissions would be to reduce the non-cooling electricity demand, as not only would it lower the emissions from grid electricity use, but it would also reduce the need for cooling. It was also expected that reducing other heat gains in the building (for example solar gains) would help to reduce the total building emissions.

The sensitivity analysis (Section 7.2.1) supports this premise. A relatively simple change, replacing fluorescent lighting with LEDs, would not only reduce the annual non-cooling electricity use by more than 12% (from 971 to 851 MWh), but also reduces the cooling system electricity use by 16% (from 248 to 208 MWh). Although there is a small increase in the heating and hot water energy use and emissions, the net impact of a change from fluorescent to LED lighting is a reduction of 11% in total building emissions. Likewise, if other electrical energy use (for example from office equipment or ancillary equipment such as pumps and fans) could be reduced through efficiency improvements or other energy saving measures, there could be further reductions in building emissions.

The sensitivity analysis also demonstrates that reducing the solar gain, either by reducing the glazed window area, or by using solar control glass (which reduces the transmittance for solar heat energy but provides good transmission of natural light), can contribute a useful reduction in total building emissions. For many modern office buildings, most of the façade is glazed, but reducing the glazed area from 80% to 40% could reduce the cooling emissions by over 30% and total building emissions by 10%. Alternatively, a similar result could be achieved by halving the solar transmittance of the glass – for example selectively coated glass is now available with a solar factor (g-value) as low as 0.28 whilst still achieving a light transmittance (Lt value) of 61% (compared with a g-value of 0.7 and Lt value of 74% for standard glazing).

The sensitivity analysis also demonstrates the trade-off between heating and cooling energy demand and emissions when the thermal properties of the building are changed. The analysis confirmed that although changing the U values of the building fabric from 2006 Building Regulation standards to typical pre-war values would increase the annual heating energy use by almost 100% and reduce the cooling energy use by 44%, the net increase in total building emissions would be less than 1.3%. This implies that for commercial office buildings the age and construction materials (with the exception of the glazing) are not major factors in terms of the total building emissions.

The Excel tool can be used to model the sensitivity of building emissions to many other parameters, such as the heating and cooling set points, the thermal capacity of the internal structure, the sizing and efficiency of the heating, hot water and cooling plant (and their distribution and delivery systems), pre-heating and cooling, occupancy profiles and ventilation rates. It could also be used to investigate the impact of alternative fuels, varying the grid electricity carbon emissions factor (to simulate the impact of renewable etc.) and the sensitivity to refrigerant leakage rate.

8.4.2 Dwelling (detached house)

The sensitivity analysis for the dwelling example is described in Section 7.2.2. The focus for this investigation was the tendency for dwellings constructed in recent years to overheat during summer months, due to the high insulation standards and air tightness mandated by modern Building Regulations. However, many of the results from the office building sensitivity analysis are also relevant to dwellings – additional simulations show the internal environment (temperature) and building emissions to be highly sensitive to parameters such as the glazed area, glass specification and the internal gains from lighting and other electrical power use.

The results of the scenario A baseline simulation (no mechanical ventilation or cooling) indicated a significant risk of the dwelling overheating, especially during the months of July and August, when the internal temperature could reach 28°C, even on an average day. In practice the occupier would almost certainly rely on opening windows to achieve some cooling from natural ventilation. However, on the hottest days in the month the internal temperature would be significantly higher than the predicted 28°C (without additional cooling measures), because the Excel simulations used daily weather data that had been averaged over all the days in the month, which smoothes out peaks. In fact, using a weather data file generated from peak hourly temperatures in each month the Excel simulation indicated that the dwelling's internal temperature could occasionally exceed 30°C between the months of May and September, with a peak of 37°C in mid-summer.

The overheating would not be materially improved by adding mechanical ventilation, according to the scenario B simulation. This reduced the peak temperatures by about 1°C but could still result in high levels of discomfort. Increasing the air change rate from 1.3 ach to 3 ach (a figure frequently assumed for natural cooling from opening windows) achieved a further small reduction in temperatures, but this would be at the expense of a significant increase in emissions due to the additional energy consumed by the fans.

Scenario C (2 kW air conditioning) on the other hand not only maintained a comfortable temperature (23°C maximum) during the summer, but also achieved a lower level of total emissions than the mechanical ventilation scenario. Even using the weather data file generated from peak hourly temperatures in each month the Excel simulation indicated that the building's internal temperature would peak at less than 27°C (compared with 35°C and 37°C for the other scenarios), while the total building emissions increased by less than 5% when compared with results from the average temperature weather file.

These results suggest that dwellings constructed to modern building standards and regulations, particularly those built since the start of the 21st century, may be prone to overheating. The requirements for low U values and permeability, which were aimed at reducing heating demand and associated emissions, have resulted in dwellings that can be heated with little more energy than provided by the internal heat gains and solar gain. If operated without additional ventilation or air conditioning they do use less energy and have lower emissions than less well insulated dwellings built to older standards. However, when taking into account comfort levels some form of additional cooling is required in summer and the simulations suggest that air conditioning can achieve lower emissions than mechanical ventilation solutions.

The practical implementation of cooling throughout existing buildings could present significant challenges unless a suitable delivery mechanism already exists. A mechanical ventilation system linked to a central air conditioning unit could be installed but the ducting could take space, compromise the aesthetics of rooms and require extensive redecoration. An alternative might be to install a reversible heat pump in conjunction with an existing underfloor or radiator system. The underfloor solution could operate with small temperature differentials which would be unlikely to result in condensation in cooling mode. A radiator based cooling system might be more difficult to implement unless larger radiators were fitted in order to reduce temperature differentials and the consequent risk of condensation in cooling mode.

8.5 Sensitivity to climate change

8.5.1 Office building

The simulations using 4 weather data files (current, 2030, 2050 and 2080) demonstrated that a comfortable internal environment of the office building could be maintained for all weather scenarios, without any need to change any operational settings or other parameters. The internal temperature remained within the range 18.5°C to 23°C under all conditions during normal work hours and the simulations also confirmed that even with the higher external temperatures associated with the 2080 weather file there could still be a small benefit from the use of night cooling.

The alternative climate scenarios impact the heating and cooling energy demand much as expected. The warmer climate reduces the space heating energy demand by 32% between present day and 2080, while the space cooling energy demand increases by 45% over the same period. The resulting increase in emissions from present day to 2080 is only 5% (assuming no change in carbon emission factors).

Since the majority of the emissions from the office building are from grid electricity use (for both cooling and non-cooling applications), changes in the grid electricity carbon emission factor will be the key determinant of emissions from such buildings in the future. When the year 2080 simulation is re-run using a carbon factor of 0.089 kgCO_2/ kWh (a reduction of 80% from the present day value) the 2080 building emissions drop by 70% (instead of increasing by 5% when the carbon factor is unchanged). Further reductions could result from lower electrical energy demand (for both cooling and non-cooling applications) due to long term efficiency improvements in equipment and plant. It would therefore not be unreasonable to assume that a greening of the electricity grid, combined with other measures, would offer the potential for emissions from commercial buildings to meet the UK’s 80% emission reduction targets in the longer term.

8.5.2 Dwelling (detached house)

The simulations for the detached house example using the 4 weather data files (current, 2030, 2050 and 2080) suggest that dwellings are likely to be impacted much more severely by climate change than commercial buildings, many of which already have air conditioning. They indicate that the potential overheating issue for dwellings that do not incorporate mechanical ventilation systems will become progressively more severe over time and that measures such as reducing window areas, adding solar control glazing or blinds and reducing internal gains may not in themselves be sufficient to bring internal temperatures within acceptable limits during the summer. Mechanical ventilation can achieve a small (but not material) reduction in peak internal temperatures, at the expense of increased electrical energy use and emissions.

A small air conditioning unit, on the other hand, is capable of maintaining an acceptable internal environment, even using 2080 weather data. The simulation predicts that net annual emissions from the building would actually fall between present day and 2080, even assuming constant carbon emission factors. When the year 2080 simulation is re-run using a carbon factor of 0.089 $kgCO_2$/ kWh (a reduction of 80% from the present day value) the 2080 building emissions would drop by nearly 50%. However, this reduction is smaller than for the commercial building because the heating and hot water energy use for the dwelling is a higher proportion of the total energy used.

The simulations therefore suggest that greener electricity grid would make a smaller contribution towards meeting the UK's 80% emissions reduction target for dwellings than for commercial buildings, so significant additional measures might be required. These would need to be aimed at reducing the heating and hot water energy demands (the hot water energy predominates for this simulation). Some options might include replacing fossil fuel and gas heating systems with heat pumps (if reversible they could also deliver the required cooling energy) and adding heat exchangers to recover and reuse heat from hot water waste. Further improvements might be achieved in newer dwellings by greater adoption of natural cooling and ventilation approaches and increased thermal mass, possibly combined with thermal energy storage or borehole systems.

Chapter 9. Conclusions

Refrigeration, air conditioning and heat pump (RACHP) systems currently account for nearly 20% of UK grid electricity use and over 7% of all UK greenhouse gas emissions. Under many scenarios, global warming and the trend towards greater urbanisation and other demographic changes, will increase both cooling demand and the associated emissions. The UK commitment to reducing greenhouse gas (GHG) emissions by 80% by 2050 requires the consideration of new and innovative approaches to the cooling of buildings. Cooling loads might be reduced through optimisation of a building's design and operation, while the use of more efficient RACHP systems, reduced emissions from the leakage of high GWP refrigerants and the use of alternative low GWP refrigerants could all help to deliver lower carbon cooling solutions.

This thesis has described an investigation into the emissions from RACHP systems and a novel approach to understanding the cooling (and heating) energy demand and emissions in buildings. A building's cooling and heating energy demands and emissions are both influenced by many of the same factors, so heating and cooling cannot be considered in isolation if the aim is to reduce the total building energy use and emissions. Assessing alternative building design concepts, RACHP system, passive cooling techniques and strategies for managing the building, requires simulation tools that allow the user to evaluate and view the building's dynamic response, energy use and emissions in near real time.

Key outcomes of investigations into the levels, sources and causes of emissions from RACHP systems, described in Chapter 4, included a significant (43%) reduction in refrigerant leakage and emissions from RACHP systems where the owners and operators have adopted the principles for refrigerant containment that were developed as part of the REAL Zero project. An improved understanding of the causes, types and location of leaks have resulted from a project to develop a structured approach to the analysis of fault reports and system logs.

A conclusion from an exercise to assess the impact of refrigerant leakage on the TEWI of RACHP systems was that for high GWP refrigerants, reducing the refrigerant leak rate is likely to be a more effective way to reduce total emissions than by reducing indirect emissions (through efficiency and other improvements), due to the 'multiplier' effect. However, once the leak rate drops to around 2%, or if low GWP refrigerants (GWP = 500 or less) are used, the direct emissions from refrigerant leakage become small relative to the indirect emissions and make only a minor contribution, so reducing the TEWI further would require a reduction in energy use. The analysis of refrigerant leakage records for 840 heat pump and air conditioning systems indicated an average leak rate of 2.7%, while the results of TEWI calculations for alternative refrigerants show that for refrigerant R134a the direct emissions contribution to the TEWI would be less than 4%. Therefore, refrigerant leakage is not expected to be a significant contributor to total emissions from buildings, in comparison with the indirect emissions.

The key objective for developing a new model and the Excel implementation was to provide a high level planning tool that is capable of rapidly simulating the impact of changes to the design and operational parameters of buildings, in order to assess the sensitivities and scope for energy and emissions reductions. Early results indicated that a building's cooling energy demand and emissions cannot be investigated in isolation from its heating and electrical energy (and associated emissions), as they are heavily interdependent, so the research was broadened to investigate total energy demand and emissions.

The development of the model and implementation of the Excel tool are described in Chapter 5. The tool provides most of the intended functionality, but does currently require that the user is experienced in using Excel. However, with some improvements (which include the addition of macros and a new user interface), it could be made simpler to use and capable of being operated by a user with only limited experience of Excel.

The Excel tool has been used to simulate the performance of an office building and dwelling and the results compared with other software (IES-VE) and benchmarking data. It has also been used to assess the sensitivity of the building energy and emissions performance to changes in the building design and operation, in order to determine the key factors influencing the building's energy use and emissions, as well as the potential impact of climate change. The results of these simulations are described in Chapters 6 and 7 and discussed in Chapter 8.

The broad conclusions from the office building sensitivity analyses were that the building fabric (with the exception of the glazing) is not necessarily a key determinant of the total energy and emissions, primarily because of the trade-offs between heating and cooling demand. Comparison of the office building simulations using pre-war and 2006 building standards indicated a difference of only 1.3% in the total emissions due to the heating - cooling trade-offs. The glazing on the other hand appears to have a much higher influence on the energy demand and emissions: changes to the glazed area and glazing material properties could impact energy use and emissions by 10% or more. Even more striking is the impact of reducing the internal heat gains from electricity use (by a large margin the largest contributor to emissions for the building analysed): a relatively small reduction in energy use, for example by changing from fluorescent lighting to LEDs, also reduces the cooling energy demand, lowering the total emissions by 11%. The simulations confirmed that emissions reductions could also be achieved through numerous other measures, including (for example) modifying the internal fabric to increase the thermal capacity, changing the temperature set points and ventilation rate and more efficient heating and cooling plant.

The dwelling simulation results suggested that buildings constructed in accordance with the 2006 Building Regulations could be at risk of overheating in summer months, even if they incorporate mechanical ventilation. They also indicated that the addition of a relatively small (2 kW) air conditioning unit could not only prevent overheating and provide a more comfortable internal environment, but also result in lower overall energy use and emissions than for a dwelling with mechanical ventilation. The simulation results also indicated that window size and glazing materials could be key factors influencing the energy demand and emissions in dwellings. Recent Building Regulations have focused heavily on high insulation levels and air tightness; these results suggest that future versions should focus more on the potential for overheating and appropriate cooling measures.

The climate change simulations indicated that for the office building the net increase in energy demand and emissions between present day and 2080 would be only 5%, a 45% increase in cooling energy demand being offset to some extent by a 32% reduction in space heating energy. A comfortable internal environment would be maintained without the need for any change to the building or plant parameters and settings. Since the majority of the emissions from the office building are from grid electricity use (for both cooling and non-cooling applications), changes in the grid electricity carbon factor will be the key determinant of emissions from such buildings in the future (an 80% reduction in the carbon factor would result in a 70% reduction in emissions for the office building).

The impact of climate change would be greater for the detached dwelling than for the office building, according to the simulations, with a major risk of overheating unless specific cooling measures, such as the incorporation of air conditioning, are implemented. Without cooling, simulations using averaged weather data (TRY and DSY) files for 2080 predict that the internal temperature would rise to 32°C on most summer days, while simulations with peak temperature data result in temperatures of around 40°C. However, with cooling (2 kW of air conditioning) the internal temperature drops to less than 25°C and the dwelling's total energy use and emissions would be no higher than for the present day. When the year 2080 simulation is re-run using a carbon factor of 0.089 $kgCO_2$/ kWh (a reduction of 80% from the present day value) the 2080 building emissions would drop by nearly 50% (this reduction is smaller than for the commercial building because the heating and hot water energy use for the dwelling is a higher proportion of the total energy used).

The results suggest that with some improvements the Excel tool could help to improve the understanding of building energy use and emissions and to rapidly predict the potential impact of changes. Some uses include:

- For existing buildings, to assess their potential for reduced energy use and lower emissions, by modelling the existing design and the impact of changing design features and operating mode.
- For new buildings, to assess and optimise the energy and emissions performance of the building preliminary design concept before the plans are finalised.
- As a strategic planning tool, to assess the potential impacts and responses to the effects of climate change and the likely impact of changes to building standards and new regulations, before they are introduced.

References

ADE (2012) *CHPA published first map of district heating schemes*. Available online at http://www.theade.co.uk/chpa-publishes-first-map-of-district-heating-schemes_827.html [Accessed 18 January 2017]

AFAES/ DOE (1991) *GW project: energy and global warming impacts of CFC alternative technologies, executive summary Oak Ridge laboratory.* Available online at http://www.ciesin.org/docs/011-459/011-459.html [Accessed 13 February 2017]

Anderson B. R., Chapman, P. F., Cutland N. G., Dickson C. M., Henderson G., Henderson J. H., Iles P. J., Kosmina L., Shorrock L. D. (2002). *BRE438: BREDEM-12 Model description 2001 update*. Watford: BRE

Anderson J. (2005) *Is STEK as good as reported? Uncertainties in the concept underlying the proposed European Regulation on fluorinated gases.* Belgium: Institute for European Environmental Policy

ASHRAE (2010) *ANSI/ASHRAE Standard 55-2010: Thermal Environmental Conditions for Human Occupancy.* Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers

Attia, S. (2011) *State of the art of existing early design simulation tools for net zero energy buildings: a comparison of ten tools.* Belgium: Université Catholique de Louvain. Available online at http://www-climat.arch.ucl.ac.be/s_attia/attia_nzeb_tools_report.pdf [Accessed 14 February 2017]

Bostock D. (2007) Designing to minimise the risk of refrigerant leakage. In: *Proceedings of IOR Annual Conference 2007*. UK: Institute of Refrigeration

BSRIA (2011) *Rules of Thumb - guidelines for building services (5th Edition).* BG 9/2011. Available online at https://www.bsria.co.uk/information-membership/bookshop/publication/rules-of-thumb-guidelines-for-building-services-5th-edition/ [Accessed 17 January 2017]

Bundesgesetzblatt (2008) *Chemikalien-Klimaschutzverordnung – ChemKlimaschutzV*. Available online at http://www.umweltbundesamt.de/produkte/dokumente/bgbl108s1139ChemKlimaSchutzV.pdf [Accessed 21 August 2013]

Carrier (2017) *The invention that changed the world.* USA: United Technologies Corporation. Available online at http://www.williscarrier.com/1876-1902.php [Accessed 11 January 2017]

CEN (2008) *Energy performance of buildings – calculation of energy use for space heating and cooling (ISO 13790: 2008).* Brussels: CEN

CIBSE (2002) *Weather, solar and illuminance data.* CIBSE Guide J. London: Chartered Institution of Building Services Engineers

CIBSE (2004) *Energy efficiency in buildings.* CIBSE Guide F. London: Chartered Institution of Building Services Engineers

CIBSE (2005) *Sustainable low energy cooling: an overview.* CIBSE Knowledge Series: KS3. London: Chartered Institution of Building Services Engineers

CIBSE (2005b) *Heating, ventilating, air conditioning and refrigeration.* CIBSE Guide B. London: Chartered Institution of Building Services Engineers

CIBSE (2006a) *Degree-days: theory and application.* TM41: 2006. London: Chartered Institution of Building Services Engineers

CIBSE (2006b) *Guide A: Environmental design.* London: Chartered Institution of Building Services Engineers

CIBSE (2008) *Energy benchmarks.* CIBSE TM46: 2008 London: Chartered Institution of Building Services Engineers

CIBSE (2013) *Thermal comfort: avoiding overheating in European buildings.* CIBSE TM52: 2013. London: Chartered Institution of Building Services Engineers

COM (2011) *Report from the Commission: on the application, effects and adequacy of the Regulation on certain fluorinated greenhouse gases*. Regulation (EC) No 842/2006. Available online at https://ec.europa.eu/clima/sites/clima/files/f-gas/docs/report_en.pdf [Accessed 11 February 2017]

Corberan, J.M., et al. (2008) Charge optimisation study of a reversible water-to-water propane heat pump. *International Journal of Refrigeration,* 2008.31 (4): p. 789-798

Cowan (2008) *Renewable Electrical Energy Strategies for Low and Zero Carbon Homes*. MSc project dissertation. London: London South Bank University

Cowan, D., Gartshore, J., Chaer, I., Francis, C., Maidment, G., (2010) REAL Zero – reducing refrigerant emissions & leakage - feedback from the IOR project. *Proceedings of the Institute of Refrigeration*, Proc. Inst. R. 2009-10. 7-1

Crawley, D.B., Hand, J.W., Kummert, M. and B. T. Griffith. (2008). Contrasting the capabilities of building energy performance simulation programs. *Building and Environment.* Volume 43(4): 661-673

Day, A.R., Jones, P.G., and Maidment, G.G. (2009) Forecasting future cooling demand in London. *Energy and Buildings.* 41 (2009) pp. 942-948

Day, A.R., Maidment, G.G., Jones, P.G. and Auston, J. (2011) *A low carbon cooling guide.*

Technical report: advice and guidance to support implementation of energy planning policy. London: London South Bank University

DCLG (2014) *Live tables on Energy Performance of Buildings Certificates.* Available online at https://www.gov.uk/government/statistical-data-sets/live-tables-on-energy-performance-of-buildings-certificates [Accessed 13 February 2017]

DECC (2010) *2050 pathways analysis.* Report URN 10D/764. Available online at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42562/216-2050-pathways-analysis-report.pdf [Accessed 17 January 2017].

Dukes (2013) *Digest of United Kingdom energy statistics 2013.* Available online at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/279523/DUKES_2013_published_version.pdf [Accessed 17 January 2017].

EC (2006) *European Commission Regulation (EC) No. 842/2006*. Available online at http://ec.europa.eu/clima/policies/f-gas/legislation/documentation_en.htm. [Accessed 21 August 2013]

EC (2009) *European Commission Regulation (EC) No. 1005/2009 on substances that deplete the ozone layer*. Available online at http://ec.europa.eu/clima/policies/ozone/documentation_en.htm. [Accessed 21 August 2013]

EC (2014) *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006.* Available online at http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.150.01.0195.01.ENG [Accessed 11 February 2017]

EEA (2010) *Annual European Union greenhouse gas inventory 1990 – 2008 and inventory report 2010.* Available online at http://www.eea.europa.eu/publications/european-union-greenhouse-gas-inventory-2010 [Accessed 25 February 2011]

EEA (2011) *Preparatory study for a review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases.* Available online at http://www.eea.europa.eu/data-and-maps/indicators/emissions-and-consumption-of-fluorinated/preparatory-study-for-a-review [Accessed 11 February 2017]

Energy Plan (2016) *Energy Plan: advanced energy system analysis computer model.* Available online at http://www.energyplan.eu/ [Accessed 18 January 2017]

ETSU (1997) *Cutting the cost of refrigerant leakage*. Good Practice Guide 178. October 1997. Didcot UK: ETSU

EU (2010) *Energy Performance of Buildings Directive.* Available online at http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1405696745374&uri=CELEX:32010L0031 [Accessed 18 July 2014]

Euroheat (2010). *District cooling: the sustainable response to Europe's rising cooling demands.* Available online at https://www.euroheat.org/wp-content/uploads/2016/04/Brochure-District-Cooling.pdf [Accessed 18 January 2017]

Europa (2006) *Ecoheatcool work package 5: possibilities with more district cooling in Europe. Final report.* Available online at https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/ecoheatcool_more_district_cooling_in_europe.pdf [Accessed 18 January 2017]

Exeter (2013) *PROMETHEUS: the use of probabilistic climate change data to future-proof design decisions in the building sector.* Available online at http://emps.exeter.ac.uk/engineering/research/cee/research/prometheus/ [Accessed 5 February 2013]

Fernando, P., et al. (2004) Propane heat pump with low refrigerant charge: design and laboratory tests. *International Journal of Refrigeration,* 2004.27(7): p. 761-773.

Francis, C. (2010) *Investigation of Refrigerant Leakage within UK Major Supermarkets*. MSc project dissertation. London: London South Bank University

GLA (2006) *London's urban heat island: a summary for decision makers.* London: Greater London Authority. Available online at http://legacy.london.gov.uk/mayor/environment/climate-change/docs/UHI_summary_report.pdf [Accessed 18 July 2014]

GLA (2011a) *The London plan: spatial development strategy for Greater London.* Available online at https://www.london.gov.uk/what-we-do/planning/london-plan/past-versions-and-alterations-london-plan/london-plan-2011 [Accessed 17 January 2017]

GLA (2011b) *Delivering London's energy future: the Mayor's climate change mitigation and energy strategy.* October 2011. London: Greater London Authority. Available online at https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/Energy-future-oct11.pdf [Accessed 17 January 2017]

GOV.UK (2008) *Climate Change Act 2008.* Available online at http://www.legislation.gov.uk/ukpga/2008/27/contents [Accessed 11 February 2017]

GOV.UK (2012) *The Energy Performance of Buildings (England and Wales) Regulations 2012.* Available online at http://www.legislation.gov.uk/uksi/2012/3118/contents/made [Accessed 17 January 2017]

GOV.UK (2015) *Final UK greenhouse gas emissions national statistics: 1990-2012.* Available online at https://www.gov.uk/government/statistics/final-uk-greenhouse-gas-emissions-national-statistics-1990-2012 [Accessed 13 February 2017]

GOV.UK (2016) *UK Government GHG Conversion Factors for Company Reporting.* Available online at https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2016 [Accessed 17 January 2017]

Heap R. (2001) Refrigeration and air conditioning – the response to climate change. *Bulletin of the IIR* No 2001-5.

Heatroadmap (2017) *Heat Roadmap Europe: a low-carbon heating and cooling strategy for Europe.* Available online at http://heatroadmap.eu/ [Accessed 18 January 2018]

Hitchin and Pout (2000) *Local cooling: global warming? UK carbon emissions from air-conditioning in the next two decades.* Watford, UK: Building Research Establishment

IES (2014) *IES Virtual Environment.* Available online at http://www.iesve.com/software [Accessed 18 July 2014]

IGU (2015) Natural gas facts and figures. *World Gas Conference, Paris. 2015.* Available at http://www.igu.org/sites/default/files/FactsFigures_contentOct2014.pdf [Accessed 17 January 2017]

IGU (2017) *Natural gas is efficient*. Available online at http://www.igu.org/natural-gas-efficient [Accessed 16 January 2017]

IIR (2015) *The role of refrigeration in the global economy: 29th Informatory Note on refrigeration technologies.* Paris, France: International Institute of Refrigeration. Available online at http://www.iifiir.org/medias/medias.aspx?INSTANCE=exploitation&PORTAL_ID=portal_model_instance__publication_notes_information_en.xml&SYNCMENU=INFORMATORY_NOTES&SET LANGUAGE=EN [Accessed 14 February 2017]

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Prepared by the NationalGreenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Japan: IGES

IPCC (2013) Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPU (2012) *CoolPack refrigeration utilities: version 1.50.* Available online at http://www.en.ipu.dk/Indhold/refrigeration-and-energy-technology/coolpack.aspx [Accessed 17 December 2012]

Kalema, T., Johannesson, G., Pylsy, P. and Hagengran, P. (2008) Accuracy of energy analysis of buildings: a comparison of a monthly energy balance method and simulation methods in calculating the energy consumption and the effect of thermal mass. *Journal of Building Physics.* Oct 2008. vol. 32: 101-130

Kim, W., Braun, J.E. (2012) Evaluation of the impacts of refrigerant charge on air conditioner and heat pump performance. *International Journal of Refrigeration,* 2012.35: p. 1805-1814

London.gov (2016) *London Heat Map – helping decentralised energy projects.* Available online at https://www.london.gov.uk/what-we-do/environment/energy/london-heat-map [Accessed 27 March 2015]

MTPROG (2007) *BNCR36: Direct Emission of Refrigerant Gases.* Market Transformation Programme. UK: DEFRA

MTPROG (2010) *Product strategies.* Market Transformation Programme. UK:DEFRA. Available online at http://webarchive.nationalarchives.gov.uk/20101125154034/http:/efficient-products.defra.gov.uk/product-strategies/viewall/briefing-note [Accessed 10 January 2017]

NBS (2014) *Building Regulations: Part L (Conservation of fuel and power).* Available online at http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/ [Accessed 29 January 2015]

ODPM (2006) *Approved document L2A: conservation of fuel and power in new buildings other than dwellings (2006 ed.).* London: NBS. Available online at https://www.planningportal.co.uk/info/200135/approved_documents/74/part_l_-_conservation_of_fuel_and_power/7 [Accessed 14 February 2017]

ONS (2014) *Neighbourhood statistics.* Office of National Statistics. Available online at http://www.neighbourhood.statistics.gov.uk/dissemination/LeadHome.do?m=0&s=1485106149388&enc=1&nsjs=true&nsck=false&nssvg=false&nswid=1366 [Accessed 17 December 2014]

Ramboll (2011) *City of London Corporation London heat map study.* London: Ramboll Energy. [Online] https://data.london.gov.uk/dataset/london-heat-map [Accessed 13 February 2017]

Refsols (2012) *RS-70 Coefficient of performance chart.* Refrigerant Solutions Ltd. Available online at http://www.refsols.com/files/RS-70/RS-70_COP_chart.pdf [Accessed 3 February 2017]

Revesz (2013) Evaluation of the influence of refrigerant charge on the performance of a ground source heat pump (GSHP). London: London South Bank University (unpublished work)

Rhiemeier, J., Harnisch, J., Ters, C., Kauffeld, M. and Leisewitz, A. (2009) *Comparative assessment of the climate relevance of supermarket refrigeration systems and equipment.* Report 206 44 300. UmweltBundesAmt, Dessau-Roßlau.

Ricardo-AEA. (2016) *UK Greenhouse Gas Inventory, 1990 to 2014: Annual Report for submission under the Framework Convention on Climate Change.* Report UK NIR 2016 (Issue 2) April 2016. Harwell: Ricardo Energy & Environment. Available online at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php [Accessed 4 January 2017]

Sand, J., Fischer, S. and Baxter, V. (1997) Energy and global warming impacts of HFC refrigerants and emerging technologies, *Alternative Fluorocarbons Environmental Acceptability Study (AFEAS),* Table 52 p186, Oak Ridge National Laboratory, Oak Ridge.

Santamouris, M. (2014) Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy,* Vol 103 pp. 682-703 Available online at http://www.sciencedirect.com/science/article/pii/S0038092X12002447 [Accessed 13 February 2017]

Shahidan, M.F., Jones, P.J., Gwilliam, J., Salleh, E. (2012) An evaluation of outdoor and building environment cooling achieved through combination modification of trees with ground materials. *Building and Environment*. Volume 58, December 2012, Pages 245-257, ISSN 0360-1323. Available online at http://www.sciencedirect.com/science/article/pii/S0360132312002004 [Accessed 13 February 2017]

Soliftec (2016) *Efficiency – not just a number.* Solid Fuel Technology Institute. Available online at http://www.soliftec.com/efficiency.htm [Accessed 10 January 2017]

Stocker, T.F., D. Qin, G.-K. Plattner, L.V. Alexander, S.K. Allen, N.L. Bindoff, F.-M. Bréon, J.A. Church, U. Cubasch, S. Emori, P. Forster, P. Friedlingstein, N. Gillett, J.M. Gregory, D.L. Hartmann, E. Jansen, B. Kirtman, R. Knutti, K. Krishna Kumar, P. Lemke, J. Marotzke, V. Masson-Delmotte, G.A. Meehl, I.I. Mokhov, S. Piao, V. Ramaswamy, D. Randall, M. Rhein, M. Rojas, C. Sabine, D. Shindell, L.D. Talley, D.G. Vaughan and S.-P. Xie (2013): Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stratego (2016) *Stratego enhanced heating and cooling plans: reports.* Available online at http://stratego-project.eu/reports/ [Accessed 18 January 2017]

Trcka, M. and Hensen, J.L.M. (2010) Overview of HVAC system simulation. *Automation in Construction.* vol 19(2): 93–99

UKCP09 (2014) *UK climate projections: maps and key findings.* Available online at http://ukclimateprojections.metoffice.gov.uk/21708?projections=23860 [Accessed 10 May 2016]

UNEP (1999) *Handbook on data reporting under the Montreal Protocol.* Available online at http://ecologic.eu/sites/files/publication/2015/oberthur_99-handbook_on_data_reporting_under_the_montreal_protocol-19982461.pdf [Accessed 18 January 2017]

UNEP (2009) *Assessment of alternatives to HCFCs and HFCs and update of the TEAP 2005 supplement report data, Task Force Decision XX/8 Report.* Nairobi: UNEP Technology and Assessment Panel. Available online at http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports/teap-may-2009-decisionXX-8-task-force-report.pdf [Accessed 13 February 2017]

UNEP (2011) *2010 report of the refrigeration, air conditioning and heat pumps Technical Options Committee.* Available online at https://acd-ext.gsfc.nasa.gov/Documents/O3_Assessments/Docs/WMO_2010/2010assessment/RTOC_2010_Assessment_Report.pdf [Accessed 13 February 2017]

UNEP (2015) *2014 report of the refrigeration, air conditioning and heat pumps technical options committee.* Nairobi, Kenya. Available online at http://ozone.unep.org/sites/ozone/files/documents/RTOC-Assessment-Report-2014.pdf [Accessed 19 January 2017]

UNEP (2016) *Report of the Technology and Economic Assessment Panel, September 2016, Volume 1. Decision XXVII/4 Task Force update report – further information on alternatives to ozone-depleting substances.* Nairobi, September 2016. Available online at http://ozone.unep.org/en/assessment-panels/technology-and-economic-assessment-panel [Accessed 4 January 2017]

UNEP (2017) *The Montreal Protocol on Substances that Deplete the Ozone Layer.* Available online at http://ozone.unep.org/en/treaties-and-decisions/montreal-protocol-substances-deplete-ozone-layer [Accessed 13 February 2017]

UNFCCC (2009) *Copenhagen Accord.* Available online at http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php [Accessed 16 December 2016]

UNFCCC (2012) *Status of the Doha Amendment.* Available online at http://unfccc.int/kyoto_protocol/doha_amendment/items/7362.php [Accessed 16 December 2106]

UNFCCC (2014) *Kyoto Protocol.* Available online at http://unfccc.int/kyoto_protocol/items/2830.php [Accessed 13 February 2017]

URS (2009) *A Study to Determine the Carbon Footprint of the City of London.* London: URS Corporation Ltd. Available online at http://www.cityoflondon.gov.uk/services/environment-and-planning/planning/planning-policy/local-development-framework/Documents/City%20of%20London%20Carbon%20Footprint%20Report.pdf [Accessed 17 July 2014]

Appendices

A. Calculation of energy demand and emissions for the UK RACHP sector

Table A-1 Excel spreadsheet for calculation of UK RACHP energy demand and emissions

Table A-2 UK RACHP input assumptions for UK GHG inventory 1990 - 2014

Table A-1 Excel spreadsheet for calculation of UK RACHP energy demand and emissions

Commercial Refrigeration (BNCR34, 2006)

Product no	Equipment Type	2004 UK Stock	2010 UK Stock	Product Life (years)	Average power (kW)	Duty cycle	Annual run hours	Annual Energy Use GWh	
1	Process chillers	11,200	11,469	15	80	0.5	4380	4,019	
2	Integral Retail display cabinets	586,766	579,773	10	0.58	0.66	5840	1,964	
3	Remote Retail display cabinets	207,766	205,290	10	3.12	0.66	5840	3,741	
4	Commercial Service Cabinets	422,219	448,194	8	0.833	0.6	5256	1,962	
5	Cellar Cooling Equipment	81,931	81,931	15	3	0.5	4380	1,077	
6	Ice Making Machines	127,664	135,518	8	1.2	0.66	5840	950	
7	Walk-In Cold Rooms	197,068	209,192	18	1.9	0.66	5840	2,321	
8	Refrigerated vending machines	74,379	81,329	8	0.5	0.66	5840	237	
9	Miscellaneous	100,000	106,152	10	0.18	0.66	5840	112	
							Total	16,382	GWh
							Total	16.38	TWh
	Total UK electricity use 2012 (Dukes 2013 Ch 5 T5.1)		318	TWh		% of UK Electricity		5.16%	
	Grid electricity carbon factor (2012 Consumed electric		0.49636	kg CO2e/kWh		DCFCarbonFactors_12_8_2015_16451_Year2012			
	Total UK electricity related carbon emissions		157.64	MtCO2e		(UK elect. 0.46002 + T&D 0.03634)			

http://efficient-products.ghkint.eu/ Market Transformation Programme

Commercial Refrigeration (BNCR KO01, 2010) http://efficient-products.ghkint.eu/spm/download/document/id/904.pdf

Product no	Equipment Type	2004 UK Stock	2010 UK Stock	Product Life (years)	Average power (kW)	Duty cycle	Annual run hours	Annual Energy Use GWh
1	Refrigerated display cases	794,000	785,000					7,850
2	Package chillers	46,000	50,000					17,000
3	Walk in cold rooms	159,000	164,000					1,990
4	Cellars	80,000	82,000					393
5	Refrigerated service cabinets	422,000	448,000					1,830
6	Ice makers	128,000	136,000					516
7	Cold vending	199,000	186,000					632
							Total	30,211
							Total	30.21
						% of UK Electricity		9.51%

Domestic Refrigeration (BNDA KO01, 2010) http://efficient-products.ghkint.eu/spm/download/document/id/945.pdf

Product no	Equipment Type	2004 UK Stock	2010 UK Stock	Product Life (years)	Average power (kW)	Duty cycle	Annual run hours	Annual Energy Use GWh	
1	Chest freezers		4,181,000					1,375	
2	Upright freezers		8,115,000					2,570	
3	Fridges		9,914,000					1,998	
4	Fridge freezers		18,220,000					8,152	
							Total	14,095	GWh
							Total	14.10	TWh
						% of UK Electricity		4.44%	

Air Conditioning (BNPAC KO01, 2010) http://efficient-products.ghkint.eu/spm/download/document/id/915.pdf

Product Category	Equipment Type	2004 UK Stock	2010 UK Stock	Product Life (years)	Average power (kW)	Duty cycle	Annual run hours	Annual Energy Use GWh
Packaged AC	Moveables		421,000					171
	Indoor		55,000					18
	Window		28,000					30
	Close Ctrl		87,000					2,165
	Rooftop		25,000					505
	D-Splits		4,000					15
	Minisplits		1,502,000					3,075
Central Plant	Air Chiller		32,000					3,972
	Wat Chiller		6,000					2,065
	Abs Chiller		1,000					1,130
	AHU		224,000					4,650
	FCU		1,100,000					515
							Total	18,311 GWh
							Total	18.311 TWh
							% of UK Electricity	5.77%

	(using BNCR34, 2006 data for Commercial refrigeration)	(using BNCR KO01 data for Commercial refrigeration)
Total RAC electricity use (TWh)	48.79	62.62
RAC % of all UK electricity use (2012)	15.36%	19.72%
RAC electricity use emissions (MTCO2e)	24.22	31.08
RAC electricity use emissions as % of all GHG emissions	4.2%	5.4%
Total RAC sector emissions as % of UK total GHGs	6.17%	7.37%

UK GHG emissions from electricity generation	157.6	MtCO2e	% of UK GHGs	27.4%
UK RAC sector emissions (halocarbons) (Table 7)	11.3	MtCO2e	% of UK GHGs	1.96%
Total UK GHG emissions 2012 (Table 1)	575.3	MtCO2e		

DECC: 20140327_2012_UK_Greenhouse_Gas_Emissions_Final_Figures_data_tables

	2012	% of Total GHGs
Net CO_2 emissions (emissions minus removals)	474.1	82.4%
Methane (CH_4)	50.6	8.8%
Nitrous Oxide (N_2O)	36.0	6.3%
Perfluorocarbons (PFC)	0.2	0.0%
HFCs (Refrigeration and Air Conditioning)	11.3	2.0%
Hydrofluorocarbons (HFC) - Other	2.6	0.5%
Sulphur hexafluoride (SF_6)	0.5	0.1%
Total UK GHG Emissions (MtCO2e)	575.3	100.0%
Kyoto greenhouse gas basket*	581.1	

DECC: 20140327_2012_UK_Greenhouse_Gas_Emissions_Final_Figures_data_tables Tables 1 & 7

*NOTE: Kyoto basket total differs slightly from the sum of individual pollutants above as the basket uses a narrower definition for the Land Use, Land-Use Change and Forestry sector (LULUCF) and has a slightly different geographical coverage.

Table A-2 UK RACHP input assumptions for UK GHG inventory 1990 - 2014

Application		2014 Parameters[b]							
CRF Sector	UK Category	Total Stock (units)[a]	Total Sales (units)[a]	Lifetime (years)	Charge (kg)[a]	Refrigerants in New Equipment	Manufacturing Loss Rate	Operational Loss Rate	Disposal Loss Rate
Domestic Refrigeration	Domestic Refrigeration	41,905,247	2,919,878	15	0.10	HFC-134a, HCs	0.6%	0.3%	31%[b]
Commercial Refrigeration	Small Hermetic Stand-Alone Refrigeration Units	2,701,221	290,369	10	0.5	HFC-134a, R-404A, R-407C, HCs	1%	1.3%	31%[b]
	Condensing Units	636,818	52,697	14	6	HFC-134a, R-404A, R-407A, R-407F,R-410A, R-507, HCs	2%	7%	13%[b]
	Centralised Supermarket Refrigeration Systems	11,407,844 (m^2)	901,627 (m^2)	18[b]	0.56 (kg/m^2)	HFC-134a, R-404A, R-407A, HCs, R-717, R-744	2%	11%	6%[b]
Transport Refrigeration	Land Transport Refrigeration	94,399	14,271	7	3.6	HFC-134a, R-404A	0.2%	10.4%[b]	13%[b]
	Marine Transport Refrigeration	527	32	25[b]	1,500[b]	R-404A, R-407C, R-717	1%	17%	13%[b]
Industrial Refrigeration	Industrial Systems	43,297	1,863	25	108	HFC-134a, R-404A, R-407C, R-410A, R-507, HCs, R-717, R-744	1%	10%	11%
Stationary Air-Conditioning	Small Stationary Air Conditioning	5,795,024	527,980	13	1.8	R-407C, R-410A	0.5%	5%	26%
	Medium Stationary Air Conditioning	331,144	28,756	15	15	R-407C, R-410A	1%	6.4%	18%[b]
	Large Stationary Air Conditioning (Chillers)	43,297	2,994	18	180	HFC-134a, R-407C, R-410A, R-717	0.5%	4%	8%
	Heat Pumps	85,683	19,773	15	3.5	HFC-134a, R-404A, R-407C, R-410A	1%	6%[b]	29%[b]
Mobile Air-Conditioning	Light Duty Mobile Air Conditioning	26,074,209	2,237,642	15	0.7	HFC-134a	0.5%	8%[b]	25%[b]
	Other Mobile Air Conditioning	518,890	91,219	10	4[b]	HFC-134a, R-407C	0.5%	9%[b]	21%[b]

[a] Except where otherwise noted.

[b] Estimates fall outside of the IPCC (2006) range but are in line with UK- and/or EU-specific estimates provided by industry or in the published literature.

[Source: Ricardo-AEA, 2016]

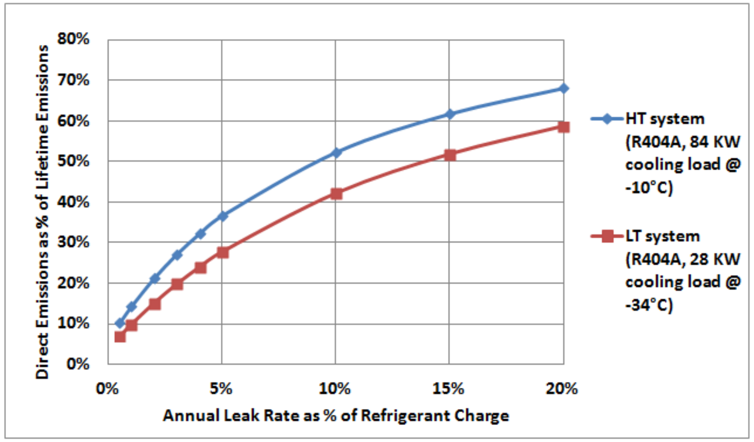
B. Example TEWI calculations for supermarket HT and LT systems

Leak Rate Scenarios (Annual Leakage %)	Model Store - High Temperature (HT) System - R404A Refrigerant								
	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	10.0%	15.0%	20.0%
Data and Assumptions									
Refrigerant Charge (Kg) (Estimated)	250	250	250	250	250	250	250	250	250
Annual Energy Consumption									
Compressors (kWh)	155512	155512	155512	155512	155512	155512	155512	155512	155512
Ancillary (kWh)	21184	21184	21184	21184	21184	21184	21184	21184	21184
Sectorial Factors									
System Operational Life Time (Years)	14	14	14	14	14	14	14	14	14
Refrigerant GWP	3922	3922	3922	3922	3922	3922	3922	3922	3922
Automatic Purges (%)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Service Release (%)	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
Accidental Sudden Release (%)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Recovery Efficiency	95%	95%	95%	95%	95%	95%	95%	95%	95%
CO_2 Emission Factor; ß (Kg CO_2/ kWh)	0.537	0.537	0.537	0.537	0.537	0.537	0.537	0.537	0.537
TEWI Calculations									
a) Direct Effect (Refrigerant Leakage)									
Refrigerant Loss (Operational) (kg)	26.25	43.75	78.75	113.75	148.75	183.75	358.75	533.75	708.75
Refrigerant Loss (Retirement) (kg)	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Total Lifetime Refrigerant Loss (kg)	38.75	56.25	91.25	126.25	161.25	196.25	371.25	546.25	721.25
CO_2 Equivalent (kg)	151,978	220,613	357,883	495,153	632,423	769,693	1,456,043	2,142,393	2,828,743
b) Indirect Effect (Energy Use)									
Indirect Effect (Kg CO_2)	1,328,401	1,328,401	1,328,401	1,328,401	1,328,401	1,328,401	1,328,401	1,328,401	1,328,401
c) TEWI									
TEWI (kg CO_2)	1,480,378	1,549,013	1,686,283	1,823,553	1,960,823	2,098,093	2,784,443	3,470,793	4,157,143
TEWI (Tonne CO_2)	1,480.38	1,549.01	1,686.28	1,823.55	1,960.82	2,098.09	2,784.44	3,470.79	4,157.14
Direct Emissions as % of Total Emissions	**10.3%**	**14.2%**	**21.2%**	**27.2%**	**32.3%**	**36.7%**	**52.3%**	**61.7%**	**68.0%**

Leak Rate Scenarios (Annual Leakage %)	Model Store - Low Temperature (LT) System - R404A Refrigerant								
	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	10.0%	15.0%	20.0%
Data and Assumptions									
Refrigerant Charge (Kg) (Estimated)	150	150	150	150	150	150	150	150	150
Annual Energy Consumption									
Compressors (kWh)	140954	140954	140954	140954	140954	140954	140954	140954	140954
Ancillary (kWh)	18359	18359	18359	18359	18359	18359	18359	18359	18359
Sectorial Factors									
System Operational Life Time (Years)	14	14	14	14	14	14	14	14	14
Refrigerant GWP	3922	3922	3922	3922	3922	3922	3922	3922	3922
Automatic Purges (%)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Service Release (%)	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
Accidental Sudden Release (%)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Recovery Efficiency	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
CO_2 Emission Factor; ß (Kg CO_2/ kWh)	0.537	0.537	0.537	0.537	0.537	0.537	0.537	0.537	0.537
TEWI Calculations									
a) Direct Effect (Refrigerant Leakage)									
Refrigerant Loss (Operational) (kg)	15.75	26.25	47.25	68.25	89.25	110.25	215.25	320.25	425.25
Refrigerant Loss (Retirement) (kg)	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Total Lifetime Refrigerant Loss (kg)	23.25	33.75	54.75	75.75	96.75	117.75	222.75	327.75	432.75
CO_2 Equivalent (kg)	91,187	132,368	214,730	297,092	379,454	461,816	873,626	1,285,436	1,697,246
b) Indirect Effect (Energy Use)									
Indirect Effect (Kg CO_2)	1,197,715	1,197,715	1,197,715	1,197,715	1,197,715	1,197,715	1,197,715	1,197,715	1,197,715
c) TEWI									
TEWI (kg CO_2)	1,288,902	1,330,083	1,412,445	1,494,807	1,577,169	1,659,531	2,071,341	2,483,151	2,894,961
TEWI (Tonne CO_2)	1,288.90	1,330.08	1,412.44	1,494.81	1,577.17	1,659.53	2,071.34	2,483.15	2,894.96
Direct Emissions as % of Total Emissions	**7.1%**	**10.0%**	**15.2%**	**19.9%**	**24.1%**	**27.8%**	**42.2%**	**51.8%**	**58.6%**

Direct Emissions as % of Total Lifetime Emissions

Refrigerant Annual Leak Rate %	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	10.0%	15.0%	20.0%
HT system (R404A, 84 KW cooling load @ -10°C	10.3%	14.2%	21.2%	27.2%	32.3%	36.7%	52.3%	61.7%	68.0%
LT system (R404A, 28 KW cooling load @ -34°C	7.1%	10.0%	15.2%	19.9%	24.1%	27.8%	42.2%	51.8%	58.6%

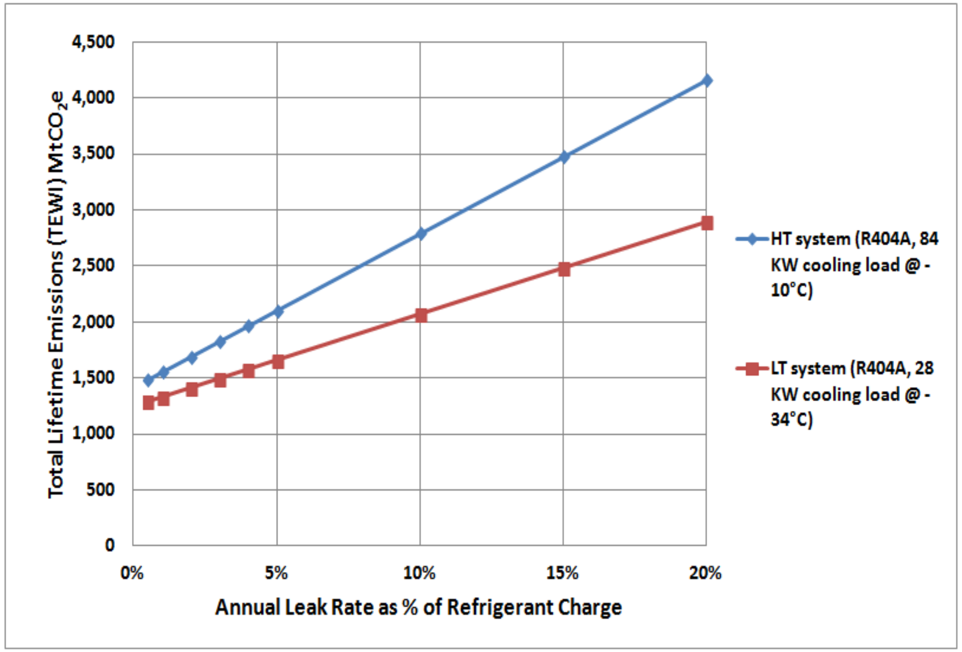


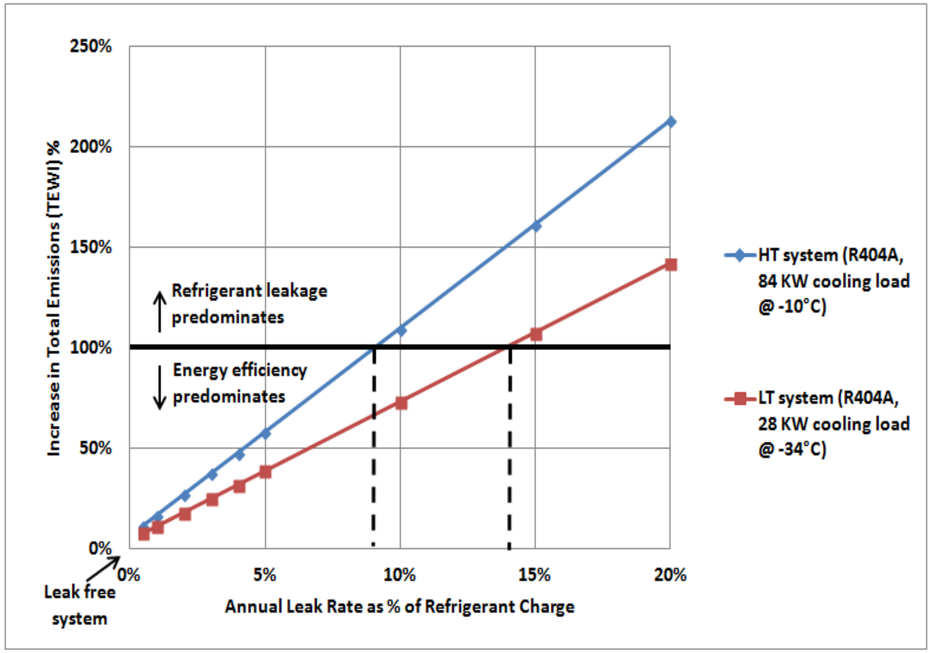
Increase in total emissions vs leak rate

Refrigerant Annual Leak Rate %	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	10.0%	15.0%	20.0%
HT system (R404A, 84 KW cooling load @ -10°C	11.4%	16.6%	26.9%	37.3%	47.6%	57.9%	109.6%	161.3%	212.9%
LT system (R404A, 28 KW cooling load @ -34°C	7.6%	11.1%	17.9%	24.8%	31.7%	38.6%	72.9%	107.3%	141.7%

Total lifetime emissions vs leak rate MtCO2e

Refrigerant Annual Leak Rate %	0.5%	1.0%	2.0%	3.0%	4.0%	5.0%	10.0%	15.0%	20.0%
HT system (R404A, 84 KW cooling load @ -10°C	1,480.38	1,549.01	1,686.28	1,823.55	1,960.82	2,098.09	2,784.44	3,470.79	4,157.14
LT system (R404A, 28 KW cooling load @ -34°C	1,288.90	1,330.08	1,412.44	1,494.81	1,577.17	1,659.53	2,071.34	2,483.15	2,894.96





C. Alternative refrigerant properties and TEWI in heat pump applications

Table C-1. Thermophysical properties, environmental and safety issues of different refrigerants

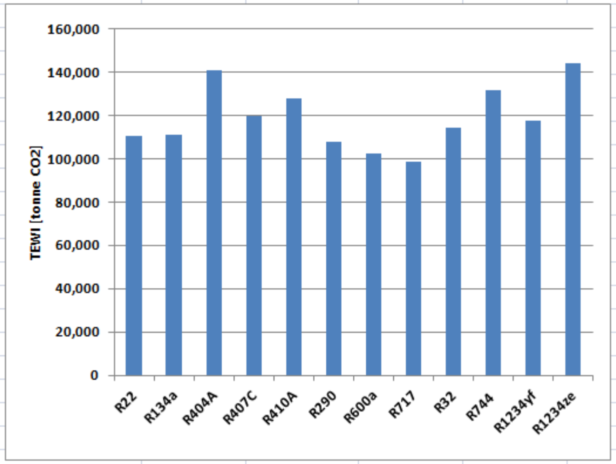
Figure C-1. Spreadsheet for calculation of TEWI, energy and refrigerant cost for alternative refrigerants in heat pump systems

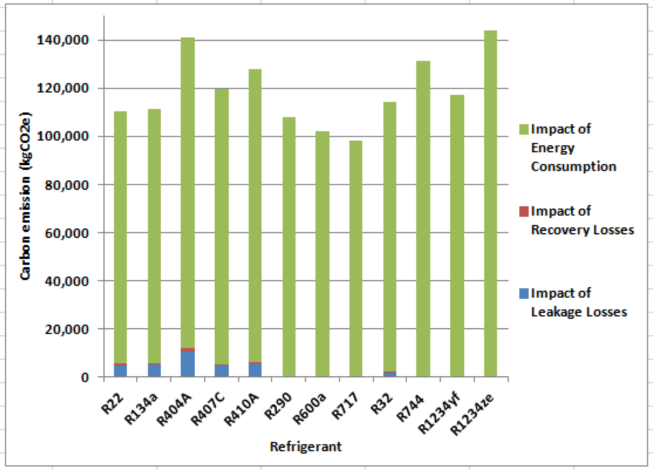
Table C-1. Thermophysical properties, environmental and safety issues of different refrigerants

	Refrigerant / Chemical name/ Blends/ compositions (Weight %)	Thermo-Physical Properties	Pressure & Density Regimes	Molecular Mass g/mol	Chemical Stability	Environmental Impact		Safety Issues				Suitability to particular refrigeration systems	Current point in development	Replacement for	Refrigerant Costs (£/kg)
						ODP	GWP	Flammability	Toxicity	Safety group	LFL kg/m^3				
Existing	**R22** Methane series Chlorodifluoromethane	BP: -40.8°C CT: 96.2°C FP: -160°C	CP: 49.9 bar VP @21°C: 9.38 bar VP @55°C: 21.74 bar VD: 3.0	86.5	Product stable under normal conditions	0.055	1810	Non flammable	Non toxic Asphyxiation risk	A1	N/A	Commercial (condensing units, supermarkets), Industrial, Heat pump, Chillers	Fully Developed	N/A	20
	R134a Ethane series 1,1,1,2-tetrafluoroethane	BP: -26.2°C CT: 122°C FP: -92.5°C	CP: 40.6 bar VP @21°C: 5.91 bar VP @55°C: 14.71 bar VP: 3.5	102.0	Product stable under normal conditions	0	1430	Non flammable	Non toxic Asphyxiation risk	A1	N/A	Domestic fridges, Commercial (stand-alone, supermarkets), Industrial, Chillers, Heat pumps, Car Air-Conditioning	Fully Developed	R22	19
	R404A Zeotropic blend R125/143a/134a (44/52/4-	BP: -47.8°C CT: 72.1°C FP: Not Determined	CP: 37.4 bar VP @21°C: 12.61 bar VP @55°C: 25.57 bar VD: 3.43	97.6	Product stable under normal conditions	0	3922	Non flammable	Asphyxiation risk	A1	N/A	Commercial (condensing units and supermarkets), Transport, Heat pump, Industrial	Fully Developed	R22	18
	R407C Zeotropic blend R32/125/134a (23/25/52)	BP: -43°C CT: 86.2°C FP: Not D	CP: 46.2 bar VP @21°C: 10.63 bar VP @55°C: 24.27 bar VD: 3.0	86.2	Product stable under normal conditions	0	1774	Non flammable	Non toxic Asphyxiation risk	A1	N/A	Industrial, Heat pump, Chillers	Fully Developed	R22 With limited product redesign	14
	R410A Zeotropic blend R32/125 (50/50)	BP: -48.5°C CT: -72.8°C FP: -155°C	CP: 48.6 bar VP @21°C: 14.84 bar VP @55°C: 33.80 bar VD: 3.0	72.6	Product stable under normal conditions	0	2088	Non flammable	Non toxic Asphyxiation risk	A1	N/A	Heat pump, Chillers, Car Air-Conditioning	Fully Developed	R22 Complete product redesign	20
	R290 Propane Hydrocarbons	BP: -42.1 °C CT: 96.7°C FP: - 186°C	CP: 42.5 bar VP @21°C: 7.51 bar VD: 1.6	44.0	Product stable under normal conditions	0	3	High Flammable gas	Chronic effects on humans	A3	0.038	Domestic fridges, Commercial (stand-alone), Transport, Chillers, Heat pump	Fully Developed, but limited availability of components.	R22 Declined production after PED	21
	R717 Ammonia	BP: -33.3 °C CT: 132.4°C FP:-77.73 °C	CP: 114.24 bar VP @21°C: 8.88 bar VP @50°C: 20.3 bar VD : 0.599	17.0	Product stable under normal conditions	0	0	Slightly flammable gas	Toxic	B2	0.104	Commercial (supermarkets) Industrial, Transport, Heat pump, Chillers	Fully Developed	No compressors for domestic heat pumps	7
	R744 Carbon dioxide	BP: 31 °C CT: -78.5 °C FP: -56.6 °C	CP: 73.77 bar VP @21°C: 57.2 bar VD: 1.52	44.0	Product stable under normal conditions	0	1	Non Flammable	In high concentration can be toxic	A1	N/A	Commercial (supermarkets), Industrial, Transport, Heat pumps, Chillers	Fully Developed	Huge market in Japan	3
Potential	**R32** Methane series Difluoromethane	BP: -51.7°C CT: 78.20 °C FP: -136 °C	CP: 53.8 bar VP @21°C: 10.3 bar VP @55°C: 35 bar VD: 1.86	52.0	Product stable under normal conditions	0	675	Low flammable	No toxic Ongoing Research	A2L	0.306	Ongoing Research	Not commercially available	Not yet determined	18
	R600a Isobutene Hydrocarbons	BP: -11.6 °C CT: 134.7°C FP: - 160°C	CP: 36 bar VP @21°C: 2.04 bar VD: 1.3	58.1	Product stable under normal conditions	0	3	High Flammable gas	No toxic	A3		Domestic fridges, Commercial stand-alone equipment, Chillers, Heat pump	Similar technology to R290	R134a	16
	R1234yf hydrofluoro-olefins 2,3,3,3-tetrafluoropropene	BP: -29.55°C CT: 97 °C FP: -150°C	CP: 33.83 bar VP @21°C: : 6.83 bar VD: 5.98	114	Product stable under normal conditions	0	4	Low flammable	Safe for use in its intended applications	A2L	6.2	Automotive, Air-Conditioning Supermarkets Medium Air-Conditioning Residential chillers	Commercially in 2015 Lack of available components	R134a Not yet determined	130
	R1234ze Hydrofluoro-olefins 1,3,3,3-tetrafluoropropene	BP: -19°C CT: 109.4 °C FP: -150°C	CP: (bar): 36.432bar VP @21°C: 3.2 bar VP @55°C: 9.7 bar	114	Product stable under normal conditions	0	6	Low flammable	Safe for use in its intended applications	A2L	7.2	Ongoing Research	Not Developed	R134a Not yet determined	20

Qc (kW)	10	Grid Electricity Carbon Factor (kgCO2e/kWh	0.52463
AEFLH (hrs)	3500	Electrical energy factor for pumps and fans	15%
Elec (£/kWh)	0.1		
Lifetime (years	15		
Recovery factor	0.9		

									CO2 equivalent emissions [kg]					Operating and maintenance Cost	
	COP (70 degC)	W [kW]	Qe [kW]	E [kWh]	Cost [£/kg]	GWP	L [kg/year]	m [kg]	Impact of Leakage Losses	Impact of Recovery Losses	Impact of Energy Consumption	TEWI [$kgCO_2e$]	Refrigerant Loss [kg/year]	Energy Cost [£/year]	Refrigerant Cost [£/year]
R22	3.02	3.31	6.69	13,328	20	1810	6%	3.00	4,887	543	104,883	110,313	0.18	1,333	4
R134a	3	3.33	6.67	13,417	19	1430	6%	4.00	5,148	572	105,582	111,302	0.24	1,342	5
R404A	2.45	4.08	5.92	16,429	18	3922	6%	3.00	10,589	1,177	129,284	141,050	0.18	1,643	3
R407C	2.77	3.61	6.39	14,531	14	1774	6%	3.00	4,790	532	114,349	119,671	0.18	1,453	3
R410A	2.6	3.85	6.15	15,481	20	2088	6%	3.00	5,638	626	121,825	128,089	0.18	1,548	4
R290	2.94	3.40	6.60	13,690	21	3	6%	1.50	4	0	107,737	107,741	0.09	1,369	2
R600a	3.1	3.23	6.77	12,984	21	3	6%	1.50	4	0	102,176	102,180	0.09	1,298	2
R717	3.22	3.11	6.89	12,500	7	0	6%	1.00	0	0	98,368	98,368	0.06	1,250	0
R32	2.82	3.55	6.45	14,273	18	675	6%	3.00	1,823	203	112,321	114,346	0.18	1,427	3
R744	2.41	4.15	5.85	16,701	3	1	6%	1.50	1	0	131,430	131,431	0.09	1,670	0
R1234yf	2.7	3.70	6.30	14,907	130	4	6%	4.00	14	2	117,313	117,329	0.24	1,491	31
R1234ze	2.2	4.55	5.45	18,295	20	6	6%	4.00	22	2	143,975	143,999	0.24	1,830	5





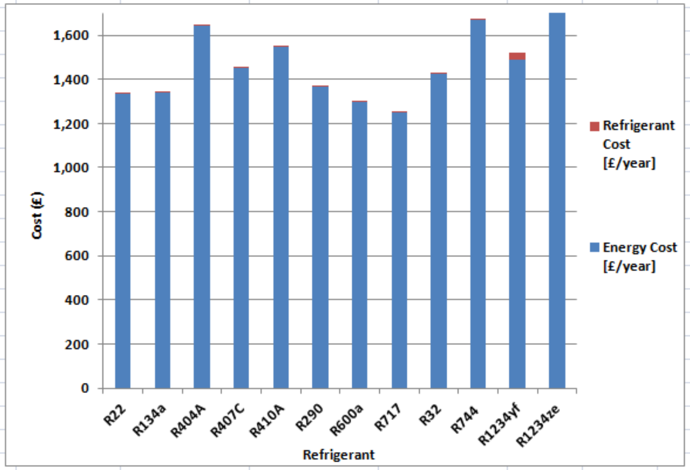


Figure C-1. Spreadsheet for calculation of TEWI, energy and refrigerant cost for alternative refrigerants in heat pump systems

D. Background information – the REAL Skills Europe project

REAL Skills Europe was a voluntary awareness, information and training initiative that provided a vehicle for individuals and organisations in EU member states to share technical information and best practice in refrigerant containment. It offered a structured methodology for undertaking site surveys and assessing and minimising leakage potential, together with a certificated e-learning training scheme, software tools and guidance notes. The project was set up and led by the author built on the previous UK project (REAL Zero) that proved effective in reducing refrigerant use at the sites that were assessed and monitored over a 12 month follow up period.

The key aims of the project were to help the RACHP industry take practical steps to reduce refrigerant leakage by:

- Raising awareness and understanding of F-Gas legal obligations and responsibilities
- Sharing refrigerant leakage and containment information and best practice
- Providing free software tools to assess the financial and environmental impact of leakage
- Offering free information and guidance on refrigerant containment and how to reduce leaks
- Promoting a site survey and inspection methodology for developing leakage reduction strategies, with templates for data capture, analysis and reporting
- Providing low cost e-learning and certificated assessment to embed this knowledge within the industry

It complemented and built on mandatory F-Gas training by taking a more proactive approach to refrigerant management, focusing on the prevention of leaks through the application of best practice in design, installation, commissioning and service and maintenance.

An important element of the project was the contribution of stakeholder groups to the development of the new materials and e-learning. The benefits to these organisations included the opportunity to influence the structure and content of the guidance notes, software tools and e-learning by reviewing and commenting on draft materials and specifications, also through participation in the pilot testing of the e-learning, prior to the public launch. Stakeholder organisations included supermarkets and retailers, refrigeration processing plant owners, building owners, trade associations, training organisations, government bodies and departments and professional and research institutions involved in standards, refrigeration and food.

During this project it was established that the scale of refrigerant leakage and F-Gas emissions varied considerably between different RAC equipment types and from country to country. In the partner countries, F-Gas emissions were reported to vary between 0.7% and 3.1% of their overall greenhouse gas emissions; this compared with an average of 1.9% across the EU 15 countries (EEA, 2010).

A key aim of the REAL Skills Europe project was to promote good practice and to encourage system operators, contractors and their staff to understand how they could use the information from their systems to reduce leakage. For example, it could be used for benchmarking against similar systems (inside and outside the organisation), to view trends, to prioritise actions and to assess the impact of changes. A new combined electronic F-Gas log and cost and emissions calculator was developed for REAL Skills Europe, based on an Excel platform, using macros and a user menu to simplify operation. Reports at system or site level can be produced on screen and printed at the push of a button. An example of a system level report is shown in Figure D-1.

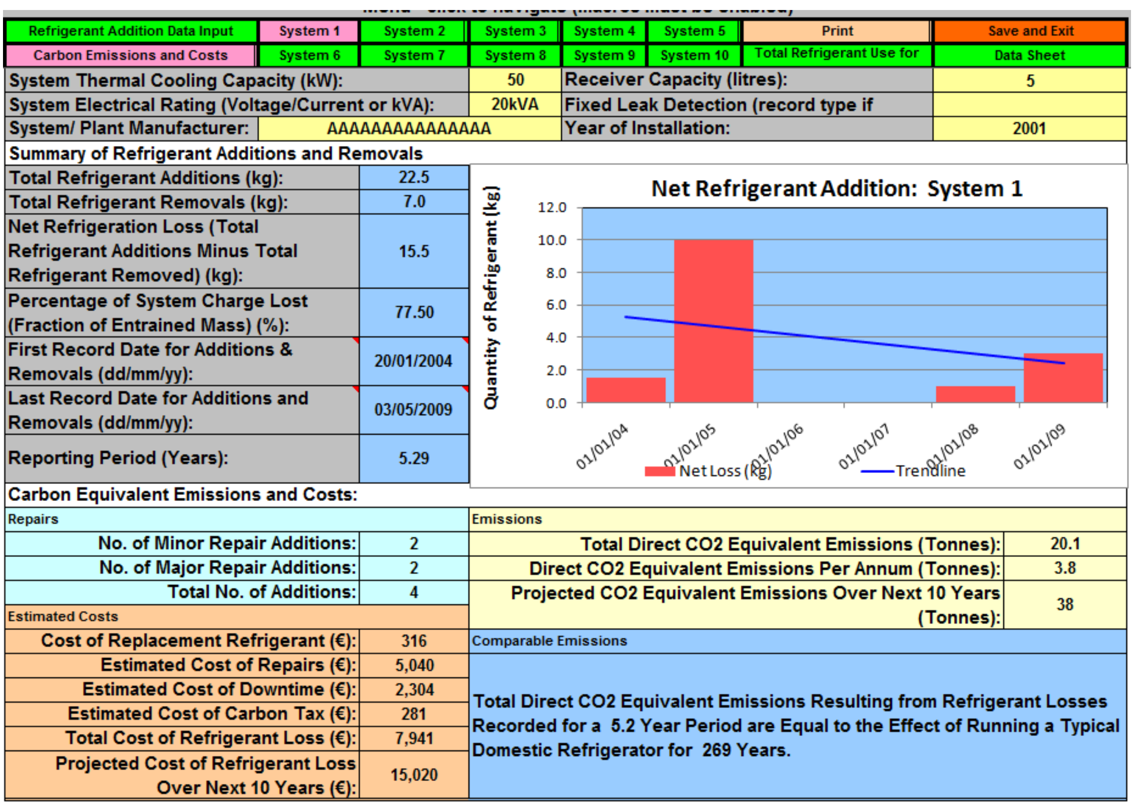


Figure D-1. System level emissions and cost report from the REAL Skills Europe calculator

An e-learning training scheme was a major element of the project and was designed to align with the general RAC Vocational and Educational Training (VET) framework of the EU partner countries and EU Standard pr EN 13313:2010 (Refrigerating systems and heat pumps - competence of personnel). The scheme complemented the mandatory F-Gas training and certification (EC 303/2008) and built on it in two key ways:

- F Gas training helps RACHP technicians and craft-persons to *identify and fix* leaks, whereas REAL Skills Europe (RSE) training helps them to identify leakage potential and to *prevent* leaks
- RSE training assists in developing additional skills

The training was aimed at refrigeration technicians, craftsmen, engineers and technical specialists who have practical on site experience of commercial and/ or industrial RAC systems and who would benefit from a more thorough understanding of the theoretical and practical aspects of proactive leak reduction than is covered within the EU and nationally accredited F-Gas and ODS refrigerant handling training schemes. The course could benefit anyone working in RAC system design and manufacture, installation and commissioning, maintenance and repair, training, consultancy (e.g. services such as efficiency advice, drawing up specifications, managing tendering processes), environmental management and carbon assessment. RAC system owners, operators and building facilities managers could also benefit from undertaking study of certain elements of the course in order to gain a better appreciation of the environmental and financial impact of refrigerant leakage and implementing a leakage reduction strategy. The e-learning used the Moodle Learning Management System as a platform and was designed so that it could be studied entirely online at a pace determined by the student, or combined with classroom teaching and practical sessions. It comprised 4 modules:

1. Environmental, cost and legal aspects of refrigerant leakage
2. Reducing leakage through appropriate maintenance and service
3. Minimising leakage – good practice for design, installation and commissioning
4. Reducing leakage through site specific surveys and advice

The content was developed from the UK REAL Zero training course, using the e-learning environment to add rich content and to provide direct links to additional supporting materials. The learning outcomes were described at the beginning of each module and online assessments were used to verify that the student has successfully assimilated the training material and achieved desired outcomes. The structure of each module allowed the student to break the study into several sessions and to revisit sections, as required. A screen shot from the e-learning is shown in Figure D-2 and includes an example of rich content (embedded video). Other downloadable materials that were made available to course participants included a site survey spreadsheet for recording data and observations while on site and a template that could be used to generate site survey reports and recommendations to users.

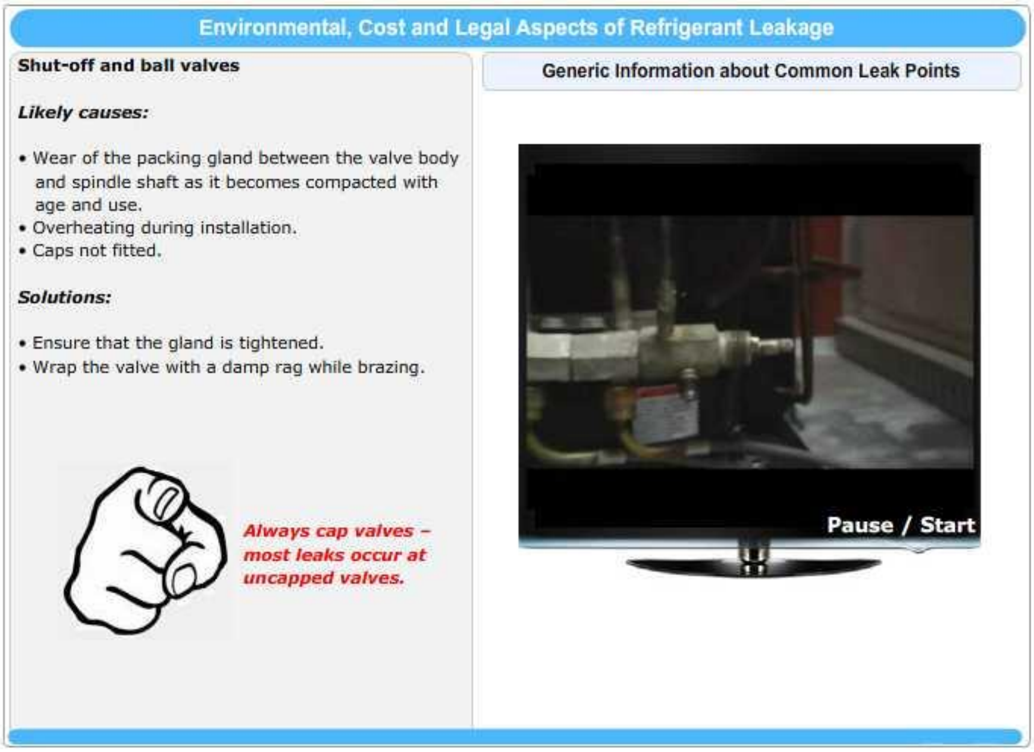


Figure D-2. REAL Skills Europe e-learning example of rich content

The online assessments each comprised 10 questions that were matched to the learning outcomes and selected at random from a question bank, so that students undertaking repeat assessments were likely to be presented with different questions. Question types included multiple-choice, calculations and matching, each assessment taking no longer than 30 minutes to complete.

A project website was set up at the start of the project with a partner workspace to share information and materials. A multi-lingual stakeholder workspace was subsequently established and allowed the project partners to share consultation documents with their own stakeholders, using their national languages. On product release users who registered using their e-mail address were able to download guidance notes and software tools from the website at www.realskillseurope.eu and to access the e-learning.

The project represented another step towards a consistent EU wide approach to skills development in the RAC sector, whilst a longer term ambition was to encourage national training bodies to include the key elements within their national training schemes. A follow up programme REAL Alternatives http://www.realalternatives.eu has been developing a blended learning approach for safe handling and use of alternative (low GWP) refrigerants such as CO_2, ammonia, hydrocarbons and hydrofluoroolefins (HFOs).

E. Evolution of Building Regulations for non-domestic buildings and dwellings

Table E-1. Evolution of Building Regulations for non-domestic buildings

Table E-2. Evolution of Building Regulations for domestic buildings (new dwellings)

Table E-1. Evolution of Building Regulations for non-domestic buildings

	Pre-War/ Solid Walls	1976	1985	1995	2002	2006	2010	2010	2013	2013
		U – Values W m^{-2} $^{o}C^{-1}$								
Reference Document(s)	CIBSE Guide A Section 3	SI 1976/1676 Part F & Schedule 11	SI 1985/1065 Part L	AD L (1995 Ed.) Part2	AD L2 (2002)	AD L2A (2006)	AD L2A (2010) Limiting Parameters	AD L2A (2010) Lower Limits for Calculations	AD L2A (2013) Limiting Parameters	AD L2A (2013) Notional Building Parameters
External Wall	2.09 (220mm brick, 13mm plaster)		0.6 net (residential/ shop/ office) 0.7 net (industrial)	0.45	0.35	0.35	0.35	0.23	0.35	0.26
Roof	2.3 (no insulation), 0.71 (50mm insulation)		0.6 net (residential/ shop/ office) 0.7 net (industrial)	0.25	0.25 (flat) 0.16-0.2 (pitched)	0.25	0.25	0.15	0.25	0.18
Floor	2.26 (vinyl, 50 mm screed, 150mm concrete), 1.37 (vinyl, 19mm timber, 100mm joists)		0.6 net (residential/ shop/ office) 0.7 net (industrial)	0.45	0.25	0.25	0.25	0.2	0.25	0.22
Windows	4.8 (single glazing, wood frame)		5.7 (for glazing as below)	3.3	2.2 (metal) 2.0 (wood)	2.2	2.2	1.5	2.20	1.6
Doors Opaque	2.7 (44mm solid wood)			3.3	2.2 (metal) 2.0 (wood)	2.2	2.2	1.5	2.20	1
Doors Semi Glazed				3.3	2.2 (metal) 2.0 (wood)	2.2	2.2	1.5	2.20	1.2
Windows as % of external walls			15% (industrial/ storage) 25% (residential) 35% (offices/ shops) (for U = 5.7)	15% (industrial/ storage) 30% (residential) 40% (offices/ shops) (for specified U values)	15% (industrial/ storage) 30% (residential) 40% (offices/ shops) (for specified U values)					
Windows as % of total floor areas						Not specified	Not specified	Not specified		
Air Permeability					10m3/(h.m2) at 50 Pa (recomendation)	10m3/(h.m2) at 50 Pa (recomendation)	10m3/(h.m2) at 50 Pa (recomendation)	5m3/(h.m2) at 50 Pa	10m3/(h.m2) at 50 Pa	5m3/(h.m2) at 50 Pa
Carbon Performance Rating Air Conditioning						10.3 kgC/m2/yr				
Carbon Performance Rating Mechanical Ventilation						6.5 kgC/m2/yr				
Whole Office CPR Nat Ventilated						7.1 kgC/m2/yr				
Whole Office CPR Mech Ventilated						10 kgC/m2/yr				
Whole Office CPR Air Conditioned						18.5 kgC/m2/yr				
Mechanical Ventilation Specific Fan Power						Same at 25% and 100% rates				1.8 W/l/s
Mechanical Ventilation Heat Recovery Efficiency										70%
Target CO2 Emissions Rate (TER) Building CO2 Emissions Rate (BER)						TER = SBEM (2005) BER <= TER	TER = TER(2005) - 25% BER <=TER		TER = TER(2010) - 9%	
Cooling SSEER										2.7 (mixed mode) 3.6 (Air Con)
NOTES:										
1. 2006 CO2 target based on SBEM 2005 calculation - improvement factor (0.15-0.2) - LZC benchmark (10%)										
2. 2010 CO2 target based on 2006 TER - 25%										
3. 2013 includes new building energy efficiency target (SAP2012) = 9% reduction on 2010 TER										
4. SI 1976/1676 Part F & Schedule 11 applies to dwellings only										

Table E-2. Evolution of Building Regulations for domestic buildings (new dwellings)

	Pre-War/ Solid Walls	1976	1985	1990	1995		2002	2006	2010	2010	2013	2013
		U – Values W m^{-2} $°C^{-1}$										
Reference Document(s)	CIBSE Guide A Section 3	SI 1976/1676 Part F & Schedule 11	SI 1985/1065 Part L	AD L (1990 Ed.) (Note 1)	AD L (1995 Ed.) SAP (1995) < 60	AD L (1995 Ed.) SAP (1995) > 60	AD L1 (2002)	AD L1A (2006)	AD L1A (2010) Limiting Parameters	AD L1A (2010) Lower Limits for Calculations	AD L1A (2013) Limiting Parameters	AD L1A (2013) Notional Dwelling Specs
External Wall	2.09 (220mm brick, 13mm plaster)	1	0.6 (net)	0.45	0.45	0.45	0.35	0.35	0.3	0.2	0.30	0.18
Ext wall perimeter average		1.8										
Party Wall									0.2	0.2	0.20	0
Roof	2.3 (no insulation), 0.71 (50mm insulation)	0.6	0.35	0.25	0.2	0.25	0.25	0.25	0.2	0.13	0.20	0.13
Floor	2.26 (vinyl, 50 mm screed, 150mm concrete), 1.37 (vinyl, 19mm timber, 100mm joists)	1	0.6	0.45	0.35	0.45	0.25	0.25	0.25	0.2	0.25	0.13
Windows	4.8 (single glazing, wood frame)	5.7 single 2.8 double glazed	5.7 (for 12% glazing)	Not specified	3	3.3	2.2	2.2	2	1.5	2.00	1.4
Doors Opaque	2.7 (44mm solid wood)								2	1.5	2.00	1
Doors Semi Glazed									2	1.5	2.00	1.2
Windows as % of external walls		17% (for U = 5.7)	12% (for U = 5.7)	-								
Windows as % of total floor areas		-	-	15%	22.50%	22.5%	25.00%	Not specified	Not specified	Not specified		25%
Air Permeability							10m3/(h.m2) at 50 Pa (recomendation)	10m3/(h.m2) at 50 Pa (recomendation)	10m3/(h.m2) at 50 Pa (recomendation)	5m3/(h.m2) at 50 Pa	10m3/(h.m2) at 50 Pa	5m3/(h.m2) at 50 Pa
Mechanical Ventilation Specific Fan Power								2.0 W/l/sec (balanced) 0.8 W/l/sec (unbal)				
Mechanical Ventilation Heat Recovery Efficiency								66%				
Target CO_2 Emissions Rate (TER) Dwelling CO_2 Emissions Rate (DER)								TER = SAP2005 - 20% DER <=TER	TER = TER(2005) - 25% DER <=TER		TER = SAP2012 + Fuel Factor	
Target Fabric Energy Efficiency Rate (TFEE)												ADL1A-2013 Table 4 x 1.15

NOTES:
1. Based on Tovey 2010 with additions and amendments. Unable to verify 1990 data as source document unobtainable
2. 2006 CO_2 target based on SAP 2005 calculation - 20%
3. 2010 CO_2 target based on 2006 TER - 25% (= SAP2005 x 0.6)
4. 2013 includes new building energy efficiency target (SAP2012) = 6% reduction on 2010 TER

F. Example building energy benchmarks from CIBSE Guide F, CIBSE TM46 and BSRIA

Table F-1. Comparison of overall building energy benchmarks from 3 sources

Table F-2. CIBSE Guide F Table 20.9 Offices: system and building energy benchmarks

Table F-1. Comparison of overall building energy benchmarks from 3 sources

Building Type	Guide F Table 20.1 Annual Energy Benchmark (Note 1)					TM46 Table 1 Annual Energy/ Emissions Benchmarks					BSRIA Rule of Thumb Cooling and Heating Benchmarks (Note 3)				
	Descriptor	Typical (kWh/m2)		Good Practice (kWh/m2)		Cat No/ Descriptor	Energy (kWh/m2)		CO_2 ($kgCO_2$/m2)		Descriptor	Cooling and Heating Thermal Loads		Annualised Cooling/ Heating Thermal Energy (Note 4)	
		Fossil Fuel	Electricity	Fossil Fuel	Electricity		Fossil Fuel	Electricity	Fossil Fuel	Electricity		Cooling (W/m2)	Heating (W/m2)	Cooling (kWh/m2)	Heating (kWh/m2)
Commercial/ Office	Office Air Con Std	178	226	97	128	1 (General Office)	120	95	22.8	52.3	Offices	87	70	95.0	101.9
Retail (General)	Retail/ Clothes Shop	108	287	65	234	3 (General Retail)	0	165	0	90.8	Retail Establishments	140	100	152.9	145.6
Residential	Residential & Nursing Homes	417	79	247	44	21 (Long Term Residential)	420	65	79.8	35.8	Residential Buildings	70	60	76.4	87.4
Industrial	Industrial Post 1995 <5000 m2			96		27 (Workshop)	180	35	34.2	19.3	Industrial Buildings		80		116.5
Education (school)	Education (secondary)	144	33	108	25	17 (Schools & Seasonal Public Buildings)	150	40	28.5	22	Educational Buildings		87		126.7
Health (Hospital)	Hospital (Teaching/ Specialist)	411	122	339	86	20 (Hospital - Clinical & Research)	420	90	79.8	49.5					
Leisure	Entertainment (Social Club)	250	1120	140	60	8 (Bar, Pub or Licensed Club)	350	130	66.5	71.5					
Large Food (Supermarket)	Retail (Supermarket)	261	1026	200	915	6 (Large Food Store)	105	400	20	220					
Sport	Sport & Recreation (Combined Centre)	598	152	264	96	13 (Fitness & Health Centre)	440	160	83.6	88					
Hotel	Hotel (Holiday)	400	140	260	80	9 (Hotel)	330	105	62.7	57.8	Hotels	150		163.8	
Restaurant	Catering (Restaurant with Bar)	1250	730	1100	650	7 (Restaurant)	370	90	70.3	49.5	Restaurants	200		218.4	

NOTES.

1. Source: CIBSE Guide F 2006 Section 20.
2. Source: CIBSE TM46: 2008 Energy Benchmarks.
3. Source: BSRIA Rules of Thumb (5th Edition) BG9/2011.
4. Annualised cooling and heating thermal energy estimates assume 1092 hrs cooling (182 days x 6 hrs) and 1456 hrs heating (182 days x 8 hrs). To convert thermal to electrical cooling energy divide by system COP.

Table F-2. CIBSE Guide F Table 20.9 Offices: system and building energy benchmarks

System	Delivered energy for slated office types / (kW.h.m^{-2}) per year							
	Type 1		Type 2		Type 3		Type 4	
	Good practice	Typical	Good practice	Typical	Good practice	Typical	Good practice	Typical
Gas/oil heating and hot water	79	151	79	151	97	178	107	201
Catering gas	0	0	0	0	0	0	7	9
Cooling	0	0	1	2	14	31	21	41
Fans, pumps and controls	2	6	4	8	30	60	36	67
Humidification	0	0	0	0	8	18	12	23
Lighting	14	23	22	38	27	54	29	60
Office equipment	12	18	20	27	23	31	23	32
Catering electricity	2	3	3	5	5	6	13	15
Other electricity	3	4	4	5	7	8	13	15
Computer room	0	0	0	0	14	18	87	105
Total gas or oil	79	151	79	151	97	178	114	210
Total electricity	33	54	54	85	128	226	234	358

Note: Type 1: cellular naturally ventilated; Type 2: open plan naturally ventilated; Type 3: 'standard' air conditioned; Type 4: 'prestige' air conditioned

[Source CIBSE, 2004]

G. Weather data and future weather data for building energy analysis

This Appendix summarises the types of weather data that are normally used in simulation, together with tables generated from the Prometheus downloads and post processing during this project. The tables list the average daily temperature, average peak hourly temperature and the minimum and maximum temperature for each month, providing a summary indication of the differences in the data due to the alternative methods of post processing the downloads.

The complete temperature datasets are available in an Excel file (PROMETHEUS_London_Weather_Data_Files_Rev5_161129) that is included in the project data disk. A description of the method of generating the datasets is included within Chapter 5.

Weather data types

The type and format of weather data used in analysing building energy demand will depend on the methodology employed in the modelling. Various types of weather data are described in detail in Section 2 of CIBSE Guide A (CIBSE, 2006b), Section 8 of CIBSE Guide J (CIBSE, 2002) and CIBSE TM41 (CIBSE, 2006a).

In its simplest form simulation weather data may be an accumulated temperature difference such as ‘degree days’ or ‘degree hours’ (which are calculated as the difference between the prevailing external dry bulb temperature and a reference ‘base temperature’ over the relevant time period). When the external temperature is lower than the base temperature, the periods are termed ‘heating’ degree hours (or days), whereas for external temperatures higher than the base temperature they are termed ‘cooling’ degree hours (or days). The heating and cooling degree data can be used with a building’s U values to provide an estimate of its heating and cooling energy demand over the selected period. However, the value of the base temperature (which is normally lower than the desired internal temperature for the building) is specified on the assumption of a pre-defined internal temperature rise associated with the building’s internal heat gains, but which may in practice vary significantly from building to building, This can lead to significant errors and uncertainties. Further, the methodology is not well suited to simulations that include the thermal capacity and the thermal response of the building with time.

Dynamic simulations using external temperature data are potentially capable of providing a more accurate estimate of heating and cooling energy demand, especially when the thermal response of the building is included in the model. Since the thermal response time of most buildings is several hours, weather data and calculations at hourly intervals are generally sufficient. Synoptic weather data, covering several years, are available for a number of areas across the UK. However, in practice most simulations make use of Test Reference Year (TRY) and Design Summer Year (DSY) data. TRY data are generated from statistical distributions of weather patterns over several years to provide typical weather files for simulations. An equivalent statistical methodology is used to generate DSY data, which simulates extreme summer weather conditions and can be used to analyse the risk of overheating in buildings.

Table G-1. Daily average temperature (14 data sources)

Month	Hrow9697.fwt	cntr_Islington_ TRY.epw	cntr_Islington_ DSY.epw	2030_Islington_ TRY.epw	2030_Islington_ DSY.epw	2050_Islington_ TRY.epw	2050_Islington_ DSY.epw	2080_Islington_ TRY.epw	2080_Islington_ DSY.epw	cntr_Heathrow_ TRY.epw	cntr_Heathrow_ DSY.epw	2050_Heathrow_ TRY.epw	2050_Heathrow_ DSY.epw	CIBSE Guide A T2.34
Jan	3.8	5.1	5.6	6.0	6.4	6.9	7.2	7.4	7.6	4.3	4.0	6.2	6.6	2.9
Feb	8.3	5.1	5.2	6.9	6.9	7.3	7.5	8.4	9.1	4.6	4.5	6.8	6.9	3.8
Mar	10.0	6.7	7.1	8.5	8.9	9.0	9.1	9.6	10.3	6.1	5.2	8.4	8.7	7.7
Apr	11.5	9.7	11.5	10.5	10.8	11.1	11.6	11.8	12.3	9.1	9.5	10.7	11.2	11.0
May	10.4	12.6	12.9	14.0	14.9	14.9	15.6	15.7	16.7	12.7	12.2	14.7	16.0	14.4
Jun	17.2	15.3	14.8	17.8	18.2	18.3	19.0	19.6	20.2	15.4	15.6	18.7	19.1	18.7
Jul	18.2	17.6	18.0	19.7	20.2	20.6	21.2	21.7	22.5	17.6	18.8	20.8	21.6	19.6
Aug	18.2	17.4	18.4	19.4	20.4	20.5	21.3	22.1	22.9	17.5	18.8	20.6	21.4	19.8
Sep	14.9	15.1	15.5	17.1	17.2	17.9	18.0	19.1	19.1	14.9	15.7	17.6	17.6	14.2
Oct	13.3	12.0	12.6	14.0	14.1	14.7	14.6	15.6	15.3	11.5	11.7	14.3	14.1	11.7
Nov	7.9	7.8	8.8	10.2	10.5	10.6	11.2	11.5	11.6	6.9	8.2	10.1	10.6	6.4
Dec	5.0	5.5	6.3	7.1	7.1	7.9	7.5	8.6	8.4	5.4	4.8	7.1	7.0	1.9

Table G-2. Daily average of the peak hourly temperatures (13 data sources)

Month	Hrow9697.fwt	cntr_Islington_ TRY.epw	cntr_Islington_ DSY.epw	2030_Islington_ TRY.epw	2030_Islington_ DSY.epw	2050_Islington_ TRY.epw	2050_Islington_ DSY.epw	2080_Islington_ TRY.epw	2080_Islington_ DSY.epw	cntr_Heathrow_ TRY.epw	cntr_Heathrow_ DSY.epw	2050_Heathrow_ TRY.epw	2050_Heathrow_ DSY.epw
Jan	9.3	11.0	12.5	15.8	12.7	17.5	12.6	16.0	15.1	11.6	10.7	13.8	12.3
Feb	12.0	10.4	9.0	13.2	12.2	13.8	11.0	14.2	15.2	10.9	12.9	13.2	13.3
Mar	13.6	15.8	11.1	17.4	14.2	16.4	15.0	18.6	16.4	12.4	11.6	15.5	14.9
Apr	17.7	14.0	16.8	15.2	17.4	17.2	17.1	17.8	18.7	14.0	14.4	17.7	17.1
May	20.1	18.3	18.3	18.7	18.9	19.6	20.4	20.6	21.1	20.0	18.8	19.2	21.3
Jun	26.3	20.2	18.8	24.2	25.6	25.4	25.3	25.7	26.6	22.5	22.4	25.1	27.9
Jul	25.4	23.8	22.5	26.0	26.8	26.5	27.5	27.8	30.1	24.4	25.0	26.3	24.6
Aug	24.2	22.5	23.9	24.0	26.5	25.9	27.0	27.8	27.8	23.0	27.0	26.6	27.5
Sep	18.8	19.0	20.6	20.7	22.6	24.9	24.6	25.1	24.4	18.9	20.4	23.6	24.5
Oct	17.1	18.9	16.5	21.8	21.8	20.6	22.2	21.5	23.7	17.6	20.2	20.3	19.9
Nov	15.8	13.8	13.3	17.0	17.0	18.3	15.9	17.6	15.6	12.5	14.7	16.3	15.5
Dec	10.5	13.0	11.3	12.3	14.1	14.4	17.6	15.0	16.9	13.3	12.7	13.9	18.3

Table G-3. Maximum temperature in each month

Month	Hrow9697.fwt	cntr_Islington_TRY.epw	cntr_Islington_DSY.epw	2030_Islington_TRY.epw	2030_Islington_DSY.epw	2050_Islington_TRY.epw	2050_Islington_DSY.epw	2080_Islington_TRY.epw	2080_Islington_DSY.epw	cntr_Heathrow_TRY.epw	cntr_Heathrow_DSY.epw	2050_Heathrow_TRY.epw	2050_Heathrow_DSY.epw
Jan	11.9	14.9	17.4	17.7	14.0	22.3	14.2	19.0	16.9	15.9	13.3	15.8	14.6
Feb	13.5	14.9	12.6	16.5	16.8	17.3	14.2	18.2	19.4	14.9	17.2	16.5	17.1
Mar	17.2	25.4	14.7	18.7	18.1	20.4	18.4	20.9	20.3	17.4	15.5	19.7	18.6
Apr	22.3	18.8	20.4	19.5	23.5	23.2	21.6	23.5	24.0	18.6	19.8	24.4	22.4
May	25.0	23.1	23.3	25.9	22.1	23.6	26.2	26.6	25.6	27.1	23.6	26.5	27.3
Jun	29.7	28.4	28.8	31.5	32.6	29.1	31.3	36.2	35.3	28.7	28.7	31.7	29.5
Jul	24.2	22.5	23.9	24.0	26.5	25.9	27.0	27.8	27.8	23.0	27.0	26.6	27.5
Aug	29.6	28.2	27.3	29.2	30.5	32.4	31.3	35.1	32.5	29.4	30.8	33.8	34.3
Sep	22.3	23.6	25.0	26.4	29.6	30.1	30.6	29.0	31.3	23.8	25.6	30.1	30.0
Oct	20.7	22.0	20.7	25.7	25.9	25.2	25.5	24.5	28.5	21.8	23.3	25.1	24.6
Nov	17.3	16.8	17.7	20.1	20.5	21.4	19.0	21.1	16.7	15.7	17.3	21.0	18.1
Dec	13.0	16.1	13.9	14.6	17.3	16.9	21.0	17.9	18.9	16.3	15.3	18.2	20.5

Table G-4. Minimum temperature in each month

Month	Hrow9697.fwt	cntr_Islington_TRY.epw	cntr_Islington_DSY.epw	2030_Islington_TRY.epw	2030_Islington_DSY.epw	2050_Islington_TRY.epw	2050_Islington_DSY.epw	2080_Islington_TRY.epw	2080_Islington_DSY.epw	cntr_Heathrow_TRY.epw	cntr_Heathrow_DSY.epw	2050_Heathrow_TRY.epw	2050_Heathrow_DSY.epw
Jan	-3.6	-6.1	-3.5	-4.8	-2.8	-2.2	-2.4	-2.4	1.3	-5.2	-5.8	-1.9	-2.7
Feb	1.2	-4.8	-0.1	-0.1	0.0	0.7	-1.5	0.6	-0.6	-4.8	-4.1	-3.5	-3.0
Mar	3.7	-0.7	-0.7	-1.6	0.8	-1.7	1.1	-1.2	1.0	-3.3	-4.9	-3.5	-1.1
Apr	3.4	-0.8	2.0	0.2	1.1	0.2	2.4	1.2	2.6	-1.3	-0.8	-0.6	-0.2
May	3.6	2.4	3.7	2.7	6.9	5.2	6.0	5.3	6.0	3.0	2.0	3.8	6.8
Jun	9.9	3.8	3.5	6.2	6.8	9.6	7.7	7.4	10.0	4.6	2.7	8.1	9.9
Jul	11.3	9.6	10.1	9.9	9.5	12.3	15.0	10.9	14.0	8.2	8.8	9.1	12.9
Aug	12.4	8.1	10.5	9.1	13.4	12.6	10.1	12.6	12.6	8.7	5.6	11.8	12.9
Sep	8.3	5.9	5.7	8.6	7.7	8.7	8.9	10.9	10.2	5.1	5.7	8.9	9.6
Oct	6.7	1.2	4.8	5.3	6.5	4.9	5.5	7.5	6.2	2.0	0.4	3.6	5.1
Nov	1.1	-2.2	0.1	3.0	-2.6	0.3	3.1	1.9	4.8	-2.6	-2.3	-1.3	1.4
Dec	-1.7	-3.4	-2.0	-0.2	-0.2	-1.9	0.0	-0.8	0.9	-4.2	-4.9	-3.8	-1.0

H. Energy and emissions data from ‘other’ sources

This Appendix summarises (in tabular form) some of the data that were downloaded, analysed and reformatted (where necessary) for this study. For brevity a description of the download and analysis methods has not been included. The data have been used for the comparisons with the Excel model results and with the benchmarks detailed in Chapter 5 and Appendix F.

Statistical data considered relevant to this investigation included demographic data such as population, occupations, dwelling types and numbers, business types and numbers, gross floor areas, population and building densities, age of building stock and energy use. It was determined that the Office of National Statistics database could potentially provide much of this data, since it allowed searches at different geographic levels and according to selected criteria. However, having undertaken a number of searches and downloads it became apparent that there were gaps and inconsistencies in the information, so other sources of data were investigated. These included the London Heat Map, Display Energy Certificates (DECs), Energy Performance Certificates (EPCs) and energy data via DECC. The areas selected for downloads were the London Boroughs of Southwark, Sutton and the City of London, as well as the whole of the Greater London Area. Searches were undertaken and data downloaded and analysed for each area. The resulting data were compared between areas and between different sources.

Data from ONS statistical downloads

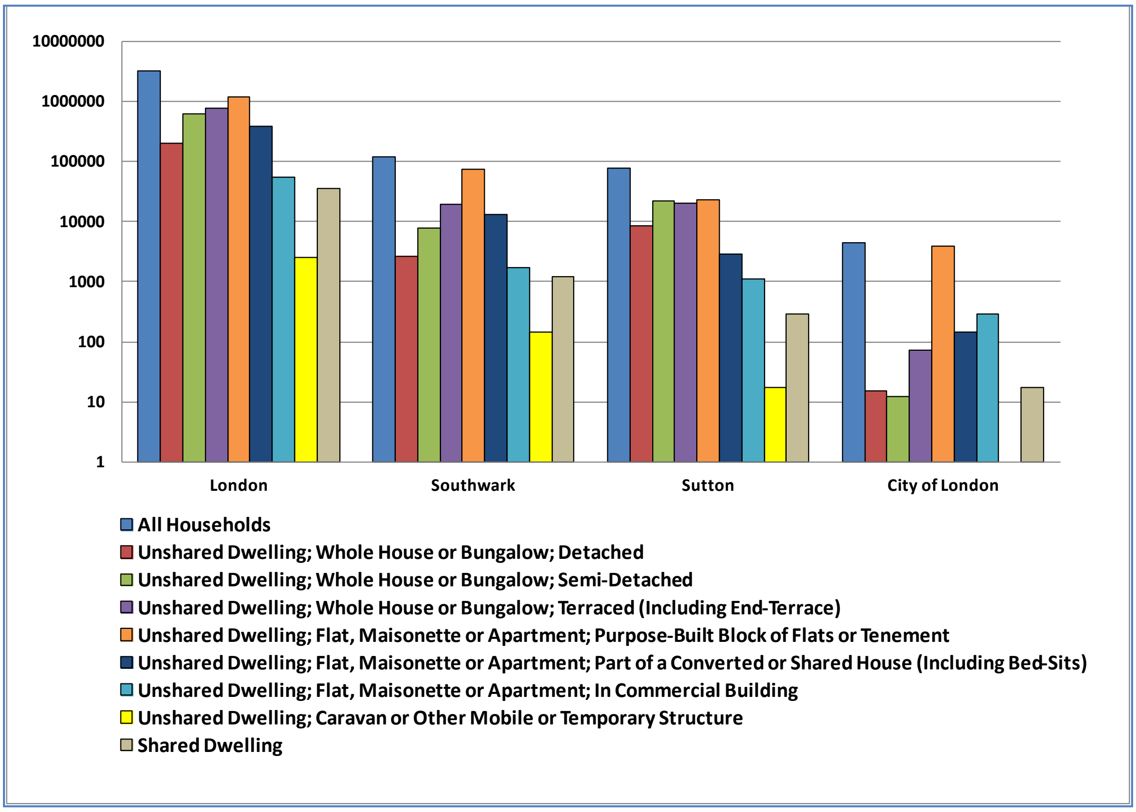


Figure H-1. Demographic data (2011) – accommodation type by number of households in each category

[Source: adapted from ONS (2014)]

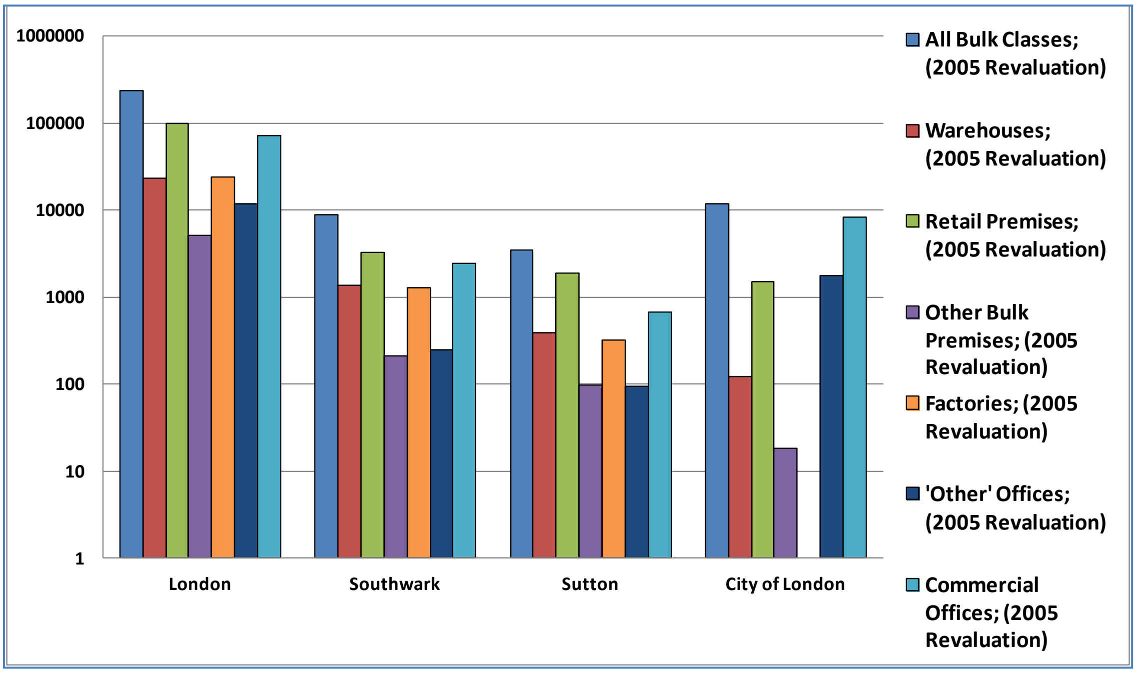


Figure H-2. Demographic data (2005) – number of commercial and industrial premises by type

[Source: adapted from ONS (2014)]

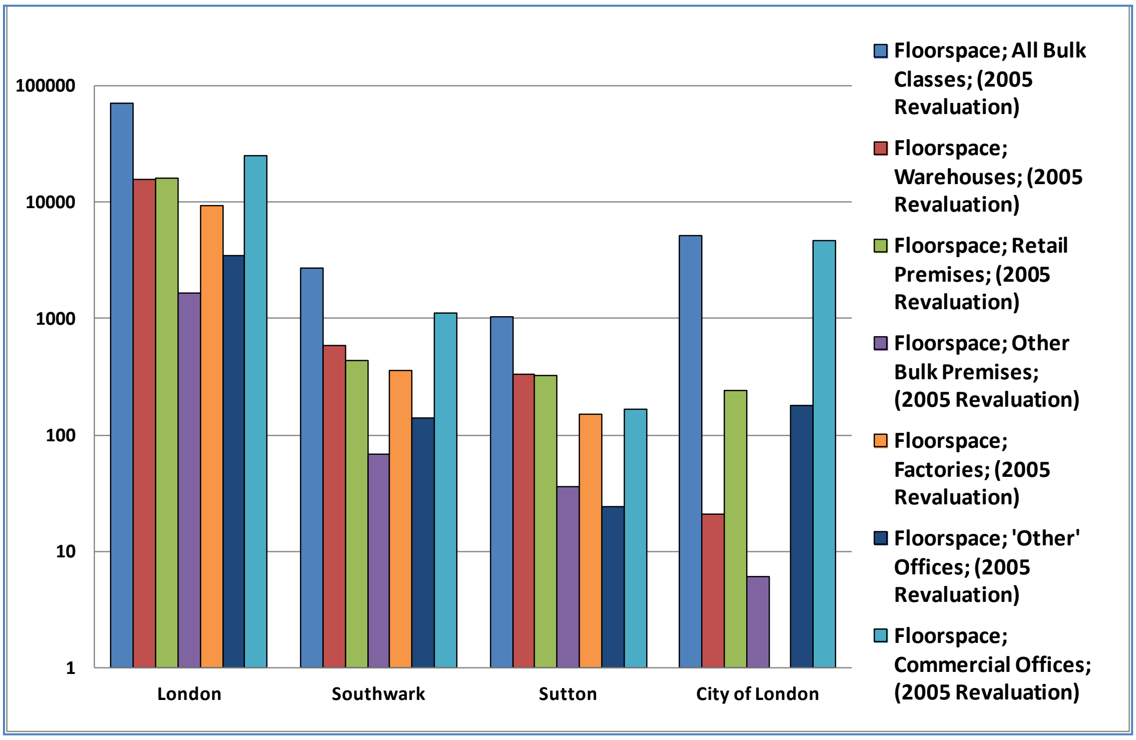


Figure H-3. Demographic data (2005) - commercial and industrial floorspace (m2 x 1,000) by type of premise

[Source: adapted from ONS (2014)]

Table H-1. Calculation of energy density by dwelling type for Greater London and 3 boroughs

Dwelling Type	Typical Dwelling Floor area m2	Total London m2x1000	Total Southwark m2x1000	Total Sutton M2x1000	Total City of London m2x1000
Detached house/ bungalow	104	21,329.2	269.4	871.4	1.6
Semi-detached house/ bungalow	89	54,941.8	692.2	1,973.8	1.1
Terraced house/ bungalow	79	59,771.1	1,522.0	1,602.2	5.6
Flat/ maisonette/ apartment	61	73,875.6	4,562.6	1,400.6	233.8
Flat/ maisonette/ apartment (conversion)	61	23,352.4	786.8	179.0	8.8
Flat/ maisonette/ apartment in commercial buiding	61	3,368.2	105.8	69.2	17.8
Caravan/ mobile home					
	Total private dwellings	236,638.3	7,938.8	6,096.2	268.7
Local Authority pre 1919	100	4,754.1	487.4	8.2	3.5
Local Authority 1919-1944	90	7,205.5	586.4	306.5	31.8
Local Authority 1945-1964	85	13,536.6	1,243.6	132.2	82.6
Local Authority post 1964	80	16,591.8	1,587.0	261.2	51.4
	Total Local Authority	42,088.0	3,904.3	708.0	169.3
	Total Housing m2x1000	278,726.3	11,843.1	6,804.3	438.0
	Average m2/ dwelling	74.8	71.7	78.9	68.8
	Energy Densities kWh/ m2/ yr (from total floor areas and ONS energy consumption statistics)				
	Electricity (std)	38.3	30.6	36.5	45.9
	Electricity (Econ 7)	9.4	7.2	14.4	12.4
	Gas	150.1	91.8	155.9	76.6

[Source: adapted from ONS (2014)]

Table H-2. Calculation of average energy densities for commercial and industrial premises in Greater London and 3 boroughs using TM46 benchmarks and total floorspace

			Estimated Energy Use using TM46 Benchmarks GWh/ yr							
Premises Type	TM46 Benchmarks		Elect	Gas	Elect	Gas	Elect	Gas	Elect	Gas
	Elect kWh/m2	Gas kWh/m2	London		Southwark		Sutton		City of London	
Warehouses	35	160	548	2,504	20.8	95.0	11.7	53.4	0.7	3.4
Retail	165	0	2,654	0	72.8	0.0	53.8	0.0	40.1	0.0
'Other bulk premises'	95	120	159	201	6.5	8.2	3.4	4.3	0.6	0.7
Factories	35	180	326	1,674	12.5	64.3	5.3	27.0	0.0	0.0
'Other' offices	95	120	331	417	13.4	16.9	2.3	2.9	16.8	21.2
Commercial offices	95	120	2,366	2,989	105.7	133.6	16.0	20.2	443.7	560.5
	Energy Use GWh/yr		6,382	7,785	232	318	92	108	502	586
	Energy Density kWh/m2/yr		89.8	109.5	85.4	117.1	89.0	103.9	98.1	114.5

[Source: adapted from ONS (2014) and CIBSE (2008)]

London energy mapping (heat map studies)

In October 2011, the Mayor of London published his revised Climate Change Mitigation and Energy (CCME) strategy, entitled 'Delivering London's Energy Future'. The strategy included a target of achieving 25% of London's energy supply from decentralised energy sources by 2025. The LDA‟s Decentralised Energy and Energy Masterplanning Programme (DEMaP) was developed to identify decentralised energy opportunities in London, to enable the Corporation to implement economical low carbon District Heating (DH) and Cooling infrastructure.

The purpose of the London Heat Map (London.gov, 2016) was to compile and make available information about heat energy demand across London to help identify opportunities to develop decentralised energy networks. To support this aim the LDA made available some funding for Boroughs to gather actual energy data and identify areas with potential for DH networks within their boundaries. Data have been collected and reports published for the three boroughs being investigated during this study (City of London, Southwark and Sutton). The reports and data spreadsheets were produced in 2010 and 2011. According to downloads available from the London Heat Map website the reports have not been updated since and the spreadsheet data which remains patchy in terms of coverage and content. Questionnaires were used to collect actual energy use data by the companies conducting the studies, however, the response rate was typically 10% or less, so much of the final data presented in the reports and spreadsheets was based on estimates using benchmark values.

After downloading the spreadsheets it became apparent that the gross internal floor area was not reported for many buildings, the number of valid data samples (those including gross floor area) being small relative to the total number of buildings listed. The downloaded data were therefore sorted and only the 'valid' line items (those including both energy and internal floor area data) were used in the analysis, to produce average figures for heating energy density across all building types in the 3 boroughs. There are shown in Table H-3. and indicate a range between 113 and 195 kWh/m^2 per year. However, the figure of 195 kWh/m^2 for Southwark, was based on only 6 data samples. The difference between City of London and Sutton is unsurprising, as Sutton has fewer commercial buildings and more residential properties than City of London, in relation to their size.

Table H-3. Heating energy per m^2 calculated from the heat map report data for 3 London boroughs

London Borough	Fuel consumption from all assets excluding CHP MWh/yr	Fuel consumption from CHP MWh/yr	Gross internal Floor Area m2	Heating Energy kWh/m2/yr	Number of valid data samples
City of London (total)	264,360	19,859	3,082,359		134
City of London (average)	**1,973**	**148**	**23,003**	**113**	
Southwark (total)	3,530	0	48,010		6
Southwark (average)	**588**	**0**	**8,002**	**195**	
Sutton (total)	156,502	0	991,084		232
Sutton (average)	**675**	**0**	**4,272**	**182**	

[Source: derived from London heat map downloads (London.gov, 2016)]

City of London study benchmarks

The benchmark values that were used in the City of London study (Ramboll, 2011) energy assessments are shown in Table H-4.. They are of limited value, but worthy of note is their 'new office' modelling result, based on Part L of the Building Regulations. This predicts an energy density of 68 kWh/m^2 per annum – this compares with 215 kWh/m^2 per annum for the CIBSE TM46 benchmark and 139 kWh/m^2 per annum for the Excel tool simulation (i.e. the Excel prediction is almost mid-range between the other two values).

Table H-4. Benchmark heat demand values used in the City of London heat map study

Building type	MWh per Annum		Reference
	per m2 GIA	per unit	
2 bed flat		8.165	Assuming 61 m2 per unit
Housing	0.134		2 bed flat gas consumption.
School - Primary (no pool)	0.113		GPG343
School - Secondary (no pool)	0.108		GPG343
Office	0.09095		Energy Consumption Guide 019
Office Cooling	0.018		CIBSE Guide F - Good Practice converted to GIA
New office modelling results part L modelling	0.068		Based on part L modelling
Future office - modelling part L 2010	0.0255		Based on Part L modelling
Hotel -Luxury		17.4	CIBSE Guide F - Good Practice
Hotel - Business/Holiday		15.08	CIBSE Guide F - Good Practice
Hotel Electricity used for cooling - Luxury		2.32	CIBSE Guide F - Good Practice
Hotel Electricity used for cooling - Business/Holiday		1.74	CIBSE Guide F - Good Practice
Hospital cooling taken as (HVAC) electricity demand for acute hospital	0.0195		CIBSE Guide F - midpoint between Typical and Good Practice values

[Source: Ramboll, 2011]

Energy Performance Certificates

Table H-5. Energy densities by dwelling type and location, using EPC lodgement data

All England 2014													
Property Type	**Number of Lodgements**	**Total Floor Area (m2)**	**Average Floor Area (m2)**	**Energy Use (kWh/m2 pa)**	**Average Per Dwelling**	**Carbon Dioxide Emissions (tonnes pa)**	**Average Per Dwelling**	**Lighting Cost (£ pa)**	**Average Per Dwelling**	**Heating Cost (£ pa)**	**Average Per Dwelling**	**Hot Water Cost (£ pa)**	**Average Per Dwelling**
Bungalow	3,738	318,418	85.2	449,217	120	6,307	1.7	197,269	53	1,283,640	343	403,143	108
Flat	49,715	3,235,378	65.1	5,499,312	111	58,902	1.2	2,274,920	46	11,581,668	233	5,313,582	107
House	79,947	8,885,591	111.1	7,540,417	94	144,057	1.8	5,391,125	67	27,442,475	343	7,930,931	99
Maisonette	1,890	168,665	89.2	210,157	111	3,063	1.6	111,061	59	603,460	319	203,072	107
All Properties	**135,290**	**12,608,052**	93.2	**13,699,103**	**101**	**212,330**	**1.6**	**7,974,375**	**59**	**40,911,243**	**302**	**13,850,728**	**102**
City of London 2014													
Property Type	**Number of Lodgements**	**Total Floor Area (m2)**	**Average Floor Area (m2)**	**Energy Use (kWh/m2 pa)**	**Average Per Dwelling**	**Carbon Dioxide Emissions (tonnes pa)**	**Average Per Dwelling**	**Lighting Cost (£ pa)**	**Average Per Dwelling**	**Heating Cost (£ pa)**	**Average Per Dwelling**	**Hot Water Cost (£ pa)**	**Average Per Dwelling**
Flat	407	27,194	66.8	34,685	85	322	0.8	17,656	43	101,219	249	40,582	100
Maisonette	6	809	134.8	918	153	23	3.8	438	73	4,722	787	1,271	212
All Properties	**414**	**28,130**	67.9	**35,831**	**87**	**350**	**0.8**	**18,159**	**44**	**107,030**	**259**	**41,959**	**101**
Southwark 2014													
Property Type	**Number of Lodgements**	**Total Floor Area (m2)**	**Average Floor Area (m2)**	**Energy Use (kWh/m2 pa)**	**Average Per Dwelling**	**Carbon Dioxide Emissions (tonnes pa)**	**Average Per Dwelling**	**Lighting Cost (£ pa)**	**Average Per Dwelling**	**Heating Cost (£ pa)**	**Average Per Dwelling**	**Hot Water Cost (£ pa)**	**Average Per Dwelling**
Flat	1,191	82,524	69.3	77,700	65	978	0.8	53,207	45	229,552	193	92,781	78
House	61	9,203	150.9	3,415	56	95	1.6	4,538	74	20,991	344	6,329	104
Maisonette	115	10,378	90.2	7,056	61	112	1.0	6,167	54	26,234	228	12,078	105
All Properties	**1,370**	**102,442**	74.8	**88,497**	**65**	**1,191**	**0.9**	**64,083**	**47**	**277,967**	**203**	**111,465**	**81**
Sutton 2014													
Property Type	**Number of Lodgements**	**Total Floor Area (m2)**	**Average Floor Area (m2)**	**Energy Use (kWh/m2 pa)**	**Average Per Dwelling**	**Carbon Dioxide Emissions (tonnes pa)**	**Average Per Dwelling**	**Lighting Cost (£ pa)**	**Average Per Dwelling**	**Heating Cost (£ pa)**	**Average Per Dwelling**	**Hot Water Cost (£ pa)**	**Average Per Dwelling**
Flat	561	34,916	62.2	62,282	111	671	1.2	23,700	42	122,918	219	77,331	138
House	102	11,244	110.2	6,381	63	126	1.2	6,345	62	29,182	286	12,349	121
All Properties	**670**	**46,622**	69.6	**69,144**	**103**	**803**	**1.2**	**30,327**	**45**	**153,699**	**229**	**90,209**	**135**

[Source: adapted from DCLG (2014)]

Display Energy Certificates

Table H-6. Energy densities and emissions for commercial and industrial premises in 3 London boroughs (based on DEC lodgements 2008 - 2015)

		Number of Lodgements	Total Floor Area (m^2) [Note 2]	Average Floor Area per Building (m^2)	ΣAnnual Energy Use- all Lodgements (kWh/m^2/year) Heating	ΣAnnual Energy Use - all Lodgements (kWh/m^2/year) Electricity	Annual Energy Use (kWh/m^2/year) Heating	Annual Energy Use (kWh/m^2/year) Electricity	CO_2 Emissions (Tonnes per year) Heating	CO_2 Emissions (Tonnes per year) Electricity	CO_2 Emissions (kg/m^2/year) Heating	CO_2 Emissions (kg/m^2/year) Electricity
City of London	**Total**	**285**	**3,165,261**	**11,106**	**57,878**	**49,038**	**203**	**172**	**101,396**	**289,089**	**32.0**	**91.3**
	(per year)	41	452,180									
Southwark	**Total**	**759**	**5,742,624**	**7,566**	**128,856**	**98,125**	**170**	**129**	**213,391**	**481,733**	**37.2**	**83.9**
	(per year)	108	820,375									
Sutton	**Total**	**587**	**2,002,020**	**3,411**	**102,963**	**52,924**	**175**	**90**	**71,868**	**123,724**	**35.9**	**61.8**
	(per year)	84	286,003									

[Source: adapted from DCLG (2014)]