Assessing the potential of heat pumps to reduce energy-related carbon emissions from UK housing in a changing climate

Robert W Irving (2013)

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ABSTRACT

This thesis describes three connected stages of development and analysis of residential heat pump energy use: firstly, the analysis of heat pump performance data from a monitoring study of ground source heat pumps; secondly, the definition and development of a generalised residential heat pump energy model embedded within an enhanced dwelling energy model; finally, the analysis of the effects of possible residential heat pump installation scenarios on the UK energy supply and carbon emissions.

The monitoring study involved three ground source heat pump installations. The data collected consisted of heat output, electric power input, system temperatures and system status indicators. Analysis indicated that these systems showed reductions in carbon emissions from homes ranging from 18% to 37% compared with their counterfactual fuel-burning systems.

The monitoring study provided empirical values to parameterise the heat pump model which was built around a linear regression relationship of heat pump COP to source / sink temperature differential based on heat pump performance data from standard laboratory test results. This model was added in a new module to enhance the BRE domestic energy model, BREDEM-8, which provides monthly estimates. Estimating rules were included for energy use from bivalent alternate, bivalent parallel operation and space cooling.

The enhanced BREDEM-8 model was used to analyse the effects of possible residential heat pump installations within a housing stock energy model developed using the English Housing Survey datasets as a data source. Baseline estimates for the current stock were created using data reduction techniques to provide parameters (u-values, glazing details) for the enhanced BREDEM-8 model.

Scenarios for heat pump deployments were created for the periods up to 2020 and 2050, selecting dwellings for heat pump application according to scenarios reflecting the perceived needs of the period, ie. the likely reduction in UK generating capacity up to 2020 and CO_2 emissions reduction targets to 2050. Results showed that up to 2020, a policy of targeting dwellings with the highest overall emissions for replacement would reduce carbon emissions by 7.6%, at the expense of a 12% increase in electricity consumption. Targeting dwellings with the highest emitting existing systems caused a smaller increase in electricity consumption of about 6.5% with carbon emissions reduced by about 6.8%.

The scenarios for the period to 2050, including 80% replacement of gas systems with heat pumps, gave an estimated 80% reduction in carbon emissions, when accompanied by an similar reduction in the carbon intensity of electricity generation and bringing about an increase in electricity consumption of somewhat over 40%. The effect of the more extreme scenario is to replace all but a small proportion of the energy used for heating and hot water with standard rate electricity, in 84.6% of the dwellings, and retaining gas in the remainder, 15.2%, bringing about a radical shift to electric heating throughout the housing stock.

DECLARATION

The candidate, Robert Irving, while registered for the Degree of Doctor of Philosophy, was not registered for any other award of a university during the programme

Robert Irving,
September 2013

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ABBREVIATIONS

AD	Approved Document (part of the UK Building Regulations)
ASHP	Air source heat pump
ASHRAE	American Society of Heating, Refrigerating & Air conditioning Engineers
BRE	Building Research Establishment
BREDEM	BRE Domestic Energy Model
CAT	Carbon Abatement Technologies
CCS	Carbon Capture & Storage
CERT	Carbon Emission Reduction Targets
CFC	Chlorofluorocarbon
CHP	Combined heat and power
CIBSE	Chartered Institute of Building Services Engineers
CO_2	Carbon dioxide
COP	Coefficient of performance
CORGI	Confederation of Registered Gas Installers
CSH	Code for Sustainable Homes
DCLG	Department of Communities & Local Government
DECC	Department of Energy & Climate Change
DER	Dwelling emission rate
DHW	Domestic hot water
DUKES	Digest of UK Energy Statistics
EAHP	Exhaust air heat pump
ECO	Energy Company Obligation
EER	Energy efficiency ratio
EHCS	English House Condition Survey
EST	Energy Saving Trust
EU	European Union
FiT	Feed-in tariff
GFA	Ground floor area
GHG	Green house gas
GIS	Geographical information system
GJ	Giga (10^9) Joules
GO	Government Office
GSHP	Ground source heat pump
GWh	Giga(10^9) watt hours
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HDD	Heating degree days
HFC	Hydrofluorocarbon
kWh	kilowatt hour(s)
kWth	kilowatt hours thermal
LCBP	Low Carbon Buildings Programme
LZC	Low and zero carbon
MtC	Million tonnes of carbon
MTOE	Million Ton Oil Equivalents
NHER	National Home Energy Rating
ODP	Ozone depletion potential
RHI	Renewable Heat Incentive
RHPP	Renewable Heat Premium Payment

SAP	Standard Assessment Procedure
SEDBUK	Seasonal Efficiency of Domestic Boilers in the UK
SEER	Seasonal energy efficiency ratio
SHW	Solar hot water
SPF	Seasonal performance factor
TER	Target emission rate
TFA	Total floor area
TRY	Test Reference Year
TWh	Tera(10^{12}) watt hours
UFH	Under floor heating

CHAPTER 1 INTRODUCTION

1.1 Introduction

As a introduction to this thesis, this chapter contains an examination of the current position of heating systems in the the UK housing stock, a brief history of how this situation has arisen and an indication of its effect on UK energy consumption. It also contains description of the drivers for change in this field and their origins, and details of the policies and regulations that will influence the direction of this change.

As a result of the issues raised, the research aims and objectives are defined and a summary of the thesis chapter structure and contents follows.

1.2 Heating systems in UK dwellings

1.2.1 History and current status

In research for this section, this writer has come across only one author, Lawrence Wright, who has chronicled the history of heating in British homes in 'Home Fires Burning' (Wright, 1964). This reveals the convoluted and eccentric ways in which we in Britain have struggled over many centuries to re-attain the heights of domestic convenience which the Romans had already reached back at the beginning of the Christian era. Nothing as sophisticated as the Roman hypocaust was installed in buildings in Britain until the 18th century and this later equivalent remained largely the preserve of public buildings, factories and stately homes when Wright was writing in 1964. At that time, the author wrote "*Only about 10 per cent of existing owner-occupied houses, and not many more of those being built, have central heating."*(Wright, 1964, p200) and thought that the equipment was far too expensive for home-owners to consider installing it. However, by 1970, the proportion of households with central heating had risen to over 30% and has continued to rise steeply over the following three decades to almost saturation levels in privately-owned houses, as reflected by the following two graphs:

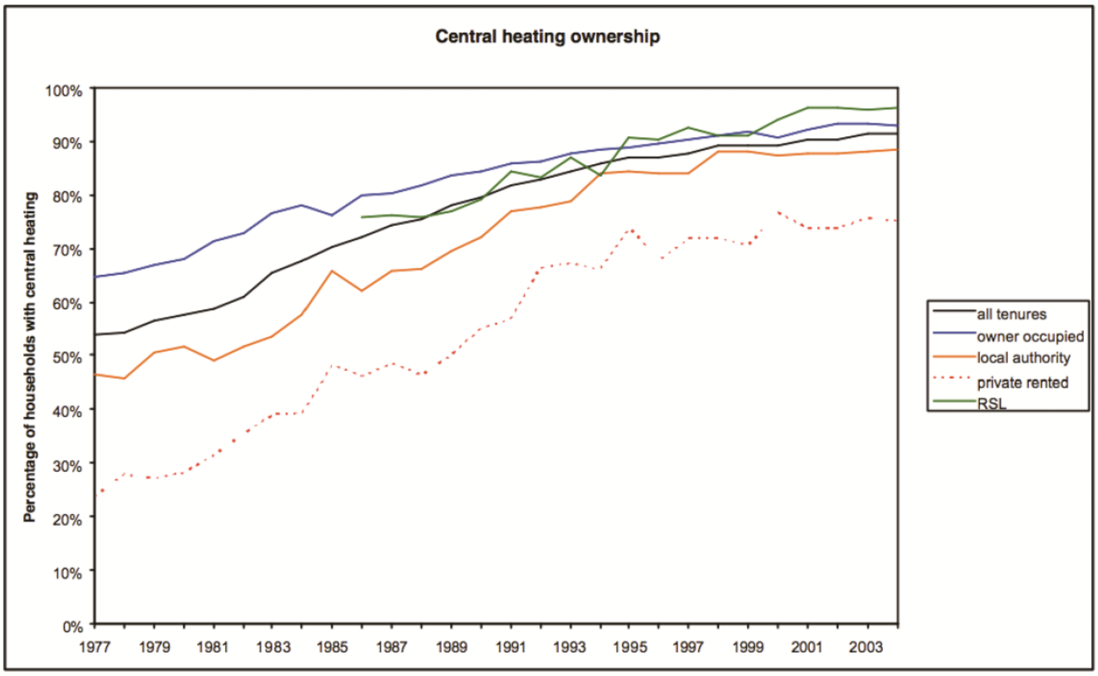

Figure 1.1 Central Heating ownership by tenure 1977 - 2004
(Utley & Shorrock, 2006)

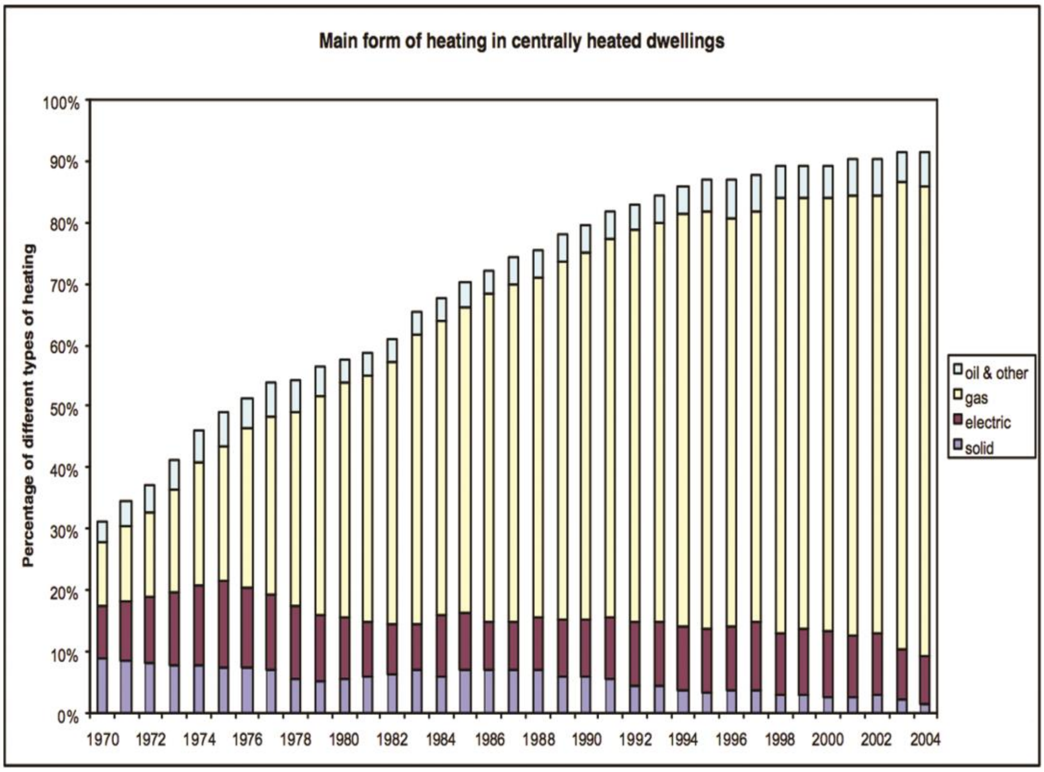

Figure 1.2 Main form of heating in centrally heated dwellings (Utley & Shorrock, 2006)

These graphs reflect the rapid take-up of central heating, especially gas central heating, throughout the UK housing stock, and leaves the reader slightly puzzled as to what had changed between Wright's pessimistic comments in 1964 and 1970, when the percentage had tripled. The answer to this question, while somewhat historic in context, is germane to this study because of some parallels between the current situation and that of 1964 which, this author considers, are as follows:

- in 1964, there existed a substantial section of the UK housing stock that lacked basic amenities, viz. bathrooms, hot water supply, heating other than coal fires (Wright, 1964); this could be considered to have a parallel in the lack of sufficient thermal insulation, draught-proofing and of sustainable, low or zero-carbon heating systems in our current stock;
- as 'work in progress' from the late 1940's and 1950's, the mechanisms of the Clean Air Act (1956), designed to eliminate the smog caused by coal-fired heating and power generation, has an parallel in the Climate Change Act (UK Parliament, 2008a), in bringing about a change of heating systems and fuels.

The up-rating of the housing stock, especially the privately-owned dwellings, appears to have been achieved by two mechanisms: firstly, the system of Improvement Grants whereby householders could claim a grant of 50% of the cost of installing the conveniences mentioned above; secondly, by the simpler mechanism of house-owners' adding the cost of the upgrades on to their mortgages (house loans), mostly by re-mortgaging, but sometimes while buying a new house (Smith, 2003, page 59). This second option allowed the spreading of the repayment over a long period at the comparatively low rates of interest charged by lenders on loans secured on property. The ability to finance house improvements in this way is dependent on the house-buyer's excess of earnings over and above that necessary to make the repayments on the basic home loan; and on the lender's confidence that the dwelling's value will continue to rise, maintaining security for the loan. These two factors are, to some extent, in opposition, in that with the continued rise in house prices, the proportion of each new buyer's income consumed by servicing the loan rises correspondingly. Only those house-owners who have been 'on the housing ladder' long enough for the process of income inflation to reduce this proportion will be able to take advantage of financing improvements in this way.

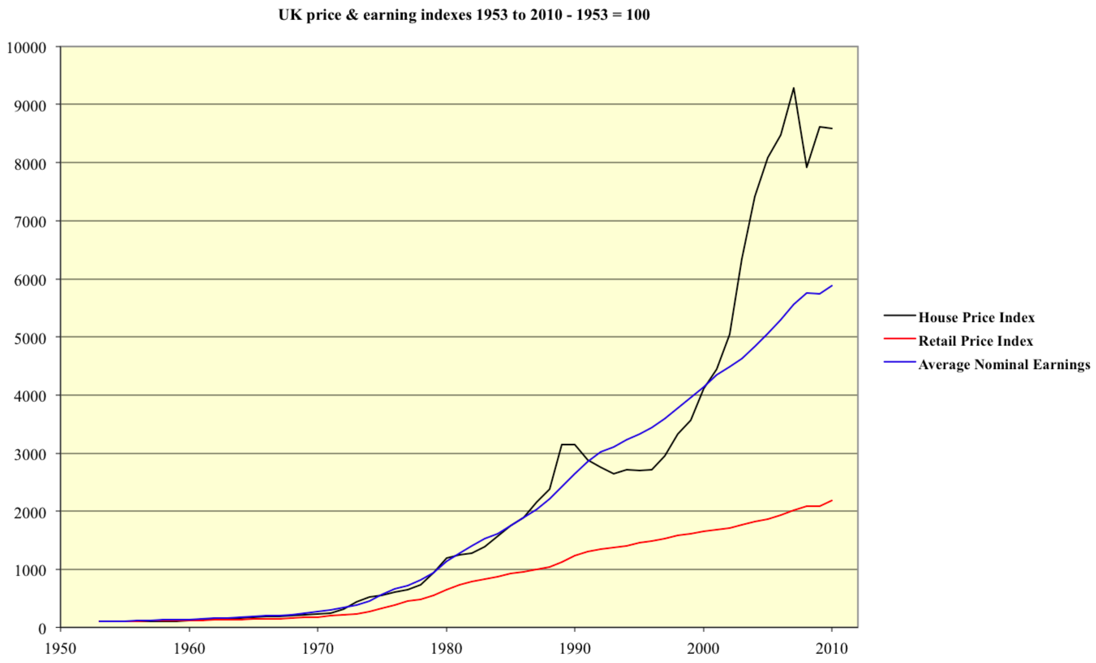

Figure 1.3 UK price and earnings index, earnings - 1953 - 2010

(Nationwide Building Soc, 2011; Office of National Statistics, 2010; Officer, 2011)

Moreover, average UK house prices have risen very substantially between 1997 and 2008, much faster than average income, increasing the level of income required to make an initial first house purchase and of those who would want to finance improvements by additional mortgage commitments.

1.2.2 Domestic energy use for heating

Domestic energy use for the period 1970 - 2012 in the UK is illustrated by Figure 1.2, Figure 1.3 which show an analysis of fuel consumption and of end use of energy (DECC, 2013), of which the source data values in the latter figure are the results of modelling rather than empirical data. The first figure shows the predominance of natural gas as a domestic energy source which, until the start of the current century, largely displaced all the solid fuels and a small proportion of petroleum-based fuel, ie. oil. In percentage terms, in 1970, 39% of consumption was coal, 24% natural gas and 9% oil; this changed to 8% coal, 63% gas and 6% oil in 1990; and to 1% coal, 68% gas and 6% oil in 2012. In terms of end use, over the period, the main relative changes have been increases of 8% in energy use for space heating and for appliances and lighting, and falls of 13% and 3% for water heating and cooking. Further modelled values indicate that in 2012, heat energy use was 14% solid fuel, 7.2% oil, 74% gas and 4.1% electricity. Gas use appears to have been at a high-point in 2008 at 83%, while solid fuel was at a low point at 7.5%. These relative changes appear to be due to a reduction in gas consumption, brought about by long-term trends to reduced heat

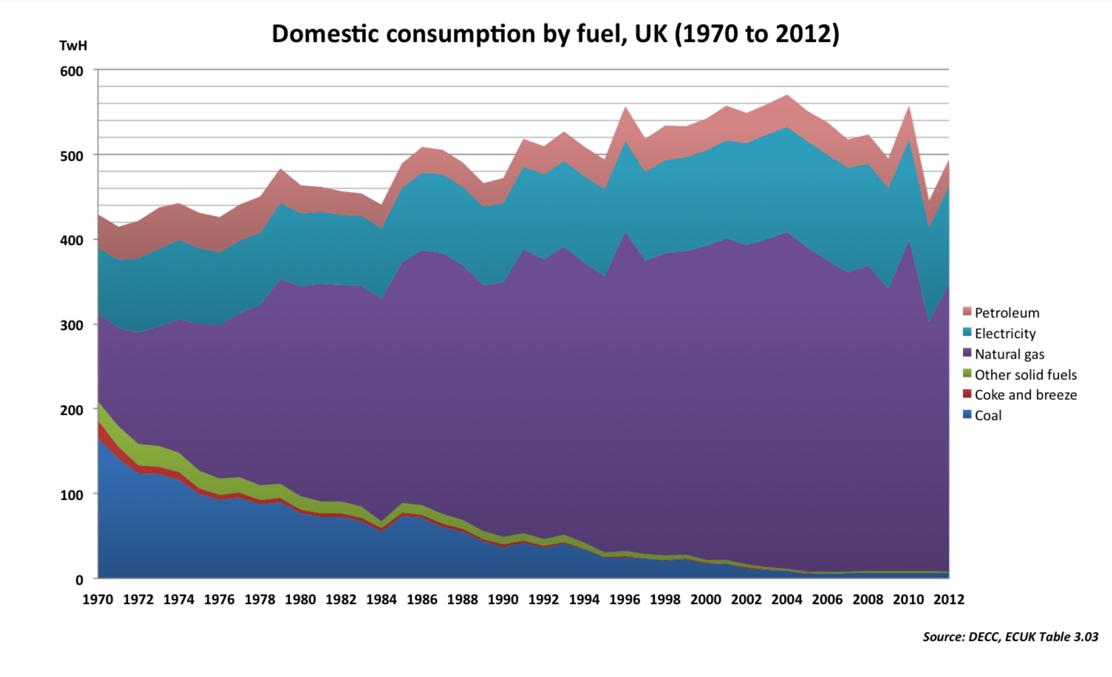

Figure 1.2 Domestic consumption by fuel, UK (1970-2012)

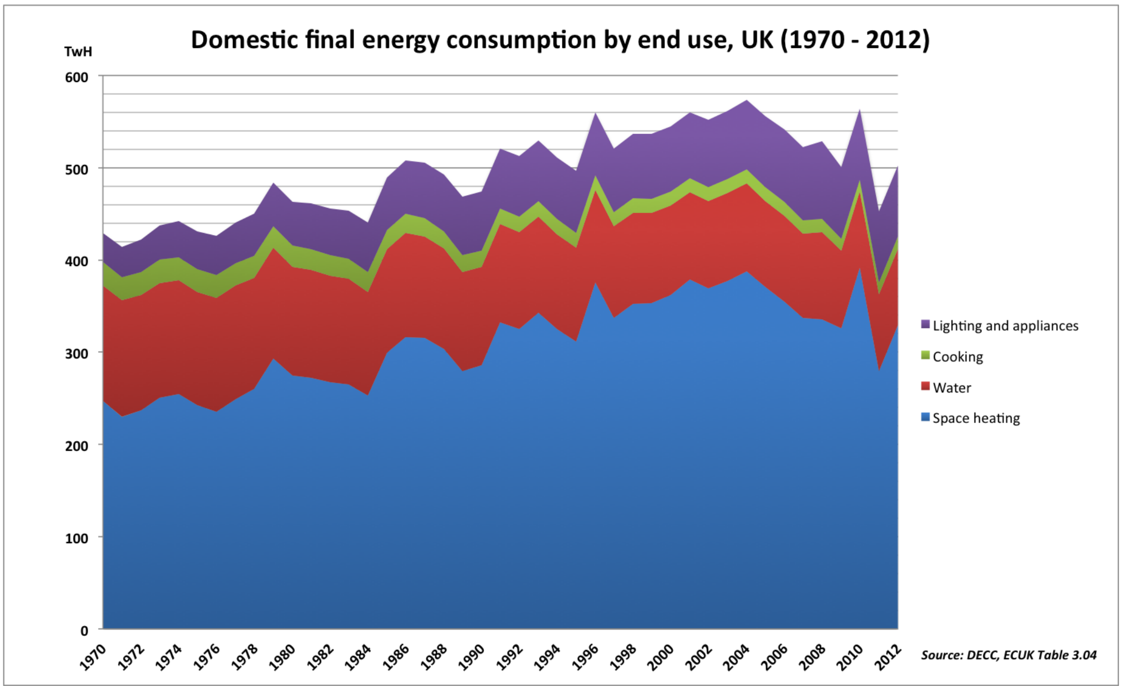

Figure 1.3 Domestic final energy consumption by end use, UK (1970-2012)

loss, increased boiler efficiency and increasing average external temperature (DECC, 2013, Tables 3.33, 3.34, 3.06). Regardless of the slow downward trend, the high gas consumption from non-renewable sources is incompatible with UK targets for CO_2 emissions.

1.2.3 Carbon emissions from domestic energy use

In carbon emission terms, the effect of the large numbers of gas central heating systems is systems is substantial, as can be seen in the following Table 1.1 extracted from the Great Britain's Housing Energy Fact file (Palmer & Cooper, 2011), though their emissions appear to be reducing. Conversely, emissions due to electricity consumption are increasing, though this would appear to be from appliance use rather than space heating, since the numbers of electrically-heated dwellings are reducing (

Figure 1.1).

Table 1.1 Carbon dioxide emissions due to domestic energy use

Year	Gas	Solid	Electric	Oil	GB total	Emission factor Electricity (kgCO2/kWh)
2000	65.3	6.3	55.3	9.6	136.5	0.518
2001	67.0	6.0	59.4	10.5	142.9	0.540
2002	66.4	4.7	59.9	9.2	140.2	0.523
2003	68.2	3.8	64.2	9.1	145.3	0.547
2004	70.0	3.3	64.3	9.7	147.3	0.543
2005	67.4	2.3	65.7	9.2	144.6	0.548
2006	64.8	2.1	64.6	9.7	141.1	0.543
2007	62.3	2.2	63.1	8.5	136.1	0.537
2008	63.5	2.5	60.7	9.0	135.6	0.531
2009	58.7	2.4	59.4	9.0	129.4	0.525

Extract from Table 3a: CO2 Emissions from Housing Energy (MtCO2) Palmer & Cooper, 2011)

1.2.4 Effect of the dominance of gas central heating

The dominance of gas central heating has had the effect of embedding this form of heating in standards and regulations. Thus, the Government's main tool for assessing the thermal efficiency of buildings, the Standard Assessment Procedure (SAP) (BRE, 2008) relies heavily on the SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) database (BRECSU, 2011) of gas-fired (and, admittedly, some oil) boilers, with an entry for each boiler make and model, to provide a basis for calculation. The

SEDBUK database is compiled from the results of manufacturers' testing under legal requirements to demonstrate compliance with the European Boiler Efficiency Directive. In comparison, it is only in the last few years that the specification of a heat pump in SAP has gone beyond a simple 'yes/no' selection and been replaced by a sub-section of the SAP Appendix Q process (BRE, 2010b). The gas installers' trade is also quite heavily regulated by the Confederation of Registered Gas Installers. (CORGI) (CORGI, 2008)

The above implies that the gas-fired condensing boiler will be 'a hard act to follow' and that there is little motivation for householders or installers to change away from them.

1.2.5 Heat pump heating systems

The basic function of a heat pump heating system as applied in a building of any sort is to acquire energy from the virtually infinite volume of its environment in the form of low-temperature heat, and 'concentrate' it at substantially higher temperature to pass into the smaller volume of the building's heat distribution system.

The source of the low-temperature heat may be either the air surrounding the building, or the top few metres of soil on the land surrounding the building, or the sub-soil below the building, or any neighbouring body of water, a lake, river or the sea, of sufficiently large size.

Currently, the acquisition of heat by the majority of heat pump systems is achieved by the vapour compression cycle, in which the heat is acquired by the evaporation of a refrigerant at the system collector, the temperature of the resultant gas is raised by a compressor, and the resultant heat is released to the distribution system by the condenser.

The majority of compressors are driven by electric motors, and can therefore employ low or zero-carbon electricity supplies, giving them their credentials as low-carbon heat supplies. If sized, installed and operated correctly, these systems will acquire at least twice as much heat energy from the environment as is required to drive them, thereby achieving a notional efficiency of 200%, which is more customarily termed a Coefficient of Performance (COP) of 2.0. That the heat collected from the environment originates from the sun gives some grounds for regarding these systems as a form of renewable energy.

The theoretical and physical basis of heat pump technology are further detailed in Chapter 2.

1.3 Drivers for change

Currently, the most significant drivers for moving away from gas central heating originate in the twin forces of the need to reduce greenhouse gas emissions to mitigate against anthropogenic climate change and that of the imminent reaching of the point where the maximum world production of both oil and natural gas is reached, called ‘Peak Oil’. These have translated into more direct drivers, firstly, policies and legal frameworks instituted by the UK government to reduce carbon emissions in response to its obligations under the main international treaty on greenhouse gas emissions, the Kyoto Protocol, and, secondly, substantial rises in the prices of oil and, consequently, natural gas.

1.3.1 ‘Peak Oil / Gas’

The dependence of virtually the whole world on the easy and cheap availability of fossil-based fuels started to become a source of concern when oil production in the USA peaked in 1970 (BP, 2008) as predicted by Hubbert (Hubbert, 1956). In the last few years, the point at which the world oil production reaches its maximum - has become widely, but not totally accepted. Opinions on when it will be or has been reached differ fairly widely (Hirsch, 2007, pp 10-12), ranging from sometime in the past few years through to 2020. Given these divergent opinions on the future oil supplies, forecasts of future natural gas supplies are even less certain. Currently the UK imports natural gas by pipeline from Norway, the Netherlands, Belgium, and Germany and limited quantities of liquid natural gas (LNG) from around the world (BP, 2008). Of these sources, Norway and the Netherlands have reserves estimated to last in the region of 19 and 33 years respectively at the current rate of production; whilst, on the same basis, the Russian Federation has reserves estimated to last some 73 years and world reserves excluding Russia have an estimated life of 60 years. Over the period since 1970 which is covered by the BP (2008) statistics, world natural gas production has increased by 192% and consumption by 287%. However, since estimating the size of the Russia Federation’s reserves is as much a political process as a physical one and the ‘current rate of production’ method of estimating the lifetime of reserves does not allow for any future increases in production, there is little to cling to in the way of certainty.

What is clear is that the UK energy supplies are very much past their peak and that the country has become a net energy importer. The graph below (Figure 1.4), derived from the BP Energy Review data (BP, 2008) by Likvern shows the current situation.

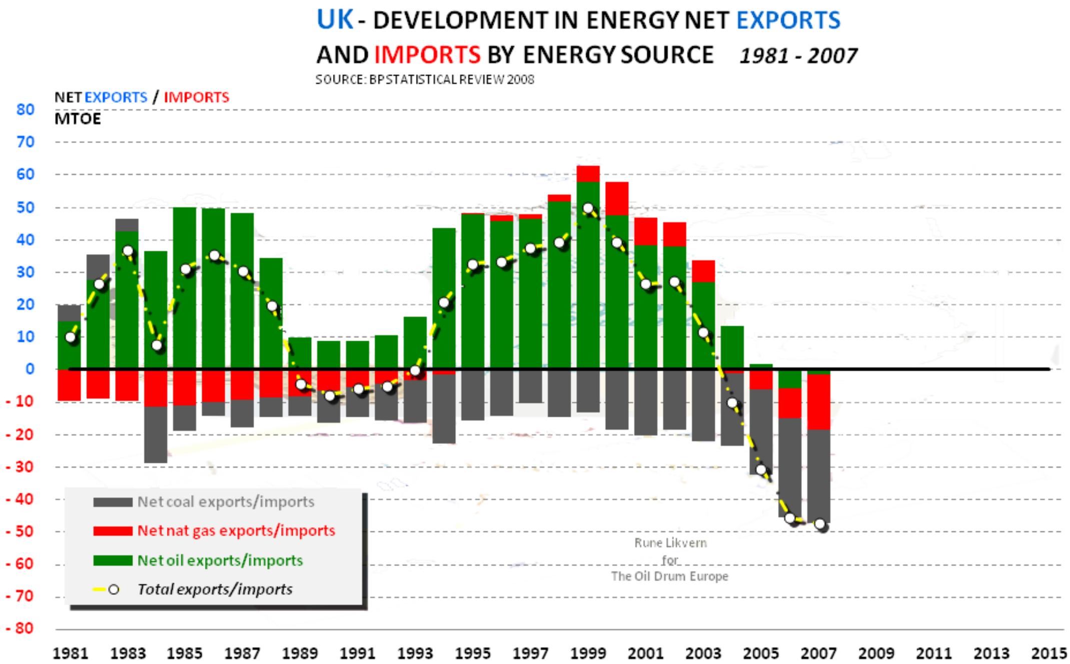

Figure 1.4. The development in net energy exports and imports split on energy sources for UK for the years 1981 - 2007 in MTOE.
(MTOE; Million Ton Oil Equivalents; 1 MTOE approximates 20 000 bbl/d (oil)) - from Likvern(2008))

The importance of the UK's dependence on imported energy is not within the remit of this thesis. While the timing or even the occurrence of these phenomena is still the subject of the controversy outlined above, it is undeniable that there were steady rises in the price of energy worldwide up to the end of 2007, and steep rises over the first half of 2008. The UK Office of National Statistics recorded that over the period from 1997 to 2007, electricity prices rose by 11%, whilst the price of gas increased by 42%, and the price of heating oils increased by 74%, allowing for inflation (Office of National Statistics, 2008). Further sharp rises occurred in the first half of 2008 (DBERR, 2008, Table 2.1.3, p10) when gas prices increased by 15% and heating oil prices by 35%, while coal rose by only 5%. Since electricity is generated using a mix of fuels, the retail price of electricity increased by only 11% over the same period. The exact reason for these sizeable rises was unclear and was almost certainly not caused by shortage of supply, but by speculation (Allsopp & Fattouh, 2008).

1.3.2 Reduction of greenhouse gas emissions

Some efforts are being made by governments to take mitigating action against climate change, of which the major international action is the Kyoto Protocol, which has allocated various carbon emission reduction targets to the ratifying countries (UNFCCC, 2008). These targets are based on 1990 levels and are due to be met by 2012. The international carbon emissions trading system (ETS) through which these reductions are to be delivered in the European Union (EU) came into force in 2005 (Pearce, 2006). The EU ETS was introduced to meet the EU's greenhouse gas emissions reduction target under the Kyoto Protocol, which is an 8 per cent reduction in emissions compared to 1990 levels in the first Kyoto Protocol period of 2008 to 2012. The UK's commitment under the Burden Sharing Agreement is to reduce its emissions of greenhouse gases by 12.5% below base year levels by 2012. The UK's target annual level of emissions implied by the Burden Sharing Agreement is 682 million tonnes of carbon dioxide ($MtCO_2$) equivalent calculated from data in the UK's 2004 inventory submission (DEFRA, 2007, p5).

In the UK, the government White Paper 'Our Energy Future – Creating a Low Carbon Economy' (DBERR, 2003), targeted a further cut in UK carbon emissions of 60% by 2050 and this target was set in a legal framework through the Climate Change Act (UK Parliament, 2008a). The 60% target was subsequently increased to 80%, which is the current objective for the UK.

1.4 UK Government policies on carbon emission reduction in dwellings

These operate at three levels: at nationwide level in the form of legal obligations on energy companies to reduce carbon emissions by reducing energy use by their customers via the Carbon Emission Reduction Targets (CERT), now being replaced by the Energy Company Obligation; at the design and specification level for dwellings via the Code for Sustainable Homes (CSH); and at the level of individual households, groups or organizations, via the UK Renewable Heat Incentive (RHI).

These three initiatives all have or may have some effect on the take-up of heat pump systems. All three are comparatively recent in their implementations, so that while their workings and limitations can be described here, their effects have yet to be seen.

1.4.1 Carbon Emission Reduction Targets (CERT)(UK Parliament, 2008b)

This initiative replaces two ‘rounds’ of a similar process, called the Energy Efficiency Commitment (EEC1 & EEC2). CERT and its predecessors function by placing legal obligations on energy suppliers to reduce their customers’ carbon emissions by providing them with subsidized or even free energy-saving equipment or house improvements. The provision of these measures is financed by a levy on each of the energy suppliers’ customers and is biased toward householders on lower incomes and/ or who are receiving social security benefits or tax credits. The majority of the measures taken so far have been to provide subsidized or free insulation and free compact fluorescent light bulbs. In the context of this thesis, the main (limited) interest is that the Statutory Instrument for CERT allows for the ‘*promotion to a householder …… of ground source heat pumps in respect of a property which does not have a mains gas supply’ (UK Parliament, 2008b, page 4)*. The CERT scheme was replaced by the Energy Company Obligation (ECO) associated with the Green Deal scheme and finished at the end of 2012.

1.4.2 Code for Sustainable Homes (CSH) (DCLG, 2008a)

This design code has been created by the UK Government’s Department of Communities and Local Government to replace previous voluntary design codes for dwellings. The Code lays down standards for all aspects of a dwelling with the intention of reducing the environmental impact of its construction and operation. The main aspects of its standards that concern this thesis are those defining carbon emissions for the dwelling. These take as the basis for the standard a value known as the Target Emission Rate, which is the maximum emission rate permitted by the Approved Document (AD) Part L1A of the Building Regulations (DCLG, 2006), which are the statutory regulations applying to energy use in new-build dwellings. The CSH rating process, at the design stage, calculates carbon emission estimates for the dwelling as designed, by the Government’s Standard Assessment Procedure (SAP) and a second estimate for a similar building which just meets the standards for insulation and heating in AD Part L1A. The first estimate is known as the ‘Dwelling Emission Rate’ (DER), the second as the previously-mentioned ‘Target Emission Rate’ (TER). The rating for the design for the dwelling depends on the percentage reduction of the DER against the TER as given by the formula:

$$\%\text{Reduction} = (1 - DER / TER) \times 100 \quad (1.1)$$

The CSH Level corresponding to percentage reduction achieved is given by the following Table 1.2:

Table 1.2 Energy and Carbon dioxide emission Assessment Criteria

Assessment Criteria

Criteria		
% Improvement 2010 DER/TER*[1]	Credits*[2]	Mandatory Requirements
≥ 8%	1	
≥ 16%	2	
≥ 25%	**3**	**Level 4**
≥ 36%	4	
≥ 47%	5	
≥ 59%	6	
≥ 72%	7	
≥ 85%	8	
≥ 100%	**9**	**Level 5**
Zero Net CO_2 Emissions	**10**	**Level 6**
Default Cases		
None		

*[1] Performance requirements are equivalent to those in previous scheme versions but are now measured using the AD L1A 2010 TER as the baseline.

*[2] Up to nine credits are awarded on a sliding scale. The scale is based on increments of 0.1 credits, distributed equally between the benchmarks defined in this table.

It should be noted that even if a particular level of carbon emission reduction is achieved, then the dwelling will not necessarily attain that CSH level, since the other criteria in the CSH must be taken into consideration. However, to qualify for a given overall CSH Level, the dwelling must achieve that Level of carbon emissions reduction.

Originally, Levels 5 and 6 were highly challenging for the developer or designer, since the only method of achieving these levels was to provide on-site generation of energy either within the boundary of the house itself or on the site from a source which is directly wired to the houses, precluding the delivery of power from the grid. The higher level of 'Zero Carbon Home' was defined as one in which all the energy for cooking, DHW and powering appliances was generated by on-site renewables as well as that for heating or cooling. However, this requirement has been reduced substantially under the current government, while still being referred to as 'zero carbon', as being too restrictive for commercial housing development in the UK, raising costs and restricting sites suitable for house-building by requiring higher build and insulation standards and reducing the number of houses any site could accommodate. The degradation of the standard was made in two ways. An initial step was to consider only carbon emissions from 'regulated energy use' - use for space heating and cooling, hot water and most lighting which are subject to Part L1A of the UK Building Regulations. The second was to change the requirement from on-site renewable generation to off-site renewables from so-called 'Allowable Solutions', defined as '*forms of carbon abatement delivered off-site which mitigate any residual carbon emissions from a building once onsite requirements have been met'*. Also included in this volte-face is a requirement that, from 2016, the 'built performance' emissions for detached houses should not exceed 10kg $CO_{2(eq)}/m^2$/year, for other house types should not exceed 11kg $CO_{2(eq)}/m^2$/year, and for low rise apartment blocks, 14kg $CO_{2(eq)}/m^2$/year, again including emissions only from energy from 'regulated' sources, ie. space heating, DHW generation, and lighting. It is these built performance emissions that are be off-set by the carbon emission abatements provided by 'Allowable Solutions'. A 'Fabric Energy Efficiency Standard' of 39 kWh/m^2/yr for apartment blocks and mid-terrace houses and 46 kWh/m^2/yr is to be required (Carbon Compliance Task Group, 2011; Zero Carbon Hub, 2011a, 2011b, 2011c).

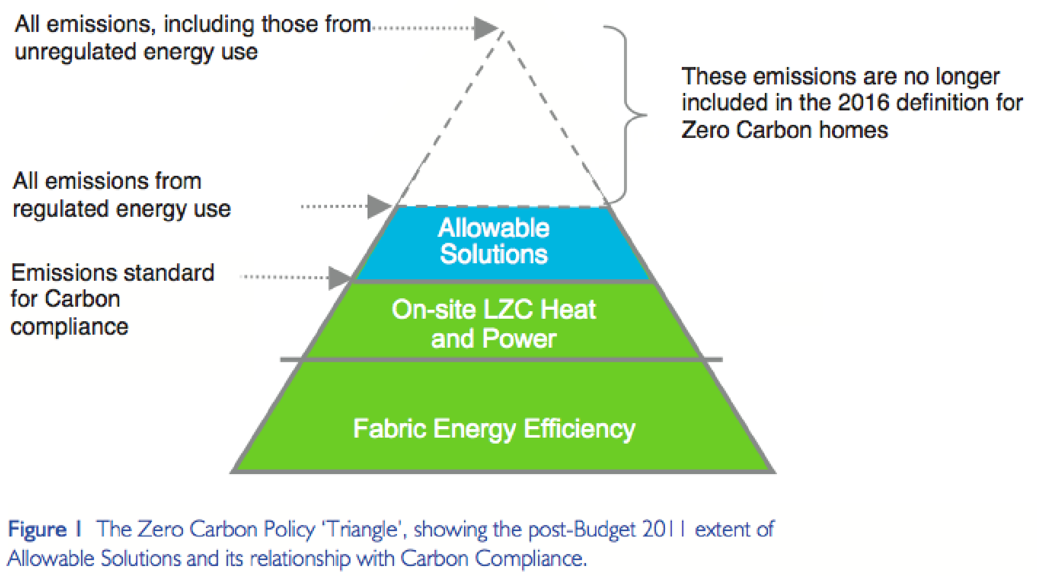

Figure 1.5 The 'Zero Carbon Policy Triangle'
(Carbon Compliance Task Group, 2011; Zero Carbon Hub, 2011b).

The built performance allowances are based an estimate of the LZC energy that can be generated on site, which is taken to be the output from an area of photovoltaic panels equal to 40% of the ground floor area of the dwelling, where the photovoltaic system is assumed to be rated at 7m^2/kWp (ZCH, 2011), with assumed ground floor areas for each dwelling built form.

The effects of this change in policy in terms of energy consumption and carbon emissions are not easy to estimate when taken in combination with unknown increases in the housing stock. It is possible that the original 'zero-carbon' policy was not implementable, in any case.

1.4.3 UK Renewable Heat Incentive

The Renewable Heat Incentive (RHI) is a system for the subsidy of what are deemed to be renewable heating systems, aimed at encouraging their installation in either domestic or commercial situations. For domestic systems, this involves ground source heat pumps, biomass boilers, and solar thermal hot water systems. The subsidy entails a payment per kilowatt hour of heat generated, which may be either metered or 'deemed', ie. calculated according to a rule depending on the size and type of installation, made to the householder, on similar lines to the Feed-in Tariff (FiT) scheme for electricity generated from renewable sources.

The RHI scheme has had a checkered history. It was originally proposed by the Labour government in 2009 to be available for any dwelling and for either ground source or air source heat pump systems. However, with a change of government in May 2010, this scheme was suspended for review, and the resultant scheme is considerably different and much more restricted. The RHI process started in July 2011 for domestic systems with subsidising payments, referred to as the "RHI Premium Payment", of a total of £15 million to support the installation of 25,000 systems. These payments were for solar thermal hot water, air source heat pumps, ground source heat pumps and biomass boilers. Eligibility depends on the house being insulated to a minimum level (but only if this is possible) and the householder being prepared to provide feedback on the performance of the equipment. The payment is aimed at dwellings without gas-fired central heating systems (DECC, 2011e) and amounts to £1250 for GSHP installations and £850 for ASHPs. Sometime after this, the main domestic RHI payments will commence, with per kilowatt-thermal payments being made for solar thermal, ground source heat pumps, and biomass boilers (but not air source heat pumps). Currently, the DECC proposal is that the output heat from these systems will be metered to calculate the payments due.

No indication has been given as to what proportion of the 25,000 planned domestic RHI installations are to be heat pump systems or whether, and by how much, this total may grow over the 20 year lifetime of the RHI. Since the UK's target is to obtain 15% of energy from renewable sources, of which the 'illustrative mix' contains 12% of heat by 2020 (DECC, 2010d; House of Lords : European Union Committee, 2008) and, in the longer term, to fulfill the legally binding requirement in the UK's Climate Change Act ("Climate Change and Sustainable Energy Act," 2006) to reduce greenhouse gas emissions by 80% by 2050, the lack of information on how these targets, (especially the short-term one for 2020) are to be reached, must be a source of concern. It is not known whether the installation scenarios proposed in the earlier background studies (NERA Economic Consulting, 2008, 2009) made by NERA for the DECC "Heat and Energy Saving Strategy Consultation Document" (DECC, 2009a) of the possible contributions that various technologies could make in reaching UK targets, are still under consideration.

1.4.4 'Green Investment Bank', 'Green Deal' scheme

Over the period 2012 to 2015, the 'Green Investment Bank', set up by the UK Government, will commence operation as an investment fund to support investment in projects to encourage 'green' growth, defined as *'environmentally sustainable, biodiverse, low-carbon and climate-resilient growth in human prosperity'* (:vivideconomics, 2011). Amongst its initial priorities is said to be support for the Green Deal scheme (DBIS, 2011). The Green Deal is a complex mechanism which is designed to allow a housholder to improve the energy efficiency of their property without any initial payment on their part. It is intended that the cost of energy efficiency measures implemented under this scheme will be recouped via the householder's electricity bills and it is one of the scheme's defining principles - *'The Golden Rule'* - that this cost should be no greater than the savings made by the energy efficiency measures. However, if significant energy savings cannot be made without measures for which the cost exceeds this level, then a subsidy may be paid via a second scheme, the *'Energy Company Obligation' (ECO)*, a scheme replacing CERT. (para 1.4.1 above). The whole mechanism has not been in operation long enough to judge its effectiveness.

1.5 Research aims and objectives

The previous sections indicate the forces and policies affecting domestic heating in the UK at present and in the future, with the take-up of heat pumps apparently being necessary to meet carbon emission reduction targets and being encouraged through regulation and incentives, but being counteracted by the domination of gas heating, apparent shortfall in electricity generation capacity and poor energy-efficiency of the UK housing stock.

To give clarity to the future of domestic heat pump systems, the main aim of this study is to estimate the potential of heat pumps to meet both the heating and cooling requirements of UK dwellings in a changing climate up to 2050, and to forecast the effect of possible take-up of heat pumps on the UK electricity demand and carbon emissions.

To meet this aim, the subsidiary objectives are to:

1. Review the theoretical and physical characteristics of heat pump systems and identify those that are most significant in the estimation of the energy use of these systems; examine currently-available models and modelling routines for estimating heating pump energy use for their inclusion of the these characteristics, their relevance to the requirements of this study, including their capability for incorporation in a building energy model;
2. Identify and review literature on the modelling approaches that could be used to forecast energy use and CO_2 emissions, and undertake a critical analysis of models that have been built to predict the future energy use and CO_2 emissions of the UK housing stock. Examine whether any of the models are both suitable and available for use in this study; whether their routines can be employed even if no model could be utilised directly and whether the scenarios were appropriate to this current study.
3. Monitor how current owners of ground source heat pumps (GSHPs) utilise this equipment, i.e. to record their use of the equipment for heating, cooling and domestic hot water provision, and the consequent energy consumption and system temperatures.
4. Develop a computer model to estimate the energy produced from, and consumed by, residential-scale heat pumps in meeting domestic heating and

cooling demands for different UK house types. Validate and calibrate the model as appropriate.

5. Extend the model to include potential future take-up of domestic heat pump equipment in order to assess:

   - The likely effects of various scenarios for the deployment and application of replacement heat pump installations in the medium and long-term (2020, 2050) on the consumption of electricity and other forms of energy, in particular natural gas.
   - Their effect on consequent carbon emissions for the UK both in their manufacture (embodied carbon) and operation.
   - the extent to which increases in electricity consumption by heat pumps due to summertime cooling are offset by reductions caused by temperature increases envisaged by the prediction of climate change from UKCIP09 scenarios.
   - the extent to which increases in electricity consumption by heat pumps might be offset by the output from building-mounted solar photo-voltaic systems.

1.6 Thesis structure

Chapter 2 contains an examination of the technical aspects of heat pump heating systems and the implications of these for the modelling of such systems. Chapter 3 and 4 review current literature, with Chapter 3 examining dwelling-level heat pump modelling studies and Chapter 4 studies of stock-level dwelling energy models. Chapter 5 describes the methodology of the study. Chapter 6 describes the heat pump monitoring study and its results, Chapter 7 the development of the heat pump model, Chapter 8 the development of the stock-level model and the results thereof. Chapter 9 contains the conclusions of the research.

Chapter 2 describes the theoretical background for heat pumps in thermodynamics, the detail of the heat pump cycle and of its components indicating the implications of these for domestic (and other) installations. It reviews the environmental credentials of heat pump systems, in terms of their status as renewable energy systems and claims of carbon emission reductions. It evaluates those factors presenting barriers to and those driving on the installation of heat pumps.

Chapter 3 presents a review of recent studies presenting research in the modelling of domestic (and where appropriate, non-domestic) heat pump systems, evaluating these in terms of how they address the main characteristic of these systems. It also details the routines contained in the heat pump model in EN15316-4-2 document which defines the main European Standard for modelling heat pump systems in buildings and considers its suitability for implementation within a computer model outside the complex overall model contained in the overall EN15316 standard. It further examines the limited set of publicly-available software tools that provide estimating facilities for heat pump systems. All these are evaluated in terms of their utility in improving the detailed modelling of heat pump systems and their possible implementation in a housing stock energy model, which confirms the requirement to develop a new heat pump energy model within a modified version of the BREDEM-8 standard dwelling energy model.

Chapter 4 initially reviews the classification of housing stock energy models, examining the applicability of the different types to the current study. It then reviews those that are most relevant to the current study, being UK-based.

Chapter 5 describes the methodology of the study. The data collection and analysis stage consists of the collection of heat pump energy and temperature data through a year-long monitoring study and the further analysis of secondary data. The initial development stage consists of the selection and enhancement of a dwelling energy model and the development of a heat pump energy model based on both primary and secondary data. The second development stage consists of the development of a housing stock level model with the third the analysis of results from this model based on scenarios of the numbers of domestic heat pump systems deployed and the dwellings chosen for the application of these systems.

Chapter 6 documents the heat pump monitoring study carried out for this study and also the extraction processes to acquire data for the heat pump regression model. The heat pump monitoring study was carried out over a 12 month period, capturing input and output energy, temperature and status data from three IVT ground source heat pump systems. The energy data is analysed to provide monthly energy and SPF values to illustrate the characteristics of these systems. Temperature data, particularly that from ground loop and distribution sensors, is analysed to provide values for the enhanced heat pump model. Data for the heat pump model was extracted from standard test result reports from the WaermenPumpen TestZentrum (WaermenPumpen Testzentrum, 2011)to form a database of heat pumps, suppliers and test results.

In Chapter 7, the current definition of heat pump parameters in BREDEM/SAP are compared with the requirements for more detailed heat pump modelling, high-lighting the enhancements to be made. The steps involved in developing the heat pump model and the corresponding modifications to the BREDEM-8 model are described.

Chapter 8 contains the description of the housing stock level dwelling energy model commencing with the building of the extract from the EHCS dataset and the creation of the baseline energy estimates. Heat pump installation scenarios for 2020 and 2050 are developed based both on current UK government scenarios and past installation of gas central heating. The results of these scenarios are analysed to show the most advantageous policies for heat pump installation, given the probable reduction in UK generating capacity up to 2020, and that it is possible that the UK target of 80% reduction in carbon emissions by 2050 could be met by large scale installation of heat pumps given the simultaneous "decarbonisation" of the UK electricity generation system.

Chapter 9 contains an overview of the findings of each chapter, especially the finding of the analysis in Chapter 8, details of contribution of this thesis to this field, limitations of the research, recommendations for further research and for further policy initiatives and actions.

1.7 Summary

This chapter has presented a brief historical background to the current state of domestic heating systems in the UK, examining the financial means by which gas-fired central heating achieved almost completely dominance of the field and the relevance of this to future changes in heating systems. It has described the factors - the possibility of 'Peak Gas' and the need to reduce carbon emissions to prevent damaging climate change - that indicate the need for change and outlined the current UK government initiatives designed to bring about that change. It contains a summary of the aims and objectives of this study and a summary of the structure of the thesis.

CHAPTER 2 TECHNICAL ASPECTS OF HEAT PUMP SYSTEMS

2.1 Introduction

The contents of this section are as follows:

- an outline of the fundamental principles behind heat pump technology;
- a review of the key components of current domestic heat pump systems;
- a review of different applications, operation modes and heat distribution systems; the potential for CO2 savings.

While this Chapter covers a wider range of topics, its primary purpose is to meet Objective 1 of this study, that of identifying the those characteristics of heat pump systems which are most significant in estimating energy consumption.

2.2 Basis in thermodynamics

Superficially, the heat pump defies the simplest statement of the Second Law of Thermodynamics viz.

Heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.

as stated by Clausius (Clausius, 1856). However, in 1852, William Thomson (later Lord Kelvin) designed a ‘heat multiplier’, a device which uses energy to transfer heat from the surroundings to an enclosed space, thereby maintaining that space at a higher temperature, which is the basic concept of the heat pump. However, the earliest application of these principles was an ice maker, designed and built by Dr John Gorrie in 1851 (Chapel, 2001) in attempt to cure, or reduce the symptoms of, yellow fever. In the UK, J G N Haldane built what was deemed to be the first heat pump for use in his house in 1930 and this remained the only one until the 1940’s when J A Sumner built some test units, following them with one for his own home in 1950 (Neal, 1978). In the UK, some interest was generated in domestic heat pump heating systems between the mid-1970's and early 1980's after the sudden rise in oil, and consequently gas, prices as a result of the Arab-Israeli wars, indicated by publication of books such as Neal (1978), Sumner (1980), McMullan & Morgan (1981) and Armor (1981). However, concerns were raised over their efficiency and cost-effectiveness when installed compared with gas-fired heating, triggering reports like Grigg & McCall (1988). In consequence, the use of heat pumps for domestic heating applications in the UK is substantially less common than in the rest of Western Europe (Curtis, 2001). Recent sales of heat pumps in the UK (Figure 2.1) are increasing but continue to be much lower than in the other major states of Europe.

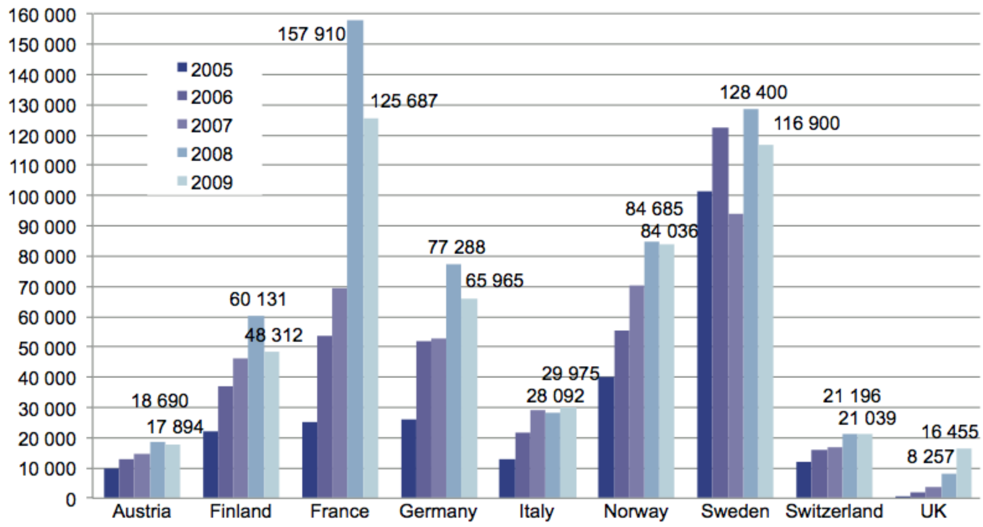

Figure 2.1 European heat pump sales to 2009

(Fors n Nowak, 2010)

2.3 Heat pump / refrigeration cycle types

Heppenstall (2000) distinguishes several refrigeration cycle types - absorption cycle, gas cycle, stirling cycle, thermionic, magnetic, Gifford-McMahon, pulse tube, optical, vortex tubes, Vuilleumier, Malone – apart from the vapour compression cycle which is most common in space heating applications. While these other cycles have niches in various applications or show promise for the future, this study will describe the working of the vapour compression cycle, as this is used to the exclusion of all others in domestic space heating systems.

2.4 Theoretical Heat Pump Cycle

In terms of thermodynamic theory, the heat pump cycle is almost the exact opposite of that of the heat engine. In the heat engine, high temperature heat is supplied to perform work as output and residual heat is rejected at low temperature. In a heat pump, the heat supply is at low temperature and is transferred to a higher temperature by means of an input of mechanical work (McMullan & Morgan, 1981, p3-4). The two systems can be shown in schematic as follows (Figure 2.2).

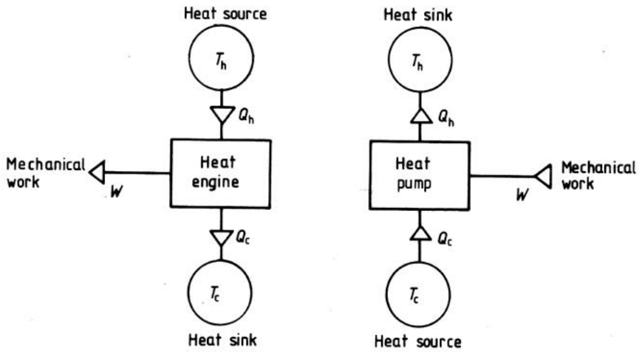

Figure 2.2. Schematic representations of a heat engine and a heat pump -
(McMullan & Morgan, 1981, Fig 1.1, p4)

The energy use for either mechanism can be described (McMullan & Morgan, 1981, p. 3) by an equation of the form:

$$Q_h = Q_c + W \qquad (2.1)$$

where Q_h is the heat flow from the source, Q_c is the heat flow to the sink, and W is work input. For a heat pump the flows are reversed, but the equation remains the same. For a heat engine, the efficiency, η, is fairly simply calculated as the ratio of the work produced to the heat input:

$$\eta = W/Q_h \qquad (2.2)$$

However, since a heat pump can be used for either heating or cooling, calculation of its efficiency must be in terms of the application, either heat rejected, Q_h, to the sink for heating, or heat absorbed Q_c from the source for cooling. This gives two ratios: for heating, of Q_h/W, the amount of heat rejected for unit work; and for cooling, of Q_c/W, the amount of heat absorbed for unit work. Rather than 'efficiency', these values are known respectively as 'Coefficient of Performance' (COP):

$$COP = Q_h / W \qquad (2.3)$$

and 'Energy Efficiency Ratio' (EER):

$$EER = Q_c / W \qquad (2.4)$$

Applying the original equation, 2.1, this gives the relationship:

$$COP = EER + 1 \qquad (2.5)$$

showing that for cooling, it might be expected that a given, reversible (ie. capable of both heating and cooling) heat pump might be less effective at cooling than heating.

2.4.1 Carnot Cycle

The heat engine as described in the previous section is referred to as a 'Carnot Engine', and the process by which it functions as the Carnot Cycle or the 'reversed Carnot Cycle' for refrigeration. This cycle forms a basis for understanding the mechanism and limitations of the vapour compression heat pump cycle. It represents the most efficient heat engine cycle allowed by physical laws and consists of two isothermal processes (where there is a change of temperature, but not of pressure) and two adiabatic processes (where there is change of pressure but not of temperature). These processes are assumed to be reversible. The Carnot cycle for a heat pump can be seen in terms of the following figures (.

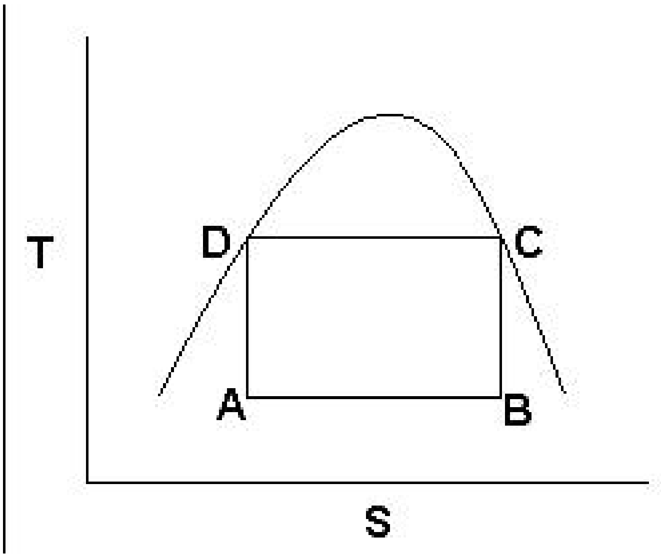

Figure 2.3 & 2.4).

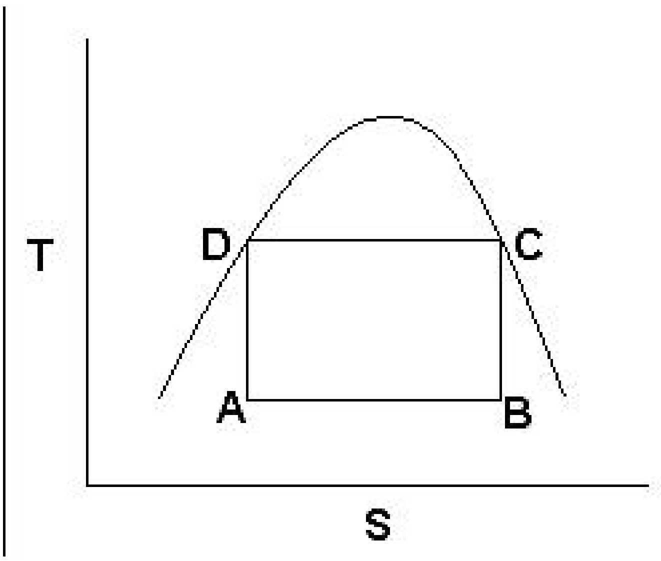

Figure 2.3 Temperature - Entropy (TS) diagram

(reproduced from fig. 2a LeFeuvre(2007))

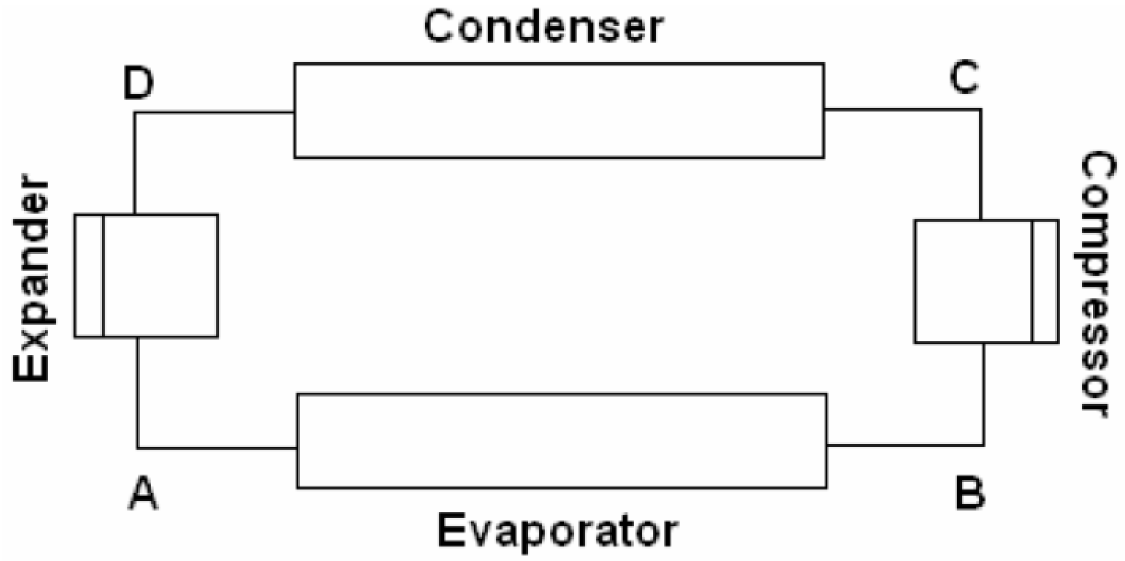

Figure 2.4 Equipment required to create ideal Carnot Cycle heat pump
(source : fig 2b, LeFeuvre(2007))

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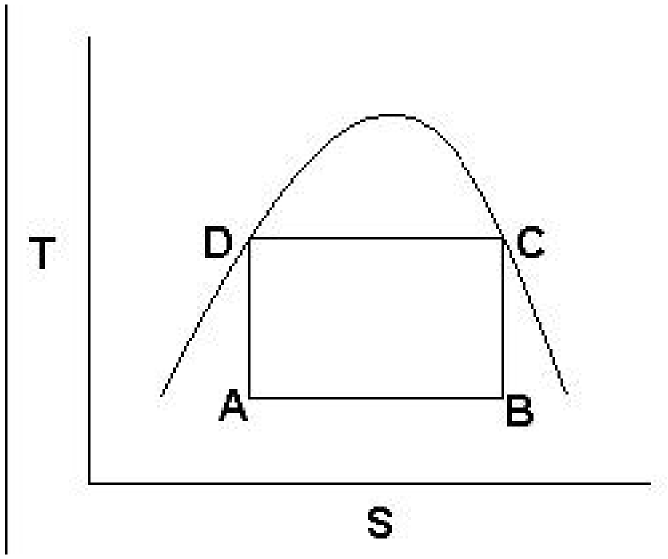


Figure 2.3, A→B and C→D represent idealized versions of the condenser and evaporator, where there is a change in energy level but no change in temperature, and B→C and D→A represent idealized versions of the compressor and expander, where there is a change in temperature but no change in energy level.

2.4.2 Coefficient of Performance

The value for every heat pump that is most significant is that which reflects the amount of energy that is passed to the sink as a proportion of that which is input to the pump.

This value is known as the Coefficient of Performance (COP) and is calculated by the following:

$$COP = \frac{\text{Delivered heat energy (kW)}}{\text{Electrical input to the compressor(kW)}} \qquad (2.6)$$

Thus a COP of 4.0 implies that the heat pump is delivering four times the energy to the sink as is being input to the system. For the Carnot Cycle heat pump above, where there are no heat losses, the COP can be calculated from the temperature difference between the heat source and the heat sink – again the evaporator and the condenser – as follows:

$$\varepsilon_c = T / (T - T_u) \qquad (2.7)$$

where ε_c = COP from the Carnot Engine

T = temperature at the condenser

T_U = temperature.at the evaporator

Temperatures are given in degrees Kelvin(ºK)

Thus a Carnot Engine heat pump raising the temperature of a source from 0 ºC (273 ºK) to 60 ºC (333 ºK) would be working at a COP of 5.55 (Ochsner, 2007). While it is impossible for a heat pump to operate at its Carnot COP, this value gives an upper bound for the actual COP for a given temperature difference and also indicates that, for an actual heat pump, the COP will be largely determined by the temperature increase (known as the "lift") required between source and sink. The significance of this for a domestic heat pump system is that the system will be required to work harder, ie. will require increased input of energy, to maintain any given temperature if the source temperature falls. This reduction of source temperatures as the heating season progresses in parallel with the requirement to balance the lower winter temperatures constitutes a significant difference between a ground source system and a fuel-burning one.

2.5 The vapour compression heat pump cycle

This heat pump cycle is illustrated below (Figure 2.5)

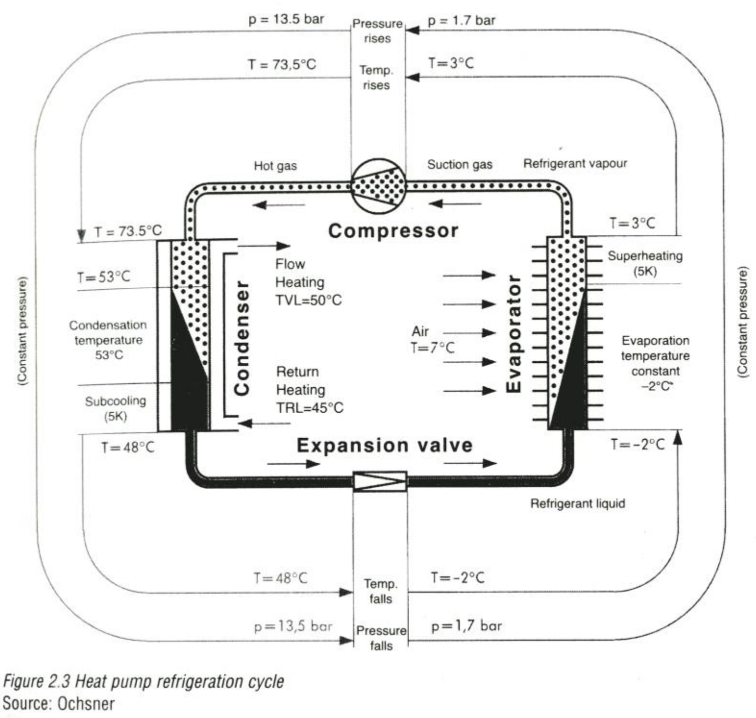


Figure 2.5 Detailed schematic of an air source heat pump showing temperatures and pressures.
Source (Ochsner, 2007)

The heat pump cycle is as follows:

a) the cooled, low pressure refrigerant arrives at the evaporator (Figure 2.5, right hand side) which is a heat exchanger. It is warmed by the heat from the source to 3 ºC (in this case, air at 7 ºC) and evaporates.

b) The refrigerant then passes to the compressor, where it rises in temperature under compression to approximately 73 ºC;

c) In second heat exchanger, the condenser, it is cooled by the 'sink' (internal air from the house at 45 ºC) to 48 ºC while the temperature of the air is raised to 50 ºC.

d) Still under pressure, the refrigerant passes through a pressure relief valve, where both its pressure and temperature fall and it returns at low temperature and pressure to the evaporator.

Thus the refrigerant has to be able to tolerate continuous heating and cooling from 3ºC to 73ºC or possibly more and back, and continual compression and de-compression.

2.6 Heat pump system components

The components of a heat pump system are as follows:

1. the heat source as indicated above;
2. the collector;
3. the heat pump itself, consisting of evaporator, compressor, condenser and pressure relief valve, refrigerant, control system, and, optionally, an accumulator and reversing and check valves;
4. the distribution system, consisting either of fan / coil unit or units for air distribution or under-floor heating piping or low temperature radiators for water distribution.

2.6.1 Sources and collectors

The choice of source largely determines the choice of collector, as per Table 2.1:

Table 2.1. Space heating heat pump sources and collectors

(modified from Table 1 (Heat Pump Centre(2008))

Heat source	Temperature Range (°C)	Most common collector
Ambient air	-10 to 15	Fan
Exhaust air	15 to 25	Fan
Ground water	4 to 10	Borehole
Lake water	0 to 10	Pipe loop
River water	0 to 10	Pipe loop
Sea water	3 to 8	Pipe loop
Rock	0 to 5	Borehole
Ground	0 to 10	Pipe loops
Waste water and effluent	>10	Pipe loop

In general, the source to be used is determined by location – particularly, the size of the site - and cost. To quote the IEA Heat Pump Centre (2008b),

An ideal heat source for heat pumps in buildings has a high and stable temperature during the heating season, is abundantly available, is not corrosive or polluted, has favourable thermo-physical properties, and its utilisation requires low investment and operational costs.

They then comment that availability is the main determinant in choice of source. This is primarily determined by location, as, for example, it is necessary to be close to the sea to use that as a heat source. However, availability and cost are not inseparable. For example, while ground water is more desirable than soil as a source on the basis of steady temperature, its availability is restricted by the increased cost of drilling the necessary borehole to reach it. Similarly, air is much more available than either ground water or ground, but carries with it the energy penalties of a lower specific heat and the need to defrost of the collector at low temperatures. Somewhat less inevitably, it also carries a noise penalty from the collector fan. Thus, availability of funds and of space form the main determinants of the choice of source. If sufficient space is available (a rule of thumb is 1.5 to 2 times the dwelling floor area) then a horizontal ground loop is preferable. If sufficient space is not available but funds are, then a borehole may be preferred. If both funds and space are lacking, then it is necessary to use air as a source.

The IEA Heat Pump Centre website (2008b) also makes reference to temperature stability as a consideration. This cannot be such a major factor as the size of the site or cost in choosing a source, but having chosen the source, its temperature stability becomes a major factor in designing the heat pump system.

2.6.2 Source and collector characteristics

Two basic types of collection exist, those using pumped fluid to transfer the heat from the source and those using air. Again, pumped fluid sources can have three different forms, using either a mixture (conventionally known as a brine) of water and an anti-freeze such as glycol in an indirect transfer, using a warm fluid source directly, or using the heat pump's own refrigerant to absorb heat from the source, a configuration termed '*direct expansion*'.

Ambient air

The standard collector type for air source heat pumps is a fan drawing or blowing air directly across the evaporator of the pump. The collector can be a separate unit, positioned outside the dwelling and pumping refrigerant to the heat pump inside (a split unit), or part of a single unit, positioned outside and blowing heated air in or positioned inside and drawing ambient air in (compact units).

Using ambient air as a source in this way has a number of features. Firstly, as noted before, when the ambient temperature falls toward 0ºC, condensation or frost will form on the collector, severely reducing its efficiency. This condensation is removed by various means, including reversing the heat pump process for a short time so that it heats the collector or by directing hot refrigerant gas from the high pressure side of the compressor through the evaporator for short period of time (hot gas defrost). While maintaining the efficiency of the evaporator, these processes reduce the overall efficiency of the system. Secondly, an external collector has a reduced life-span due to weathering. Thirdly, an external fan can be noisy in operation, especially if positioned too close to a wall. Taken together, these factors can make an air source heat pump inherently less desirable despite its lower capital cost and the reduced disruption involved in its installation.

The energy available from air is, of course, determined by its temperature which, in a typical UK location (Figure 2.6), has a more or less symmetric pattern either side of the summer and winter solstices.

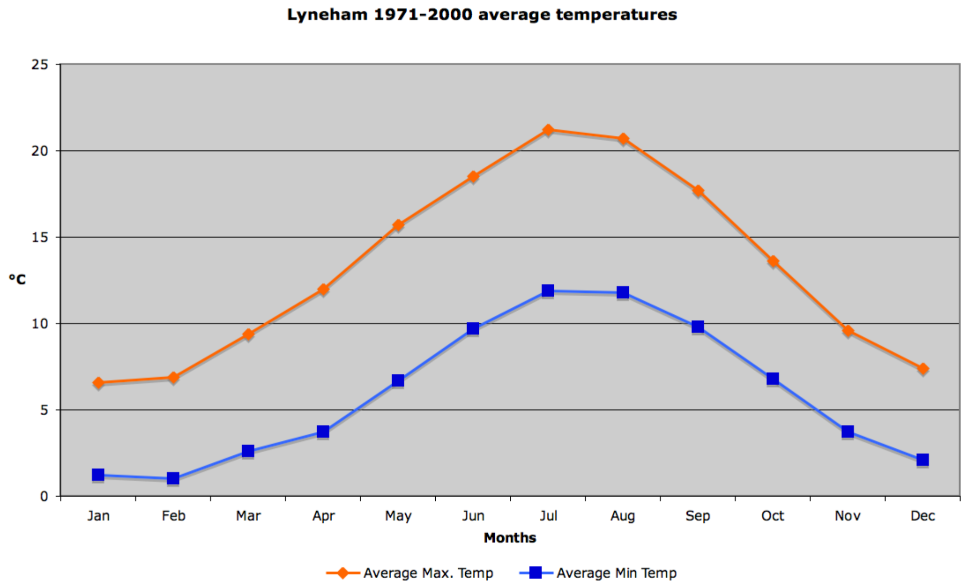


Figure 2.6. Averaged maximum and minimum temperatures for 1991 - 2000 from Lyneham weather station
(Met Office, 2008)

Assuming that the volumetric specific heat capacity of air is 1300 J/m^{3}K and that it is undesirable to reduce the temperature at the collector by much more than 5 °C to avoid its temperature going below 0 °C, then in order to acquire a Kilowatt-hour of energy from the air, it will be necessary to collect heat from at least 554 m^3 of air per hour.

Exhaust air

The collectors used in this application are similar to those for ambient air. While exhaust air is mostly used as a heat source in industrial and agricultural applications since these are the most common sources of waste heat, it may also be included in mechanical ventilation with heat recovery (MVHR) systems in domestic applications (Total Home Environment Ltd, 2012) where smaller heat pumps are utilised to recover heat from extracted air to heat the incoming supply or to generate DHW.

Ground water

Ground water can be used in either an open loop system, where the water itself is pumped up pipes in one borehole, through the evaporator, and returned through a second, in a closed system, where a borehole closed loop heat exchanger consisting of polyethylene pipe, grouted into the borehole with bentonite clay, is used. As the geology in the UK varies considerably over quite small areas, the amount of heat to be sourced from ground water in any location is not readily determinable, though around 75% of the UK has quite a shallow water table. The variations in geology make the effort involved in drilling boreholes unpredictable (Curtis, 2001). Extraction of ground water in the UK is subject to a licensing system with a possible extraction charge (Brown, 2009, pp. 28-29).

The energy available from ground water, particularly flowing water, is more or less constant throughout the year.

River and lake water

As noted by the IEA (2008b), this "*has the major disadvantage of low temperature in winter (close to 0°C)*", requiring care over the brine content of the heat exchanger fluid to avoid freezing. Its availability is also location-dependent and its extraction to an open-loop system is subject to the same licensing system as ground water.

Sea water

Since sea temperature is high and constant (5-8°C) at a depth of 25-50 metres, and its freezing point at -1°C to -2°C) is low, sea water can be a useful heat source, especially for larger systems. Its use in open systems requires corrosion-resistant equipment with filtering to avoid organic fouling.

Rock (geothermal heat)

Since this is used where there is little ground water, it is not often required in the UK. It requires bore holes in the region of 100 to 200 metres in depth and uses a brine system with welded plastic pipes. Some rock-coupled systems in commercial buildings use the rock for heat and cold storage. The deep boreholes make this source economically unattractive for domestic use. Where the application is dominated by either heating or cooling, then careful sizing is required to reduce the possibility of long-term 'exhaustion' of the source. Borehole heat exchanger sizing has been much researched, notably by (Eskilson, 1987; Fisher, Daniel E., Rees, Padhmanabhan, & Murugappan, 2006; Kummert & Bernier, 2008; Kyriakis, Michopoulos, & Pattas, 2006; Sanner, Karytsas, Mendrinos, & Rybach, 2003) and others.

Ground source systems

These are currently the most common systems in the UK in both residential and commercial applications. As a collector of solar energy, the ground has similar advantages to a ground-water source with relatively high annual temperatures. Heat is extracted from horizontal ground coils, mostly in spread out coils known as 'slinkies' and both direct expansion and brine systems can be used, though brine systems are most common. Direct expansion systems are more efficient as they avoid the need to transfer heat from the soil to brine, and hence can work with a shorter ground loop. Conversely, the pipework required is more expensive (currently copper) and has to be carefully designed to avoid leakage of refrigerant into the soil.

The thermal capacity of the soil varies with the moisture content and the climatic conditions. Because of the extraction of heat, the soil temperature around the ground loop will fall during the heating season and may freeze around an undersized loop, causing frost heave. However, in summer the sun will raise the ground temperature, and complete temperature recovery should be possible if the loop has been correctly sized.

2.6.3 Heat pump configurations

Space heating heat pump units come in a range of configurations depending on application, ranging from very small units of ~2 kW output rating judged suitable for very low energy demand houses ie. German 'passivhaus' standard, to commercial units of ~1300 kW, which have multiple compressors and are capable of simultaneous heat and cooling (Calorex Heat Pumps ltd, 2008; Dimplex UK, 2007, and others; Kensa Engineering, 2007d; Ochsner Wärmepumpen Gmbh, 2007), with a corresponding range of physical size. In the domestic context, some contain dedicated domestic hot water (DHW) tanks as buffer store for the distribution system, for others, this is a separation installation. Air source systems are substantially different in external appearance from ground source, due to their fans and associated grilles and the need for waterproof casings.

While all, apparently, contain the same basic components, some variation is present in choice of compressor and of refrigerant, for which some analysis is required since these are the areas in which most performance improvements has been made in the recent past.

2.6.4 Compressors

The most recent improvement in heat pump performance has come from the introduction of scroll compressors, currently fitted to the majority of domestic heat pumps, replacing, in most cases, reciprocating ones (Bachman, 2012).(Wikipedia, 2008). This type of compressor, at its most basic level, consists of two interleaved scroll castings, one of which moves eccentrically with respect to the other. See Figure 2.7. The scroll compressor has fewer moving parts and its casing does not have to cope with stress due to reciprocating parts. The basic mechanism of a reciprocating compressor consists of a piston moving in a cylinder, in the head of which are valves controlling the air flow. This must be designed such that space always remains above the top of the piston at the top of its stroke, to avoid a clash with the valves. Thus the complete volume of the cylinder is never emptied. This restriction does not apply to the scroll compressor where virtually 100% of the volume may be compressed. Discharge and suction processes in scroll compressors occur for a full rotation whereas a reciprocating compressor's compression cycle may be as little as 25% of its rotation, producing strongly pulsed output which places stress on the rest of the system. Without the noise and impact of opening and closing valves, the scroll compressor is quieter and vibration-free. While the scroll compressor is therefore more efficient, the same traits that bring the increase in efficiency can also make it less robust. Since the refrigerant is rarely completely evaporated before entering the compressor, the present of fluid in the compression chamber can cause stress on the scroll mechanism avoided by the reciprocating one. An accumulator tank is therefore added to the heat pump system to trap fluid before it enters the compressor. Since the direct of scroll compressor’s rotation cannot be reversed, reversible heat pumps (those designed for cooling as well as heating) achieve the required change of direction by a four-way valve in the refrigerant flow.

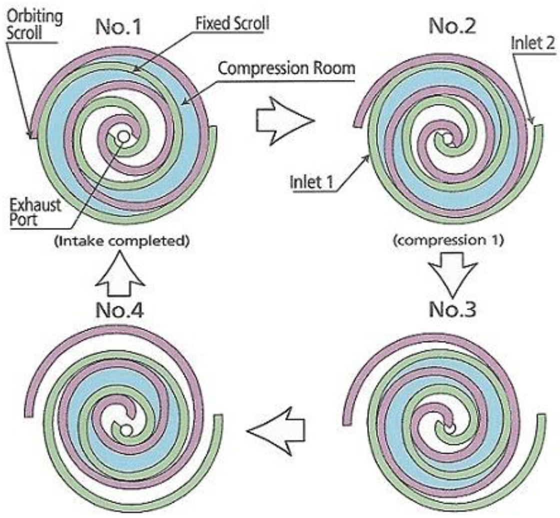


Figure 2.7. Scroll compressor cycle
(Air Compressor Equipment (2008))

2.6.5 'Soft start' power supply

These are required to prevent surges in the mains electricity circuits when larger heat pumps are started. This is particularly important because of the single-phase, lower voltage supply that is the norm in the UK, which currently (2008) restricts the maximum size of domestic heat pumps to around 11 kW (Curtis, 2001; Energy Saving Trust, 2007).

2.6.6 Additions to the basic compressed vapour heat pump cycle

Because no evaporation process is complete, a vapour-liquid separator known as a "suction-line accumulator" is added to the system to trap low pressure liquid before it reaches the compressor since this can only compress vapour. Such liquid would also wash out the layer of lubricating oil which the compressor relies on as a sealant (Danfoss Refrigeration & Air Conditioning, 2008). A second, possible, addition to the basic cycle is called an 'economizer' which is used to improve the performance of scroll compressors at low temperatures (Ma & Chai, 2004), and a third is an 'intercooler', which performs a heat exchange between the output of the condenser and the input to the compressor to assist with superheating (Reay & Macmichael, 1988, p 21). Not all of these can be present in every heat pump design.

Where the main use of the system is for cooling, then an additional bleed, referred to as a 'desuperheater' may be taken from the refrigeration circuit immediately after the compressor to provide heat to generate domestic hot water.

2.6.7 Controls

Most heat pumps have comprehensive, programmable micro-processor controls which allow for their operating times to be co-ordinated with periods when cheaper, 'off-peak' charging rates are applied by electricity suppliers or for any other pattern of operation required by the householder. Controllers can also provide diagnostic data for solving performance problems via an interface to a computer (Ochsner, 2007, p23).

Control system characteristics that are, to a degree, specific to heat pumps consist of the following:

- 'weather compensation' controls
- auxiliary heating controls

Weather compensation

To operate a heat pump system in as efficient a manner as possible, it is necessary to employ only the minimum amount of temperature "lift" necessary to maintain the desired indoor temperature. This is ensured by using "weather compensation", where changes in ambient temperature are detected by an external sensor which then causes the heat pump controller to vary the output temperature of the heat pump according to a factory set curve of the relationship between this and external temperature. Thus the output of the heat pump is increased before the temperature inside the dwelling falls in response to the external temperature, rather than delaying the increase until the internal temperature has fallen, thereby allowing a reduced "lift" (Energy Saving Trust, 2007). However, where the prevailing electricity pricing system has reduced rates for 'off-peak' periods, then the advantages of weather compensation are less clear, as it is financially beneficial to run the system at maximum output (while avoiding overheating) during the cheaper rate period (Kensa Engineering, 2007a).

Auxiliary heating

Where it is not financially viable for the main heat pump system to be sized to fulfill the entire demand for space heating in what is referred to as a 'monovalent' system, then additional heating (usually direct electric) is provided in a 'bivalent' system. This can be controlled in two ways: either as a 'bivalent parallel' system where both forms of heating function simultaneously or as a 'bivalent alternate' system, where only one form of heating is used at a time. The former system is deemed capable of attaining a temperature of 65ºC, whilst the latter can attain 90ºC according to Ochsner(2007), making both types of system suitable for retro-fitting to older houses, with the 'bivalent-alternate' operation being particularly suitable where the existing boiler is still functional. Careful specification and use of auxiliary heating is necessary to avoid reduction in efficiency and increases in heating bills. Further analysis of the system sizing and set-points for the different types of operation will be described in the chapter on heat pump modelling.

2.6.8 Refrigerants

The working fluid for a heat pump must absorb heat by evaporation and release it by condensation and is therefore required to change phase at 'useful' temperatures and pressures. The evaporation cycle is particularly important since incomplete evaporation can cause ingress of fluid into the compressor which is undesirable mechanically (Reay & Macmichael, 1988, p 16). The refrigeration fluid must therefore be heated beyond the normal evaporation temperature (superheated) to achieve a safety margin. However, beyond this, the choice of fluid is not limited through thermodynamic considerations. To quote Reay(1988, p 49), "*Any fluid which can be made to evaporate between 1 bar and 20 bar at useful temperatures is interesting*". Refrigerants in heat pumps have been selected for:

- their ability to withstand the higher temperatures present, especially at the compressor discharge port;
- low toxicity for ease of handling;
- low flammability for safety in domestic situations; and
- low costs.

The list of refrigerants used in heat pumps has been subject to considerable change over the last 20 years, largely for external reasons rather than for technological reasons. The substances chosen have more or less come full-circle from commonly-available, relatively natural fluids through various types of hydrocarbon only to return to the initial list of 'natural' fluids (IEA Heat Pump Centre, 2008a).

Initially, basic substances such as ammonia, carbon dioxide, propane were used, which were disadvantageous in that carbon doxide required higher pressures than were easily maintainable in a refrigeration circuit at the time and ammonia and propane are highly inflammable (IEA Heat Pump Centre, 2008a).

In the early 1930's, the freon 'family' of refrigerants, composed of chlorofluorocarbons (CFCs), were developed and were, for a long time, considered to be ideal refrigerants, being chemically stable, of low toxicity and fairly inexpensive. However, with the discovery in 1974 of the environmental damage – the destruction of the Earth's ozone layer - caused by the reaction of the chlorine content of the chlorofluorocarbons with atmospheric ozone at high altitudes, production of these was phased out by 1995, under the Montreal Protocol, within the developed countries of the world and being totally banned in 1996 (IEA Heat Pump Centre, 2008a).

To avoid the wholesale replacement of refrigeration equipment, CFCs have been replaced on a transitional basis by hydrochlorofluorocarbons (HCFCs), which have a lower global warming potential (GWP) and ozone depletion potential (ODP) and are able to act as a direct replacement for CFCs. HCFCs are being further replaced over the period up to 2020 by mixtures of hydrofluorocarbons (HFC)s which, though not presenting problems due to ODP, have been found to possess high global warming potential. The need to phase out all these substances has been the motivation behind the European SHERHPA project to develop heat pumps using so-called 'natural' refrigerants including carbon dioxide, hydrocarbons such as propane, and ammonia. (SHERHPA, 2007). However, most current heat pumps use R-407C, R-404 or R-410 HFC mixtures (IEA Heat Pump Centre, 2008a).

The 'R' (for refrigerant) numbers used to designate these fluids are determined by their molecular composition, with numbers determined by (starting from the right) the number of fluorine atoms; the number of hydrogen atoms plus 1; the number of carbon atoms minus 1; and the number of unsaturated carbon-carbon bonds in the molecule. When the third or fourth numbers are zero, then they are omitted. Mixtures are allocated numbers in the 400 or 500 series, 400 if they are zeotropic (evaporating over a temperature range), 500 if they are azeotropic, with a capital letter distinguishing between mixtures in different proportions of the same substances. Non-fluorocarbon organic substances are numbered in the 600 range and inorganic substances in the 700 range (IIFIIR, 2001).

2.6.9 Distribution System

The choice of distribution system, ie. the means by which the heat collected by the heat pump is used in heating the dwelling, is very much determined by whether an existing dwelling or a new build is being considered. Available systems are ducted air, direct air, wet radiant underfloor, wall or even ceiling systems, or wet radiators.

Ducted Air

This type of system is not popular in the UK, probably because heating systems have customarily been used to provide hot water as well as heating, thereby making the whole task part of the plumber's remit. Building-in ducts occupies a considerable amount of space, but could have advantages in providing ventilation in well-sealed dwellings, particularly with heat recovery. Since the output temperature from a heat pump is on the low side, large volumes of air must be moved to provide sufficient warmth and this can cause draughts. Other potential problems and hazards include the spreading of smells and noise and the feeding of air to fires. The use of air distribution also has advantages. Importantly it provides a much more rapid heating response(Armor, 1981, p14). It facilitates the reverse use of the system to provide cooling and the incorporation of air filters to reduce dust and humidifiers (McMullan & Morgan, 1981, p108). Air outlet grilles occupy less space compared with radiators, allowing more flexible placing of furniture (Armor, 1981, p14).

Direct air

Used by standalone units – usually ASHPs. The output from a fan blown over the condenser is passed straight into the house, directed by louvres.

Wet radiant systems (floor, wall or ceiling)

Because these systems do not rely on convection air circulation to warm the room, they can provide sufficient warmth at much lower temperatures (30 – 35°c) than radiator systems. The lower temperatures allow the efficient operation of heat pumps, since this is a much lower 'lift' than the 80°C required to warm a room using radiators. The difference in efficiency is illustrated by Kensa Engineering's sizing tables for radiator-coupled and under-floor coupled heat pumps where the heat pump current usages for typical running conditions are reduced by about 25% for UFH and Kensa claim a COP of 4 when operating with an underfloor system and 3 with radiators (Kensa Engineering, 2007b, 2007c) McMullan and Morgan (1981, pp106-107) show that an under-floor system at 30°C with air temperature at 20°C can provide a heat transfer by convection and radiation of 70 W/m^{-2}, which was deemed adequate even at the time they were writing. Unfortunately, retro-fitting of this form of heat distribution is not easy to achieve. Additionally, use of UFH conflicts with the customary use in the UK of wooden floors and carpets, which act as good insulators and require special fittings in suspended floors to ensure that heat is reflected upwards.

While reversible heat pumps (those that can provide cooling) are available, their use for cooling in such systems is not recommended without protection against condensation (Energy Saving Trust, 2007).

Wet radiator systems

These are the most common systems to be found in centrally-heated dwellings in the UK and throughout the EU (Iles, 2002). They are, in general, sized to suit the higher temperatures (80°C) generated by fossil-fuel boilers and therefore do not provide sufficient heat output at the lower temperatures at which heat pumps are most efficient. Ochsner (2007, p87) states that radiator "*supply temperatures should be limited to 55 °C*" or 65 °C for renovations. He provides a graph (Figure 2.8) from standard DIN EN442 relating the increase in radiator size to the required reduction in temperature.

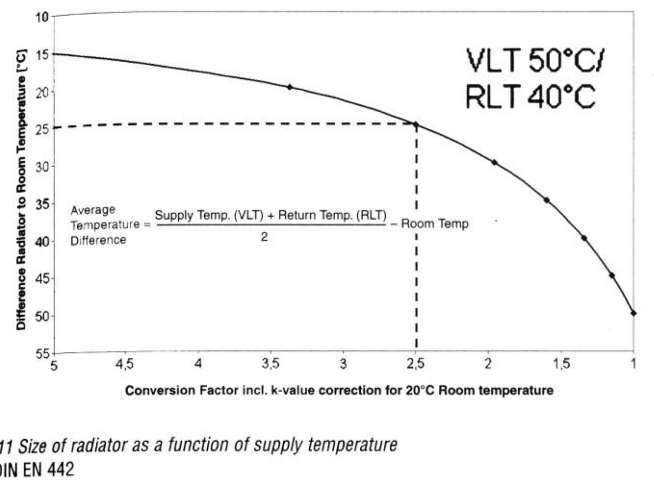


Figure 2.8. Size of radiator as a function of supply temperature.
Source DIN EN442 reproduced from (Ochsner, 2007)

Practical experience seems to indicate that a significant proportion of radiators in UK dwellings are already oversized because of the fitting of oversized boilers(McMullan & Morgan, 1981), leading Peapell(2007, pp300-301) to suggest that existing radiators should be left in place until found wanting in cold weather.

2.7 Environmental credentials of heat pump systems

2.7.1 Heat pump space heating as renewable energy

The basic function of a heat pump is to transfer heat from one body to another. The most everyday version of this function is that of transferring the small amount of heat inside a domestic refrigerator to the outside world, thereby making the inside desirably cooler and the outside a little, probably irrelevantly, warmer. A heat pump space-heating system has almost the reverse function, taking the low temperature heat energy from a large body and 'compressing' it into higher temperature heat in a smaller body. The 'large body' can be either the surrounding air, a layer of surrounding earth down to about 1.2 metres, the body surrounding a borehole, a river or a lake, or any combination of these as available. The smaller body is usually the distribution fluid in a hot water central heating system or the air in a house. The warmth in the large body is, more or less, solar gain, so that the heat pump is using its source as an inter-seasonal store, which is being 'filled' in the summer by solar energy and 'emptied' during the winter by the heat pump (Ochsner, 2007; Peapell, 2007). Using a reversible heat pump, the heat source can be re-charged by cooling the dwelling during the summer, if necessary. In making use of this solar energy, these types of heat pump systems are judged to be utilizing renewable energy.

2.7.2 Carbon dioxide emissions reduction

The main objective in installing a heat pump is to provide a low-carbon heat source which can either replace existing heat sources or take advantage of new-build, highly-insulated homes. Figure 2.9 shows that, given a heat pump of a sufficiently high COP(ε = 3.0), the use of heat pump heat systems can balance out generation and transmission losses, allowing the available energy delivered to a household to equal primary energy, unlike the other forms of heating shown. Of course, this 'balancing out' is not truly saving energy, merely the acquisition of extra energy to replace the system losses as the additional flow of energy into the heat pump system in the bottom row of Figure 2.9 indicates.

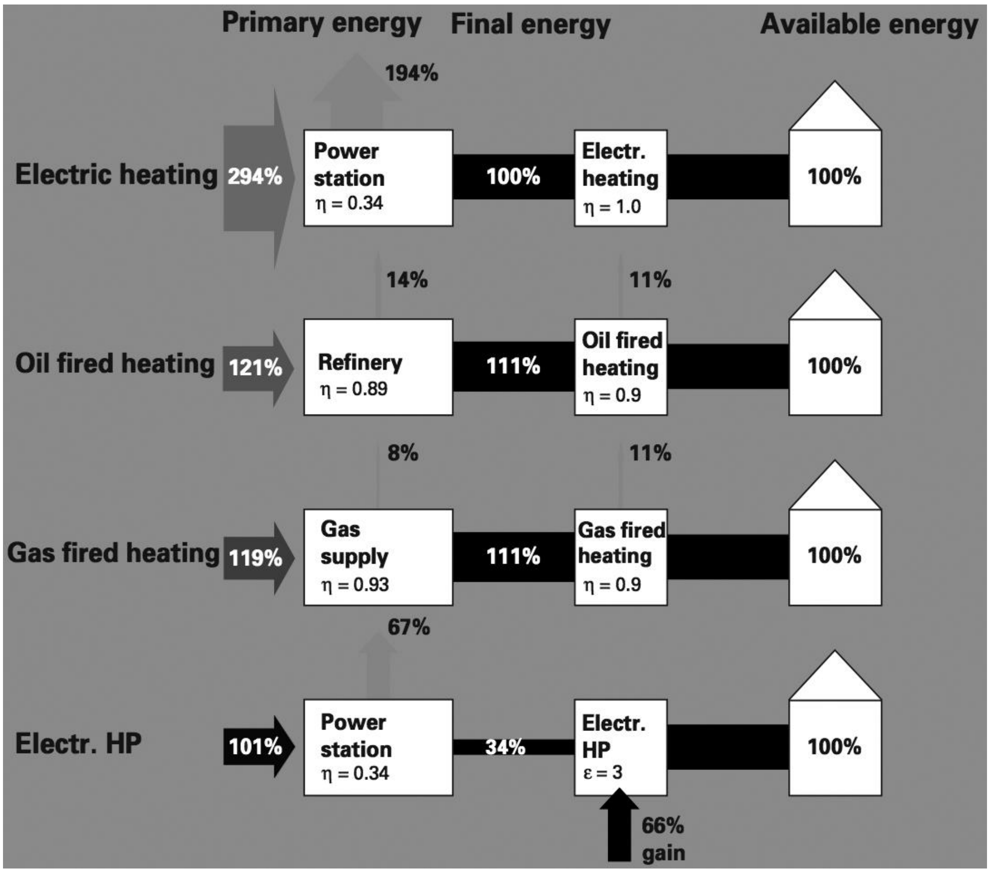


Figure 2.9 Relative energy use of different heating systems

(Viessmann UK, 2004)

In the current edition of their Good Practice Guide (CE82) (Energy Saving Trust, 2007) on ground source heat pumps, the Energy Saving Trust present the following graph (Figure 2.10) as an indication of the emissions savings.

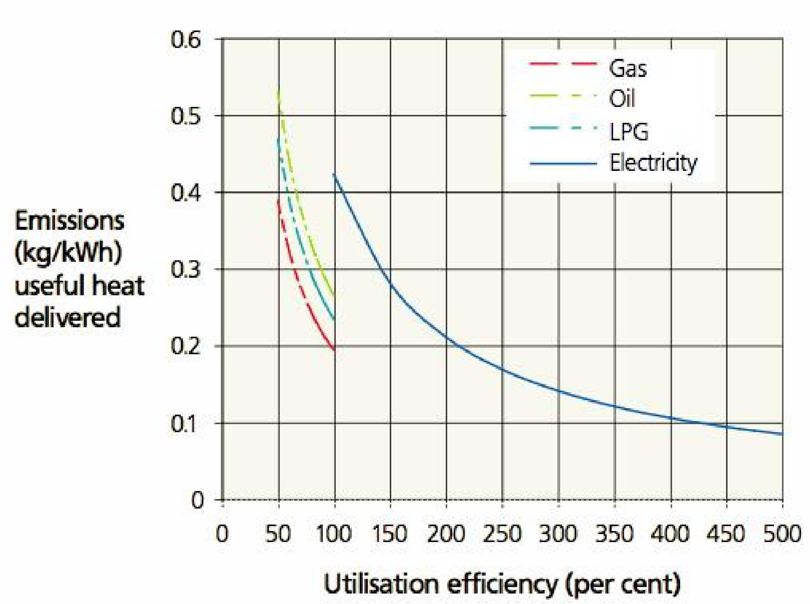


Figure 2.10. Ground-to-water heat pump systems: CO2 emissions and fuel use efficency

(Fig 2 from Energy Saving Trust, 2007)

This graph is based on the CO_2 emission factors used in the current version of the UK government Standard Assessment Procedure (SAP, 2005) (BRE, 2008) viz. Electricity = 0.422kg/kWh delivered, gas = 0.194 kg/kWh, LPG = 0.234 kg/kWh, oil = 0.265 kg/kWh. Using these values, they quote that a condensing gas boiler at a seasonal efficiency of 85% would emit 0.23 kg CO_2 for every kilowatt-hour of output, whilst a ground source heat pump with a seasonal efficiency of 350% would emit 0.12 kg CO_2 for every kilowatt-hour of useful output, claiming an almost 50% reduction in emissions for the GSHP (Energy Saving Trust, 2007, p4). This also implies that the Seasonal Performance Factor for the heat pump need only exceed 1.8 to provide CO_2 emission savings. However, the validity of this claim is highly dependent on the CO_2 emission factor for grid-supplied electricity which is again highly dependent of the fuel mix used in generation. Since the value used by BRE (2008) is now some several years old, recent recalculation (Mackay, 2008) based on the DBERR Energy Trends for March 2008 gave a value of 0.554 kg/kWh, some 31% higher. This has the effect of shifting the Energy Saving Trust curve for emissions for electricity upwards in Figure 2.10, giving emissions of almost 0.16 kg CO_2 for every kilowatt-hour for a GSHP at 350% efficiency and a 'break-even' point against the gas boiler of 240%.

2.8 Barriers and drivers to the take-up of domestic heat pumps

2.8.1 Barriers

Some of these points have been included in previous sections but are included here for completeness.

Capital Cost

The main barrier against the adoption of heat pumps, particularly GSHPs, is the initial cost of the equipment and its installation as illustrated by Table 2.2 below.

Table 2.2 Indicative capital costs* for individual ground-to-water heat pump systems

System type	Ground coil costs **(£/kW)**	Heat pump cost **(£/kW)**	Total system costs **(£/kW)**
Horizontal	250 - 400	350 - 750	600 - 1150
Vertical	550 - 750	350 - 750	800 – 1500

*Costs include installation and commissioning of the heat pump and ground loop but exclude costs for the heat distribution system.

(Energy Saving Trust, 2007. p17)

This gives a cost of £4,800 - £9,200 for a typical 8kW system with a horizontal collector and £6,400 - £12,000 for one with a vertical borehole. Even with a maximum grant from the RHPP of £1250 (EST, 2012), this represents a sizeable extra cost against a condensing gas-fired system. The costing issue is compounded by the complexity of design decisions to be made: the use of borehole or horizontal collector; different horizontal collector types; the sizing of the collector according to the heat load of the dwelling and the soil type; the requirement for, or suitability of the distribution system for cooling; the provision made for generation of domestic hot water (DHW). Bigger systems (> 11Kw) bring additional problems with the need to uprate the power supply to the house from single phase to three phase.

Since the size of the collector represents 35-40% of the system cost, accurate calculation of the heat load required and consequent sizing of the system and its collector is crucial to minimise costs. Methods of reducing ground collector size by means such as re-charging soil temperature from solar thermal collectors in the system can be considered, but bring their own increases in complexity and cost (Harrogate Borough Council, 2007).

Plot size

This is mainly a concern with GSHPs using a horizontal collector, since a ‘rule of thumb’ is that these will occupy 1.5 to 2 times the floor area of the building. Consequently, for a building of $150m^2$, a horizontal collector will occupy between $225m^2$ and $300m^2$. Further, the collector must be 2m. from trees, 1.5m from cables and 3m from septic tanks, water, waste and sewage pipes because of possible freezing (Nottingham Energy Partnership, 2006). As the average plot size for new UK houses is $89m^2$ (Wolsey Securities, 2006), the current generation of GSHPs in individual homes is restricted to the upper end of the housing market or to country properties. In the retro-fit applications which concern this study, digging of the collector trenches is severely disruptive to the garden of an existing house. 'Split' ASHP systems also require some external space for the collector unit which is judged to be 4 m^2 (Energy Saving Trust, 2011). Borehole collectors can be accommodated on much smaller sites, but carry the cost penalty indicated above in Table 2.2.

Expertise

Because heat pumps of all kinds are still unfamiliar to designers in the UK, it is likely that they will be unwilling to specify them unless specifically requested by the client.

Equally, the installation of the systems is unfamiliar to the construction industry, which may cause problems, particularly with collector installation (Harrogate Borough Council, 2007).

With the lack of expertise in installation, there is a possibility that poor installation may cause systems not to meet manufacturers' standards for performance. This appears to be an implication of the findings of the EST heat pump monitoring study (Bradford, 2009; Bradford, Carmichael, & Bean, 2011) where the performance of heat pumps in UK dwellings was found to be significantly poorer than the equivalent European systems.

Electricity supply

One of the problems highlighted in heat pump installations is the low capacity of the power supply to UK homes, which is usually only 230v 50 Hz, single-phase, which is sufficient only for heat pumps up to 11kw (unless fitted with a 'soft start'). This is especially true of country areas, off the gas grid, where the difficulty and expense of upgrading the power supplies are greatest, but the potential improvement in comfort and well-being for the occupants from pump installations is greatest. The conversion of a single domestic power supply to three-phase power by Eon distribution company costs around £1000 plus the cable burial costs of about £70 / metre (E-ON Energy Services, 2008). The original connection to the electricity supply may have been made to such an inferior standard that the supply capacity for a community is only sufficient for the installation of a heat pump in only one house in two, as was found in the village of North Blyth (Lacey, 2010).

Heat distribution systems

As heat pump systems operate more efficiently at lower temperatures, they are most frequently coupled to underfloor heating systems (UFH) or to low-temperature radiators that appear over-sized to those accustomed to gas or oil-fired systems (Butcher, 2007).

Standards

The standards for calculating energy requirements for heat pump heating systems – EN15316-4-2 - had draft status from 2005 until consultation ended in January 2006 and were only given approved status in August 2008. Butcher (2007) in his paper for NHBC Foundation describes it as "*complex and difficult to interpret*" which might go some way to explain this position. There are, as yet, no standards for the required efficiency of heat pumps similar to the SEDBUK ratings for gas or oil-fire boilers, which renders their specification for dwellings more complex.

External Collectors

Air source heat pumps, while not requiring underground collectors, do require external fan-driven collectors, which can be noisy if incorrectly positioned. Because these are largely exposed to the weather, their life expectancy is much reduced compared with GSHP collector loops.

Geology

Britain has an extensive range of geology. To quote Curtis (2001), '*almost all known geological sequences exist within the UK'*. This causes difficulties both with drilling boreholes, but also with calculating ground loop sizes because of the wide variation in thermal conductivity that occurs over quite small areas.

2.8.2 Drivers

Renewable Heat Premium Payment / Renewable Heat Incentive

As previously stated, heat pump systems are classified as renewable energy devices and their installation is eligible for the Renewable Heat Premium Payment payments of £1250 for a GSHP or £850 for an ASHP in single homes without mains gas heating, providing that the house has the basic measures of cavity wall insulation (where appropriate) and 250 mm of loft insulation (EST, 2012). This provides only a limited incentive, as it does not reflect the cost differential between conventional heating and a heat pump installation. However, the future implementation of the Renewable Heat Incentive, which will probably make 4.7p per kilowatt hour payments for ground source systems, may constitute more of an incentive to householders despite the "off the gas grid" restriction (Ofgem, 2011).

Operating Costs

At July, 2008 prices, energy costs for GSHPs are estimated to be similar to gas-fired heating. Costing for ASHPs are about 60% higher. The only cheaper form of heating is unseasoned wood (Nottingham Energy Partnership, 2008). The major cost advantage of heat pump equipment is its apparent low maintenance requirement, with suppliers claiming that heat pumps do not require the annual inspection required by gas or oil-fired equipment.

Convenience

Of the 'low carbon' technologies currently available, heat pumps are the only type that approaches or possibly exceeds the level of convenience of gas central heating. They require no fuel storage facilities or delivery, do not suffer from variations in fuel quality, do not require flues or airflows and are completely electronically controlled, requiring minimal interference from their owners (Energy Saving Trust, 2007, p5.).

Obviating the need for a mains gas connection in new developments

The installation of a heat pump system obviates the need for the developers of new housing to provide (and pay for) the connection of a mains gas supply for the site, reducing their costs, though the lack of gas provision may make those dwellings less attractive to buyers.

2.9 Distinctive characteristics of heat pump systems over 'fuelled' systems

Of the characteristics of heat pump systems, those that are distinctive from gas and oil systems are as follows:

a) Heat pump systems have lower temperature output due to the characteristics of the vapour compression cycle, especially that of degradation of refrigerants at higher temperatures. Higher temperatures are only possible with multi-stage compressors or additional heaters.

   Output temperature is very significant in radiator systems because the heat transfer by radiation is approximately proportional to the fourth power of the temperature difference between the emitter and the surroundings.

   Because of their lower output temperatures, heat pump systems require a control system based on weather compensation rather than internal temperature in order to reduce the size of temperature 'lift' required to match a fall in outside temperature. This is not necessary for fuel burning systems.

b) For fuel burning systems, the energy available is dependent only on the fuel supply. For ground source heat pumps, there is a reduction in source energy over the heating season due to depletion of the ground as an inter-seasonable store. For air source heat pumps, there is a reduction in source energy from October – February with the fall in air temperature due to reduced solar gain.

c) CO_2 emissions from operating electric heat pumps are almost solely due to the carbon intensity of electricity generation, not of the fuel itself.

d) The cost of installation of GSHP systems is highly dependent on the size of the system, especially of the collector, so it is important to ensure that system is not oversized. However systems are even more expensive to uprate once installed as it is not possible just to fit a more powerful boiler.

e) The cost of operating an oil/gas fire system probably increases uniformly with the size of the inside / outside temperature differential to be maintained. Additional heat (above balance temperature) with a heat pump system is at a COP < 1.0.

f) Heat pump systems are capable of providing cooling as well as heating, either in the form of air cooled directly from a ground loop collector or by reversing the heat pump to cool the distribution system. While these both can have the effect of re-charging the source, providing more heat in the winter, they can also imply an increase in domestic electricity use during the summer.

2.10 Summary

This chapter has examined information on the following:

- an outline of the fundamental principles behind heat pump technology;
- a review of the key components of current domestic heat pump systems;
- a review of different applications, operation modes and heat distribution systems; the potential for CO2 savings.
- a review of the drivers for and the barriers against the mass take-up of domestic heat pump systems.
- the significant differences between heat pump heating systems and fuel burning heating systems.

The chapter has necessarily limited its scope to consideration of heat pump technology as used in the UK, both because of particular circumstances in the UK and also to limit the volume of information to be considered.

In terms of the study Objective 1, the following issues are raised by this chapter:

> The important relationship, shown in Section 2.4, in estimating heat pump energy use is that between efficiency (COP) and the "lift" - the difference between the source and sink temperatures required from the system - as expressed by Equation 2.6.
>
> The construction of a model of this relationship, therefore, will rely on the estimation of the source and sink temperatures appropriate for the dwelling and site involved, requiring rules determining the source and sink types, based on detail of outside space and of the heat distribution system.
>
> Where a heat pump system is sized such that it cannot balance the heat load of winter temperatures, then additional heat is required, from either a parallel or alternate system. At a dwelling level, the desired model must encompass the sizing of the system, the degree to which it balances the system loads and the resultant use of additional heat.

To include the above factors, modelling for this study must therefore be based at dwelling level, with sufficient detail of built form and surroundings. However, this raises problems of creating dwelling-level estimates within a data structure which will allow their grossing up to stock-level estimates.

CHAPTER 3 MODELLING OF DOMESTIC HEAT PUMP ENERGY CONSUMPTION

3.1 Introduction

The previous section identified the technical characteristics of the heat pump heating systems designed for use in domestic situations and the incentives and barriers to their take-up in the UK. A substantial proportion of the barriers involve the questions surrounding the performance of the systems, which is a crucial determinant of their status as low-carbon heating systems and positions them as "follower" technology behind the de-carbonisation of the electricity supply. For the first part of Objective 1 of this study, it identified the theoretical and physical characteristics of heat pump systems that are most significant in the estimation of the energy use of these systems.

For the second part of Objective 1, this section examines the models which have been developed for the estimation of heat pump performance under categories covering research studies, official standards and freely-available software.

3.2 Heat pump modelling studies in research

3.2.1 Aims of this thesis and filtering of model descriptions

The main aim of this thesis is predict and understand the effects of a substantial take-up of heat pump heating and DHW systems in dwellings in the UK on that country's electricity supply on a monthly and yearly basis. As part of this estimation process, it is required to improve upon the current implementations of the modelling of heat pump characteristics in dwelling energy models, which generally mask the differences between heat pump systems and fuel-burning systems. Hence this chapter examines studies of heat pump models, which are based either on thermodynamic theory or statistical analysis of the results from monitoring studies, standard models of heat pump energy use, and software packages for estimation of heat pump energy use. However, because it is not required to analyse the performance of these systems for engineering improvement, the papers reviewed have been restricted to those relating to unmodified, "off-the-shelf" systems and to studies of generic systems.

The annual and monthly timescale implies that any modelling studies need not operate at time intervals outside this range, on the assumption that any performance variations within shorter periods will not be significant over a longer period, while longer term variations appropriate for borehole heat sources do not register either. The study will also assume that systems, especially ground source heat collectors, have been sized correctly, that only readily available sources are employed and that no additional equipment has been incorporated into the heating and DHW system beyond a standard heat pump, either ASHP or GSHP as appropriate, thereby excluding prototype or one-off systems. So that the process should be as transparent as possible, a further requirement is that any modelling should avoid proprietary software models of HVAC equipment.

The characteristics of heat pump systems for dwellings, particularly in temperate climates such as the UK, differ significantly from commercial systems, in that commercial systems are frequently required to provide cooling as well as heating, and sometimes both at the same time, especially for a high density of computer equipment in a server room operating in mid-winter in an office block. The UK's particular housing stock, with its characteristic of large numbers of old, much extended houses with poor energy efficiency, also brings its own flavour to the analysis, as does the widely varying geology in the UK, making the installation of ground heat exchangers '*a minor nightmare for ground coupled installers*' (Curtis, 2001).

This study will not include detailed thermal modelling of ground loops in the analysis and will assume that ground loops are correctly sized for the heating load of the system. While the sizing of ground source heat collectors is crucial both to the efficiency of GSHPs and to the cost of these systems, and widespread under-sizing could cause excess electricity consumption, it is not possible to allow for any mis-sizing of collectors without conducting a long-term study of collector sizes and loads to ascertain the size and variation of discrepancies.

analysis of heat sources other than air and soil using closed, indirect ground loops is not thought to be appropriate for this study. A generalised housing stock sample does not provide exact location data and therefore it is not possible to identify whether a house is close to a suitable, available body of water or another less conventional source. Open ground loop systems involving the extraction of ground water are subject to a licensing system in the UK and possibly to an extraction charge, which might be tolerated in a commercial situation, but the increased expense and bureaucracy are likely to deter a private householder (Brown, 2009, pp. 28-29). Currently, direct evaporation systems, ie. those where the collection fluid is evaporated in the ground collector and passes directly to the compressor without the use of a separate evaporating heat exchanger, are uncommon in the UK, probably due to the requirement for a expensive corrosion-resistant, copper ground loop capable of maintaining the necessary high pressure (Brown, 2009, pp. 27-28; Ochsner, 2007, pp. 21-22, 58-62).

Eschewal of studies involving systems that incorporate other equipment - examples being solar collectors to provide additional heat for the system source, or buffer storage to avoid short-cycling of the system due to the lack of thermal mass in a radiator system - is based on the necessity to reduce complexity in modelling and to reflect the need to keep down the capital cost of and space requirement for the system modelled. While studies involving prototype systems may provide indications of future performance levels, prototypes are not necessarily configured optimally and specifications will change with manufacture.

The requirement to ensure transparency through use of available software has the effect of eliminating some studies from this review, since these employ pre-compiled modules within their models for which the source code is not available and the software environment itself is only available at a price unrealistic for individual users.

3.2.2 'Filtration' of research papers

The definition of the above criteria allows the 'filtering' of the not-inconsiderable number of publications on the subject of heat pump heating systems, necessary because these are fairly numerous, with a search of "Web of Science" (Thomson Reuters, 2012) with key words "building", "heat", "pump", "model" returning 440 entries. The same search using "Google Scholar" (Google, 2012) returned some 25,700 entries. The extent to which it is necessary to examine the full gamut of literature on this subject is not clear. In the basic structure of a heat pump system, there are a limited number of variables and therefore a limited number of relationships which require to be reflected in a model.

Using the criteria above in 3.2.1 it is possible to filter this substantial volume of papers somewhat, excluding the following:

Detailed modelling:

Exergy and energy analysis of individual heat pump components and system (Hepbasli & Tolga Balta, 2007); modelling of the internal components of the heat pump system, particularly those with scroll compressors (Jin & Spitler, 2002); modelling of systems which provide DHW only (Bourke & Bansal, 2010); thermo-economic optimisation of heat pump system and ground-coupled heat exchanger (Sanaye & Niroomand, 2010);

Ground loop modelling:

modelling of energy flows in ground loops (particularly vertical boreholes) in detail over short timescales (Parker, 1985; Spitler, Liu, Rees, & Yavuzturk, 2003), (Yavuzturk & Spitler, 1999), (Bai, Zhang, Zheng, Zhang, & He, 2009); studies of the optimisation of borehole ground loops using artificial neural network techniques (Esen & Inalli, 2009; Esen, Inalli, Sengur, & Esen, 2008c), or adaptive neuro-fuzzy inference systems (Esen, Inalli, Sengur, & Esen, 2008a, 2008b); detailed modelling over annual and multi-year timescales using EnergyPlus software (Fisher, Daniel E. & Rees, 2005; Fisher, Daniel E., et al., 2006), using HVACSIM+ in optimisation (Haider Khan, 2004); a study comparing results from TRNSYS simulations of dynamic and steady state simulation of ground loops and heating systems (Kummert & Bernier, 2008); long-term (10 years) modelling of vertical ground source collectors for commercial buildings using HVACSIM+ (Underwood & Spitler, 2007); modelling of vertical GLHEs with variable convective resistance and thermal mass of the fluid (Xu & Spitler, 2006); simulation using finite element modelling of temperature distribution development around the boreholes of ground-coupled heat pump systems over a 48 hour time interval (Esen, Inalli, & Esen, 2009);

Modelling using proprietary software:

modelling, using the proprietary software TRNSYS, of a larger than residential size system capable of simultaneous heating and cooling through the addition of extra buffers (Byrne, Miriel, & Lenat, 2009);

modelling of the use of ground water and road pavements, both as heat sources and for heat rejection (Chiasson, 1999); a study of the issues surrounding the retro-fit of direct expansion ground loops (Bangheri, 1994); a comparative study by simulation of different forms of heating and cooling including both compressor and adsorption heat pumps (Bolling & Mathias, 2008); an hourly simulation model within the HVACSIM+ environment of a GSHP system with hot water heating using a desuperheater for a small residential apartment in Hong Kong (Cui, Yang, Spitler, & Fang, 2008); energy analysis of a vertical ground source heat system with Matlab (Michopoulos & Kyriakis, 2009);

comparison between design and actual energy performance of a ground source and air source heat pump system in cooling and heating operation using TRNSYS(TESS, 2012) simulation (Magraner, Montero, Quilis, & UrchueguÌa, 2010);

Systems using additional components:

evaluation of a low energy home with a GSHP used for space heating and cooling, photovoltaic modules, wind power and solar collectors (Hamada, Nakamura, Ochifuji, Nagano, & Yokoyama, 2001); modelling and energy evaluation of a GSHP system incorporating a solar collector (Ozgener & Hepbasli, 2007); modelling and evaluation of an experimental CO_2 heat pump with a counter-flow tripartite gas cooler (Stene, 2005).

3.2.3 Relevant heat pump models in research

The following works have been found relevant to this study:

3.2.3.1 Boait, Fan, & Stafford (2011)

The objective of this study is to examine the effects of modifications to the operation of the weather compensated control algorithm for a heat pump controller to overcome characteristics which have been found unsatisfactory in use. These systems appear to have a slow response to user control, causing dwellings to be excessively warm at night and to be more costly to operate than expected. This is apparently caused by the unmodified system's continuous operation without any 'set-back' (off or reduced temperature) period and the lack of influence of the internal temperature sensor on the operating temperature. The control mechanism relates the return temperature from the distribution system to the set point temperature and the external temperature by the following equation:

$$\frac{(T_r - T_s)}{(T_s - T_e)} = K \qquad \textbf{(3.1)}$$

where

T_r = distribution return temperature

T_e □ external ambient temperature

T_s = set-point temperature

K = constant set by user, know as the 'controller slope'

To examine the effects of changes to the configuration of the system controller, Boait, Fan, & Stafford (2011) initially define a simple model for the dwelling temperatures as follows:

$$(T_r - T_e) = \tau \cdot \frac{dT_r}{dt} \tag{3.2}$$

where

T_r = room temperature

T_e = external ambient temperature

τ = thermal time constant of the dwelling (thermal capacity / heat loss rate)

and a heat pump model based on the following relationships:

$$Practical\ COP = \frac{\mu \cdot (T_L + T_g + T_e + 273)}{T_L} \tag{3.3}$$

where

μ = multiplier representing mechanical and other losses in the heat pump system

T_L = temperature lift between the heat pump output to the radiator circuit and the ground loop output temperature

T_g = difference between the external ambient temperature and the ground loop exit temperature.

T_e = external ambient temperature

The multiplier, μ, is estimated from data collected from a monitoring project in the dwellings in which the issues with control were found and is, apparently, estimated by a linear regression of the form:

$$\mu = a \cdot W + b \qquad \textbf{(3.4)}$$

where

W = heat pump output power (Watts) (W)

thereby calculating the system COP as a proportion of the Carnot COP, according to the system output. Thus, according to Boait, Fan, & Stafford (2011), though the system COP reduces as heat output increases with the increase in T_L, it is partly offset by an increase in μ, as the mechanical and electrical losses reduce as a proportion of overall output. Boait, Fan, & Stafford (2011) validate the model from Equation 3.2 by comparing the internal temperature results from the model with results from their monitoring study using the following equation:

$$C\delta T_r = (W_h + W_a + W_o)\delta t - L(T_r - T_e)\delta t \qquad \textbf{(3.5)}$$

where

C = thermal capacity (kWh/ºC)

W_h = Power output from heat pump (W)

W_a = Casual gains from appliance use(W)

W_o = Gains from occupancy (100w assumed from a single occupant)

L = Specific heat loss (kW/ºC)

and provide an example of the comparison:

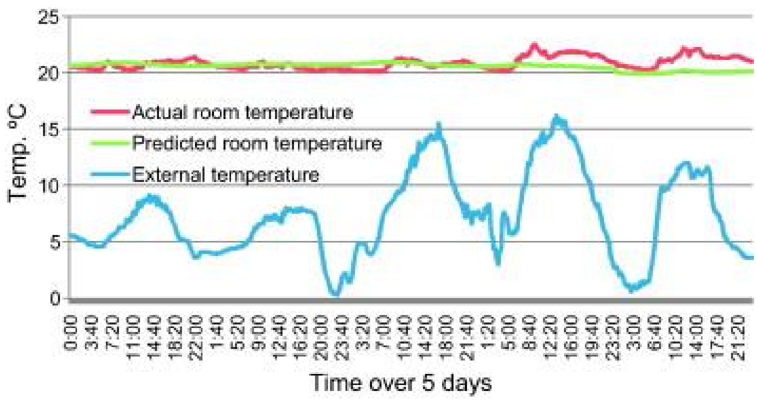


Figure 3.1 Comparison of model results with monitoring data

(Fig. 5 from Boait, et al., 2011)

and the heat pump model is validated by comparing the actual electricity consumed over a 24 hour period with the model's prediction based on the actual output and temperature lift values. For Equation 3.4, values for *a* and *b* of 0.2 and 0.033 were used to compute μ, giving the following results in Figure 3.2:

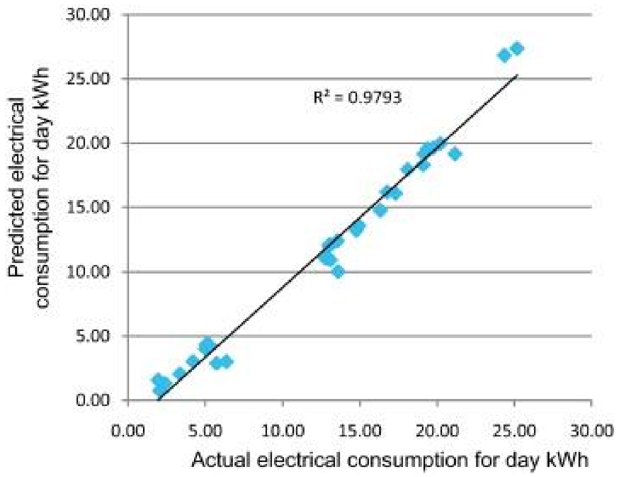


Figure 3.2 Validation of heat pump model

(Fig. 6 from Boait, et al., 2011)

which show that the predicted results correlate well with the actual consumption of the system.

The remaining part of this study uses these models to compare the effects of a night-time setback of the system with those of continuous running which is set as a default.

3.2.3.2 Jenkins, Tucker, Ahadzi, & Rawlings (2008)

This study modelled the effects of replacing gas boilers and conventional air conditioning in a four storey office block, 4000 m^2 in floor area, with air source heat pumps used for both heating and cooling. The objective of the study was to indicate the possibilities for carbon savings with heat pump systems, given improvements to the energy efficiency of the building fabric, reduction in internal gains due to the energy use of office equipment and the increases in external temperature due to climate change. Two scenarios were used for the building modelled, the first with 2005 fabric, internal gains in terms of computer equipment and lighting, and climate, the second for 2030 with U-values for walls, roof & floor improved from 0.65, 0.87 and 0.27 to 0.15, 0.14

and 0.22 W/m^2 K respectively, windows with standard double-glazing with U-value of 2.75 W/m^2 K improved to triple-glazed argon-filled with reduced solar transmission (U-value = 0.78 W/m^2 K), lower-energy computer hardware and lighting, and climate 'morphed' to temperatures deemed possible for 2010-2040. For gas heating, the efficiency of the boiler was increased by about 5% for 2030, to simulate a condensing boiler. The effect of the second scenario on annual energy loads is to reduce the heating load from 173 to 199 kW and the cooling load from 272 to 177 kW, leading to the comment that *"the 2030 office is more heating-dominated than the 2005 office, which has very large cooling loads"*.

To provide a heat pump model, the authors calculate two factors, f_{COP} and f_{QH} against test reference values:

$$f_{COP} = \frac{COP}{COP_{Ref}} \tag{3.6}$$

where:

COP_{Ref} = the nominal value of the system COP at reference conditions (outdoor dry-bulb temperature = 7 ºC, wet-bulb temperature = 6 ºC, indoor dry-bulb temperature = 20 ºC.) and f_{COP} is given by the following expression:

External wet-bulb temperature (degC)	f_{COP}
$T_{wb}>11$	= 1.056
$11> T_{wb} > 6$	= 0.0112 x (T_{wb}-6)+1
$6 > T_{wb} > 4$	= 0.075 x (T_{wb}-4)+0.85
$4 > T_{wb} > 1$	= 0.017 x (T_{wb}-1)+0.799
$1 > T_{wb} > -1$	= -0.0405 x (T_{wb}+1)+0.88
$-1 > T_{wb} > -4$	= 0.88
T <$_{wb}$ -4	= 0.0257 x (T_{wb}+4)+0.88

$$f_{QH} = \frac{QH}{QH_{ref}} \tag{3.7}$$

where QH and QH_{ref} are the calculated and reference heating capacities.

From external data sources, Jenkins, et al.(2008) have calculated f_{QH} as follows:

$$f_{QH} = 0.00000142T_{wb}^6 - 0.00002305T_{wb}^5 - 0.00005736T_{wb}^4 + 0.00166753T_{wb}^3 + 0.00209494T_{wb}^2 - 0.00778015T_{wb} + 0.77224212 \tag{3.8}$$

for -6ºC< T_{wb} < 12ºC

$$f_{QH} = 0.026T_{wb} + 0.8513, for\ T_{wb} > 12ºC$$

$$f_{QH} = 0.019T_{wb} + 0.817, for\ T_{wb} < -6ºC$$

where T_{wb} = external wet-bulb temperature, f_{QH} = heating capacity factor.
with the relationship between -6ºC and 12ºC allowing for the reduced capacity because of the defrost cycle (though the temperature range for this relationship would appear somewhat extended, since the defrost requirement above 5ºC should surely be minimal).

Similar factors are calculated for cooling:

$$f_{EER} = \frac{EER}{EER_{Ref}} \quad \textbf{(3.9)}$$

where:

EER_{Ref} = the nominal value of the system EER at reference conditions
(outdoor dry-bulb temperature = 35 ºC, indoor wet-bulb temperature = 19 ºC,
indoor dry-bulb temperature = 27 ºC.

$$f_{eer} = -0.0244T_{db} + 1.854 \quad \textbf{(3.10)}$$

The cooling capacity factor, f_{QC}, is defined as:

$$f_{QC} = \frac{QC}{QC_{ref}} \quad \textbf{(3.11)}$$

where QC and QC_{ref} are the calculated and reference cooling capacities.

Again, Jenkins, et al. (2008) have calculated Q_{QC} from external data sources as follows:

$$f_{QC} = -0.0044T_{db} + 1.154, valid\ for\ 10ºC < T_{db} < 35ºC \quad \textbf{(3.12)}$$

where T_{db} = external wet-bulb temperature, f_{Qc} = cooling capacity factor.

Jenkins, et al. (2008) also calculate a part-load factor, which attempts to allow for the reduction in the efficiency due to the on and off cycling of the system when the demand for heating or cooling is low. This is defined as a function of the part-load capacity, the ratio between the current load at any one time and the system capacity, with Jenkins, et al. (2008) employing a curvilinear equation derived from a set of curves specified by the US Department of Energy for residential air-conditioning plant (Henderson, H., Huang, & Parker, 1999). The formula derived is as follows:

$$PLF = \frac{1.44(PLC^2 + 2.91PLC)}{PLC^2 + 4.6PLC + 0.339} \quad \textbf{(3.13)}$$

where:

PLF = part load factor and PLC = part load capacity.

The above equations are used with heating and cooling loads and associated climate data in calculations on an hourly basis as follows:

- a 'baseline' heating and cooling system, sized according to CIBSE calculations for HVAC (CIBSE, 2005), consisting of a gas boiler and chillers, is assigned to the 2005 version of the building, with a higher efficiency boiler and the same chillers assigned to the 2030 version.
- Given the wet (or dry) bulb temperature for the current hour, the current capacity and nominal rated heating capacity of the ASHPs is calculated for heating or cooling as appropriate.
- The actual heating or cooling supplied over the current hour is determined from the minimum of the predicted demand and the available capacity of the machine.

  The part-load factor is then calculated using the ratio of actual to current capacity (heating or cooling as appropriate) of the ASHPs.

Depending on whether the system is in heating or cooling mode, the current COP or EER is calculated using the wet (heating) or dry (cooling) bulb temperatures for the current hour, and the nominal rated value for COP or EER. This value is multiplied by the part-load factor to determine actual current COP or EER which is then divided into the actual heating or cooling energy supplied to give the power consumption for the current hour. The hourly values are totalled over all hours and converted to an equivalent annual CO_2 emissions.

The energy consumption values for space heating and cooling are then combined with consumption for DHW generation, 'small power' (energy consumed by office equipment), and lighting to analyse the two scenarios for the office building. The effects of the change from gas heating to the ASHP system in the 2005 office are, firstly, to reduce the energy consumption for cooling somewhat, due to the improved efficiency of the modern heat pump system over what is assumed to be an older air conditioning system, and, secondly, to substantially reduce space heating energy, because of the much improved COP of the heat pump system over an older gas system.

Table 3.1 Total annual energy consumption for a ''current'' four-storey office for ''baseline'' and ASHPs scenario

	Annual energy consumption (kWh/year)							
	Heating	Cooling	Fans/pumps/ventilation	Small power	Lighting	Hot water	Electrical total	Gas total
Baseline	55,319	34,071	11,760	235,784	213,800	48,000	495,415	103,319
ASHPs	4,514	27,874	9,141	235,784	213,800	48,000	501,113	48,000

(Jenkins, D., et al., 2008, Table 3)

In the equivalent table for the "2030" office, the results for the "baseline' version show an increase in space heating energy use over the "2005" office, which is assumed to be due to the reduction in internal gains from office equipment and, possibly, to a reduction in solar gains because of the change in glazing, both of which are also responsible for the reduction in cooling demand. The major part of the energy savings between the "2005" and "2030" scenarios are substantially due to the improvements in efficiency of office equipment and lighting.

Table 3.2 Total annual energy consumption for a ''2030'' four-storey office for ''baseline'' and ASHPs scenario

	Annual energy consumption (kW h/year)							
	Heating	Cooling	Fans/pumps/ventilation	Small power	Lighting	Hot water	Electrical total	Gas total
Baseline	87,439	17,808	11,779	93,465	50,777	41,532	173,829	128,971
ASHPs	23,347	15,946	9,141	93,465	50,777	41,532	192,676	41,532

(Jenkins, D., et al., 2008, Table 4)

Table 3.3 contains estimates of CO_2 emissions for the different scenarios. Within the "2005" and "2030" scenarios, alternative methods of generating DHW are included, either by direct electric heating or by gas. The effect of electric heating of DHW has the effect of considerably reducing CO_2 emission savings due to the conversion to the heat pump system, from savings in the region of 20% to virtually zero. This is, of course, due to the much higher carbon intensity of electricity generation, quoted in Jenkins, et al.(2008) at 0.43 kg CO_2/kWh compared with gas heating at 0.19 kg CO_2/kWh.

The basic difference between this modelling study and the work for this thesis is, of course, the application to a commercial building. The larger size of such a building in proportion to the size of the heating equipment allows for a more complex system involving, for example, more than one heat pump unit or systems of more than one type. The authors also assume the use of heat distribution by air, a method which is employed in just over 1% of UK dwellings (DCLG, 2010c), as opposed to 'wet radiator' systems used in about 92%. For these reasons, the study is less than applicable to the current thesis.

The results and inferences from Jenkins, et al. (2008) are somewhat unhelpful to the study of the effectiveness of heat pump systems as low carbon systems. The main point being made appears to be that reductions in heating and cooling loads due to improvements in the efficiency of building fabric and office equipment make other energy loads more significant and that without due attention being paid to these, the carbon advantage of the main system will be reduced or disappear altogether.

While the assumptions made in the study about the means of supplying DHW to the "2030" office block are, of course, viable, consideration could easily have been given to including solar thermal heating, possibly bringing a significant reduction in the CO_2 emissions over the gas system. Another alternative would have been to provide DHW from a subsidiary heat pump system, which might have also provided a lower carbon supply.

Table 3.3 Emissions and savings associated with different office scenarios

	2005 office emissions (tCO2/year)				2030 office emissions (tCO2/year)			
	HVAC[a] only		Total for office		HVAC[a] only		Total for office	
	Gas HW	Elec. HW	Gas HW	Elec. HW	Gas HW	Elec. HW	Gas HW	Elec. HW
Baseline	35	35	233	233	33	33	99	99
ASHPs	27	35	225	232	25	33	83	99
Savings (%)	22.8	1.9	3.5	0.3	25.7	0.3	16.5	-0.1

[a] Refers to heating, cooling, ventilating and hot water (Jenkins, D., et al., 2008, Table 6)

3.2.3.3 Jenkins, Tucker, & Rawlings (2009)

This study assesses the effects of replacing a domestic gas boiler system with a GSHP system in terms of energy, carbon dioxide emissions and costs by the creation of a GSHP model. Within this scenario, it further examines the effects of varying some of the factors significant in heat pump performance, such as output temperature to the distribution system or the ground depth of the system collector.

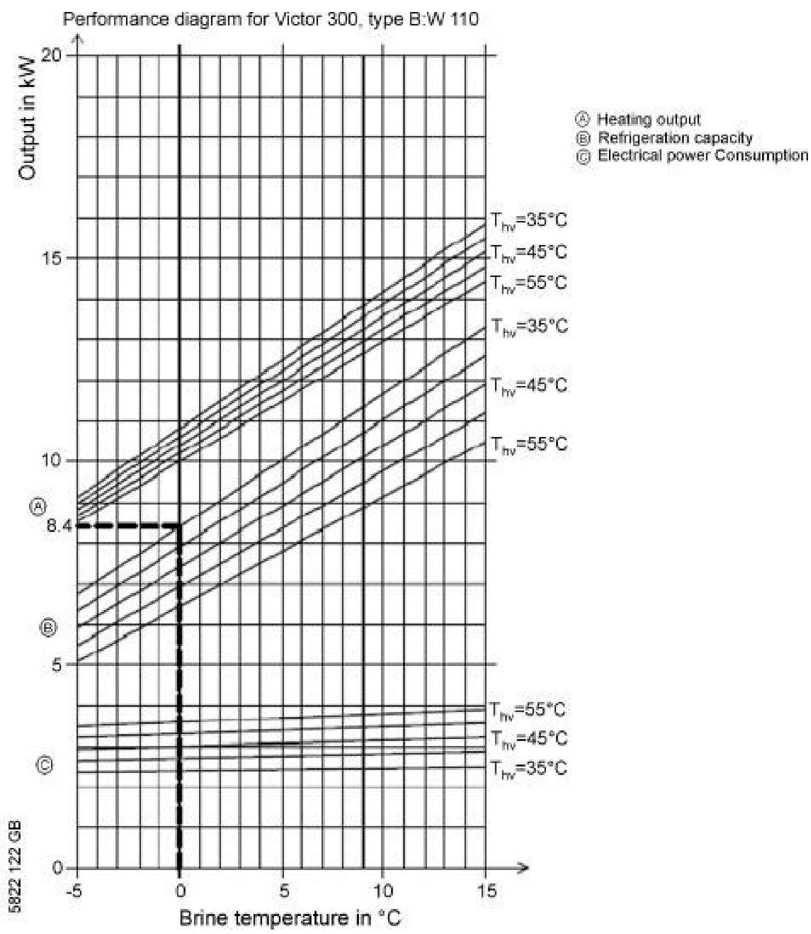


Figure 3.3 Performance diagram for Viessmann Vitocal 300

(Fig. 2 from Jenkins, D. P., et al., 2009)

The starting point for the model described is a set of performance curves for a specific heat pump product, Figure 3.3, showing electricity consumption and heating and cooling output related to the temperature of the brine returning from the ground loop or source. Each set contains a curve for the values corresponding to system output temperatures from 35ºC to 55ºC, with intermediate curves at 5ºC intervals. The curve range covers a source range of -5ºC to 15ºC. A "Reference" value for each of the graphed values is defined at a source value of 0ºC and sink value of 35ºC. Relationships for COP with source and sink temperatures, and heat capacity with source and sink temperatures are then derived from the performance curves, again in terms of f_{COP} and f_Q as per the previous paper, relating these factors to the COP and capacity at the reference temperatures. For the given heat pump, this provides equations from which COP and capacity values can be calculated for a given source temperature and any of

35ºC, 45ºC or 55ºC sink temperatures according to the distribution system in the dwelling.

Jenks et al.(2009) starting position for determining source temperature is defined in Equation 3.14 (Labs, 1979) which relates soil temperature to collector depth, soil type and surface (air) temperatures as follows:

$$T(x_s,t) = T_m - A_s \exp\left\{ -x_s \left(\frac{\pi}{365\alpha} \right)^{1/2} \right\} \cos\left\{ \frac{2\pi}{365}\left[t - t_0 - \frac{x_s}{2}\left(\frac{365}{\pi\alpha} \right)^{1/2} \right] \right\} \quad \textbf{(3.14)}$$

where $T(x_s, t)$ is the temperature at soil depth x_s on day t (in Julian day format, where 1st January = 0, 31st December = 364 in a non-leap year and t_0 is the day when the minimum soil surface temperature occurs), T_m is mean soil temperature, A_s is annual surface temperature amplitude (maximum temperature – minimum temperature divided by 2), α is the soil thermal diffusivity in m^2/day. Thermal diffusivity = $k / (\rho . c_p)$, where k is thermal conductivity (W/(m·K)), ρ is density (kg/m³), c_p is specific heat capacity (J/(kg·K)) and is a measure of *"thermal inertia"* (Venkanna, 2010, p. 38). This model of soil temperature is verified against data from the Environmental Change Network's site at Rothamsted, using values of mean soil temperature of 10 ºC, annual surface temperature amplitude of 8ºC, minimum temperature occurring at 24 days and soil diffusivity of 0.05 m2/day, with comparative results from actual and predicted data shown in Figure 3.4.

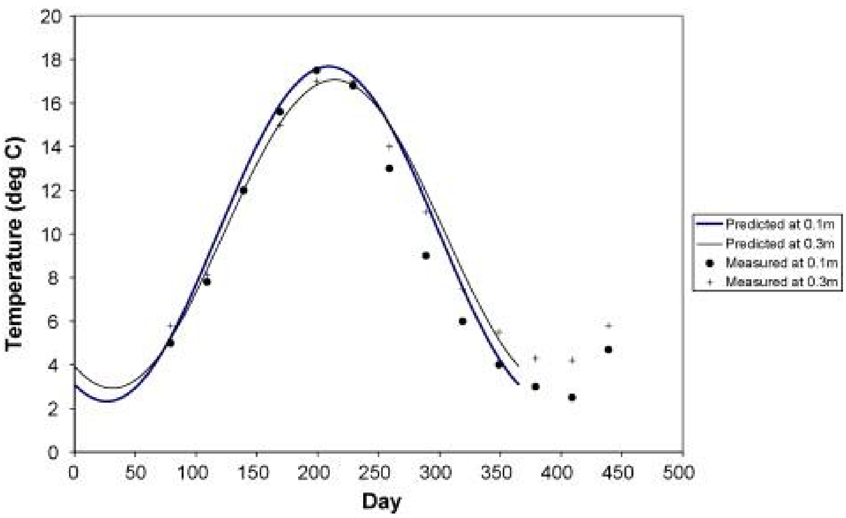


Figure 3.4 Measured and predicted temperatures from Equation 3.14

(Fig 3 from Jenkins, D. P., et al., 2009)

Given the soil temperature, Jenkins, et al. (2009) adjust this value by the addition of 6ºC to give a source (*"brine"*) temperature returning from the ground loop, when the heat pump is operating at its rated capacity, and state that this value will reduce in proportion to the ratio of heating demand to GSHP rated capacity, such that as the heat output from the system falls, then the difference between soil temperature and the return temperature from the ground loop will decrease.

With the adjusted ground loop temperatures from Equation 3.14, and a dataset of hourly thermal loads for a year for an existing house, Jenkins et al. (2009) calculate energy consumption, overall SPF and CO_2 savings for that dwelling on an hourly basis, then perform analyses to observe the effects of varying the system output temperature and the ground loop depth on the system performance, carbon dioxide emissions and running costs.

Further analyses are carried out to determine the optimum sizing of the heat pump system with respect both to carbon emissions and cost savings. Figure 3.5 indicates that maximum carbon emission reductions of 44% are realised when the heat pump system meets 100% of the peak load of the dwelling, with substantial savings of around 38% at 60% of peak load, at which level about 95% of the total annual heating load will still be met. From Figure 3.6, Jenkins et al. (2009) infer that 80% of peak load will achieve very close to the maximum cost savings of about 30%, and that therefore the replacement heat pump system should be sized between 60% and 80% of peak load.

Finally, Jenkins et al. (2009) examine the effects of the carbon intensity of electricity generation, shown

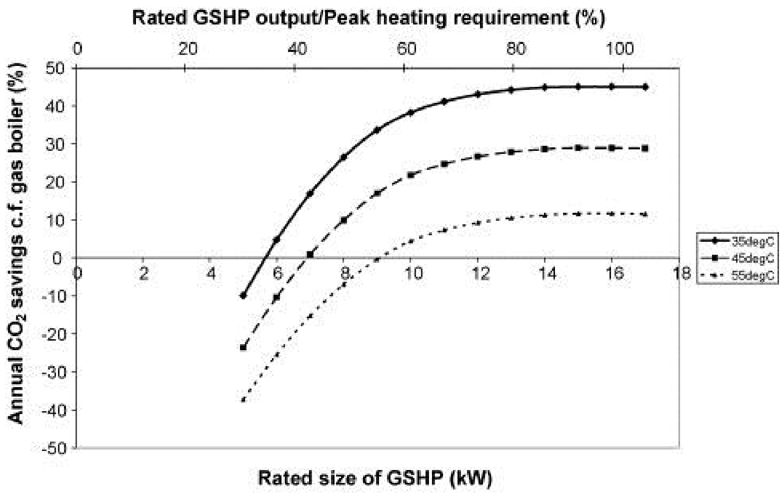


Figure 3.5 Effect of heat pump size on predicted carbon emissions savings (Fig 9 from Jenkins, D. P., et al., 2009)

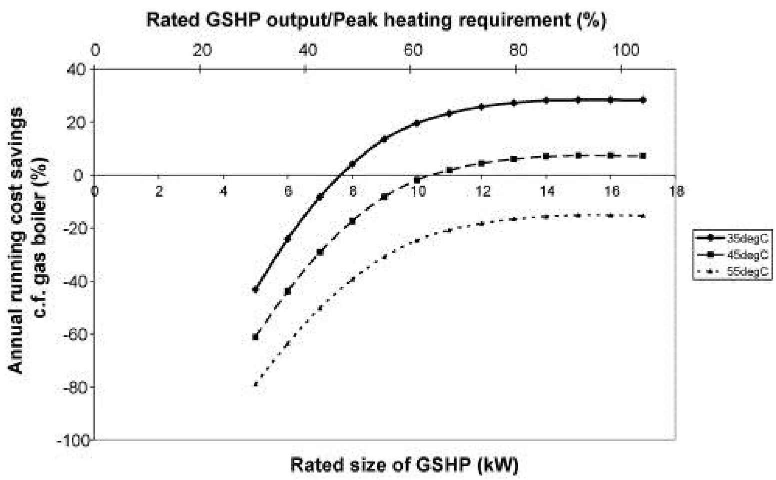


Figure 3.6 Effect of GSHP size on predicted running cost savings (Fig. 10 from Jenkins, D. P., et al., 2009)

in Figure 3.7 that the carbon reducing potential of heat pump systems is strongly dependent on grid carbon intensity, with the currently-accepted values indicating that the lower level of system performance at higher temperature not unexpectedly produces lower levels of reduction.

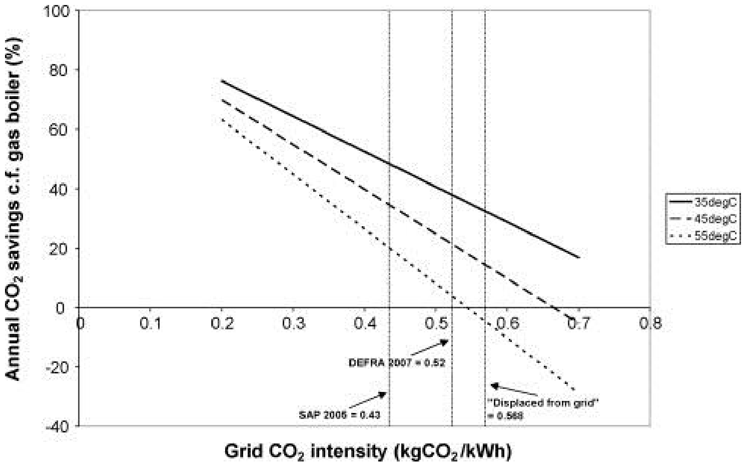


Figure 3.7 Effects of grid CO_2 intensity on annual CO_2 savings
(Fig 11 from Jenkins, D. P., et al., 2009)

The Jenkins et al. (2009) study raises questions as to whether the adjustment to soil temperature to obtain a return temperature from the system ground loop will decrease according to the ratio of the system output to the heat pump capacity and also as to whether the use of a single constant value for the distribution temperature is valid. The validity of the first of these assumption must be dependent on the variation of the speed of the ground loop pump with output. A constant speed pump would, presumably, maintain the same temperature difference throughout. A variable speed pump will cause the output temperature from the ground loop to rise with an increase in flow rate, thereby reducing the differential between the soil temperature and the output temperature and increasing the temperature differential across the ground loop.

The use of a single output temperature is questionable because the model treats the generation of DHW as part of the normal heating load, ignoring the requirement that water should be heated to 60ºC to prevent the growth of Legionnella bacteria. This is particularly significant if the output temperature for estimating is at the lowest value of 35ºC.

3.2.3.4 Kelly & Cockroft (2010)

This study examines the effectiveness of retro-fit domestic ASHP systems in reducing costs and carbon emissions via a performance monitoring and modelling process as follows:

- a model of an ASHP system was developed and calibrated using laboratory test data;

- this model was integrated into a whole-building simulation model of a house in a field trial;
- the predictions of the whole-building model were validated against data from the field trial; and
- after being reconfigured to reflect the actual characteristics of the heat pump system as installed, the model was used in estimating the annual energy and economic performance of the ASHP compared with alternative heating systems.

The modelling of the ASHP in this study is described by the authors as '*grey-box*', in that it reflects the underlying physical features of the device but with characteristics approximated using empirically derived expressions. Thus, for the heat pump itself, the model contains one module representing the system collector and compressor, modelling the acquisition of heat from the environment, and modules representing either side of the system condenser, modelling the passing of heat to the distribution system Figure 3.8.

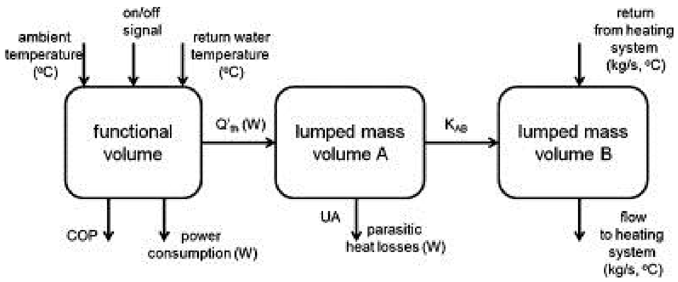


Figure 3.8 Diagrammatic representation of the heat pump model
(Fig. 2 from Kelly & Cockroft, 2010)

The equations for the collector and compressor calculate the COP and heat output Q at each time-step as a 2nd-order polynomial function of the heat pump 'lift', ie. the difference between the output temperature to the distribution system and the temperature at the collector, with the polynomial coefficients derived from the heat pump performance test results. A comparison of the model output and the test results is shown in Figure 3.9.

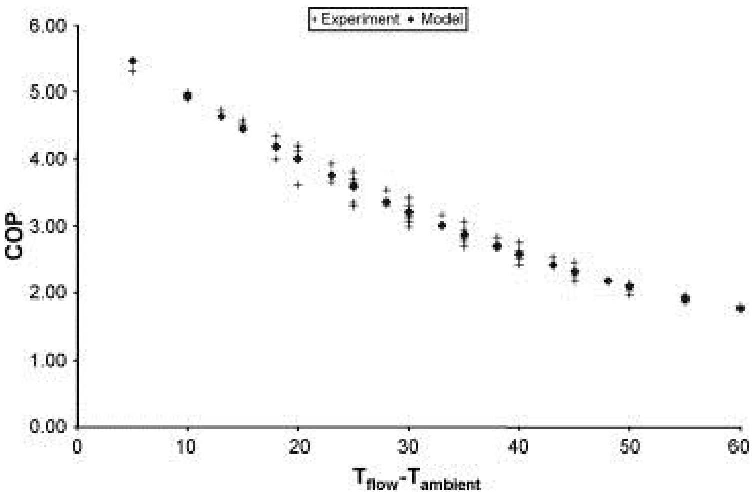


Figure 3.9 Test results for COP vs temperature 'lift' compared with estimates from model
(Fig. 3 from Kelly & Cockroft, 2010)

The resultant heat pump model was then integrated into a dynamic simulation model reproducing one of the dwellings in the ASHP trial in room layout, constructions, distribution system and air-tightness, with occupancy assumed from current practice. Inconsistency between the results from this model and data collected from the field trial showed that the system as installed had been configured incorrectly, and therefore the model was amended to match the actual configuration. The two set of results, before and after the change, are shown in Figure 3.10 (a) and (b), indicating the much improved fit obtained by the modification.

Further detailed simulation was carried out comparing the ASHP with a condensing gas boiler boiler rated at an efficiency of 88% and a direct electric radiator system rated at 100% efficiency, efficiency, with results as per

Table 3.4 &

Table 3.5. Similarly to the previous studies, these indicate the potential for carbon emission reductions but with higher running costs of heat pump installations over gas boilers, contrasting with substantial carbon emissions and cost reductions compared with direct electric heating. The carbon dioxide emissions estimates are based on 0.54 kg/kWh for grid electricity and 0.19 kg/kWh for natural gas.

Table 3.5 also shows the monthly variation of COP over the year, which varies by about 8% below the yearly average in February to about 12% above in September.

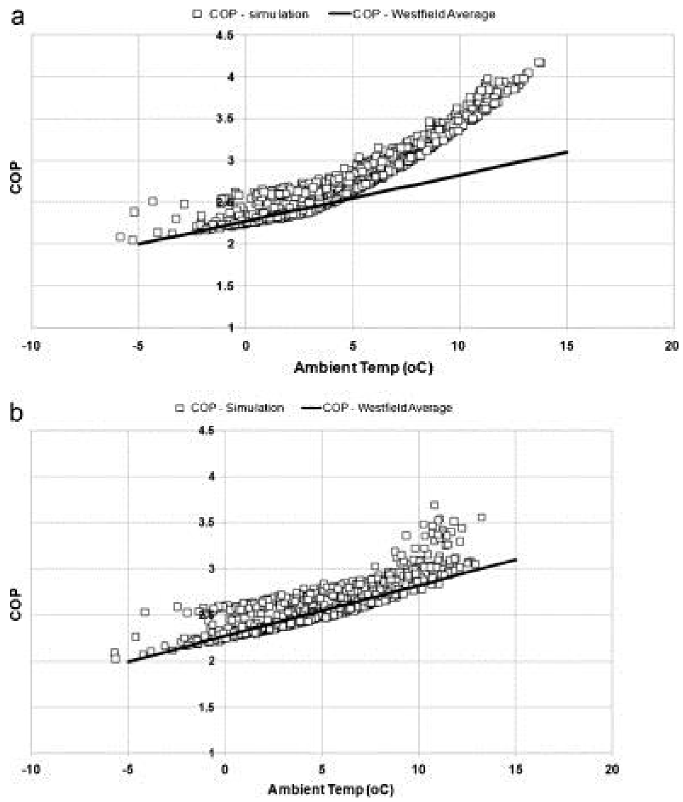


Figure 3.10 (a) Predicted COP vs. monitoring average COP and (b) predicted COP (no temperature compensation) vs. monitoring average COP.

(Fig. 5a & b from Kelly & Cockroft, 2010)

Table 3.4 Comparison of ASHP, gas condensing boiler & direct electric space heating systems.

	Fuel price (p/kWh)	Annual energy use (kWh)	Annual cost (£)	Annual CO2 emissions (kg)
ASHP heating	12.11	1631	197.51	881
Gas condensing boiler heating	3.41	5275	179.88	1002
All-electric heating	12.11	3,640	440.8	1966

(Table 3, Kelly & Cockroft, 2010)

Table 3.5 (a) ASHP detailed simulation results; (b) boiler detailed simulation results; (c) direct electrical heating annual simulation results.

	January	February	March	April	May	June	July	August	September	October	November	December	Year
(a)													
Actual COP	2.58	2.55	2.71	2.77	2.9				3.1	2.91	2.78	2.67	2.77
Electrical (kWh)	308	261	219	113	57				37	143	221	272	1631
ASHP heat out (kWh)	793	667	593	314	164				113	418	613	727	4403
System heat loss (kWh)	46	44	41	35	30				22	37	39	42	335
Total system heat out (kWh)	747	623	552	279	134				91	381	574	685	4067
ON/OFF cycles	459	456	477	301	166				116	388	478	470	3311
(b)													
Efficiency	0.88	0.88	0.88	0.88	0.89				0.89	0.88	0.88	0.88	0.88
Gas (kWh)	937	788	701	385	203				144	521	732	865	5275
Boiler heat out (kWh)	821	691	617	341	180				128	459	643	759	4638
System heat loss (kWh)	34	40	45	47	41				38	56	42	36	379
Total System Heat Out (kWh)	787	652	571	294	139				91	403	601	722	4259
ON/OFF cycles	1087	932	911	528	282				206	758	964	1044	6712
(c)													
Total system heat out (kWh)	692	572	496	250	116				69	320	505	620	3640

(Table 2, Kelly & Cockroft, 2010)

3.2.3.5 Staffel (2009)

This paper is a review of a large number of data sources for heat pump performance data, with samples from laboratory testing to EN14511 and EN255 by the Wärmepumpen-Testzentrum (WPZ) for both ASHPs and GSHPs, from manufacturers' data sheets for ASHPs and GSHPs (Nibe, Calorex, Ciat, Thermia, Nordic, Daikin, Hitachi, IVT, Viessmann, Worcester Bosch), from independent testing by BRE of a Mitsubishi ASHP system, and from field trials of ASHPs in Slovenia, Belgium, Japan (2 trials), Germany, and of GSHPs in Slovenia, UK, Germany and Japan. Of the field trials, the German trials by the Fraunhofer Institute for Solar Energy Systems are the most significant, consisting of some 110 systems from 7 manufacturers.(Miara, 2007)

The main analyses in this review are plots of COP against 'lift' - difference between input temperature and output temperature - for the WPZ data and SPF against lift for the Fraunhofer Institute trial data in Figure 3.11. This last figure is not that used by Staffel(2009), but another in the same source document using monthly rather than daily values.

Staffel(2009)'s analyses of the test results appear to show a simple, linear relationship between COP and 'lift', with the parameters of this relationship varying depending on system type (ASHP or GSHP). Unfortunately the originals are of too poor quality to include here. The plot of the field trial is much less clearly linear, a result which may be caused by the inclusion of electricity for back-up heating within the system boundary for the electricity consumption data collected(Miara, 2007, p. 11).

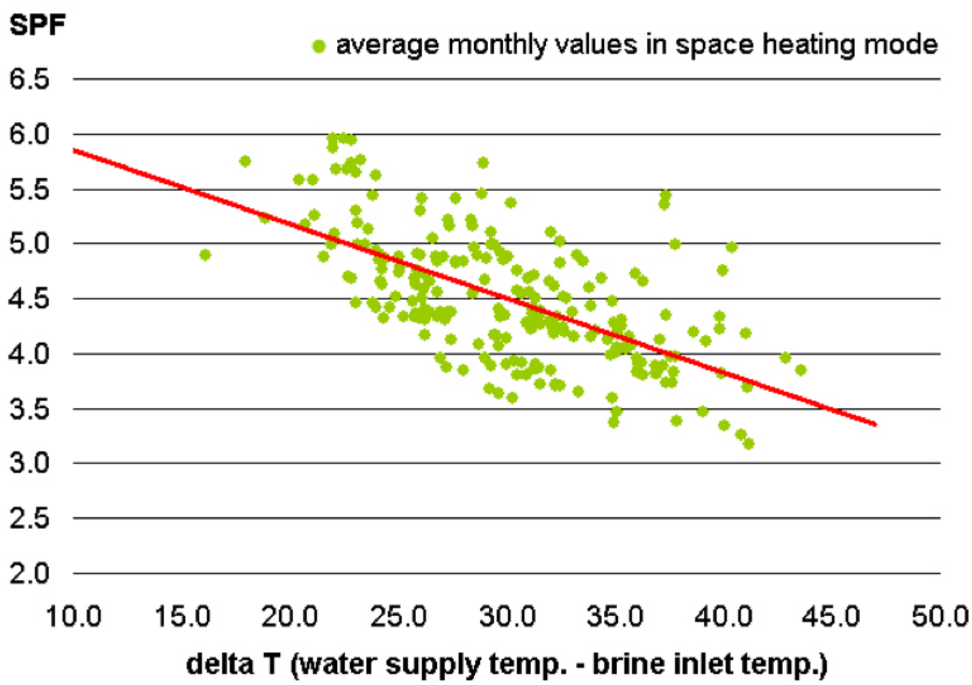


Figure 3.11 SPF vs 'lift' (Miara, 2007, p. 13)

3.2.3.6 Westergren(2000)

This paper details an approach to modelling energy consumption in a single family home using a GSHP system as part of a larger project to estimate the total energy need in such houses in Sweden. The estimation for this type of system has been separated into a separate paper and method because of the relation of the performance of GSHP systems to the temperature difference between the heat pump source and the dwelling interior, rather than simply to the difference between internal and external temperature;

and because of the requirement to estimate the energy consumption of an additional backup heating system.

From a conventional heat balance model for the energy requirement of the dwelling, the procedure starts from an approximation of average daily temperature over the heating season (≤ 10ºC) based on a sinusoidal inequality as follows:

$$a_\theta + A_\theta sin\left(\frac{t + \varphi_\theta}{365} \cdot 2\pi\right) \leq \theta_0 \quad \textbf{(3.15)}$$

where

a_q = Annual average temperature

A_θ = Daily average temperature amplitude

t = Day no. starting from 1^{st} January

φ_θ = Phase shift to day of minimum temperature correct.

θ_0 = Limit temperature for meteorological summer (≤ 10ºC) or set-point for the additional heating system (not given in paper)

Given the equation defining the surface temperature, Westergren(2000) gives the equation for the temperature amplitude at depth *d,* which is reduced in range and lagged behind that at the surface, as follows:

$$A_d = A \cdot e^{-\frac{d}{D}} \quad \textbf{(3.16)}$$

where

A_d= Temperature amplitude at depth d

A = Temperature amplitude at surface

D = Damping depth.

The 'damping depth' is a constant measuring the decrease in temperature amplitude with soil depth and is a function of soil thermal diffusivity.

The lag at depth d is assumed to be proportional to the distance below the surface, giving the phase shift as:

$$\varphi = \frac{d}{D} \cdot \frac{365}{2\pi} \ days \quad \textbf{(3.17)}$$

where

φ = Phase shift (in days)

d = Collector depth

D = Damping depth.

Westergren(2000) then derives a formula for the COP of a generalised heat pump based on the assumption that this is directly proportional to the Carnot COP for the system

$$\eta(t) = k \cdot \frac{\theta + 273.15}{\theta - a_\theta - A_d sin\left(\frac{t + \varphi_\theta - \varphi}{365} \cdot 2\pi\right)} \tag{3.18}$$

where

k = a constant representing the actual COP of the heat pump system as a proportion of the theoretical maximum COP at the given input and output temperatures

a_θ = Annual average temperature

A_θ = Daily average temperature amplitude

t = Day no. starting from 1st January

φ_θ = Phase shift to day of minimum temperature

φ = Phase shift to day t

θ = System output temperature

given by $^{T_H}/_{T_H - T_C}$ where T_H and T_C = the system output and input temperatures, both in degrees K. Given a fixed output temperature, denoted by θ, and substituting the previous equations in the Carnot COP calculation, the following equation is given for heat pump performance:

The remaining section of the Westergren (2000) paper describes the details of regression-based dwelling energy models, both static and dynamic, utilising this expression for the heat pump COP, which also include estimation of the energy consumption of a secondary, back-up system. The data on which these model are based was collected from Swedish dwellings in a monitoring study.

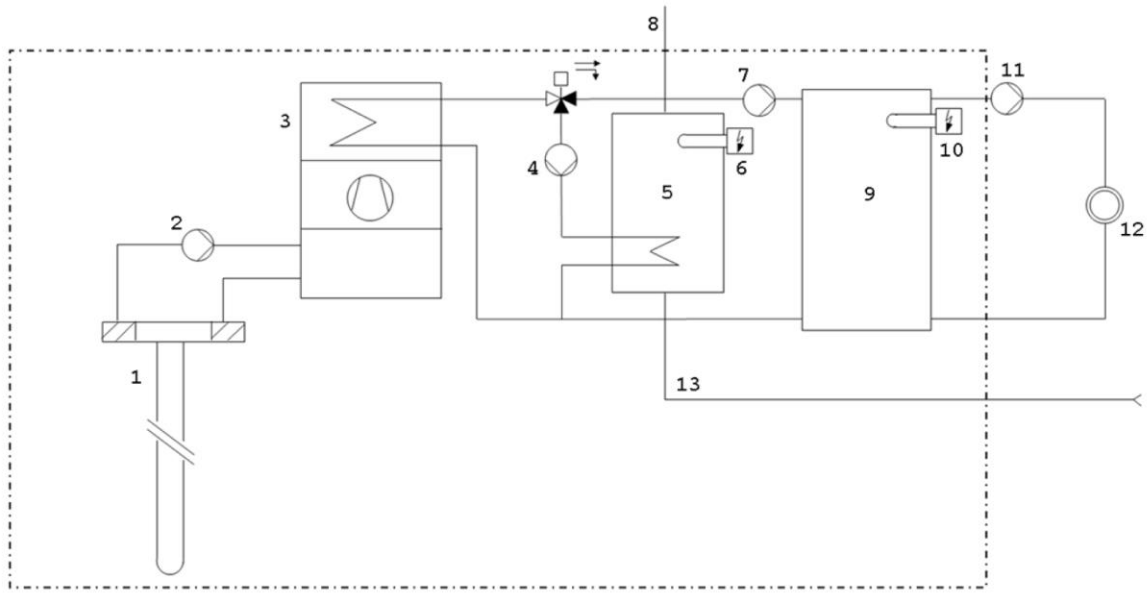
3.3 Models in standards

3.3.1 British Standard EN15316-4-2 (British Standards Institution, 2008a)

3.3.1.1 General

BS EN 15316-4-2 (hereinafter referred to as 'The Standard') is a long (130 pages including annexes) and complex set of standards that applies not only to the electrically-driven, vapour-compression heat pumps which are the subject of this thesis but also to combustion engine driven vapour compression and thermally driven absorption cycle heat pumps. It also defines two forms of model to estimate heat pump energy consumption and efficiencies, of which the simpler, the '*system typology*' method, is defined only in general terms in the standard, while the more complex, *'component efficiency'* or *'bin-method'* method is defined at length, with a worked example in Annex D. The Standard states that the detail of the simpler method should be defined in a national annex for each country, which has not been specified for England and Wales, apart from the heat pump-related parameters in SAP. The Standard was developed through the International Energy Agency Heat Pump Programme Annex 28 (Wemhöner & Afjei, 2006a, 2006b).

The heat pump system configuration to which this Standard relates is shown in Figure 3.12. This differs from those in the monitoring study in this thesis in that it allows for a buffer store associated with the distribution system, with corresponding heat losses. The effects of this buffer can, presumably, be nullified in calculations by zeroising the parameters for the buffer and pipework.

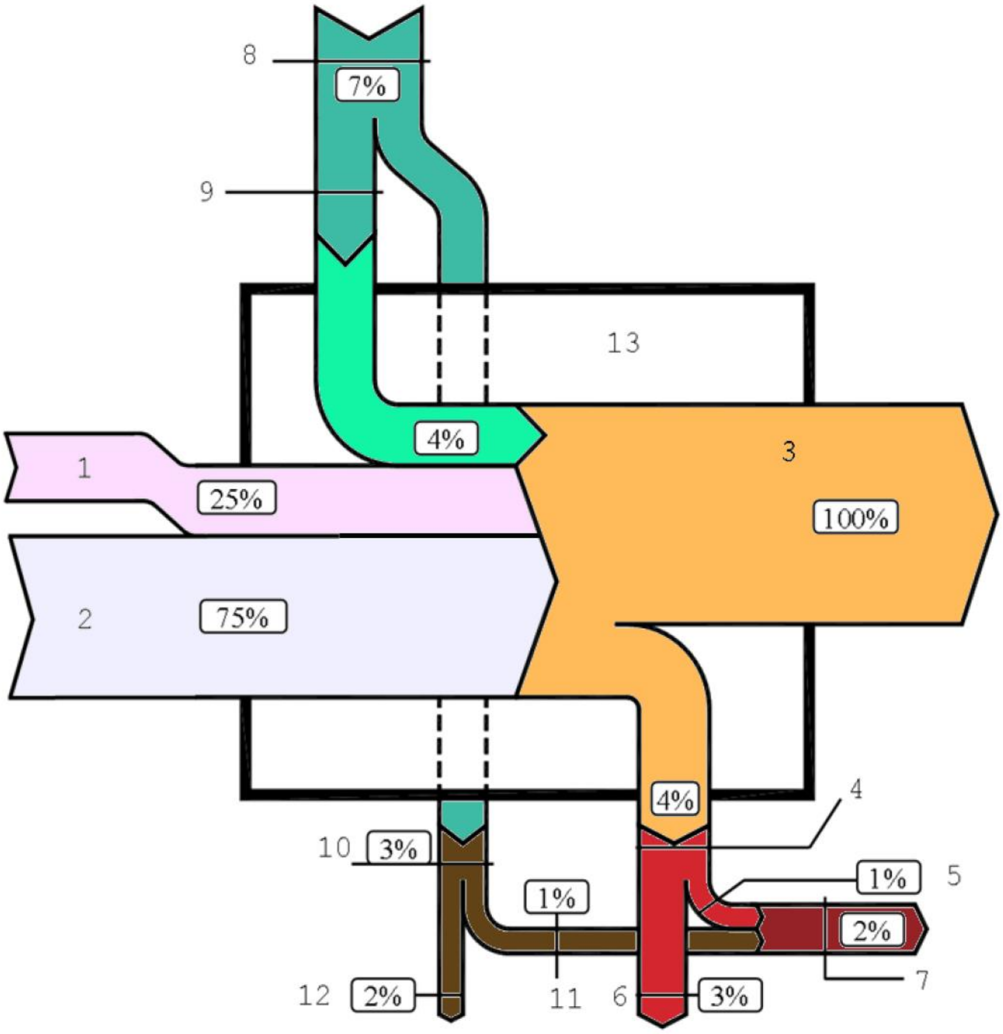


Key

1 heat source system (here: vertical borehole heat exchanger)
2 source pump
3 heat pump
4 DHW storage loading pump
5 DHW storage
6 DHW back-up heater
7 primary pump
8 DHW hot water outlet
9 heating buffer storage
10 space heating back-up heater
11 circulation pump space heating distribution subsystem
12 heat emission subsystem
13 DHW cold water inlet

Figure 3.12 Heat pump system boundaries

(Fig. 1 from British Standards Institution, 2008a)



1	driving energy input to cover the heat requirement (e.g. electricity, fuel) $E_{HW,gen,in}$	8	generation subsystem total auxiliary energy $W_{HW,gen,aux}$
2	ambient heat used as heat source of the heat pump $Q_{HW,gen,in}$	9	generation subsystem recovered auxiliary energy $Q_{HW,gen,aux,ls,rvd}$
3	heat output of the generation subsystem corresponding to the heat requirement of the distribution sub- system(s) $Q_{HW,gen,out} = Q_{HW,dis,in}$	10	generation subsystem unrecovered auxiliary energy $Q_{HW,gen,aux,ls}$
4	generation subsystem thermal losses $Q_{HW,gen,ls}$	11	generation subsystem recoverable auxiliary energy $Q_{HW,gen,aux,ls,rbl}$
5	generation subsystem thermal loss (thermal part) recoverable for space heating $Q_{HW,gen,ls,rbl}$	12	generation subsystem non-recoverable auxiliary energy $Q_{HW,gen,aux,ls,nrbl}$
6	generation subsystem thermal loss (thermal part) non-recoverable $Q_{HW,gen,ls,nrbl}$	13	generation subsystem
7	generation subsystem thermal loss recoverable for space heating $Q_{HW,gen,ls,rbl,tot}$		

Figure 3.13 Energy balance of EN15316-4-2 generation system

(Fig. 2 from British Standards Institute, 2008 - colouring additions by author)

The energy flows included in this Standard are shown in Figure 3.13, of which the percentage values '*are intended to give an idea of the size of the respective energy flows*' and are therefore not definitive.

The Standard states that the method is based on standard test results (British Standards Institution, 2007) and is to be carried out with the heat capacity and COP data for a specific system. The procedures in the Standard revolve around the partitioning of the calculation period (which may be a month or a year) into 'bins'. In this context, the meaning of a 'bin' is a division of the calculation period into temperature intervals for which are accumulated the hourly averaged frequency values for temperatures in the bin range. Thus, if a bin is defined as the interval from 0ºC to 10ºC, then a total for this bin is the number of hours during which the external average temperature was in this range. Within each bin, the operating conditions are assumed to be those of the central value, the '*operating point*', in the example 5ºC.

According to the Standard, bins should be chosen to have an even spread of operating points across the temperature range, where possible with operating points coinciding with the test points at which the performance results were measured and bin limits half-way between operating points. It is unclear as to how overlapping source/sink ranges should be handled. As an alternative to bins determined by test points, bins can be defined as 1 K only in size, with COP values interpolated between test results.

3.3.1.2 'Detailed case specific calculation based on component efficiency data' method

The flow of this procedure is shown in Figure 3.14.

After initial configuration, the procedure allows for the two operating modes: monovalent and bivalent. Estimating methods for the bivalent mode are defined at two levels of complexity, of which the simpler level requires the knowledge (or assumption) of a value for the system balance point, which is not required for the more complex one.

A further high-level decision point is made depending on whether the heat pump system is capable of simultaneous space heating and hot water generation, which introduces an extra level of complexity into the system running time calculations.

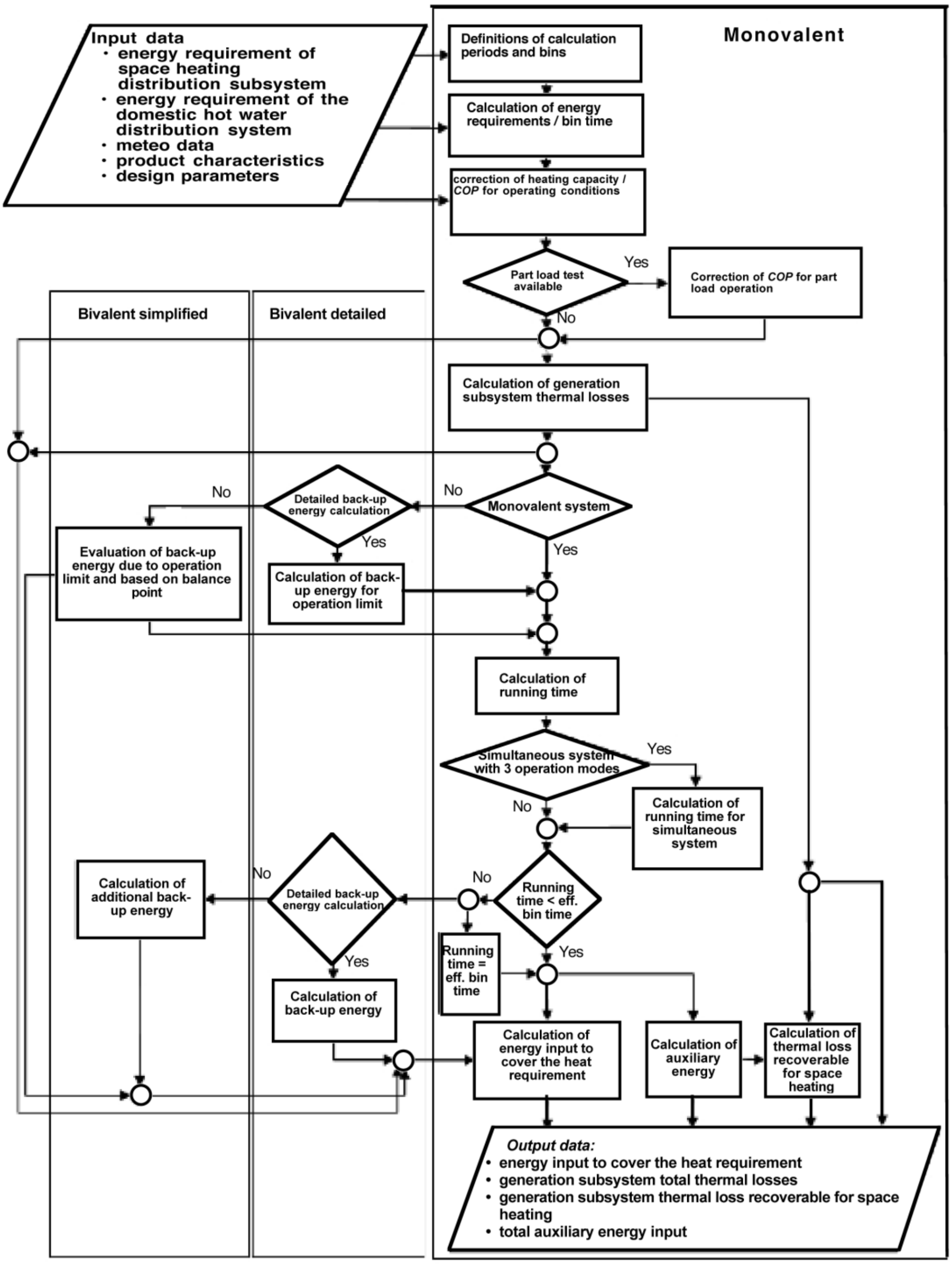


Figure 3.14 Flowchart of detailed process (British Standards Institute, 2008) Captions inserted from key by author

The main steps of the estimating procedure appear as follows:

a) definition of the calculation periods (month, year) and bins

b) calculation of energy requirements for each bin

c) correction of the system's heating capacity and COP according to the operating conditions, ie. source and sink temperatures, for each bin;

d) if the results of part-load testing on the system are available, the COP value is corrected for the effects of part-load running;

e) calculation of heat losses from the system, particularly from a buffer tank and associated pipework if present;

f) the previous steps establish the total energy consumption in each bin directly for space heating or hot water generation, allowing the calculation of back-up energy use for either of these functions where such back-up is included in the configuration;

g) calculation of the heat pump running time in providing the required energy;

h) calculation of auxiliary energy, i.e. that consumed by the system pumps, not only in the main operation of importing heat from the source and distributing it to the sink, but also in stand-by operation while the system controller is monitoring temperatures for weather compensation control.

i) estimation of thermal losses from the system which are recoverable via the ambient - either inside the casing of the system itself or the dwelling.

j) final calculations total the energy output and the losses from the system for space heating and hot water generation and divide by the system COP to obtain estimates for the electricity consumed for these purposes by the heat pump.

3.3.2 Calculation Rules

These are lengthy as is may be judged by the flowchart in Figure 3.14, involving the evaluation of a table of bin entries (containing the number of hours during which the ambient temperature lies between an upper and lower value), with options for more or less complex computation methods. The detail of the computation rules is described in Appendix I.

3.3.2.1 Boundary conditions

The Standard has the following data parameter requirements (also known as boundary conditions):

Boundary conditions

Meteorological data:

- *frequency of the outdoor air temperature of the site at 1 K resolution or hourly average values of the outdoor air temperature for an entire year;*
- *outdoor design temperature of the site.*

Space heating (SH) mode:

- *indoor design temperature;*
- *heat energy requirement of the space heating distribution subsystem according to EN 15316-2-3;*
- *type and controller setting of the heat emission subsystem (flow temperature of the heating system dependent on the outdoor air temperature, e.g. heating characteristic curve or characteristic of room thermostat), temperature spread at design conditions, upper temperature limit for heating;*
- *heat pump characteristics for heating capacity and COP according to product test standards (e.g. according to EN 14511 for electrically-driven heat pumps) and guaranteed temperature level that can be produced with the heat pump;*
- *results for part load operation, e.g. according to CEN/TS 14825 for electrically-driven heat pumps, if available;*
- *for the simplified calculation method of the back-up energy, the balance point;*
- *system configuration:*
  - *installed back-up heater: operation mode, efficiency (fuel back-up heater according to EN 15316-4-1);*
  - *installed heating buffer storage: stand-by loss value, flow temperature requirements;*
  - *power of auxiliary components (source pump, storage loading pump, primary pump, stand-by consumption).*

Domestic hot water (DHW) mode:

– heat energy requirement of domestic hot water distribution subsystem according to EN 15316-3-2;

– temperature requirements of DHW operation: cold water inlet temperature (e.g. 15 °C), DHW design temperature (e.g. 60 °C);

– heat pump characteristics for DHW heating capacity and COP according to product test standards (e.g. according to EN 255-3 for electrically-driven heat pumps);

– set temperature for the energy delivery by the heat pump (e.g. at 55 °C due to heat pump operating limit);

– parameters of the domestic hot water storage (stand-by loss value);

– installed back-up heater: operation mode, efficiency (fuel back-up heaters are calculated according to EN 15316-4-1).

This is a considerable number of data items, particularly for the controller settings, rendering it almost impossible to use this routine for sizing a heat pump.

3.3.2.2 Overall totals

The Standard requires the following overall totals to be calculated:

a) Electricity input to the heat pump for space heating operation

b) Electricity input to the heat pump for domestic hot water operation

c) Energy input to back-up system, for either of

Electrical back-up heater

Fuel back-up heater

d) Total driving and back-up energy input to cover the heat requirement

e) Seasonal performance factor and expenditure factor of the generation subsystem

f) Total heat produced by the heat pump and the back-up heater

3.3.3 Discussion

3.3.3.1 UK approval of the overall EN 15316 Standard

Neither the Standard being discussed here nor any of the other Standards in this series have been accepted by the UK government. In the National Foreword to the document, it is stated that "*the UK voted against this standard on the grounds that it was considered disproportionate to the essential requirements of the EU Energy Performance of Buildings Directive (2002/91/EC), which it supports. In the opinion of the UK committee, EN 15316*[sub-section number] *is regarded as unsuitable for existing buildings where the data required are unlikely to be available."* Amongst other provisions, the Directive (EU Parliament, 2002) requires member countries to provide a method for the assessment of the energy performance of buildings, the output from which is an Energy Performance Rating and associated Certificate which must be made available to a prospective purchaser or tenant at the initial handover of a new building and whenever a building is to be sold or rented out. For the purpose of this Certificate, the method currently used for rating dwellings in the UK is the Reduced Data SAP (RdSAP) procedure, a version of the main SAP routine employing parameter reduction techniques to estimate the values of lower level construction parameters (BRE, 2010a). Many other Standards are involved in the definition of the Energy Performance Rating assessment process and therefore the failure to endorse the EN 15316 series of Standards does not appear to have much effect. Some parts of the EN 15316-4-2 Standard have been invoked in the full SAP assessment in the generalised estimation of heat pump energy consumption and also in the Appendix Q process (BRE, 2009b; Hayton, 2010).

3.3.3.2 Data availability

The initial values used in the Standard's calculations are listed in section 3.3.2.1. To create a generalised model from the equations in the Standard to meet the objectives of this research, it is necessary to examine how these values might be derived for this general case. For the conditions listed above, the following comments apply:

a) Meteorological data at the level of detail required by the routines is not currently used by any of the standard UK domestic energy models. Weather data in BREDEM-8 (Anderson et al., 2001) and BREDEM-12 (Anderson et al., 2002) consists of average monthly temperatures for each of 21 UK regions which are defined by similar heating degree day values, whilst in SAP 9-90 (BRE, 2010a), meteorological data is limited to one set of monthly average temperatures based on a single UK location. Within these routines, values for heating design days are calculated by a standard equation, with the monthly average temperature and month length in days as parameters.

To generalise the meteorological data, it would be necessary to create a table of outdoor air temperature frequencies for each month in each degree-day region.

b) A suitable default value would be required for the outdoor design temperature, as this is not explicitly specified for any of the current UK standard models.

c) Details of the type and settings of the system controller are not available in the UK standard models. The Standard provides an equation (Section B.1, page 70) to describe the relationship between external temperature and the distribution flow temperature, which is the value required in computation, but this requires knowledge of further parameters, the design flow and return temperature to the distribution system, for which general values are not available in the UK standard models. This equation also requires an outdoor design temperature value.

d) Heat pump performance test results are available from the Wärmenpumpen Testzentrum (WaermenPumpen Testzentrum, 2011) for individual heat pumps. A guaranteed temperature level value is usually only available in manufacturer's documentation (IVT Industrier AB, 2004).

e) Performance test results according to CEN/TS 14825 for part-load operation are not, to the author's knowledge, available in significant numbers comparable with the EN14511 and EN255 results published by WPZ.

f) House balance point temperatures are not usually available for existing houses, requiring analysis to obtain a suitable general value.

g) The parameters required for estimation of the energy use of domestic hot water generation and storage would appear to raise the same issues as space heating.

3.3.3.3 Complexity and interconnectivity of Standards documents

As a somewhat crude measure of complexity, the Standard under consideration contains some 58 equations to estimate the energy use of a heat pump heating system alone whereas the BREDEM-12 specification (Anderson, et al., 2002) contains about 70 equations in its dwelling energy model, including some calculations of heating system energy use which would be included within the EN 15316-4 series of Standards. The calculations example in Annex D of the Standard contains 47 steps for 4 bins, but covers one calculation period only, ie. a month, requiring 12 repetitions for a complete year of estimates which equates to about 2250 calculations. The method used in Annex D is the 'simplified' method and the 'detailed' method would require perhaps the same number of calculations again, depending on the temperature range of the climate at the site.

The Standard under consideration is one of a set of 14 parts in BS EN 15316. It also references eight other Standards which themselves reference further Standards and so on. Since these are all part of a structure aimed at the *"European harmonisation of the methodology for the calculation of the energy performance of buildings",* to quote the Foreword of BS EN 13790 (British Standards Institution, 2008b), then it is to be hoped that, as far as possible, the estimating methods defined in the Standards in this series are in step. It is however, another matter as whether the heat pump model as defined in this Standard can be employed in a domestic energy model that is not part of the structure, since the available standard UK dwelling energy models pre-date these European Standards, and SAP (BRE, 2005, 2010a) makes reference to a single Standard, BS EN13790 (British Standards Institution, 2008b).

3.3.3.4 Computer processing

While the author has no definite evidence, his impression is that reproducing the BS 15316-4-2 routines in a spreadsheet routine, especially one which analysed many dwelling samples, would require excessively lengthy processing times. The detailed method, particularly the estimation of back-up energy, would require the processing of a table of 9 bins (rows) times 14 columns for each period (eg. a month) for each sample, a total of 1512 cells per sample to provide a year's estimate.

3.3.4 BREDEM/SAP models

3.3.4.1 General

The BREDEM series of models have been used by BRE as their main means of estimating the energy use of dwellings since the inception of the basic energy model, named BREDEM-1, as documented by Christine Uglow in 1981 (Uglow, 1981). Since then, BREDEM has been developed through versions 2 to 12 and adopted as the basis of commercial energy assessment software, with BREDEM-9 being spun off as the basis for SAP (Shorrock & Anderson, 1995). BREDEM-8 and 12 models form the basis of the BREHOMES modelling at national level of domestic energy use (Henderson & Shorrock, 1988; L D Shorrock, Henderson, & Bown, 1991(Shorrock & Dunster, 1997) providing analyses of energy consumption for the English House Condition Survey (Utley & Shorrock, 2008) and SAP forms the basis of the system for approving the design of new dwellings laid down by the Approved Documents of Part L1 of the UK Building Regulations (BRE, 2008). These are, therefore, accepted standard models for the estimation of energy consumption and carbon emissions in the UK.

The BREDEM models (Anderson, et al., 2001) are based on a static space heating equation, in which the heating requirement is determined by the difference between internal and external temperatures and by the specific heat loss coefficient for the building, as calculated from the resistivity of its construction elements and its ventilation losses. The various heat gains, ie. solar gain, casual gains from occupants, from hot water generation and cooking, etc. that also determine the heating requirement are estimated using empirical relationships based on appropriate characterising data, viz. window area, location and orientation, floor area etc. The dwelling is divided into two heating zones, each with its own heat loss coefficient, with the transmission of heat between zones estimated by the definition of an interzonal heat loss coefficient. External temperatures are determined from a table of average monthly temperatures according to the building's location. Mean internal temperatures are determined from the demand temperature required by the occupants, conventionally set to 21°C; from a 'responsiveness' parameter determined by the type of heat distribution system and its controls; from the heating pattern adopted by the occupants; and from the heat loss coefficient. The responsiveness parameter indicates how long the heating system takes to return to background temperature after it has been turned off and varies from 1.0 for a completely responsive system like a hot air system to 0.00 for electric underfloor heating.

The estimated space heating energy load is then calculated on a monthly basis from the heat loss coefficients, the heating degree days for each month and the mean internal temperature and from this, the required input fuel or energy use from the efficiency of the chosen heating system or systems according to the relative proportion of the dwelling heated by each system(Anderson, et al., 2001).

A base-line efficiency for each heating system is selected from the tables provided and is then adjusted according to more specific characteristics of the system. In the case of the BREDEM models, the heating system types are generic only, while for SAP, specific models of gas or oil boilers may be specified. A later addition to SAP provides a facility to estimate for a specific heat pump model selected from a limited database via a process known as Appendix Q.

3.3.4.2 Parameters used for heat pump systems in BREDEM and SAP

The characterisation of heat pump systems in BREDEM can be summarised in Table 3.6. In SAP, exactly the same values are used for the Seasonal Performance Factor, but additional parameters are present as in the following Table 3.7.

Table 3.6 Heat pump system parameters in BREDEM-8

Ref.	Source	Heat pump system parameters in BREDEM-8				
1	**Table D1 Efficiency & responsiveness**		**Efficiency / SPF**	**Responsiveness (from Table D4)**		
		Heat distribution by water		**With radiators**	**UFH in insulated timber floor**	**UFH in screed or concrete slab**
		Ground-to-water heat pump	320			
		Ground-to-water heat pump with auxiliary heater	300	1.0	1.0	0.25
		Water-to-water heat pump	300			
		Air-to-water heat pump	250			
		Heat distribution by air		**Responsiveness (from Table D1)**		
		Ground-to-air heat pump	320		1.0	
		Ground-to-air heat pump with auxiliary heater	300		1.0	
		Water-to-air heat pump	300		1.0	
		Air-to-air heat pump	250		1.0	
2	**From Table D.7**	**Fraction of heat supplied by secondary systems**				
		Main heating system	**Secondary system**	**Fraction**		
		Central heating system with boiler and radiators, central warm-air system or other gas fired systems	gas fires	0.15		
			coal fires	0.10		
			electric heaters	0.05		
		Electric heat pump systems with heat storage or fan-assisted storage heaters	gas fires	0.15		
			coal fires	0.10		
			electric heaters	0.05		

Table 3.7. Summary of heat pump system-related parameters (additional to SPF tables) extracted from SAP 2005, 2008 update specification(BRE,2008)

Ref	Source	Additional heat pump system parameters in SAP 2005	
1	**Distribution type**	**Adjustment to <u>Efficiency of main space heating system</u> value for:**	Adjustment based on max. heat distribution temp. of 50°C.
		Underfloor heating	1.0
		With radiators and with load and weather compensation	0.75
		With radiators, without load or weather compensation	0.7
2	**Domestic Hot Water**	**Adjustment to <u>Efficiency of domestic hot water generation</u> value for percentage supplied**	Adjustment
		All DHW supplied by h p	0.7
		50% of DHW supplied by h p	1.0
		<u>DHW Efficiency</u>	
		If both a heat punp and immersion heater are present (assumes each contributes 50% of heating)	100 / (50 ÷ SPF) + 0.5
3	**Mean internal temperature**	Addition for where no time or thermostatic control fitted or programmer only	+0.3 °C
4	**Fraction of heat supplier by secondary heating system**	All heating system types	0.1

The fourth entry in the above table 3.7 is substantially the same as the second in the previous BREDEM table, but, in the SAP case, does not distinguish between secondary system types.

The absence of calculations 1 - 3 in the above table from BREDEM-8/12 appears anomalous as their effect on the system efficiency value is quite considerable. It is considered by the author that this is sufficiently significant to warrant modifying the BREDEM procedures to include them, subject, of course, to their improving the accuracy of the estimate.

3.3.4.3 SAP Appendix N/Q process

This was introduced in SAP version 9.82 as an 'add-on' to the UK Standard Assessment Procedure (SAP) for assessing the energy performance of dwellings (BRE, 2009b, 2010a, 2010c). The objective of the procedure is to estimate the carbon dioxide and energy consumption savings for the installation of a selected specific heat pump model in the dwelling being assessed, replacing the generic heat pump system for which standard parameters are provided in SAP. The calculation process is documented both in Appendix N of the SAP specification and in a separate document (Hayton, 2010) available from the Appendix Q website (BRE, 2009b). The accompanying database of thermal performance data for heat pump systems which have been verified by testing to EN14511-2 or prEN255-3 standards is contained in a spreadsheet containing an implementation of the calculation method and is available for download from the Appendix Q website. The database is updated with data provided by suppliers or manufacturers. The Appendix Q calculation is additional to and separate from the SAP calculations in that it uses some intermediate results from the SAP calculations, returning results for input at a later step in the SAP calculation. The Appendix Q specification (Hayton, 2010) is said to be based on the British Standard BS EN 15316-4-2 (British Standards Institution, 2008a) document and therefore the test result data values in the database are those required for this calculation. The Appendix Q method largely replaces the parameters as specified in Tables 3.6 and 3.7 when a specific heat pump ‘package’ is selected from the database. However, an initial comment in the attached documentation in the Appendix Q calculations spreadsheet states '*[the procedure] is only valid for the carbon dioxide calculations and shows additional energy saved (or consumed) compared to the default heat pump specified in the SAP calculator; calculations for consumption and costs are invalid*' (BRE, 2010b).

3.3.4.4 SAP Appendix Q database

As stated above, the test results data stored in this database are those generated by the EN14511-2/EN255 test procedures and required as input to the EN 15316-4-2 calculation. The range of equipment for which the database is designed is not limited to the ‘classic’ ASHP or GSHP systems but also allows for test results for exhaust air source equipment with different heat recovery options. Hence some data items are irrelevant to the simpler configurations.

The data consists of a set of items which apply to each heat pump (unique identifier, make, model name, data source, heat source, etc.), followed by two sets of test results for that heat pump, the first of which is the heat recovery results for results containing a group for each emitter type (UFH, radiators or convectors), within which there are results for each of a list of plant size ratios (ratio of system output to design heat loss). The full list of the data items is shown below in Tables 3.8 & 3.9.

Table 3.8. Table N1 from BRE (2010)

Table N1: Package general information

Data item	**Unit**
Package main fuel (see Table 12)	-
For heat pumps, the heat pump source, one of: - ground - water - air - exhaust air MEV - exhaust air MVHR - exhaust air mixed	-
Service provision, one of - space and hot water all year - space and hot water in heating season only - space heating only - water heating only	-
Product index number for MEV/MVHR (for exhaust air MEV, exhaust air MVHR or exhaust air mixed)	-
Hot water vessel, one of - integral to package - separate, specified cylinder - separate but unspecified cylinder - none (DHW not provided by package)	-
Hot water vessel volume (where relevant)	litres
Hot water vessel loss (where relevant)	kWh/day
Hot water vessel volume heat transfer area (where relevant)	m!

Table 3.9. Table N2 from BRE (2010)

Table N2: Set of intermediate results

Data item (applicable to both heat pumps and micro-cogeneration unless indicated otherwise)	**Symbol**	**Unit**
Daily heating duration (24, 16 or 11[18] or variable)		hours/day
Effect of weather compensation included in test data (yes/no)		-
Central heating circulator power including in test data (yes/no)		-
Water heating thermal efficiency for test schedule number 2 [19]	$\eta_{hw,2}$	%
Electricity consumed or, if negative, net electricity generated, during test schedule number 2, per unit of heat generated for water heating	$e_{hw,2}$	kWh of electricity per kWh of heat
Water heating thermal efficiency for optional test schedule number 3 [20]	$\eta_{hw,3}$	%
Electricity consumed or, if negative, net electricity generated, during optional test schedule number 3, per unit of heat generated for water heating	$e_{hw,3}$	kWh of electricity per kWh of heat
For heat pumps - the emitter type to which the results are applicable, one of: - Radiators (including both radiators and underfloor) - Fan coil units (fan convectors) - Underfloor only - Warm air system		-
For exhaust air heat pumps - the air flow rate for which the PSR dependent results apply.		l/s
PSR dependent results		
Plant size ratio for which the data below apply	PSR	-
Space heating thermal efficiency	η_{space}	%
Electricity consumed for space heating or, if negative, net electricity generated, per unit of heat generated for space heating	e_{space}	kWh of electricity per kWh of heat
For exhaust air or mixed air heat pumps - running hours	h_{hp}	hours per year

The Appendix Q data most relevant to this study is the table of entries for each plant size ratio/emitter type combination which consists of:

heating capacity (maximum space heating output for this emitter type);

heating seasonal performance factor (SPF);

heat pump running hours per year.

3.3.4.5 Appendix N/Q calculation process

A large section of the Appendix N/Q process involves the derivation of an estimate for the effect of a possible difference between the standard SAP assumptions for dwelling occupancy – 9 hours on weekdays, 16 hours on Saturday and Sunday - and the heat pump system operating hours – up to 24 hours every day. This creates a replacement equation with which to estimate the Mean Internal Temperature for the dwelling living area in Table 9c. For Section 9a, Energy Requirements, of the main SAP process, a value for the Secondary Fraction (fraction of the heat energy provided by a secondary system) is obtained from reference table N8 according to the PSR and this value is used in field 201 in the SAP worksheet. A value for space heating thermal efficiency is obtained from the Appendix Q database entry for the heat pump, PSR, and emitter type used by the system.

3.3.4.6 Discussion

The characteristics and deficiencies of the BREDEM/SAP heat pump parameters are discussed in Chapter 7.

3.4 Publicly-available software models

These are limited in number. Most publicly-available calculators for heat pump sizing consist only of limited web-based facilities (Encraft Ltd, 2012; Nu-Heat Ltd, 2011; Vaillant Ltd, 2011). A limited, educational spreadsheet tool is available from John Cantor, a UK heat pump expert(Cantor, 2008). A package known as RETScreen is the only reputable and professionally-supported software tool that the author has found.

3.4.1 Encraft heat pump calculator

3.4.1.1 Description

The Encraft heat pump calculator (Encraft Ltd, 2012) is a web-based tool which can be accessed freely by registered users under restricted conditions and embedded in a user's own website if required. Paid versions allow programming access to the tool so that the user can pass parameters avoiding the standard interface.
Samples of the input and output web pages are shown in Figure 3.15 and Figure 3.16.

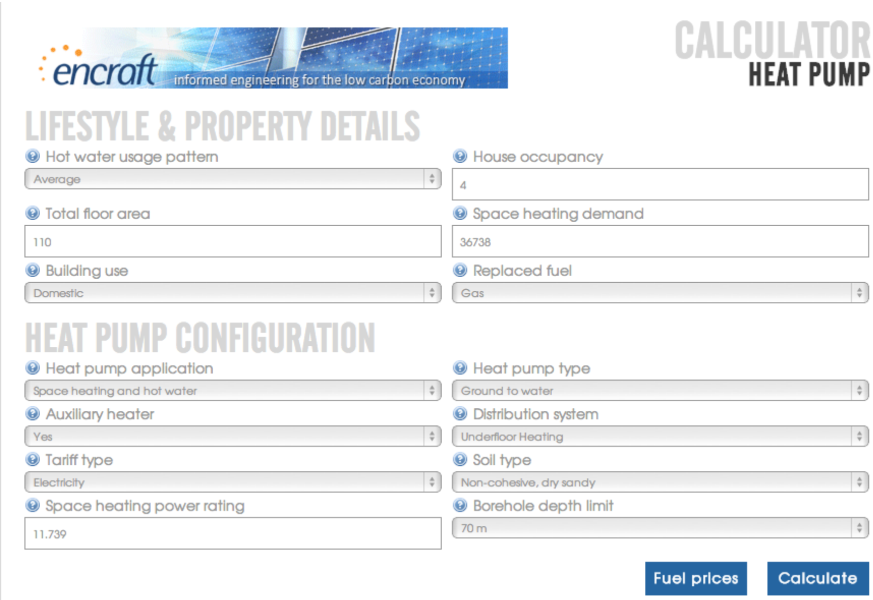


Figure 3.15 Encraft heat pump calculator: sample input

Heat Pump Configuration

Heat pump application	Space heating and hot water
Heat pump type	Ground to water
Auxiliary heater	Yes
Distribution system	Underfloor Heating
Tariff type	Electricity
Soil type	Cohesive ground, damp
Borehole depth limit	70 m
Space heating power rating	11.739 kW

Lifestyle & Property Details

Hot water usage pattern	Average
Occupancy	4
Total floor area	110 m^2
Replaced fuel	Gas
Building use	Domestic
Space heating demand	36,738 kWh/a

Heat pump system

Heat pump size	14.5 kW
Ground collector trenching	605 m^2
Number of boreholes	3
Depth of each borehole	70 m

Estimated annual fuel cost for heating

Existing boiler	£ 1,724
Heat pump	£ 1,993
Total annual cost savings	**£ -269**

Estimated annual energy demand

Existing boiler	42,738 kWh
Heat pump	16,246 kWh
Total annual energy savings	**26,492 kWh**

Estimated annual CO_2 emissions

Existing boiler	9.56 tonnes
Heat pump	8.4 tonnes
Total annual CO_2 savings	**1.16 tonnes**

Figure 3.16 Encraft heat pump calculator - sample output

Input to the calculator therefore firstly consists of details of the dwelling and its occupants' lifestyle: indication of hot water use; house occupancy; total floor area; space heating demand (in terms of energy); domestic or commercial use of the building; and the fuel type to be replaced by the heat pump. Secondly, details of the required heat pump configuration are input, ie. application, whether space heating and DHW or space heating only; whether air or ground source; whether auxiliary heating is present; the type of distribution system; the soil type for a ground collector, the depth limit for borehole collectors and the heat pump power rating. Either of two tariffs for electricity supply are permitted, green (ie. zero-carbon) or conventional. The calculator responds with output of: sizing for the heat pump and ground collector trenching, the number and depth of boreholes; estimated annual energy demand, energy cost and CO_2 emissions for existing system and the heat pump. Only annual values are computed.

Using the output Energy Demand and input Space Heating values to calculate the effective SPF for the systems, it was found that the SPF values assumed by the Calculator are basically those in SAP/BREDEM with a maximum value of 3.2 for a GSHP and 2.50 for an ASHP when used for space heating only with distribution by UFH. The effect of replacing "UFH" with "Radiators" or "Space heating only" with "Space heating and hot water" is to reduce the SPF, with the lowest values being 1.57 and 1.84 for ASHP and GSHP respectively. The effect of changing the soil type from the more useful type of "Saturated ground" to "Non-cohesive, dry, sandy" is to increase the "Ground collector trenching" value, rather to effect the SPF in any way.

3.4.1.2 Discussion

The main restriction in this calculator is that it is only available as a web page requiring a user login and interaction to trigger each calculation. Its heat pump model is restricted to a single, annual SPF value, which would not be affected by changes to ambient temperature and the relationship of SPF to the various input parameters is not publicly available.

3.4.2 Heat pump energy efficiency evaluator

3.4.2.1 Description

A typical evaluation from this facility (Cantor, 2008) is shown in Fig 3.17.

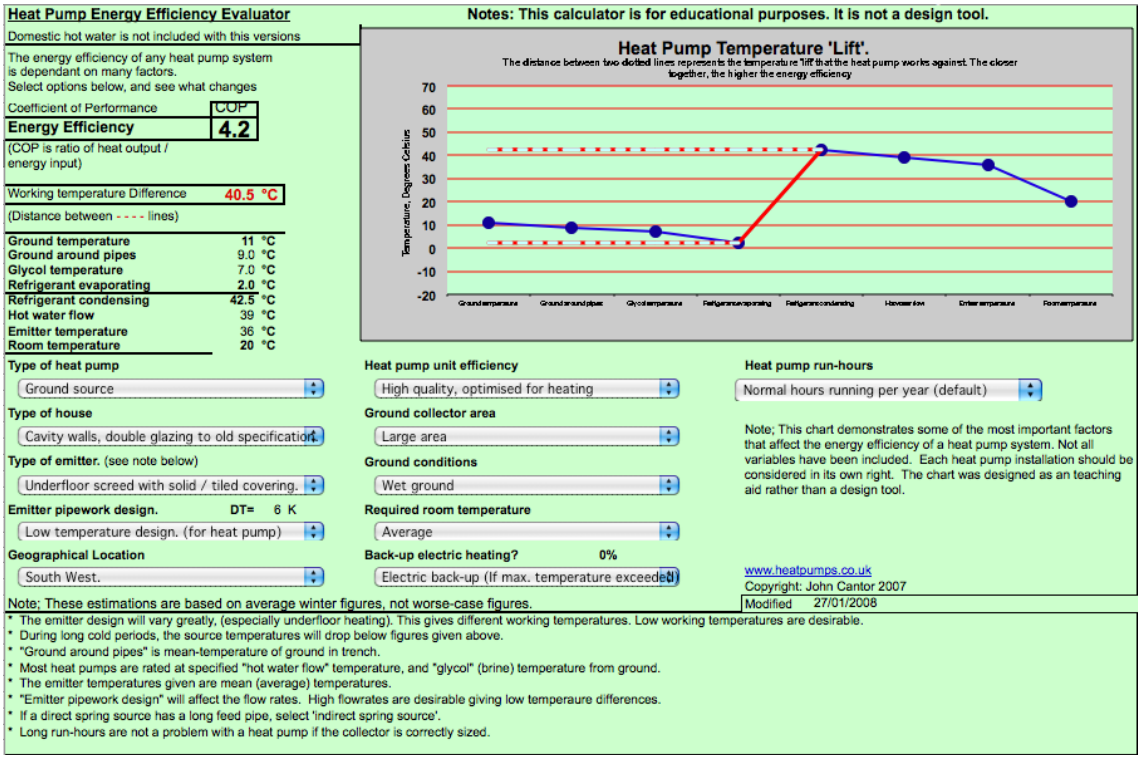


Figure 3.17 Sample of Evaluator output

The output from the spreadsheet is a COP value, shown on the lefthand side, towards the top. This is calculated from a relationship with the Working Temperature Difference value (in red, below the COP value) shown by the values indicated by the dotted red lines on the chart. The Working Temperature Difference is calculated from the difference between the heat pump refrigerant evaporation and condensation temperatures with the values for these temperatures set by 11 controls as per the following table:

Table 3.10 Effects of controls on COP in Heat pump energy efficiency evaluator

Ref.	Control	Setting
1	Type of heat pump	Refers to the type of ground source collector, with values of "ground source", "spring source indirect", & "spring source - direct". Varies the evapotion temperature, with "ground source" giving the lowest

		value and "spring source - direct" the highest.
2	Type of house	Refers to the energy efficiency of the house, varying the condensation temperature from the highest for "Old building, solid walls, badly insulated house" down to the lowest for "Super insulated eco-home"
3	Type of emitter	Refers to the output of the distribution system, varying the condensation temperature from the highest for "Radiators" down to the lowest for "Underfloor screed with solid / tiles covering"
4	Emitter pipework design	Refers to the output of the distribution system, varying the condensation temperature from the higher value for "Standard (as used for boilers)" down to the lower for "Low temperature design (for heat pump)"
5	Geographical location	Refers to the Ground temperature value, with "North East, Scotland" being the lowest at 9ºC and "South West" the highest at 11ºC.
6	Heat pump efficiency	Allows two values, "High quality, optimised for heating" and "Lower quality (cheaper)". The first value both increases the evaporation temperature and decreases the condensing temperature compared with the second.
7	Ground collector area	Affects the evaporating temperature value, with the "Small area" setting reducing its value and "Large area" increasing it.
8	Ground conditions	Again, affects evaporating temperature value, with the "Dry ground" setting reducing its value and "Wet ground" increasing it.

9	Required room temperature	The three values for this control have the obvious effect of changing the Room Temperature value, but also have the effect of changing all the temperatures back to the condensing temperatures.
10	Backup electric heating?	The effect of this control are different from those of the others. The "Electric back-up (small heat pump)" value apparently sets a value for energy use from back-up of 20% of energy consumption, regardless of other parameters. The "Electric back-up (if max. temperature exceeded)" adds that percentage on to the energy consumption value depending on how much the Working Temperature Difference exceeds 60ºC.
11	Heat pump run-hours	The three values allowed for this control have the effect of changing the Evaporation temperature value, with the "Light use..." value causing an increase and the "High run hours..." causing a decrease.

The effects of these controls are cumulative. Thus, the effect of specifying values of "Old building...", "Radiators" and "Standard (as used with boilers)" for controls 2, 3 and 4 increases the refrigerant condensing temperature up to 72.4ºC, whereas the same values of controls 3 and 4 result in a temperature of 50.5ºC when 2 is set to "Super-insulated eco-home". Similar effects are observed in setting those controls affecting the condensing temperature.

3.4.2.2 Discussion

The major consideration concerning this software is that details of its relationships and of the values of the parameters corresponding to the various control settings are not available for incorporation into another model. By sampling values of COP for different values of Working Temperature Difference, it is possible to obtain a relationship for these two variables. However, it is still unclear what the characteristics of a dwelling are represented by, for example, parameter 2 and a similar lack of clarity applies to most of the other parameters. Hence, as the author indicates, the tool is useful for illustrating the characteristics effecting the efficiency of a heat pump system, but does not allow the specification of a system based on any description of a dwelling built form.

3.4.3 RETScreen

This section describes the heat pump project estimating facility within the RETScreen (Renewable Energy Technology Screen[ing?]) software developed by, and available freely from, Natural Resources Canada (Minister of Natural Resources Canada, 2005b, 2011). It is written in Microsoft Excel but has a facility to save project files in its own format. The software contains facilities for examining the feasibility in terms of costs and GHG emissions of different forms of renewable energy and energy efficiency measures for new-build and retro-fit, domestic and non-domestic buildings and, where required, comparing the new measures with the existing provisions. The RETScreen software currently available brings together modules for each project type, of which one was for estimating energy and costs for GSHP projects (Minister of Natural Resources Canada, 2005b). Further documentation is provided by a second manual (Minister of Natural Resources Canada, 2005a)

The measures for which estimates can be prepared include energy efficiency improvements to the fabric of the building (or buildings), effects of various renewable and non-renewable methods of electricity generation and of the replacement of heating and cooling systems. Electricity generation methods include fuel cells, wind, hydroelectric, solar thermal and PV, landfill gas, biomass, biodiesel, biogas, hydrogen, natural gas, oil/diesel, coal, and municipal waste. Heating systems include biomass, solar air and water, gas and oil boilers and heat pumps. Cooling system types include vapour compression (conventional air conditioning) adsorption, desiccant, heat pump and 'free'.

The RETScreen software has two analysis levels, denoted Method 1 and Method 2 of which Method 2 provides a greater level of information and therefore has greater data requirements which depend on the type of project concerned. Use of Method 2 inserts additional worksheets into the spreadsheet for data input for cost, emission, financial and risk analysis and for tools relevant to the type of project involved. The 'Tools' worksheet is used to acquire the more detailed data required to size the heat pump and its ground loop.

To analyse the feasibility of the proposed project, the RETScreen model requires definition of existing energy consumption and climate for the location. From the climate data, temperature bin values and ground temperatures are calculated. The heating and cooling loads and balance point temperatures are calculated from the built form data for each temperature bin. An initial estimate of the system capacity is calculated with the size of the ground heat exchanger, from which the system COP and capacity by temperature bin is estimated, which allows the need for additional heating to be evaluated and the annual system energy consumption to be calculated. This flow is illustrated in Figure 3.18.

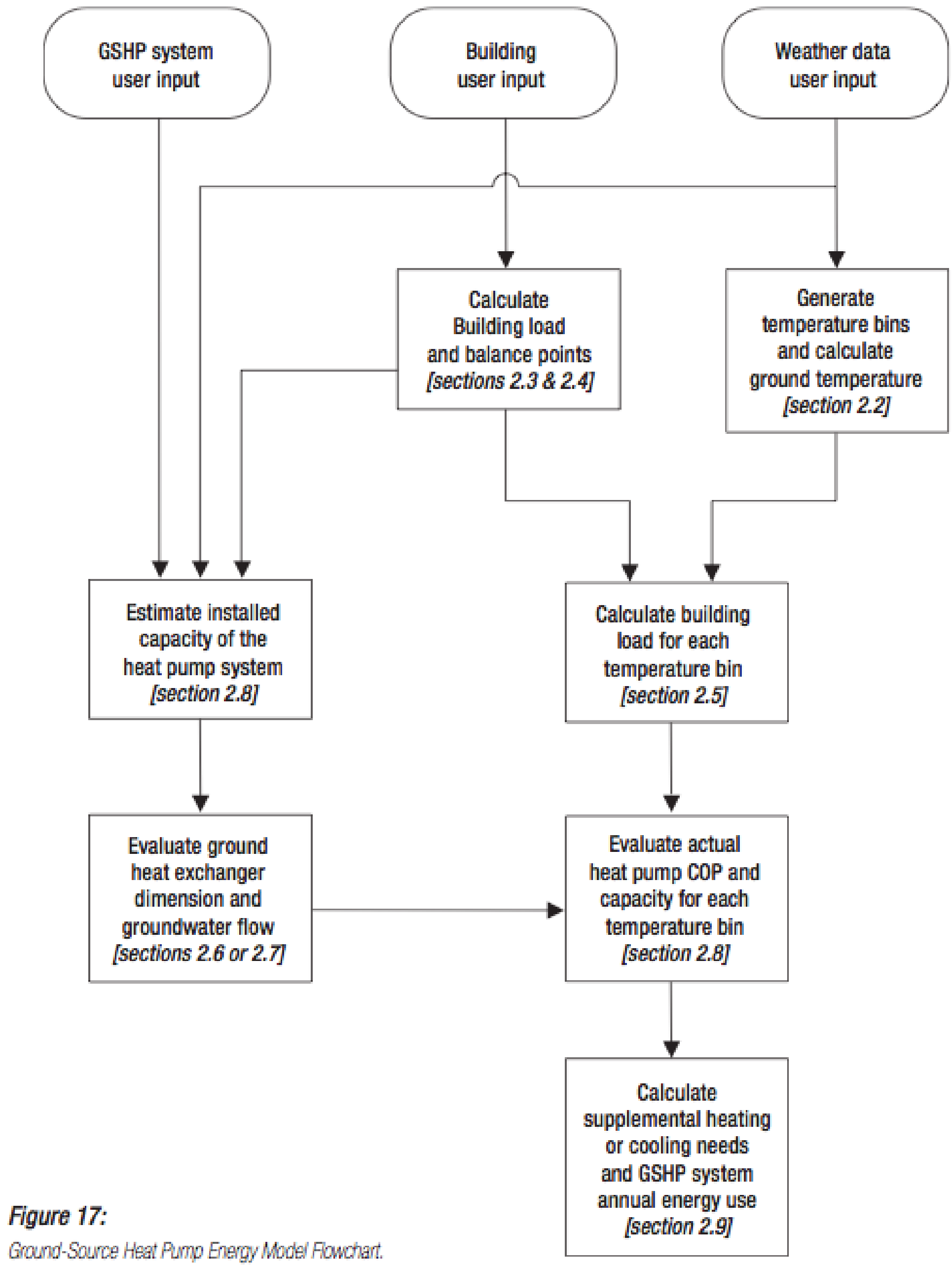


Figure 3.18 RETScreen GSHP energy model system flow

(Fig 17 from Minister of Natural Resources Canada. (2005a))

3.4.3.1 Data requirements for RETScreen

Climate data for the model is set by the user choosing a location from a list within the model data. The locations available for the UK are at UK airports and RAF airbases, not all coinciding with those in the CIBSE datasets used in UK standard models (CIBSE, 2007). In a similar way to the EN 15316-4-2 model documented above, the weather data is 'binned' by degree hours, ie, a 'bin' is defined by an external temperature and is allocated the number of hours during which the temperature was in the range halfway between the bin temperature below and that halfway between the bin temperature above, eg, if bin temperatures were -10, -8, -6, etc. then the value assigned to the bin with temperature -8ºC would be the number of hours during which the temperature was between -9ºc and -7ºC. RETScreen uses separate degree hours binning for day-time and night-time and for the coldest month and warmest month, but because of the substantial volume of data that would be involved holding such data for all regions of the world, the software uses a generator routine to create the hourly temperature values, based on design temperatures and latitude values for the location.

The next stage of the calculation is to estimate the source temperature for the heat pump. For a vertical borehole this is assumed to be the annual average surface soil temperature. For horizontal ground loops, the RETScreen routine calculates the maximum and minimum ground temperature, $T_{g,max}$ and $T_{g,min}$, based on annual average surface soil temperature, $\overline{T_g}$, the surface temperature amplitude A_S, the given heat exchanger depth X_S, the soil thermal diffusivity, α, from equations 3.19 and 3.20:

$$T_{g,min} = \overline{T}_g - A_s \exp\left(-X_S\sqrt{\frac{\pi}{365\alpha}}\right) \tag{3.19}$$

and

$$T_{g,max} = \overline{T}_g + A_s \exp\left(-X_S\sqrt{\frac{\pi}{365\alpha}}\right) \tag{3.20}$$

3.4.3.2 Building load calculation

RETScreen contains two methods for calculating the building energy load: the *descriptive data method,* for which the details of the built form and thermal characteristic of the building elements are entered; or the *energy use method* for which summary energy load and use values are entered, for which knowledge of an existing building is required. For the descriptive method, the relationship between external temperature and the different building heating and cooling loads is calculated, with the loads involved being as follows (Minister of Natural Resources Canada, 2005b, p. GSHP.30):

Transmission losses (conductive and convective)

Solar gains (sensible)

Internal gains (sensible)

Fresh air load (sensible)

Fresh air load (latent)

Internal gains (latent)

The descriptive data input allows the relationships between the above loads and external temperature to be calculated, which, combined with the bin degree hours, enables total load values to be calculated for each bin.

The data required for the descriptive method does not differ substantially from data used in other models and therefore will not be described in detail here. The assumptions made about the built form by the RETScreen model are more significant. The building load calculation makes assumptions about the built form, viz. the building is assumed to have a square built form, with windows evenly distributed across its aspects and orientations. Dwellings are all assumed to have a single heating zone and identical occupation of two adults and two children for the whole day, while occupancy in commercial building is assumed to be 5 persons per 100m^2 for 24 hours, though this is not stated (Minister of Natural Resources Canada, 2005a). It is assumed that ventilation losses for dwellings are related to insulation levels, but these are defined only as *"high"*, *"medium"* and *"low"*, rather any specific values. The actual insulation values associated with these levels are defined in a Canadian source (Hydro-Quebec, 1994).

The results of the descriptive method input are used to form a quadratic equation, relating energy load to external temperature. Used with the bin temperature hours, this is used to calculate energy consumption for each bin. It is also solved to find a balance point temperature.

The energy load method relies on detailed data having been collected from an existing building, a method which is not available when estimating for the entire housing stock.

3.4.3.3 Heat pump ground loop sizing

Two formulae are given for the collector length, one for heating, one for cooling, which are basically similar in structure. For heating, the formula for the length is as follows:

$$L_h = q_{d,heat}\left[\frac{\frac{COP_h - 1}{COP_h}}{T_{g,min} - T_{ewt,min}}(R_p + R_s F_h)\right] \tag{3.21}$$

where:

$q_{d,heat}$ = design heating load

COP_h = the design COP for heating of the system

R_p = the pipe thermal resistance,

R_s = soil/field resistance

F_h = heat exchanger part load factor for heating

$T_{g,min}$ = minimum undisturbed ground temperature

$T_{ewt,\ min}$ = minimum design entering water temperature

$$L_c = q_{d,cool}\left[\frac{\frac{COP_c + 1}{COP_c}}{T_{ewt,max} - T_{g,max}}(R_p + R_s F_c)\right] \quad \textbf{(3.22)}$$

where:

$q_{d,cool}$ = design cooling load

COP_c = the design COP for cooling of the system

R_p = the pipe thermal resistance,

R_s = soil/field resistance

F_c = heat exchanger part load factor for cooling

$T_{g,max}$ = maximum undisturbed ground temperature

$T_{ewt,\ max}$ = maximum design entering water temperature

Units for these variables are determined by user preferences for SI or Imperial units. Choice of which of the two possible sizes of heat exchanger will be determined by user input deciding the priority of heating or cooling. Where either length is insufficient for its function, then the system indicates that additional heating or additional heat rejection is required. Of the variables in equations 3.42 and 3.43, $T_{g,min}$ and $T_{g,max}$ are calculated as per equations 3.40 and 3.41 above, $T_{ewt,\ min}$ is calculated as $T_{g,min}$ - 8.3 K (stated as 15ºF in (Minister of Natural Resources Canada, 2005a) section 2.6.2), $T_{ewt,\ max}$ is calculated as the minimum of $T_{g,max}$+ 11 K and 43.3 ºC (again, temperature values stated as 20ºF and 110ºF in section 2.6.2), the part load factors F_h and F_c are calculated as the ratio between the average load and the peak load for the months of January for heating and July for cooling using the values calculated from the appropriate bin. The methods of determining R_p and R_s are stated as coming from the IGSHPA 'Installation Guide' (IGSHPA, 1988) without further details.

A further of section of the RETScreen manual (Minister of Natural Resources Canada, 2005a) details calculations for sizing open loop groundwater heat exchangers. These are not often used in the UK in residential applications because of the requirement to license the extraction of the ground water from the appropriate authority and the possible cost of the extraction (Brown, 2009, p. 34). Consequently this the calculations for this source type will not be examined here.

3.4.3.4 Heat pump system

The RETScreen model relates heat pump COP and capacity to entering fluid temperature by two equations:

$$COP_{actual} = COP_{baseline}(k_0 + k_1 T_{ewt} + k_2 T_{ewt}^2) \quad \textbf{(3.23)}$$

$$Q_{c/h} = \chi(\lambda_0 + \lambda_1 T_{ewt} + \lambda_2 T_{ewt}^2) \quad \textbf{(3.24)}$$

where:

COP_{actual} = COP of the heat pump at T_{ewt}, the given entering fluid temperature

$COP_{baseline}$ = system COP under test conditions (RETScreen assumes 0ºC and 25ºC for heating and cooling respectively)

T_{ewt} = entering fluid temperature

λ, k are regression coefficients for which RETScreen provides a table of values.

χ = heat exchanger part load factor for heating or cooling

The value of χ is determined by whether heating or cooling is prioritised by the design criteria, ie. whether the heat pump system is chosen to match the cooling or the heating load. It is defined by two further equations:

$$\chi = \frac{q_{d,cool}}{(\lambda_0 + \lambda_1 T_{ewt,max} + \lambda_2 T_{ewt,max}^2)} \quad \textbf{(3.25)}$$

where:

$q_{d,cool}$ = design cooling load

$T_{ewt,max}$ = maximum entering fluid temperature as above

$$\chi = \frac{q_{d,heat}}{(\lambda_0 + \lambda_1 T_{ewt,min} + \lambda_2 T_{ewt,min}^2)} \quad \textbf{(3.26)}$$

where:

$q_{d,heat}$ = design heating load

$T_{ewt,min}$ = minimum entering fluid temperature as above

For cooling-based priority, χ is calculated from Equation 3.47, while for heating-based priority, it is calculated from the maximum of the results of Equations 3.46 and 3.47.

The next stage is that of calculating the value of the entering water temperature for each bin which is assumed to be a linear function of external temperature, given by the formula:

$$T_{w,i} = T_{min} + \left(\frac{T_{ewt,max} - T_{ewt,min}}{T_{d,cool} - T_{d,heat}}\right)(T_{bin\,i} - T_{d,heat}) \quad \textbf{(3.27)}$$

where:

T_{min} = the soil temperature when air temperature = 0ºC and other variables are as previously defined.

This formula applies to closed loop collectors with the open loop collector calculation again omitted.

In the final stages, the system run-time for each bin is calculated by dividing the load by the heat pump capacity and a part load factor, F, is calculated as follows:

$$F = \frac{RunTime}{1 - c_d(1 - RunTime)} \quad \textbf{(3.28)}$$

where:

c_d = degradation coefficient, set to 0.15

and the electricity consumption of the heat pump as follows:

$$HP_{e,demand} = \frac{Q}{COP} \quad \textbf{(3.29)}$$

where:

Q = heat pump capacity

For the electricity consumption of auxiliary equipment, auxiliary building loop pumping power is assumed to be 17 W per kW of installed cooling capacity. The supplementary heating or cooling needs for each temperature bin are calculated by the building load minus the capacity of the heat pump. The total electricity consumption, Q_e, of the system in each bin is calculated as:

$$Q_e = Bin(h)\left[\left(HP_{e,demand}F\right) + AUX_e\right] \quad \textbf{(3.30)}$$

where:

Bin(h) = the number of hours in the bin

F = the part load factor calculated in equation 3.49 above.

AUX_e = Electricity demand for all auxiliary loads

The design auxiliary loads for heating and for cooling are calculated differently since additional cooling capacity is required if sufficient heat to meet the cooling load cannot be rejected via the ground loop, whereas additional heating is required if the heat pump capacity is insufficient to meet the heating load. Thus the additional heat requirement is calculated by subtracting the system's heating capacity at minimum entering water temperature - the lowest value - from the building design load, while the additional heat rejector load is calculated by subtracting the GHX capacity at maximum entering water temperature from the building design cooling load.

3.4.3.5 Discussion

Software characteristics

While the RETScreen software is written using Microsoft Excel as a platform, it is highly 'packaged' and providing interfaces to pass data into its spreadsheets is only possible to a limited extent. While, for example, it is possible to add an additional worksheet into the RETScreen workbook and link data from that worksheet into the RETScreen ones, it does not appear possible to set the control required to make the building element data variables available for input.

Assumptions

The assumption within the descriptive dwelling energy load model that glazing is assigned to all four aspects of the building implies that all dwellings are detached houses, which, applied to the UK housing stock, would exclude the most common built forms since detached houses form only about 16% of the English stock (Utley & Shorrock, 2008, p. 75). The assumed occupancy levels for houses, being two adults and two children for 24 hours per day, differ from those used in UK standard models both in people and in duration. The gains per person at 76.6 W/person differ somewhat from UK standards at 60w/person (Anderson, et al., 2002; BRE, 2009a). Calculations regarding heat losses from cellars, which, while they may be disregarded, form a distraction as cellars are not particularly common in the UK, being present in only slightly over 1% of dwellings in the English housing stock (DCLG, 2010c). The building energy model uses a set point of 23ºC for both heating and cooling, which is 2 K higher than that for heating in the standard UK models.

Integrity of model description

Though it was found not to be possible to incorporate the RETScreen Excel spreadsheet itself into a heat pump model, the possible use of the documented routines as the basis of a new model was considered. This raised the following points:

- some references in Minister of Natural Resources Canada (2005a) are missing or outdated and no longer contained the information referenced; in section 2.6.2, describing the heat pump system calculations, there is a citation of "Tarnawski(1990)" which has no corresponding entry in the reference list at the end of the document. Unfortunately this reference forms the basis of the approach used for the relationships determining COP values in RETScreen; in section 2.9.1, a document "*Standard for Ground-source Closed-Loop Heat Pump Equipment, ARI 330-93*" is cited as a source for a constant value in Equation 81, for which no information was found in the ARI 330-98 Standard which replaced that cited(AHRI, 1998).
- the documentation of these routines is unclear, failing to differentiate clearly between "load", "capacity", and containing a number of definitions of a part load factor, F, without distinguishing subscripts;
- the value of the part load factor, F, from equation 3.46 seems excessive or even erroneous; calculated for values of the variable RunTime, it varies from 0 for RunTime = 0, continuously increasing to a limiting value of 6.666 (recurring) as RunTime tends to very large numbers. The comment in this document that "*The smaller the values of RunTime, the greater the penalty due to the degradation coefficient*" is not reconcilable with these results;
- the system configuration assumed is a water-to-air system, whereas the most common distribution system in the UK is a wet radiator system; the model does not allow for air source heat pumps in any configuration;
- the assumptions detailed above in section 3.4.3.2 are unsuitable for a UK environment and would be inconsistent with standard UK model studies.

3.4.4 Summary of findings

In this section, the examination of the models has shown that:

The RETScreen model, while comprehensively documented and freely available, does not attempt to address the seasonal character of heat pump energy use. Its software is packaged such that it cannot be used in other applications. It does provide comparative values for energy consumption, costs and carbon dioxide emissions. Since it is designed as an interactive tool with facilities to select parameter values from lists and with internal routines that create or delete worksheets according to user input, the package would appear to be too complex to link to other routines.

European Standard EN15316 is complex and relies on the knowledge of many parameters that are not available without reference to a particular heat pump system in a particular dwelling. Thus it has not been accepted as a standard for the UK since it requires data which is not usually obtainable for existing buildings. Its many rules would be computationally demanding and hence not suitable for a large number of executions in a disaggregated housing stock model.

3.5 Discussion

From the review of heat pump models and modelling tools above, it would appear that no software is readily available for utilisation within an overall dwelling energy model and that it is necessary for such a model to be developed based on the general physical characteristics of a heat pump system.

3.5.1 General relationships within a heat pump model

The analysis performed by Staffel (2009) shows a substantial degree of correlation between temperature 'lift' ('heating amount') across a heat pump system and COP (Figure 3.11), particularly within the data for systems with the same source type, as do the results of the comparison between Kelly & Cockroft (2010)'s model estimates and heat pump test results in Figure 3.9. These three set of results all show a significant negative relationship between COP and 'lift' which is substantially linear in nature. Conversely, Figure 3.10 (b) shows a significant positive linear relationship between ambient temperature and the COP of the ASHP systems in the monitored data.

Given the significance of this temperature difference, some consideration has to be given to the temperature values employed in estimation. For an air source system, Jenkins, Tucker, Ahadzi, & Rawlings (2008) use external wet-bulb temperature and appear to assume a fixed system output temperature of 20ºC. Jenkins et al. (2009) estimate soil source temperature from external surface temperature using equation 3.9 and create estimates for output temperatures of 35ºC, 45ºC and 55ºC, apparently assuming that these temperatures are fixed for each distribution type. Kelly & Cockroft (2010), with ASHPs, take the source temperature from climate data, and use a set point of 45ºC for the sink temperature, with the output from their simulation showing temperatures between 30 & 50ºC for the return from the distribution system. The derivation of source temperature in the Westergren(2000) study uses much the same sinusoidal function as that in Jenkins et al. (2009) and this is conjoined with the Carnot COP equation to provide an estimate for actual COP, on the basis of a fixed, but unknown, sink value.

Whilst all these models allow variation of source temperature to affect the system COP, there appears to be an assumption that, for estimating purposes, the system sink temperature is not deemed to vary other than between the requirements of different distribution systems. Since a high proportion of heat pump systems are controlled by weather compensation controllers, as detailed by Boait, Fan, & Stafford (2011), which monitor external temperatures in order to reduce the system output temperature required to meet an increase in system load by anticipating the internal temperature fall, some investigation of this assumption is required, which will emerge from the monitoring study documented later on in this thesis.

3.5.2 Additional or back-up heating

This use of energy is estimated in two ways in the models examined. One, in Jenkins et al. (2009), is by subtraction of the capacity of the heat pump system from the heating load of the house. The second, included in BS EN15316-4-2(British Standards Institution, 2008a) is by determining an external balance point temperature below which the additional heating facility is switched on and estimating energy use according to degree hours or days above and below that temperature, further allocating these energy estimates according to whether the additional system replaces the heat pump system (bivalent alternate) or operates in parallel (bivalent parallel). This refinement in estimation is not possible with the first method, which is only able to estimate for a 'top up' configuration. Whether it is necessary for a model to estimate energy use for bivalent alternate operation is not entirely clear. Ochsner (2007, p. 40) states that bivalent alternate operation is necessary for *"renovations"*, while Brown (2009) only states that it is inefficient and undesirable.

3.6 Final conclusions for this chapter

For the second part of Objective 1 of the study, this Chapter has analysed studies and models of heat pump energy use in buildings as documented in research studies, standards and available software for the main determinants and characteristics of heat pump energy use. The main intention of these models is to estimate the effect on energy use and carbon emissions of various measures to improve the energy efficiency of dwellings. Of these, it was found that the research studies lacked generality in one aspect or another, particularly in climate data and the heat pump systems modelled. The model embedded in the British and European Standard was found to be very complex, requiring the estimation or defaulting of many parameters. Freely-available software was found to be restricted to interactive use and hence not available to be embedded in another model. No simple routines were found for the calculation of energy used in bivalent operation in either mode. However, the basis for a comparatively simple regression model relating heat pump COP to source - sink temperature differential ("lift") was shown to be a valid approach as discused in section 3.5.1 . Within the research papers, the routine for estimation of soil temperature (Jenkins, D. P., et al., 2009) and the generalised relationship between COP and 'lift' (Staffel, 2009) were found to be applicable to the current study.

Having examined the models of individual heat pump systems, the next Chapter examines the significant work in the field of housing stock-level domestic energy models, which is the next logical level above.

CHAPTER 4 DOMESTIC ENERGY MODELS FOR THE UK

4.1 Introduction

To meet Objective 2 of this study, this section contains:

- a review of the accepted classifications of energy models for the domestic sector, the techniques involved and their applicability for use in the current study;
- a review of the significant models and studies which are most directly applicable to this study, ie. domestic sector energy models for the UK;

The aspects of these models to be considered are: firstly, the studies for which they are employed; secondly, the estimating methods that they use; thirdly, the data on which they are based; fourthly, the degree to which their estimating methods, assumptions and data are open and available to scrutiny.

The review of these models will examine:

- whether the actual software is both available and suitable for use in the current study, either 'as is' or modified as necessary;
- if the software is unavailable, whether the estimating techniques involved are available and suitable for use in the current study.

From this review, the requirements, both for estimating methods and additional data, for the current study will be identified.

4.2 Model Requirements

In the context of the current study, the following criteria will be used in the evaluation of the models and modelling systems reviewed:

because one of the aims of this study is to examine the variation of heat pump systems' energy consumption across the year, largely ignored by other modelling, it is essential that any model involved accepts monthly external temperature data and can produce estimates on a monthly basis;

since both air and ground source heat pump systems typically require external space for installation beside a dwelling, it would be desirable if this plot size requirement was reflected in the relationship between heat pump installations and the housing stock;

similarly, an initial indication of dwelling heat loss should be available within the model data since heat pump systems are deemed unsuitable for dwellings with high heat loss because of their lower temperature output;

the inclusion of estimates for embedded carbon values to examine the effects of the possible large-scale replacement of current heating systems by heat pumps throughout a substantial proportion of the 24 million dwellings in the UK housing stock.

In default of any models that are both available and have structures that do not preclude the analyses required in this study, then consideration will be given to the re-use of the embedded routines where these have sufficient documentation.

4.3 Model types

Swan & Ugursal (2009) provide a concise summary of the characteristics of the different model types which is shown in the following Figure 4.1. They and Kavgic et al(2010) divide model types into 'Top-down' and 'Bottom-up' by referring to the level of aggregation of input data and the level of estimates that are inferred from them. Swan & Ugursal (2009) describe the top-down modelling process as one that assigns proportions of the total residential energy sector energy consumption to different characteristics of that sector, with bottom-up modelling calculating consumption for sections of the housing stock and extrapolating from these to the total value.

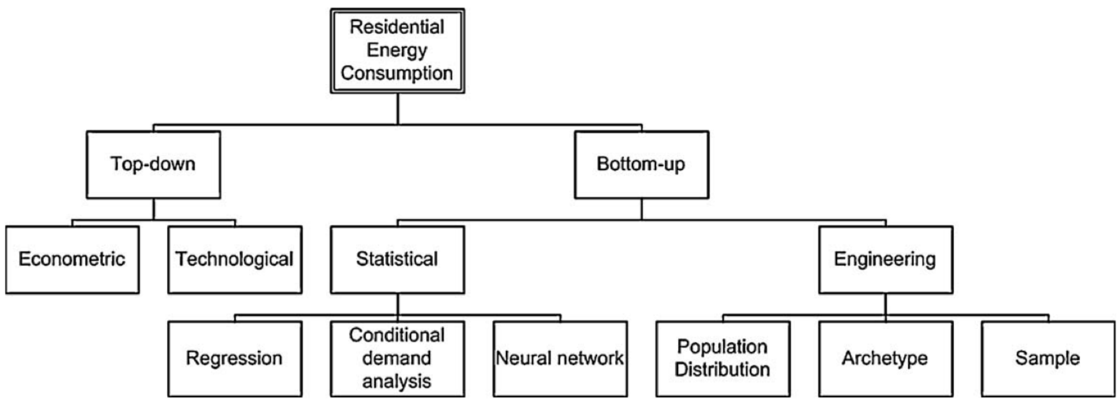


Figure 4.1. Top-down and bottom-up modelling techniques for estimating the regional or national residential energy consumption (Figure 2 from Swan & Ugursal, 2009)

Thus, in the 'econometric' pathway in Figure 4.1, the expected change in energy use in the sector is related, for estimation, to changes in gross domestic product, rates of employment, income and fuel prices, and rates of house construction and demolition, while in the 'technological' pathway it is related to changes in appliance ownership estimates or population-weighted changes in temperature.

Relationships in these type of models are estimated from historical data and, consequently, are only valid for existing, installed technology and, therefore, reduce in validity as time passes after their creation and the further forward they are required to predict. This also implies that they are unlikely to provide accurate predictions of the effects of new technology, though because these paradigm shifts occur infrequently in housing, they remain effective at predicting in the shorter term and for smaller variations (Swan & Ugursal, 2009).

4.4 MARKAL model family

Of this 'top-down' type, the most significant system involved in UK energy modelling is the MARKAL (MARKet ALlocation) family of models (ETSAP, 2008) which has a lengthy history dating back to 1976 (Fishbone & Abilock, 1981). This set of models is the basis of major UK energy studies - Energy White Papers in 2003 and 2007, Carbon Abatement Technology strategy, Climate Change Bill, Carbon Budgets - by the UK government (Strachan, Anandarajah, Pye, & Usher, 2010), including the Departments of the Environment, Food and Rural Affairs (DEFRA), for Trade and Industry, and latterly the Department for Energy and Climate Change and the Committee on Climate Change (Committee on Climate Change, 2010). Strachan, Anandarajah, Pye, & Usher (2010) list seven named variants of the UK MARKAL model and indicate that others exist for specific projects.

The MARKAL models differ from conventional, predictive modelling in that they focus on optimisation of energy characteristics over the modelling period, with the standard MARKAL minimising discounted total energy system cost and MARKAL-Macro maximising discounted total welfare through energy use, both with optimisation performed by linear programming. Based on a start year of 2000, a pass by the model performs optimisation every 5 years for the period up to 2070.

A simplified MARKAL structure is illustrated by Figure 4.2, showing the relationships which form its basis, starting from supply curves for fuel resources (energy against price), fuel processing and energy conversion, transmission and distribution, through to end energy use. Since MARKAL models the entire energy system, the residential energy end use forms only one module within it, for which the relationships are as shown in Figure 4.3. In this figure, the left-hand energy inputs are linked to other modules defining the resource levels, generation processes, infrastructure, and electricity and heat generation,

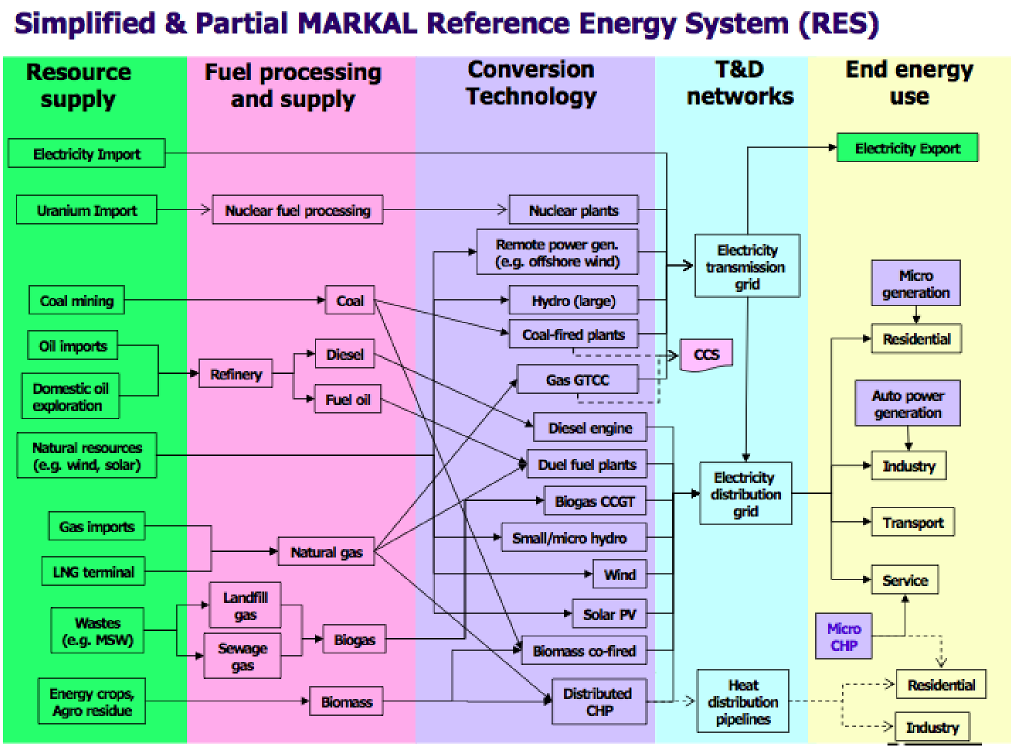


Figure 4.2 MARKAL energy system

(Strachan, et al., 2010, p. 5)

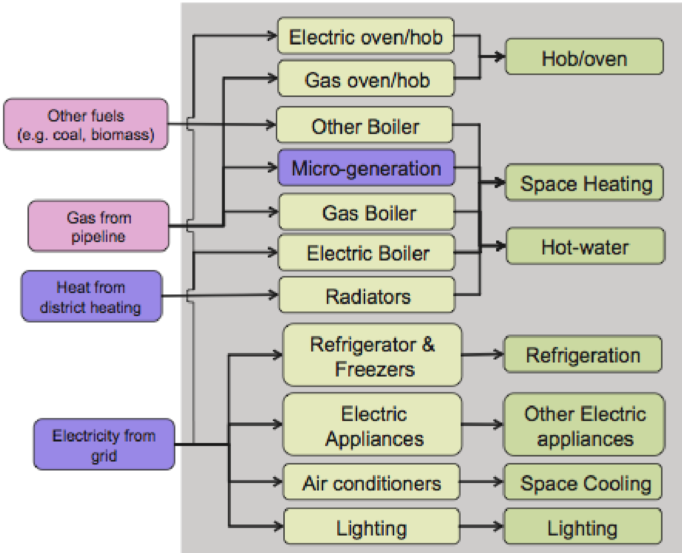


Figure 4.3 Structure of residential sector in UK MARKAL
(Fig R-1 from UKERC, 2007)

Within the module, energy service demand types are shown in the right-hand column of Figure 4.3. These energy demands may be met by various end-use technologies, as in the second column of Figure 4.3. As the MARKALL models operate at a sectoral level, all these characteristics are aggregated values across the whole housing stock (UKERC, 2007). Thus, initialisation of the MARKAL system at its base date of the year 2000 is in terms of the single values for each of the main energy service demand types as follows (Table 4.1):

Table 4.1 Energy demand services for MARKAL residential energy module in base year 2000

Type of residential energy demand services		Units
Space heating	827.5	PJ
Space cooling	-	PJ
Hot-water	336.9	PJ
Lighting	63.8	PJ
Other electrical appliances	114.7	PJ
Hob	25.3	Million units
Oven	25.3	Million units
Refrigerators	12.6	Million units
Fridge freezer	15.9	Million units
Chest freezer	4.4	Million units
Upright freezer	6.6	Million units

(UKERC, 2007, Table R-1)

These are the initial variables for which values are set for the existing housing stock in 2000 based on the actual final energy use for 2000 from DUKES (DECC, 2010b), with new values being assigned for each 5-year period of a MARKAL pass, and a separate set of the same variables being maintained for houses constructed post-2000. Energy efficiency measures are applied by modifying only the values for the existing housing stock. Apart from the single values in Table 4.1, each energy service demand can have an option to specify variable demand in terms of seasonal or diurnal fractions, corresponding to the real demands for space heat and cooling or for lighting. The correct definition of these fractional demands is apparently important for the accuracy of the output estimates (UKERC, 2007, p. 4).

4.4.1 End-use/demand technologies

Various demand technologies may be specified to meet each energy demand, of which the most obvious example is the meeting of space heating by a boiler fuelled by either gas, electricity or other fuel or directly by radiators heated by a district heating system. Demand technologies are defined in terms of several parameters, as per Figure 4.4.

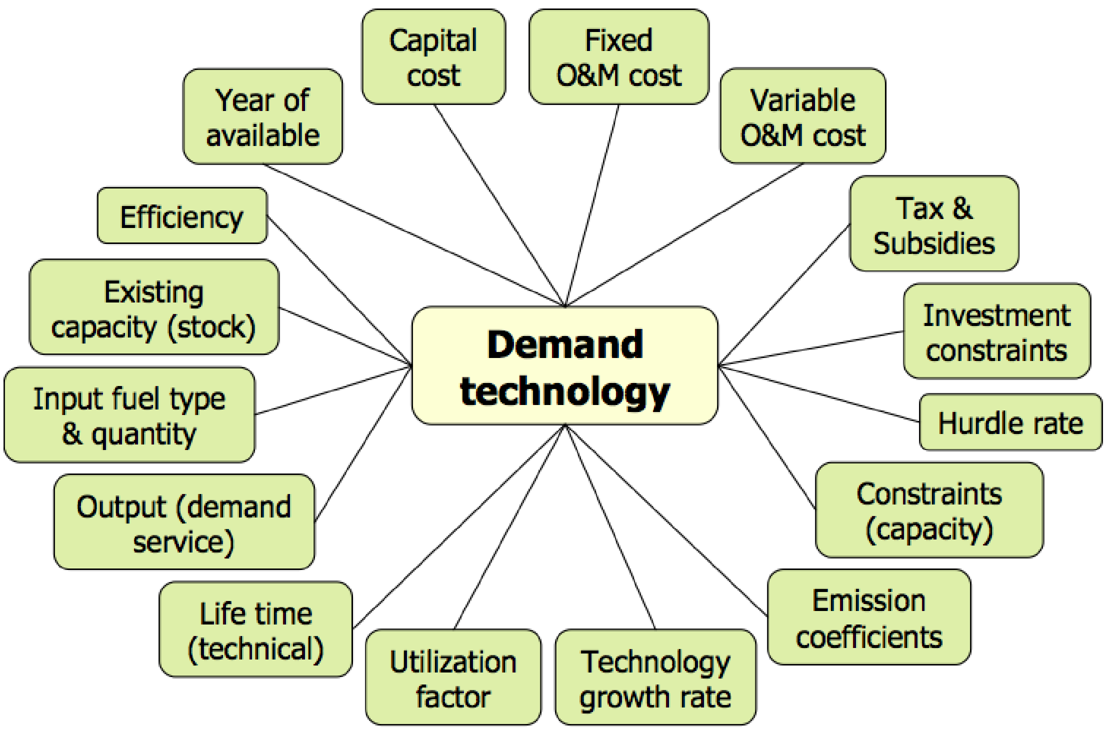


Figure 4.4 Parameters specified for demand technologies (Fig. R-2 from UKERC, 2007)

Of these, efficiency, existing capacity, capacity constraints, lifetime, year of available (availability?) capital and operating and maintenance (O & M) costs are mandatory to define a demand technology. To model improvements in efficiency over time, variants of a technology are defined with applicable availability dates, with conservation measures applied as dummy energy technologies which require no input. As an example, Figure 4.5 indicates that gas condensing boilers become available in 2005 and improved heat pumps from 2010.

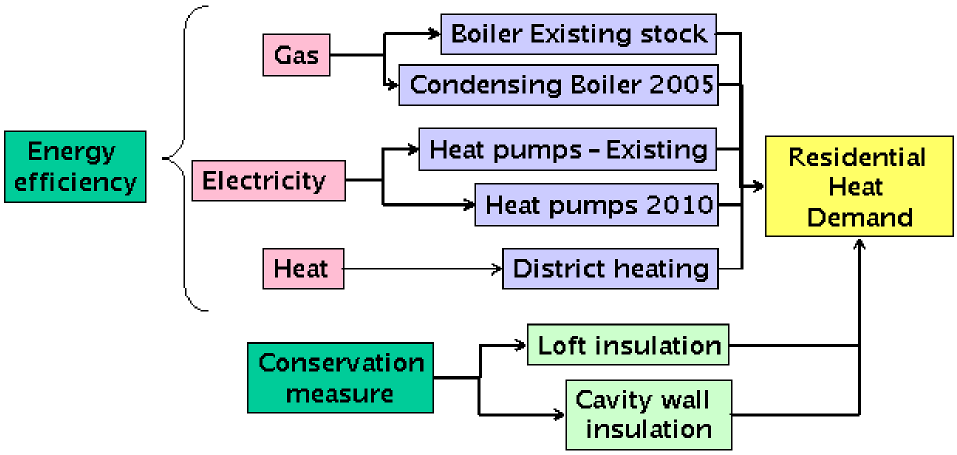


Figure 4.5 Energy conservation versus energy efficiency in MARKAL (Fig. R-3 from UKERC, 2007)

Despite its fitting the criteria as a 'top-down' model, it would appear that, to some extent, the MARKAL model is able to estimate for scenarios involving technological change, though the mechanism does not provide for any element of selectivity across the housing stock for the installation of new technology. As the MARKAL system models the entire energy system including transportation, industry, electricity generation, etc. for a nation, it does not fit the criteria for this study.

4.5 Disaggregated (bottom-up) models

4.5.1 General characteristics

Models of this type estimate energy consumption of individual end-uses, individual houses, or groups of houses which are then grossed-up to provide estimates for the required section of the housing stock, for example a region or nation, based on the representative weights of the modelled sample.

The sub-division of this type in Figure 4.1 from Swan & Ugursal (2009) into 'statistical' and 'engineering' depends on the type of sub-model utilised, with an engineering model employing physically-derived relationships, ie. heat loss calculations based on the thermal properties of construction elements, internal and external temperature data, and a statistical model being one where the estimating function is based on data observation, eg. energy consumption for lights, cooking and appliances related to the floor area of the dwelling. For the modelling of the complete energy use of a dwelling, it is not possible to maintain a strict division between these two model types since energy consumption for appliance use, cooking and lighting is determined by the dwelling occupants, rather than by any physical relationship. In general, the disaggregated or bottom-up / statistical models have the same disadvantages as the top-down / econometric model in being unresponsive to changes in technology.

Of the sub-types under *'Engineering'* in Figure 4.1, the *'Population Distribution'* technique utilises distributions of the ownership and the use of appliances with common energy ratings to calculate the energy consumption of each end-use. Thus the product of appliance ownership, usage, energy rating and the inverse of appliance efficiency results in energy consumption values which are aggregated to provide an estimate for the residential energy consumption on a regional or national scale. The resultant model does not account for interactions amongst end-uses, eg. a change in internal gains from appliances and cooking will not be reflected in changes in space heating energy consumption. Studies using this technique in countries other than the UK include Saidur et al. (2007), Kadian et al. (2007), Jaccard & Baille (1996), Cappaso et al. (1994), but no similar studies exist for the UK (Swan & Ugursal, 2009). The accuracy of this technique would appear to hinge on the appliance use value, which, for any given house, would be dependent on occupancy hours, heat loss, and external temperature or, alternately, heating degree days in the year chosen. Estimation of all these would require substantial effort, equivalent to a second model, in a housing stock like the UK's where there is a wide variation in all these variables.

This technique would appear to raise problems in the study of energy efficiency improvements to construction elements and space heating equipment. If detailed actual energy consumption data and heating appliance distribution is available, then the effects of changes in either heating system efficiency or technology may be estimated from the specifications of the new and old systems. However, if no detailed consumption data is available, then basing space heating energy consumption estimates solely on appliance distribution, hours in use, rating and efficiency for heating systems will render it difficult to separate the effects of the different efficiencies of construction elements. It is noticeable that the studies cited (Jaccard & Baille, 1996; Kadian, et al., 2007) do not provide estimates for space heating or are from locations where space heating is un-necessary.

The *'Archetype'* technique

This technique involves the creation of a dataset of archetype dwellings to be representative of the housing stock, in which the number of members are determined by the dwelling characteristics most significant in the estimation of energy consumption, and the categories into which these characteristics are appropriately divided. To be representative, the values assigned to each characteristic of each archetype must be derived from survey data from the actual housing stock and a weight must be calculated for each archetype to gross any estimates up to values for that stock. The archetypes in the model dataset are then utilised to generate estimates for energy consumption and carbon emissions for the whole stock. Kavgic, et al. (2010) provide a summary table of five residential energy models of this type for the UK which vary in the numbers of archetypes used from 2 in the Johnston model up to 20,000 in the Environmental Change Institute's UK Domestic Carbon Model and these are reviewed below. An additional model by Fawcett (2005), reviewed by Kannan & Strachan (2009), uses the same mechanisms as Johnston (2003), with slightly different initial assumptions, to examine the possibilities of reducing carbon emissions through carbon rationing. Insufficient information was available to complete a table entry for this model.

The *'Samples'* technique

This technique is a variation of the *'archetypes'* technique substituting sample data from housing surveys for archetypes to provide a higher degree of variation in the built form / construction types / heating system configurations included in the model. Again, to provide stock level estimates, weighting factors must be calculated to gross up individual dwelling estimates, and this represents only a variation of the issue inherent in the '*archetypes'* technique. Models of this type for countries other than the UK have been developed by Farahbakhsh, Ugursal, & Fung (1998) and Larsen & Nesbakken (2004).

While the *'samples'* technique has not been employed to create a UK housing stock energy and emissions model, use (Jones, Lannon, & Williams, 2001) has been made of sampling to improve archetypes in the domestic sub-model in the Energy and Environmental Prediction (EEP) model developed by Cardiff University, in which data for archetype dwellings was enhanced with that collected from surveying to allow energy consumption estimates to be created for a UK post code area. This was further developed in the Solar Energy Planning (SEP) system (Gadsden, 2001; Gadsden, Rylatt, & Lomas, 2003a, 2003b; Rylatt, Gadsden, & Lomas, 2003a, 2003b) to estimate the potential for solar design in new dwellings and for solar thermal and solar photo-voltaics more generally from GIS data; and in DECoRuM (Gupta, 2005a, 2009a, 2009b) which considers the feasibility of a complete package of energy efficiency and LZC measures for individual dwellings cased on a combination of a "walk-past" survey and GIS measurement. This system is further examined in Section A.7 of the appendices.

Table 4.2 Disaggregated domestic energy models - summary of features

Name	BREHOMES	Johnston	UKDCM	DECarb	CDEM	DECORuM
Developer	Building Research Establishment (BRE)	PhD thesis (Leeds University)	Environmental Change Institute, Oxford University	University of Bath, University of Manchester	Loughborough University, Loughborough, UK	Gupta, Oxford Brookes University, UK
Year	Early 1990s	2003	2006	2007	2009	2005
Embedded calculation model	BREDEM-12	BREDEM-9 (modified version)	BREDEM-8	BREDEM-8	BREDEM-8	BREDEM-12 / SAP
Data output & temporal resolution	Annual energy consumption	Annual energy consumption & CO_2 emissions	Monthly energy consumption & CO_2	Monthly energy consumption	Monthly energy consumption & CO2 emissions	Annual energy consumption & CO_2 emissions. Installation, operating costs
Level of disaggregation (spatial resolution)	1008 dwelling types (defined by age group, built form, tenure type and the ownership of central heating)	Two dwelling types (pre- and post-1996)	20000 dwelling types by 2050	8064 unique combinations for 6 age bands	47 house archetypes, derived from unique combinations of built form type and dwelling age	Dwelling level within selected area
Level of data input requirement	Medium (national statistics)	Medium (national statistics)	Medium (national statistics)	Low (defaults from national statistics)	Medium (national statistics)	High (dwelling level by survey)
Time dimension (projections to the future)	Two scenarios until 2020: (a) reference (business-as-usual), (b) efficiency	Three scenarios until 2050: (a) business-as- usual, (b) demand side, (c) integrated	Three scenarios until 2050: (a) business-as-usual, (b) 44% emission reduction, (c) 25% emission reduction below 1990 levels	Back-cast scenario from 1970 to 1996 and UKCIP02 climate change scenarios and additional runs to test the BREHOMES, Johnston and UKDCM scenarios	Predictions only for one point in time (2001 housing stock)	Predictions only for current housing stock
Aggregation level of data output (spatial coverage)	National	National	National	National	National, City, Neighbourhood	Neighbourhood
Inter-model comparison	Extensive	Comparison with results obtained from BREHOME	Comparison with regional statistics provided by BERR	Comparison with results obtained from BREHOMES	Local sensitivity analysis, linearity and superposition tests to quantify the impact of input parameters on output uncertainties	Comparison with other dwelling-level models

Empirical validation with existing data	Extensive	Comparison with empirical data from the BRE Domestic Energy Fact File	Comparison with regional statistics provided by BERR	Comparison with DUKES provided by BERR and the BRE Domestic Energy Fact File	Comparison with DEFRA aggregate domestic space heating consumption figure for 2001	Not applicable
Application	Policy advice tool (used by DEFRA	Policy advice tool	Policy advice tool (Oxford)	Policy advice tool	Policy advice tool	Local authority policy & intervention tool
Current availability		Used only by the developer	Freely available	Open framework	Open structure	Uses available BREDEM model with commercial GIS

(Kavgic, et al., 2010) DECORuM details added by author.

4.6 Model details

The models from Table 4.2 are described in Appendix A.

4.7 Review of models

4.7.1 Modelled scenarios

With the exception of one, CDEM (Firth, Lomas, & Wright, 2010), which was designed and developed to examine the results from previous studies, the objectives of all the studies are to examine the effects on the UK carbon emissions of the implementation of a range of measures to reduce energy consumption by improving dwelling fabric, by improvements to heating systems, and by installing low and zero carbon technologies, improved lighting and appliances. On the supply side, studies employing reduced carbon intensity of electricity generation included BREDEM [down to 0.29 CO_2/kWh (Shorrock, Henderson, & Utley, 2005)], Johnston (2003) (reduce to the same intensity as gas (0.184 kg CO_2/kWh). In DECARB, the value is variable across the modelling period, while in UKDCM and CDEM it is allowed to remain unchanged from the value of 0.43 kg CO_2/kWh used in SAP at the time those models were developed. As DECoRuM (Gupta, 2005b, 2009a, 2009b) is aimed at planning for energy efficiency upgrades, it automatically uses the current value.

The modelling studies reviewed here were mostly developed before the passing of the Climate Change (UK Parliament, 2008a) and hence before the target of 80% reduction in carbon emissions was in place in the UK. Following the setting of this target, it is now more realistic to include such a reduction in the carbon intensity of electricity generation in scenarios.

The scenarios also tend to suggest a range of heating system technologies in future, particularly micro- and community CHP and fuel cells apart from heat pumps and the current gas boilers. As the UK housing stock has been tending towards a monoculture of gas-fired central heating since the early 1970's, with central heating in 96% of dwellings and 80% of central heating using gas (Palmer & Cooper, 2011, pp. 36-37), all using conventional gas boilers, it would seem more plausible that if a new generation of heating system is to take over, this could be equally uniform in its make-up.

4.7.2 Availability and suitability of model software

Of the models reviewed in this chapter, the UKDCM model is the only one that is available currently (2011) for download from the Environmental Change Institute's website. The DECARB model is, apparently, also available from its author. However it would appear from their basic structures that neither model would allow the allocation of heat pump systems to a specified selection from their datasets of archetypal dwellings as heating system types are allocated on a percentage basis across the housing stock in both systems. Moreover, attempting to restrict heat pump assignments to dwellings by, say, heat loss parameter, would require an addition pass at that part of the model.

Neither model has any routines associated with embedded carbon or life-cycle analysis, and creation of these would require additional development.

4.7.3 Routines

Of the 5 models reviewed by Kavgic et al (2010), all use a variant of the BREDEM routines, with some modification, as the central dwelling-level energy model in the model, as does Gupta (2005b, 2009a, 2009b), though in conjunction with SAP routines for carbon emission estimates, thereby making the use of the BREDEM routine at least acceptable for this type of study.

Where the information is available or appropriate, an equal degree of unanimity occurs in the techniques used to populate the parameters required for the BREDEM model. The three latter models reviewed by Kavgic plus Gupta rely upon the age of construction bands to provide a set of u-values for the construction elements, for heating system efficiency, ceiling heights, presence / absence of chimneys and fans and DHW system characteristics. They similarly relate built form type to other characteristics, in particular the division of floor, exposed wall, and roof areas between heating zones, the proportion of window to wall areas. The prevalence and acceptance of these relationships, all of which are based upon the same original research and survey work, in these models provides confidence of their validity.

The appropriate tables from the DECoRuM model are available to the author.

4.7.4 Additional data

Reference to the documentation of the version of the English Housing Survey current at the time of commencing the modelling section of this study showed that dwelling plot size data (widths, depth of front and rear plots) was present amongst the survey data and a SAP rating was present in the calculated variables.

4.8 Summary and Conclusions

To meet Object 2 for this study, this chapter has reviewed a wide range of different domestic energy models, the structures of which have basic similarity but which vary in detail according to their studies' objectives and the software environment espoused by their developers. The objective of this review was to examine whether any of the models were both suitable and available for use in this study; whether their routines could be employed even if no model could be utilised directly and whether the scenarios were appropriate to this current study.

It was found that, of the available models, those that were publicly available were not structured in a way that allowed the desired method of allocating new heating systems, since both required allocation across the housing stock by percentage distribution and neither had the ability to filter by dwelling plot size or heat loss coefficient. These omissions are significant and need to be remedied to meet the objectives of this study in modelling the effects of air and ground source heat pump installations, which require some outdoor space for installation and are deemed unsuitable for high heat loss dwellings. The source of suitable data was found to be the English Housing Survey (previously the English House Condition Survey) and the use of this data will be described in a later chapter.

The following chapter describes the methodology to be used in this study.

CHAPTER 5 METHODOLOGY

5.1 Introduction

Previous chapters have reviewed relevant energy models at two levels; at individual dwelling / heat pump system level and at housing stock level. The perspective of the former models has been found to range between a simplistic view of heat pump characteristics, which fail to reflect the characteristics of these systems, and a complex view demanding more parameters than are generally available. The housing stock models present problems of open-ness, of comprehensiveness and of structure. Of those reviewed, BREHOMES references data and uses rules which are not publically available, while others define the housing stock in terms of a very limited number of dwelling types. Those for which the software is freely available appeared to present problems of structure, whereby it was not possible to make assignments of heat pump installation to a specified segment of the dwelling stock without considerable alteration of the structure of the model.

From the review of individual dwelling / heat pump system modeling, it was concluded that the requirement for a model of residential heat pump energy performance that reflects these systems' characteristics while retaining simplicity could be fulfilled by a linear regression model using heat pump performance test results from WPZ (WaermenPumpen Testzentrum, 2011) as base data.

From the review of disaggregated housing stock energy models, it was concluded that the requirement to examine the future effects of heat pump adoption on the UK energy mix would be best answered by building a 'bottom-up' domestic energy model with the freely-available English Housing Survey dataset. A BREDEM-style model provides dwelling-level estimates obtaining the majority of the necessary parameters from the EHS data, answering the open-ness criticism made by Kavgic, et al (Kavgic, et al., 2010). This will further be answered by developing the required models in Microsoft Excel, since this software is reasonably widely known and available.

This chapter contains a description of the methodology to be used in meeting these requirements and details of the reasoning behind its use.

5.2 Aims of the research

To re-cap, the aims of this research are as follows:

the overall aim of the study is to estimate the potential of heat pumps to meet both the heating and cooling requirements of UK dwellings in a changing climate, and to forecast the effects of possible take-up of heat pumps on the UK electricity demand.

To meet this aim, the subsidiary objectives are to:

1. Review the theoretical and physical characteristics of heat pump systems and identify those that are most significant in the estimation of the energy use of these systems; examine currently-available models and modelling routines for estimating heating pump energy use for their inclusion of the these characteristics, their relevance to the requirements of this study, including their capability for incorporation in a building energy model; this objective was fulfilled in Chapters 2 and 3;
2. Identify and review literature on the modelling approaches that could be used to forecast energy use and CO_2 emissions, and undertake a critical analysis of the work that has been undertaken to predict the future energy use and CO_2 emissions of the UK housing stock; examine whether any of the models are both suitable and available for use in this study; whether their routines can be employed even if no model could be utilised directly and whether the scenarios were appropriate to this current study.this objective was fulfilled in Chapter 4;
3. Monitor how current owners of ground source heat pumps (GSHPs) utilise this equipment, i.e. to record their use of the equipment for heating, cooling and domestic hot water provision, and the consequent energy consumption and system temperatures.
4. Develop a building energy computer model to estimate the energy produced from, and consumed by, heat pumps in meeting domestic heating and cooling demands for different UK house types. Validate and calibrate the model as appropriate.
5. Extend the model to include potential future take-up of domestic heat pump equipment in order to assess:
    - The likely effects of various scenarios for the deployment and application of replacement heat pump installations in the medium and long-term (2020,

2050) on the consumption of electricity and other forms of energy, in particular natural gas.

- Their effect on consequent carbon emissions for the UK both in their manufacture (embodied carbon) and operation.
- the extent to which increases in electricity consumption by heat pumps due to summertime cooling are offset by reductions caused by temperature increases envisaged by the prediction of climate change from UKCIP09 scenarios.
- the extent to which increases in electricity consumption by heat pumps due might be offset by the output from building mounted photo-voltaic systems.

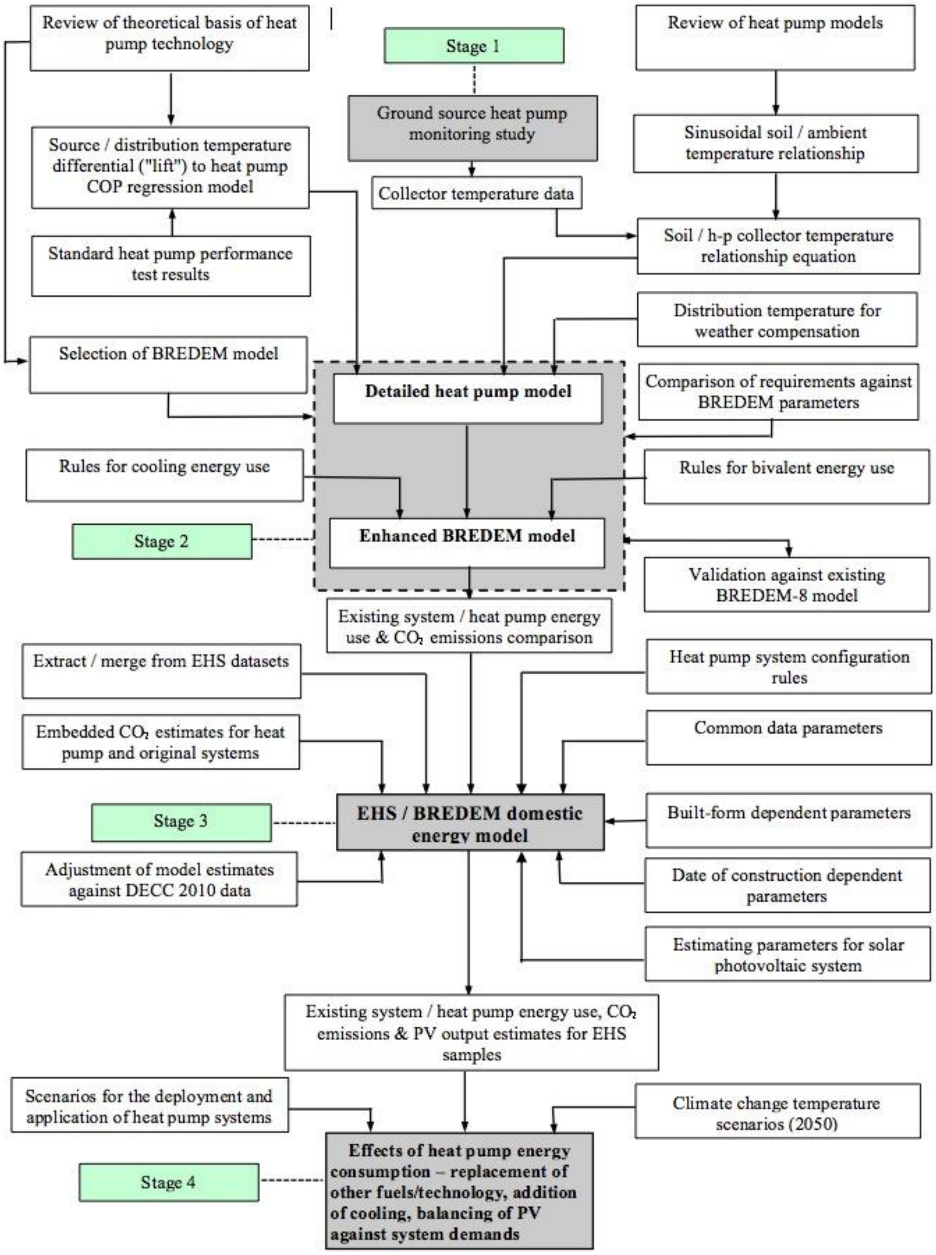


Figure 5.1 Summary flowchart of development

5.3 Stages of the research

The aims of this research are fulfilled by the following stages of the development, illustrated in Figure 5.1:

a) over a 12-month period, the collection and analysis of energy consumption and output and system temperatures from ground source heat pump systems installed in typical UK dwellings; this step is Stage 1 of the development and fulfills Objective 3 of the research;

b) the definition and development, using primary and secondary data, of a model of heat pump energy consumption reflecting the required improvements identified from the review in Chapter 2 and 3;

c) the incorporation of the heat pump model into an existing dwelling energy consumption model, including estimating rules for energy use from bivalent operation and space cooling; this step and step (b) make up Stage 2 of the development which fulfills Objective 4 of the research;

d) the definition and development of an energy and carbon dioxide emissions model for the English housing stock based on the dwelling energy model from (c) using the data reduction techniques employed by the DECORuM system to estimate for each of a reduced dataset of dwellings extracted from the English Housing Survey data. This forms Stage 3 of the development;

e) the building of forecasts for future UK electricity consumption, both in terms of annual and peak monthly loads, based on different scenarios for the level of take-up of heat pump systems and for the replacement of existing heating systems. For the longer-term, these forecasts would include allowance for the predicted effects of climate change and for the parallel installation of roof-mounted solar photovoltaic systems to counterbalance the increase in electricity consumption. This forms Stage 4 of the development and Objective 5.

5.4 Heat pump data collection and analysis

This constitutes Stage 1 from Figure 5.1.

5.4.1 Collection and analysis of energy data from dwellings with heat pump systems

This section of the study is intended to provide empirical data to estimate relationships between variables for which simple theoretical relationships are not available, but which are required to complete the model.

Data for the monitoring study was collected by a datalogging unit which acquires and stores the temperature and status data using an existing diagnostic facility. Additionally, heat output and electricity consumption data is collected by dedicated meters in the distribution and DHW circuit and the electricity mains connection, respectively, and passed to the datalogger. Data values were stored at 15 minute intervals, tagged with a collection date and time stamp. The stored data is down-loaded in batches to a personal computer via a wireless connection.

The data batches from the datalogger for each system were combined into an overall spreadsheet for each heat pump system to create a dataset for the whole logging period. Editing functions within the spreadsheet software were used to cleanse the data of erroneous values. The sample-level data was summarised by day and then by month. Where data samples were missing due to faults in the dataloggers, the summarised energy values were adjusted according to either the heating degree hours or the operating hours in the period lost. Using the sub-system statuses recorded with each sample, the energy data was analysed into categories: space heating or DHW generation, with or without the use of auxiliary heaters, energy use for distribution system pumps.

The following analyses were performed to obtain values for the enhance heat pump model:

Analysis of ground loop return temperatures was performed to obtain a relationship between these and the values calculated by the sinusoidal function estimated by Kusuda & Achenbach (1965) for soil temperature as a function of air temperature.

A frequency analysis of external temperature and energy use by the system auxiliary heaters was performed to calculate a balance point for the systems.

Monthly average and maximum space heating distribution system temperatures were compared with the conventional values.

5.4.2 Acquisition and transformation of heat pump performance data

The objective of this part of the study is to provide performance data for a wide range of heat pump systems from an authoritative source (WaermenPumpen Testzentrum, 2011). As this information is only available in report format, it was transformed into look-up tables using software to convert it into an initial Excel spreadsheet. This initial spreadsheet was further edited to create tables of heat pump suppliers and heat pump systems, and two tables of heat pump test results, one for air/water systems, the other for soil/water systems. A set of linear regression parameters were calculated for each heat pump system based on the lift and COP values from the test values for that system and an overall set of linear regression parameters are calculated for each of the two test results tables.

This completes Stage 1 from Figure 5.1.

5.5 Development of an enhanced building energy computer model

This constitutes Stage 2 from Figure 5.1.

5.5.1 Requirements

The development of the enhanced building energy computer model for this study has two purposes, firstly, to provide an estimate of energy use for a single dwelling, with the intention that the characteristics of the new model will feed into the current UK building energy regulatory process, and, secondly, as part of a mechanism to estimate UK-wide energy use. Thus it is necessary for the new computer model to function on both these levels, requiring that default values are available for its parameters in the UK-wide use while allowing individual values for individual dwellings.

As the model is also required to provide estimates of energy use under conditions of climate change as predicted in the UK Climate Projection , it must also be capable of a) creating estimates using different weather datasets; b) estimating cooling loads as well as heating loads.

Because the main focus of this research is on the effects of domestic heat pump deployment, the aim of the first part of this stage is to develop a heat pump model to provide estimates that reflect the effect of the changing climate and of cooling loads, given the set of characteristics described in Section 2.9 and the performance - temperature relationship documented in Section 3.5.1 .

5.5.2 Domestic heat pump model development

The development is in three parts:

The first part of this process is to examine the estimation methods for the energy use of the different types of heat pump systems in the BREDEM/SAP models used in the UK domestic energy model and in Standards for energy efficiency.

The second part is to identify where these methods are substantially deficient in modelling the characteristics of heat pump systems.

Thirdly, more appropriate methods are identified for characterizing heat pump systems within an improved BREDEM-style model and to specify the equations and processing involved.

5.5.2.1 Original methods for estimating heat pump energy use in BREDEM / SAP

These were described in Section 3.3.4 in which the following were found:

Table 5.1 Estimating methods for heat pumps in BREDEM / SAP

Ref	Parameter / variable	BREDEM /SAP version
1	Space heating COP/SPF	Single annual value dependent on source type, reduced if system is fitted with auxiliary electric heaters.
2	Water heating COP/SPF	As above
3	Additional heating	Allowed for in reduction in COP
4	Cooling load	Not estimated in BREDEM. Single annual value for EER in SAP

5.5.2.2 Heat pump system characteristics

These were identified in detail in section 2.9, viz.

a) lower temperature output due to the characteristics of the vapour compression cycle heat pump;

b) variation of source energy over the heating season due to depletion of the ground as an inter-seasonable store or to the fall in air temperature;

c) CO_2 emissions from operating electric heat pumps are due to the carbon intensity of electricity generation rather than the fuel it consumes;

d) cost of installation of GSHP systems is highly dependent on the size of the system, especially of the collector;

e) Non-uniform increase in operating cost and CO_2 emissions with increase in indoor/outdoor temperature differential when outside temperature falls below the system balance point temperature; this being due to the use of additional heat at a COP < 1.0;

f) Heat pump systems are capable of providing cooling as well as heating.

5.5.3 Heat pump model rules

In Section 3.5.1 , it was determined that the COP of a heat pump system was related to the source-sink temperature differential or 'lift' in an inverse linear relationship which differs between system source types, specifically between air source and all the water source types (horizontal ground loop or vertical bore hole). Data to estimate coefficients for the COP / lift relationships for air and water source systems was obtained from the Swiss testing laboratory WPZ (WaermenPumpen Testzentrum, 2011).

Having built relationships from this data, rules had then to be developed to relate the lift value to the available parameters of a dwelling energy model such that a suitable COP value can be obtained for the estimation of monthly energy consumption. In the case of the BREDEM-8 model, this parameter is the monthly average external temperature, from which values for the source and sink temperatures at the heat pump system boundaries must be computed.

Given a monthly average external temperature, different relationships are defined to estimate the source temperature at the system boundary for each of the three different source types, as follows:

for an air source heat pump, then the source temperature can be assumed to coincide with the external monthly average temperature;

for a GSHP system linked to a borehole heat exchanger, the soil temperature is judged to be equal to the annual average air temperature (Ochsner, 2007);

for a GSHP linked to a horizontal ground loop or similar, then the soil temperature for an air temperature value may be estimated from the sinusoidal equation 3.14 defined by Labs (1979) (Section 3.2.3.3), for appropriate values of its parameters;

a relationship can then be derived between the estimated soil temperature from this equation and the source temperature by comparing the output values from that equation with the ground loop return temperature values from the monitoring study.

In estimating sink temperature values, the main determining factors are:

the presence or absence of weather compensation control within the system controller, since this varies the system output temperature with variations in external temperature;

the choice of heat distribution by radiators or UFH as the latter conventionally require a lower temperature flow for a given room temperature.

Conventionally, temperatures of 35ºC and 55ºC are used in calculations for heat pump output to UFH and to radiators, respectively (Ochsner, 2007), while weather-compensated control utilises a 'curve' relating the target distribution temperature to the current external temperature, with the gradient of this curve being set to a higher value for radiator distribution than for UFH. Thus the estimating mechanism for a sink temperature may be defined from the graph of the controller curve provided by the heat pump supplier, if weather compensation is installed, or the conventional values used if not.

The final stage steps of the heat pump model are to calculate a 'lift' value from the source and sink temperatures and, thence, a COP value from the regression function for the heat pump type.

5.5.4 Enhanced dwelling energy model

5.5.4.1 Choice of energy model

As the major focus of this thesis is to measure the impact of domestic heat pump systems on the UK energy supply, it is therefore appropriate to choose a version of BREDEM as a basis for this enhanced model. While other building energy models which include heat pump system calculations exist and were presented in Chapter 3, they do not have the particular relevance of the BREDEM models in the assessment of the UK situation.

As indicated in Section 3.3.4.1, three versions of BREDEM exist. BREDEM-8, BREDEM-12 and SAP (being in effect, BREDEM-9). Of these, the most regularly updated has been SAP, which has been through several versions since its inception. Since the SAP calculations are the basis for pass/fail decisions for the energy efficiency of the dwelling design (DCLG, 2006) according to Part L1A of the UK Building Regulations, they contain additional complexity, of which the most obvious is the calculation of a SAP rating for a dwelling of identical built form which meets the minimum standard of the Regulations for comparison with that of the design dwelling to determine a pass or fail. In compiling an energy rating for a dwelling, it has previously been deemed that this should be unaffected by its geographic location and therefore this element has been omitted from SAP up to now, rendering the energy consumption estimates from SAP insensitive to change of climate across the country or across time. The SAP procedures also now include procedures for evaluating community schemes, for evaluating a dwelling as built, and for proposing energy saving measures for existing dwellings, though the latter are not included in the energy calculations. In mid-2009, further substantial revisions were proposed, including the monthly calculation of space and water heating loads, and of space cooling, the explicit calculation of the effects of thermal mass, revisions to the carbon dioxide emissions factors, boiler efficiency and the calculation of internal heat gains.

A version with fewer input parameters, known as “Reduced data SAP” (RD SAP), has been created to create Energy Performance Certificates to conform with the European Energy Performance of Buildings directive. RD SAP has a preliminary process which expands the reduced set of parameters into the full set required for the full SAP assessment to be performed.

While the current version of SAP contains relevant methods for the estimation of elements that concern this study, the added complexity of the calculations for regulatory purposes makes it unwieldy for the current purpose, implying that a version of BREDEM would be more suitable. A distinction must be made between the different BREDEM models, since two main versions, BREDEM-8 and BREDEM-12, exist. These have different emphases, BREDEM-8 calculating monthly estimates for 12 months of the year based on monthly average external temperatures, while BREDEM-12 calculates a year's estimate only using heating degree days. BREDEM-8 contains different calculation modules for the effects of different heat system types. As this thesis concerns itself with the effects of changes in energy available to heat pump heating systems across the year, BREDEM-8 appears to be the appropriate choice as the baseline version for modification.

5.5.4.2 Enhancements to BREDEM-8

These consist of the following:

the insertion of an additional module to provide estimates for energy consumption by an appropriately sized heat pump; processing within this module is controlled by parameters as follows:

a) bivalent operating mode - either monovalent, bivalent parallel or alternate parallel;

b) balance point temperature: the temperature below which auxiliary heating is switched in;

c) the system source type: air, vertical borehole, horizontal ground loop;

d) the distribution type: radiators, underfloor heating;

e) presence/absence of weather compensation control.

within this module, the heat pump model is invoked for each month of the year with the appropriate monthly average temperature, returning a corresponding COP value.

routines are added to the heat pump module to estimate the effect on energy consumption of each of the three operating modes based on the balance point parameter;

a separate module is added to the overall BREDEM-8 to estimate space cooling loads employing either the installed heat pump system in reverse or a stand-alone air-conditioning unit;

A routine is added to calculate CO_2 emissions for all the energy consumed in the dwelling, depending on the type of fuel consumed and the overall model is modified to provide a comparison between the energy use of an existing heating system and a comparable heat pump system.

5.5.5 Model validation

This consists of comparing the energy loads of a dwelling or dwellings using both the new software, the current version of the same software and the data collected from the monitored installations.

5.6 EHS / BREDEM domestic energy model

This constitutes Stage 3 from Figure 5.1.

5.6.1 Development process

Following on from the enhanced dwelling energy model development, this section describes that model's use in the development of a domestic energy model for England based on the dwelling sample data from the English Housing Survey.

The initial steps in this development are as follows:

a) the extraction of the relevant data, both in terms of samples and of variables, from the EHS data tables held in SPSS format and the compilation of these extracts into a single MicroSoft Excel table;
b) the creation of additional variables required by the enhanced BREDEM model, including plot size variables;

c) the addition of versions of the DECORuM reference tables relating the values of common, built form and construction date variables from EHS to parameters required by the BREDEM-8 model;

d) the definition of rules for the configuration of heat pump installations for dwelling;

Following on from these steps, a pass of the extract table is made to create estimates for both the existing system and a putative heat pump system:

energy consumption for primary and second space heating, space cooling, DHW, heat distribution, appliances and cooking;

CO_2 emissions;

energy cost.

The estimates for each sample are grossed-up by the sample weight to obtain their effect within the whole housing stock and the grossed-up values totalled to form estimates for the entire stock.

After the creation of this baseline model, future scenarios for heat pump energy use in 2020 and 2050 are developed as follows:

a) the definition of scenario tables of possible heat pump installations for 2020; conventionally other research and reports have divided the installations between air and ground source systems without further division;

b) definition of application scenario rules for the installation of heat pump systems in dwelling samples;

c) translation of each of these rules into model processing and execution of the required model runs to create energy consumption and CO_2 emission estimates for these scenarios;

d) summarisation and analysis of results from these runs;

e) estimation of electricity output from roof-mounted photovoltaic systems for each sample in the EHS extract, based on roof areas derived from the survey variables, assigned values for the system characteristics and dwelling orientation;

f) the creation of scenario data for temperature changes under conditions of climate change in 2050 based on UKCP09 predictions;

Repeat of steps (b) to (d) for the 2050 scenarios.

The following sections describe this methodology in greater detail.

5.6.2 EHS Survey data

The EHS survey and its database is described in detail in the survey User Guide (DCLG, 2010b). It is a continuous survey of virtually all aspects of a sample of English dwellings, carried out for the UK Department of Communities and Local Government (DCLG) and was formed in 2008 as a merger between the English House Condition Survey (EHCS), and the Survey of English Housing (SEH). As this merger occurred during the compilation of the dataset used in this survey, the previous names (particularly the EHCS name) were still in use in sections of the survey documentation. The data is freely available from the Office of National Statistics in two data formats, of which the SPSS format (SPSS Inc, 2010) was used as the basis for this study. It has been chosen for this study as it is a definitive source for all reporting for the English housing stock (DCLG, 2011).

Three types of data are collected:

household data concerning their tenure, composition, occupations and income;

physical data concerning the dwellings' location, built form and services, state of repair, surroundings, disabled access, health hazards;

valuation data concerning the dwellings' market value.

Management of the Survey is conducted by the Office of National Statistics whose researchers conduct household interviews while a firm of chartered surveyors perform the physical surveys using questionnaires developed by the Building Research Establishment (BRE). The property valuations, based on the physical surveys and photographs, are made by the government Valuation Office Agency, the property valuation agency for the UK Revenue and Customs department (DCLG, 2010b).

The sample size for the survey is approximately 8000 dwellings each year, with the current '2007' release consisting of data collected between in the two years between April 2006 and March 2008, a total of 16,217 dwellings and 15,604 households (the sample includes vacant properties) (DCLG, 2010b). The data as obtainable from the

Economic and Social Data Service (DCLG, 2010b) is spread over some 29 primary data tables and 14 derived tables. These tables are linked by a unique identifier for each sample with the *'general'* table forming a starting point from which to link to all the others. Entries in the tables mostly form a one-to-one relationship with the *'general'* table entries, ie. there is one entry in the *'firstimp'* table for each entry in the *'general'* table, but in tables such as *'windows'*, there are entries for each window type / material combination for each sample dwelling.

Each sample carries a weight estimated according to the probability of the dwelling being selected from the UK housing stock, adjusted for bias created by non-response to the survey, then scaled such that the grossed-up number of dwellings by tenure and GO Region in the sample equals that of control totals from Census values for the same partitioning of the housing stock. The implication of the weighting is that a value calculated from an EHCS sample can be grossed up to an estimate for the whole English housing stock using the sample dwelling weight. This extends to the estimation of dwelling energy use with SAP and BREDEM routines, with such calculations being included in the EHCS Technical Guide Chapter 7 *'Using EHCS data to model Decent Homes Thermal Comfort'* (DCLG, 2010a, p47).

5.6.3 EHS Sampling method

The EHS is described as '*a multi-stage clustered sample stratified by tenure*' (DCLG, 2010a, p. 9). For this sampling method, the total population is divided into the groups (or clusters) and a sample selected from these groups. The required data is collected from the elements within each selected group, either from the totality of the elements or from a sub-sample. The 'multi-stage' element implies that there are layers of grouping in the sample. ie. groups within groups. In the case of the EHS sampling process, the clusters are based on tenure (owner-occupied, privately-rented etc.) within Government Region. The objective of this strategy is to allow sample bias towards social housing to provide more accurate results for this sector. See section 8.2.2.

To provide information on building condition, some additional longitudinal sampling was introduced from 2005-2006, whereby successful sample addresses from the three-year previous survey were included (DCLG, 2010b).

5.6.4 Sample bias

Because the survey is commissioned by central government, which is concerned with the meeting of targets for the reduction in numbers of social housing which are unfit for habitation or which fail to meet standards for the cost of heating, social housing is deliberately over-represented in the sampling process as indicated in Table 5.2, where owner-occupied dwellings are reduced to 50% of the sample, with the equivalent value for the whole housing stock being 70%. This, according to the EHS Technical Report, ensures that the Survey provides information about "*rarer tenures*" (DCLG, 2010b, p. 7).

Table 5.2 Sample bias towards social housing

Table 2.1: Tenure distribution of target achieved sample compared with the national stock

Tenure	Target achieved sample	Target achieved sample (%)	National stock[1] (%)
Owner-occupied	4,150	50	70
Private rented	1,040	13	13
Local authority	2,070	25	18
Registered social landlord	1,040	13	
Total	**8,300**	**100**	**100**

[1] Taken from Table S101 Trends in tenure, Survey of English Housing 2008 (based on LFS data)

Table 5.2 indicates that owner-occupied housing is deliberately under-represented in the sample by 50% as against 70% with local authority housing stocking comprising 25% of the sample while being less than 1% of the UK housing stock.

5.6.5 Primary Survey data

This is of two types: household data and dwelling data. Data for dwellings vacant at the time is also treated as household data but recorded separately. Household data is based on an interview with the householder and consists of details of: the individuals in the household including ages, relationships, work status; amounts and sources of income, including benefit payments; attitudes to the dwelling and surroundings; occupants' type of tenure; disabilities (if any). For the dwelling, it also collects details of: adaptations to the dwelling to assist with disabilities; which rooms are occupied or shared; responsibility for repairs and repairs done; damp problems in the dwelling fabric; improvements or significant maintenance done by occupants or landlord.

Dwelling data is based on a lengthy questionnaire (Appendix I) and collects data on many aspects of the dwelling which increase in number and complexity depending on the type of dwelling with a single, detached house as the most simple and flats as the most complex.

Table 5.3 EHS Primary data captured from questionnaire

a) interior	Presence/absence, condition / safety of facilities including cold & hot water supplies, waste outflows, kitchen cooking facilities, cupboards, work top, facilities for food preparation, appliances, bathroom, shower room, wc's. Presence / absence of gas / electricity supply, normal or off-peak; condition of electrical system, type, fuel, age, safety etc of space and water heating systems; loft condition and insulation.
b) shared facilities	Presence/absence/condition of shared facilities, eg. common rooms, stores, laundries, drying rooms, offices, parking or garages, communal heating, alarms systems, external lighting, lifts, refuse chutes, security systems, fire safety systems, balconies, decks, corridors, lobbies. Condition of building elements - damp, stability, drainage, lighting etc.
c) external	Dimensions, built form, materials and finished for dwelling plus details of defects, alterations, improvements, including type of accommodation and date of construction; presence/ absence/ condition of chimneys, bays, dormers, porches, conservatories, balconies, roof features; presence / absence / condition of a damp proof course; type / position / age / condition of doors and windows. Additionally for flats: numbers of flats in module, non-residential uses within module, details of wall exposures (external/ internal / accesses).
d) surroundings	Presence / absence / condition / size / positioning / fences or walls of external plot. Accessibility of dwelling entrance; condition of plot drainage; details of parking provision; exposure of dwelling position; characteristics of surrounding housing - density, built form, construction data, tenure; social character of neighbourhood - incidence of vandalism, graffiti, intrusive industry, empty

	buildings, noise etc.

While it is possible that not all sections of the survey for a sample dwelling are completed, eg. the surveyor may not be able to arrange an interview or the householder may refuse to participate, these 'unsuccessful' samples are not included in the version of the database on public release.

5.6.6 Derived/computed data

This is of two categories: firstly, data summarised up from the individual questionnaire variables; secondly, data estimated using modelling techniques, specifically SAP 2005, and the values used as input parameters to that model. A summary of the data types is in **Table 5.4**.

Table 5.4 EHS derived data variables by data file

Data file	Content type
general	Tenure, categorised in different ways
	Government Office Region (GOR)
	Surroundings, categorised in different ways
	Environment: upkeep, traffic, utilisation, liveability, quality assessments;
	Valuation of dwelling
	Assessed demand in area
	Nation Regeneration Fund (NRF) status of district
	Index of Multiple Deprivation (IMD) ranking
	Market area factor score for housing demand, number of properties on market plus ranking of score
	Rural / urban morphology
	Dwelling weight for grossing-up
	Household weight for grossing-up
physical	Dwelling type, categorised in different ways
	Construction date, banded in different ways
	Summarised dwelling dimensions: floor area, number of floors
	Predominant types of : roof covering and structure, wall finish and structure, windows.

	Extent of double glazing Security of windows and doors Parking provision Presence/ absence of basement or cellar Heating system: type, distribution, age, fuel type, fuel DHW system: type, boiler type Loft insulation: thickness, categorised in different ways Walls: Cavity / non-cavity / insulated/ non-insulated SAP rating: rating, code Environmental impact: rating, code Decent homes assessments Repairs cost: different categories
energy_performance	SAP estimates for existing dwelling : CO_2 emissions; costs: lighting, DHW generation, space heating, total energy; primary energy consumption; Presence / absence of lower cost energy upgrades for: loft insulation, cavity wall, cylinder insulation; Presence / absence of higher cost energy upgrades for: cylinder thermostat, heating controls, boiler, biomass system, storage radiators, warm air system; Post improvement values: SAP rating, EI rating, CO_2 emissions.
energydims	Area: ground floor, highest floor Ceiling height of each floor External face area of each face external window areas on each face
dimensions	number of habitable rooms total floor area total floor area + 50% external walls floor area occupied by : partition walls; stairs; balconies; garages internal wall area internal doors number of habitable rooms number of floors in main, additional part

	Lowest, highest floors in main, additional part
	External front, back wall areas
	Front, back window areas
	Damp proof course perimeter, front, back
	External front, back roof plan area
	External front, back roof slope area
	External front, back eaves perimeter
	External main, back eaves height

5.6.7 Extraction of model variables from EHS datasets and creation of main data table

Since the BREDEM-8 model is not capable of providing estimates for flats or apartments (Anderson, et al., 2001), the initial entry point for the extract was the derived dataset (file name 'physical.sav') for the physical survey, which contains several variables containing codes indicating the built form of the dwelling, of which the variable 'housex' has the simplest coding - either "flat" or "house". The resultant extract table was then cross-referenced by the Sample ID (variable name 'aacode') to further EHS tables to extract the variables required. The tables referenced are listed in Table 5.5.

Table 5.5 EHS tables used in main extract

File name	Description of file
around	Dwelling surroundings: dimensions of plot, relative location of plot
dimensions	Number of rooms, wall and floor areas
energy_performance	SAP ratings, energy efficiency ratings, light, water and space heating costs, energy upgrade costs
energydims	Area of ground and highest floor, ceiling heights, external wall and window areas.
firstimp	Key information on the first impressions of the dwelling and neighbourhood as recorded by interviewer
general	Tenure, dwelling condition, location, housing market in locality
physical	Built form, date of construction, construction details, heating system, SAP rating.
services	Details of heating systems
shape	Dwelling shape: external dimension of dwelling; material and construction of dwelling.

Thus the data collected in the EHS provides the majority of the conventionally-collected built form and services data, i.e. dwelling type, i.e. detached, semi-detached, end/mid terrace, bungalow, purpose-built/converted flat, dwelling age in 11 bands from 'post 1850' to 'post 2002', floor area, ceiling height, main and secondary heating system type and fuel, DHW generation system and fuel, glazing area and type, plot size and a limited amount of insulation information.

5.6.8 Creation of baseline energy estimates for samples in the EHS extract

5.6.8.1 Additional variables for main EHS extract

Based on variables from the 'around' table, two new variables are calculated for the useable plot size - that available for the installation of a GSHP ground loop, and the rear plot size - that area assumed to be sufficiently secure for an ASHP installation, which are deemed prone to vandalism. The value for the useable area of the dwelling plot is calculated as the greater of the front or rear sections, ie. plot width times plot depth, assuming that either the rear or front section, but not both, can be used for the burial of a ground source collector, with the latter applying to the rear plot only.

A new variable is created for the heating degree region appropriate to the Government Office Region code value for each sample. BREDEM-8 utilises a table of external temperatures with entries for 21 heating degree day regions to determine heating load whereas location data on the EHS samples is limited to a variable for the 8 Government Office Regions. As one GO Region can encompass more than one heating degree day region, and a heating degree day region may overlap GO Regions, a routine was written that randomly assigned each sample to a heating degree day region according to the relative numbers of houses in each county or other administrative area in its GO Region.

To provide estimates of embodied CO_2, a value is calculated based on the Total Floor Area, the built form type (detached, semi-detached, terraced) and the wall construction type (cavity wall, sold wall) of the sample using the relationships defined by Johnson (2011).

Table 5.6 Summary of additional variables

Variable	Source and derivation
Useable plot area	Calculated from plot depth times width
Rear plot area	Calculated from rear plot depth times width
Heating degree day region	Derived from Government Office Region, randomly assigned according to proportion of housing stock in constituent counties.
Embodied carbon dioxide	Calculated from dwelling total floor area using relationships from Johnson (2011).

5.6.8.2 Assignment of heat pump configurations to dwelling samples

The characteristics of the dwelling sample are used to determine the configuration of the putative heat pump system in terms of the source and the mode of operation assigned. Initially, the source type is determined according to the sample plot size calculated above, with a horizontal ground loop source being selected if plot size is at least twice the dwelling total floor area, an air source if the rear plot area is greater than 4 m^2, defaulting to a vertical bore hole for smaller areas of plot (Energy Saving Trust, 2011; Nottingham Energy Partnership, 2006).

The second configuration variable is the operating mode which is set according to the a) contruction date of the dwelling; b) its SAP rating; and c) whether it currently has an installed central heating system; and has possible values of monovalent, bivalent parallel or bivalent alternate.

5.6.8.3 Heating systems and fuel type mappings

Each sample has variables containing details of heating system types, fuels used and age for a Primary and 'other' heating systems, plus hot water generation system, allowing that these may be the same items of equipment. To provide energy consumption estimates in the BREDEM model, it is necessary to create tables cross-referencing combinations of the EHS variables to the BREDEM efficiency and other parameter values. Thus, to determine the efficiency, responsiveness, BREDEM heating type, and fuel type of the primary heating system, a table was constructed relating all these values to the *'primary heating system - type of system', Main fuel type', 'main heating fuel', 'Boiler group'* variables from the EHS Extract. A second table was constructed for the efficiency and responsiveness of the secondary heating system and a third relating the primary heating type, fuel type and secondary heating type to the proportion of primary system energy consumed by the secondary system.

5.6.8.4 Linkage of EHS sample table to the enhanced BREDEM-8 model

After the addition of the additional variables to each sample and the construction of the heating system tables as indicated above, each EHS Extract sample is used as input to the enhanced BREDEM model to create energy, carbon dioxide and cost estimates. The building elements data collected in the Survey are not sufficient to provide all the parameters required for the BREDEM model and therefore recourse must be made to techniques of data reduction, i.e. the inference of multiple parameter values from a single value, being 'data reduction' in the sense that the technique reduces the data required to be collected by surveying to populate the model parameters. Because of good access to the techniques in this process, the author opted to use the data reduction techniques from DECoRuM (Gupta, 2005a, 2009a, 2009b), derived from Rylatt (Rylatt, et al., 2003a, 2003b) in which date of construction and the built form of the dwelling are proxies to set the values of lower level parameters in BREDEM-8.

Built form, ie. detached, semi-detached, mid-terrace etc., is used to specify the following:

a) the proportion of the dwelling surface areas (roof, ground floor, total floor area, external walls) assigned to each of the two heating zones;

b) the proportion of window area assigned to front and rear walls, and also between zones;

c) the number and type (inside, outside) of exterior wall corners forming thermal bridges.

d) number of sheltered walls which varies between zero for a detached house and 2 for a mid-terrace.

The values chosen by Gupta (2005a) for c) above effectively simplify the floor-plan of each sample dwelling to a simple rectangle. The actual floor-plan of each dwelling is collected in the EHS physical survey, but does not appear to be encoded in the survey variables in a way that permits any improvement on Gupta's (2005a) assumption.

Date of construction, for which the EHS variable has 9 ranges, from 'Pre 1850' to 'Post 1990', determines:

a) u-values of opaque construction elements, ie. walls, ground floor and roof
b) Thickness of wall construction (solid/cavity)
c) Tightness of windows and doors
d) Draught stripping on doors
e) Tightness of doors
f) Type of hot water tank insulation
g) Thickness of hot water tank insulation
h) Insulation of primary pipe-work
i) Presence of hot water cylinder thermostat
j) Sealing of loft hatch
k) Number and type of extractor fans

Further values are assumed to be identical for all houses:

a) Control of primary space heating system
b) Off peak tariff for hot water
c) Single outlet for hot water
d) Floor type (suspended timber unsealed=0.2, sealed=0.1; other floor=0)

5.6.8.5 Processing of EHS Extract to create baseline estimates table

A Excel routine is then required which loads the required parameters into the enhanced BREDEM model, executes its processing, and then extracts the required estimates into a new table of results for use in the development of scenarios. In each table, the sample-level estimates are grossed-up by the sample weights for the stock-level effect of this sample.

To implement the requirement to prepare a set of estimates under conditions of climate change, an suitably-amended table of monthly average temperatures is loaded over the original and the Excel process re-run to create a new output table.

5.6.8.6 Validation and adjustment of model estimates against DECC (2010c) data

To verify and adjust the total estimates calculated by the baseline model, these are compared with the actual values for domestic energy consumption from the 2010 update of *'Energy Consumption in the UK: Domestic data tables: Table 3.7: Domestic energy consumption by end use and fuel 1990 to 2008'*, using data for the central year of the EHS survey, 2007, making a necessary conversion from energy values in thousands of tonnes equivalent to Gigawatt hours. This provided adjustment factors for each of the main fuel types (solid fuel, natural gas, heating oil and electricity) to be applied to the estimates from the model.

5.6.9 Estimation of possible solar photovoltaic output

To estimate the possible power output from roof-mounted photovoltaic systems on sample dwellings, a separate table of monthly estimates was created, with one entry for each sample, keyed with the EHS Sample Number. The maximum output value (0.193 kWp/m^2) from the RenSMART comparison table of photovoltaic modules (RenSMART Ltd, 2013) provided a standard value for the per-area output of the modules, assuming that this maximum value will become a typical value by 2050. A value for the monthly output of the system was derived using the methods from the current draft SAP 2012 calculation (BRE, 2011, pp. 81-82) and accompanying supporting Technical Paper (Henderson, J., 2011).

Equations relating solar output to annual solar radiation, peak output of the modules and overshading are provided by the Appendix M of SAP 2012:

$$AnnualOutput = 0.8 \times kWp \times S \times Z_{PV} \qquad (5.1)$$

where kWp is the peak output of the system, *S* is the annual solar radiation in kWh/m^2 and Z_{PV} is the overshading factor.

Appendix U of SAP 2012 relates *S*, solar radiation, to orientation, tilt and month of the year, based on a factor converting horizontal radiation values to a given inclination, again for a given orientation and tilt, as follows:

$$S = 0.024\sum_{m=1}^{12} n_m \times S(orient, p, m) \tag{5.2}$$

Given that S is an annual value, then a monthly value for solar radiation S_m (kWh) will be given by:

$$S_m = 0.024 \times n_m \times S(orient, p, m) \tag{5.3}$$

and monthly output by:

$$MonthlyOutput = 0.8 \times kWp \times S_m \times Z_{PV} \tag{5.4}$$

Section U3.2 of SAP 2012 gives the derivation of $S(orient, p, m)$ as follows:

$$S(orient, p, m) = S_{h,m} \times R_{h-inc}(orient, p, m) \quad (5.5)$$

and

$$R_{h-inc}(orient, p, m) = A \times \cos^2(\phi - \delta) + B \times \cos(\phi - \delta) + C \quad (5.6)$$

where:

n_m = number of days in month m;

orient = orientation of the roof surface (N, NE, E, SE, S, SW, W or NW)

p = tilt of the surface in degrees from horizontal (e.g. 0° is horizontal, 90° is vertical), 30° assumed;

$S_{h,m}$ = horizontal solar flux (W/m^2) for the month and heating degree days region.

$R_{h-inc}(orient, p, m)$ = factor for converting from horizontal to vertical or inclined solar flux in month m for a given orientation *orient* and tilt p;

ϕ = representative latitude in degrees N for the heating degree region of the sample dwelling;

δ = solar declination for the applicable month in degrees;

A, B and C are further determined by a set of quadratic expressions in the sine of the tilt angle with coefficients determined by orientation (BRE, 2011, Table U5).

The area of photovoltaic modules used to estimate output is determined by the area of uppermost floor of the dwelling (SPSS variable '*higharea*' from table '*energydims*'), of which an arbitrary fraction (0.33) is deemed available for this purpose.

5.6.10 Scenarios for future UK electricity consumption

This section constitutes Stage 4 from Figure 5.1.

5.6.10.1 Objectives

There are two objectives for this section of the study. One is to examine the effects on the UK energy "mix" - and in particular electricity demands - of the current UK Government initiative, the Renewable Heat Incentive, to encourage the take-up of renewable heating devices to meet European Union targets over the period to 2020 and to examine alternative application of these systems. The second is to examine the electricity demand effects of much wider deployment of domestic heat pumps in order to meet the UK's target for 80% reduction in carbon emissions by 2050, including the possibility of substantial cooling loads from reversible heat pumps under conditions of climate change.

5.6.10.2 Structure of scenarios

Scenarios for heat pump installations are defined in two levels: firstly, the number of systems that may be deployed by the end of the scenario period, termed here as 'deployment scenarios'; secondly, the selection of dwelling samples to which these systems are to be applied, termed 'application scenarios'. The application scenarios, in terms of installation numbers, are translated into weights on each sample assigned to the scenario to accrue the sample estimates for a scenario.

5.6.10.3 Temperature data for climate change condition in 2050

The table of monthly average temperatures for each Heating Degree Day region is 'morphed' by temperature increase estimates taken from the UK Climate Projection (DEFRA, 2011) “high emission”, ‘central estimate” data for GO Regions.

5.6.10.4 Application scenario rules

These define which samples are selected for each scenario by setting a value for the weighting to be applied to the samples, zero weighting implying that the sample is excluded from the scenario and the maximum value equalling to the EHS sample weight. Samples are selected by the selection routine until the total of the weights assigned for each system type exceeds the total number of systems for the scenario.

The rules utilised for 2020 application scenarios were as follows:

a) samples were selected by a pseudo-random process - one that allows for the process to be repeated - and the weighting applied to the selected sample also assigned by a similar pseudo-random process;

b) an identical sample set to that in (a) but with a limited set of energy efficiency measures applied to the samples;

c) samples are selected according to the total carbon emissions of the dwellings starting from the highest;

d) samples are selected according to the carbon emissions of heating system fuel, starting from the highest.

5.6.10.5 Model processing

Two methods of processing were used. For scenarios (a) and (b), rows were selected from the Output estimates table by a randomly-generated row number. Each selected row was then assigned weight values for each scenario by generating a second random number with a maximum value of the Sample Weight. This process was repeated for each deployment scenario until the total of the weights assigned exceeded the value for the scenario at which point no further assignments were made. When the highest deployment scenario value - the 'Stretch' scenario - was exceeded, then the assignment routine was terminated. As the scenario values are divided between ASHPs and GSHPs, separate totals are maintained for each type during the assignment process with the appropriate total being incremented according to the heat pump type allocated to the sample in Section 0.

For scenarios (c) and (d), rows were processed according to the appropriate CO_2 emission value, either the dwelling value or that for the primary heating fuel, in descending order of magnitude. In this case, the entire sample weight is assigned to the scenario weight for each sample selected, rather than a proportion. Again, weights are assigned for each scenario until the total scenario is exceeded, with the process continuing until the 'Stretch' values are reached.

5.6.10.6 Analysis of results

Results from the assignment process for the scenarios are summarised by fuel type and by total emissions between existing heating systems and heat pump systems on an annual and monthly basis to provide appropriate tables and charts to observe the scenario effects.

5.7 Summary

This chapter has reviewed the requirements for fulfilling the study objectives and specified the methodological steps required to achieve those objectives. The salient points of these steps are:

a long-term monitoring study of domestic heat pumps for collection of detailed performance data with the objective of informing the development of a heat pump model;

the development of an enhanced BREDEM-8 dwelling energy model, at the kernel of which is a regression-based heat pump model, which will provide energy consumption and carbon emission estimates both for an existing system and for a heat pump system; and the linking of this BREDEM-8 model to the English Housing Survey extract using parameter reduction techniques; the creation of sample energy consumption and emissions estimates for both existing heating systems and putative heat pump systems;

creation of housing stock consumption and emission estimates for installation and policy scenarios for 2020 and 2050;

analysis of these final estimates against the UK electricity generation capacity and carbon emissions reduction targets.

BREDEM-8 was chosen as a starting point because of its position as an accepted standard for dwelling energy modelling and for its ability to provide monthly estimates. It is also capable of being implemented in the chosen platform of MicroSoft Excel.

The English Housing Survey data was chosen because of its completeness and public availability and the presence of sample weights which allow sample estimates to be grossed-up to housing stock values.

The following chapter describes the monitoring study for domestic heat pumps and the analysis of the output data to provide empirical values as parameters for the heat pump model.

CHAPTER 6 PRIMARY AND SECONDARY DATA COLLECTION

6.1 Introduction

Chapter 5 described the methodological approach to be taken in this study. This chapter describes the initial stage in that methodology, the collection of data, both primary and secondary. Apart from forming a basis for this study, the primary data collection had the additional objective of providing independent verification of the performance of the industrial partner's heat pump products. This stage meets Objective 3 of this study.

6.2 Collection of energy and temperature data from residential heat pumps

6.2.1 Approach

The approach used in building the monitoring system for the heat pumps was determined by the requirements of the industry partner, who required a datalogging unit to acquire diagnostic data for heating systems whose performance was unsatisfactory. The datalogging unit replaces an existing facility by which data is output via a diagnostic socket on the heat pump controller to a computer for monitoring by a maintenance technician. The unit is plugged into the same diagnostic socket and acquires the same diagnostic data as the existing facility plus the additional energy data for this research. The data values are stored every 15 mins and the unit (known as a SPIE box) has a capacity of 1638 samples, slightly over 17 days' worth of data.

6.2.2 Monitored dwellings and heat pump installations

6.2.2.1 Selection of dwellings for the study

The number of installations involved in this study was restricted to three by the lack of availability of the custom-made logging equipment, due to circumstances outwith the control of the author.

In selecting dwellings for this study, the intention was to include a range of different built forms and ages of dwelling as possible. This intention was difficult to fulfill because of the current state of the GSHP market in the UK, where, due to their high capital cost compared to almost all other types of heating systems, to their comparative novelty, and requirement for a reasonably large garden in which to install the ground loop, installations have largely been restricted to larger, detached, new-build houses in country locations. With the aid of the industrial partner, installations in two older, smaller properties were located, with a third installation in one of the afore-mentioned new-build houses being chosen for comparison. A summary table of the dwelling and heat pump systems is in Table 6.1 and more detailed descriptions follow.

Table 6.1 Summary of characteristics of dwellings and monitored heat pump systems

Dwelling Ref.	1	2	3
Date of construction	1965 extended 1980's	1951, extended 2007	2007
Built form	'Chalet' bungalow	2 storey semi-detached	2-storey detached
Floor area (m^2)	122	139	309
Occupants	4	2 adults. 2 teenagers	2
Current heating system	IVT Greenline C6 rated at 6kW with radiators	IVT Greenline C4 rated at 4kW with radiators	IVT Greenline E11 rated at 11kW with underfloor heating
Previous heating system	Boiler fired by liquid petroleum gas (LPG)	Boiler fired by mains natural gas.	n/a
Construction			
External walls	Cavity brick walls - (insulated in extensions – 57% of area)	Solid brick walls in original house (57% of area), insulated cavity brick walls in extension (43%).	Insulated cavity walls throughout, part rendered.
Roof	Clay tiles, 50 mm glass fibre insulation	Clay tiles, 50 mm glass fibre insulation	Clay tiles, Insulation to 2005 Building Regs.
Floor	Solid ground floor, partly vinyl, partly carpetted. Insulation unknown	Solid ground floor, partly vinyl, carpetted and tiled Insulation unknown	Solid ground floor, partly tiled, partly carpetted, partly vinyl. Insulation to 2005 Building Regs.
Windows	Double glazing (6mm gap) with µPVC frames	Double glazing (6mm gap) with µPVC frames	Double glazing (6mm gap) with wooden frames.

6.2.2.2 Dwelling 1

Dwelling 1 is a detached bungalow built in 1965, which was extensively extended in the 1980's, acquiring both front and rear extensions and a loft conversion. It is situated on a fairly exposed, but low-lying, site on a country road, with open fields across the road and a long garden behind. The effects of exposure are reduced by the close proximity on one side to the house next door and by high, dense hedges on both sides and at the front. Energy efficiency improvements were limited to about 50mm of insulation in the attic and double glazing with 6mm cavities in the downstairs windows.

At the time of the study, the occupants were a family – two parents and adult son and daughter, of whom three worked 'normal' office hours, while the fourth worked irregularly. This lead to a fairly high demand for hot water, consisting of one bath and 7 showers per week day.

The heat pump system is installed in a garage beside the house and distributes heat via the original radiators used with the previous LPG system. The installation in this location is somewhat disadvantageous as any faults in the equipment can go un-noticed. The heat pump is rated at an output of 5.9kW (0ºC source/ 35ºC sink) by the manufacturers.

6.2.2.3 Dwelling 2

Dwelling 2 is a semi-detached, 2 storey house built in 1951, which was extended at the rear in 2006-2007 by a substantial kitchen dining room on the ground floor and extra bedroom on the first floor. Replacement, double-glazed windows with µpvc frames were fitted around the same time, though these were not of good quality since the trickle vents on some had failed, no longer closing properly. The house is situated on a village road on an exposed corner, facing due south. To the rear, the lawn under which the heat pump collectors had been installed is sheltered by hedges.

At the time of the study, the occupants were a family, two adults and two teenage daughters, of whom the daughters were at school and further education college, one adult worked both a 12-hour shift pattern and at a part-time building job and the other worked from 9 am. to 5 pm. in a local shop. With teenage daughters, the hot water demand was thought to be fairly high but irregular.

The heat pump is installed in the former kitchen in the middle of the house and distributes heat via the original radiators used with the previous mains gas system. Additional heating is available from a solid fuel stove in the sitting room. The heat pump is an older model no longer sold by the manufacturer, rated at 3.9kW.

During the course of the monitoring period, the external temperature sensor, GT2, which provides the main influence over the heat pump controller weather compensation algorithm was moved from a position where it received undesirable, direct sunlight to a shaded location, but there was no apparent effect on the monitored values.

6.2.2.4 Dwelling 3

Dwelling 3 is a detached, 5 bedroom, 5 bathroom house built in 2007 to replace an older, smaller house. It is on a fairly sheltered site, facing north, with a garden rising slightly to the rear. Though it is detached, it is quite close to the neighbouring houses and surrounded by mature trees.

The occupants at the time of the study were a married couple, of whom the wife worked conventional office hours four days / week and the husband, a consultant, either worked at home or made long-ish day trips on business. Relative to the house size, the hot water demand was quite low, mostly running at 4 showers / day, except during family visits.

The heat pump system is installed in a utility room inside the house and distributes heat via underfloor heating. The installation configuration was slightly unconventional in that the weather-compensated control had been configured to ignore the internal sensor, so any casual gains from activity inside the house did not effect the system's operation. The system was the largest one in the study, rated at 11kW and the only one to have a separate DHW storage tank.

6.2.3 Data collected

Four types of data are collected for the full analysis of the operation of the heat pump system:

a) data from the energy input and output from the system;

b) temperature data at the significant points of the system;

c) data for the operational status of the system,

d) data of the current status of the interval timers maintained by the controller.

The characteristics of the different types of data, acquisition method, cleansing and accuracy are detailed in appendix B.

6.2.4 Data summarisation and analysis

6.2.4.1 General

Data was stored in a separate MicroSoft Excel spreadsheet for each location, with each sample being stored in a separate row of the spreadsheet. The sample-level data was then summarised by day, week and month, with temperature values averaged over the summary period and energy values totaled. Values from samples when the compressor was not operating were not included in the average temperature values.

6.2.4.2 Analysis for SAP / BREDEM comparison

The SAP/BREDEM routines (Anderson, et al., 2001; BRE, 2008) estimate values for primary and secondary heating loads, requirements for DHW generation and energy used for heating system pumps and fans. Actual values for these were calculated using an analysis based on the Status indicators in the data.

Using the cumulative electricity consumption and heat output values from each sample, a value was calculated for the consumption and output in each 15 minute period by simple subtraction from the values for the previous sample. This was then analysed according to the Status Indicators set on the current sample. Totals were accrued for all combinations of the following indicators.

a) Compressor

b) Additional heating element 1

c) Additional heating element 2

d) Heat carrier pump

e) Radiator pump

f) Three-way valve

g) Alarm

It was found that the Ground Loop Pump status rarely, if ever, differed from Compressor status and therefore this was omitted. The indicators for the ‘Mixing Valve’ status were irrelevant for the heating systems under consideration, since these indicators are used only when the heating system contains both radiators and underfloor heating, which requires that cooler water is mixed into the floor system water to prevent this becoming excessively hot.

Of the selected indicators, those for ‘Additional heating’ were treated as one. Any samples where the ‘Alarm’ indicator was set were included in a separate total as this is an indication that the pump was not operating correctly. This left thirty-two status combinations, of which ‘all off’ does not occur, since the heat pump controller defaults to setting the three-way valve to ‘DHW generation’ status during periods when the external temperature exceeds 18 ºC.

It was, however, realised that where more than one status was set, the consumption and output values will consist of contributions from each sub-system within the heat pump. Moreover, because the various sub-systems of the heat pump may switch in or out between the logging of samples, the consumption and output values might be made up of indeterminate contributions from these sub-systems due to the change of circumstances in the 15 minute period between samples. It was therefore necessary to estimate the contributions of the less variable sub-systems - additional heating and system pumps - using other methods detailed in the following paragraphs.

6.2.4.3 Additional heating

The IVT heat pump models which are the subject of this part of the study contain two additional heaters, the first rated at 3 kw and the second at 6 kw, which are switched in either separately or together, depending on the heating load that must be balanced and the controller settings. If the status for either is set on for a given sample, it can be assumed that its load will be present for at least part of the period between the samples before and after the current one, but no other assumptions can be made. For the benefit of this exercise, it will be assumed that if the status is set, then the heaters will operate for a standard duration of 7.5 minutes (half the interval between samples). Thus a value for the electricity consumption, E_{Add}, in kWH, by the additional heaters is given by the formula:

$$\boldsymbol{E_{Add} = (S_{H1} \cdot 3 + S_{H2} \cdot 6) \cdot 0.125} \qquad \textbf{(6.2)}$$

where S_{H1}, S_{H2} are the statuses of heater 1 and heater 2 respectively. This consumption value is then further analysed by means of the ‘Three-way Valve’ status, which if set, indicates that DHW is being generated, otherwise the system is providing space heating.

6.2.4.4 Distribution system

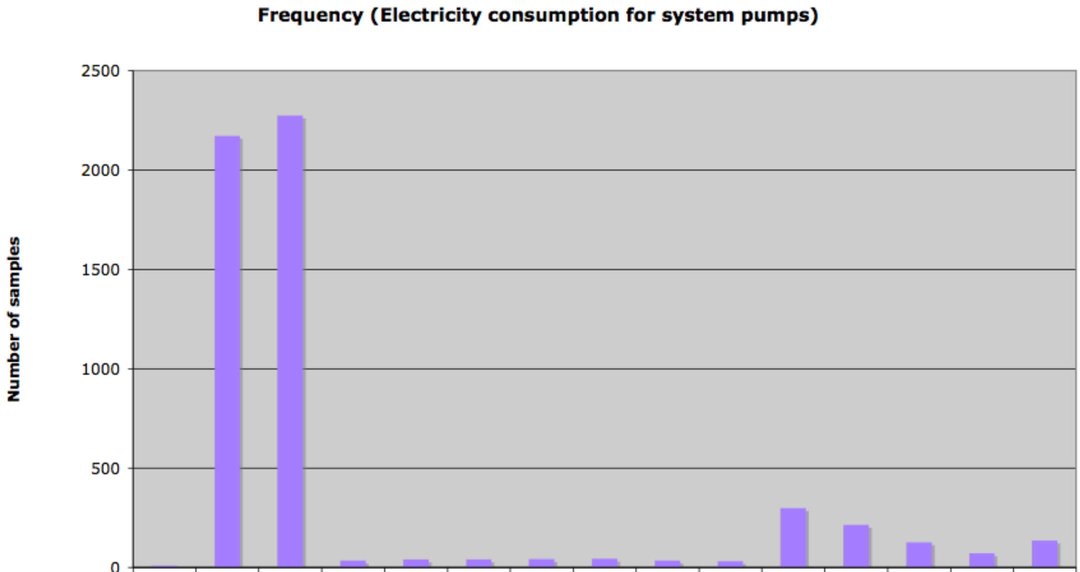
For the IVT heat pumps, this consists of two pumps, one, P1, for circulation of heating water specifically around a radiator or underfloor heat distribution system, and another, P2, for circulating water around the DHW system and as a return from the distribution system. These pumps appear to operate in tandem since an analysis of their status indicators for Dwelling 1 showed that, of 21972 samples, 18403 samples had the P1 status set, 18737 had the P2 status set and 18379 had both statuses set. Inspection of the data indicated that there were many samples in each dataset where these pumps were the only part of the system in operation. This situation occurs because the heat pump controller is continuously monitoring the return temperature (from sensor GT1) from the distribution system against the required set-point value calculated from the weather compensation curve for the current external temperature and requires this return temperature to be updated according to the current conditions in the dwelling. This process will only cease if the external temperature rises above the 'summer disconnection' set-point (usually 18ºC).

To calculate the consumption attributable solely to the distribution pumps, a frequency table of electricity consumption was calculated for those samples when only the pumps were operating, of which an example (Figure 6.1) is shown below.

This shows that, for this dwelling, the average electricity consumption for the distribution pumps for each sample is approximately 0.025 kWh, since it is probable that the higher values are due to consumption by other components of the system during the sample period, for which the appropriate status was not registered. Similar frequency tables were created for the other dwellings with similar results and these values were used to calculate a value for the distribution electricity consumption using the following simple formula:

$$E_{dist,m} = \sum_{N=1}^{N(m)} s_m \cdot E_s \qquad (6.3)$$

where $E_{dist,m}$= electricity consumption for heat distribution for month m, s_m = the number of samples collected in month m, and E_s= electricity consumption (kWh) per sample.



	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1	0.2	0.3	0.4	0.5	1
Frequency	9	2173	2274	35	41	40	43	44	34	32	298	215	127	72	135

Figure 6.1 Frequency distribution of electricity consumption for samples when only pumps operating

6.2.4.5 Analysis of electricity consumption

The following totals are calculated for electricity consumption:

Table 6.2 Electricity consumption totals

	Electricity consumption sub-total	Calculation method used
1)	Bivalent operation – space heating	Value calculated using method from Section 6.2.4.3 where '3-way valve' status is not set
2)	Bivalent operation – DHW generation	Value calculated using method from Section 6.2.4.3 where '3-way valve' status is set
3)	Circulation	Value calculated using method in Section 6.2.4.4
4)	Space heating from compressor	Total of all consumption values where 'Compressor' status is set and '3-way valve' status is not set, less values for bivalent operation and distribution(Items 1 and 3)
5)	DHW generation	Total of all consumption values where 'Compressor' status is set and '3-way valve' status is set, less values for bivalent operation and distribution(Items 1 and 3)

6.2.4.6 Analysis of heat output

The same analysis totals are calculated as in section 6.2.4.5, with the exception that no separate total is created for circulation since this does not represent a separate output. Where an output heat value has been logged for a sample where only the Statuses for the two pumps are set, then this is included in the "Space heating from compressor' total.

6.2.4.7 Other totals calculated

Additional values for each period were calculated for:

total heating degree days, based on 15 ºC – calculated, initially as degree hours, by interval length (0.25 hrs) times base temperature minus sample external temperature, then divided by 24.

total logged hours, based on 15 min. per sample.

6.2.4.8 Adjustment of results

Because of faults in the datalogging equipment, a considerable proportion of the possible data was not captured during the collection period. This amounted to approximately 37% of the possible data for dwelling 1, 19% for dwelling 2 and 1.35% for dwelling 3. In order to allow more useful comparison between the data, adjustments were applied to the monthly totals for dwellings 1 and 2 as follows:

- Use was made of the fairly close proximity of all three dwellings – dwelling 1 is about 7 km from dwelling 3, dwelling 2 is about 34 km away. On this basis, it was judged there would be only minor differences between the average temperatures at the sites and hence only minor differences between the degree days experienced at the three sites. This was found to be a reasonably correct assumption from the data as shown by the following Figure 6.2 & Figure 6.3, which indicate that i) that the temperatures at all three sites were closely related, and ii) there is a strong correlation between heating degree days and electricity consumption for space heating.
- It was therefore deemed reasonable to adjust those values largely determined by temperature, viz. electricity consumption and heat output for space heating, in proportion to the monthly heating degree days. Those values which are related to occupancy, viz. electricity consumption and heat output for DHW generation, and those which are simply related to operating hours, were adjusted according in proportion to the hours of data collected against the monthly hours.

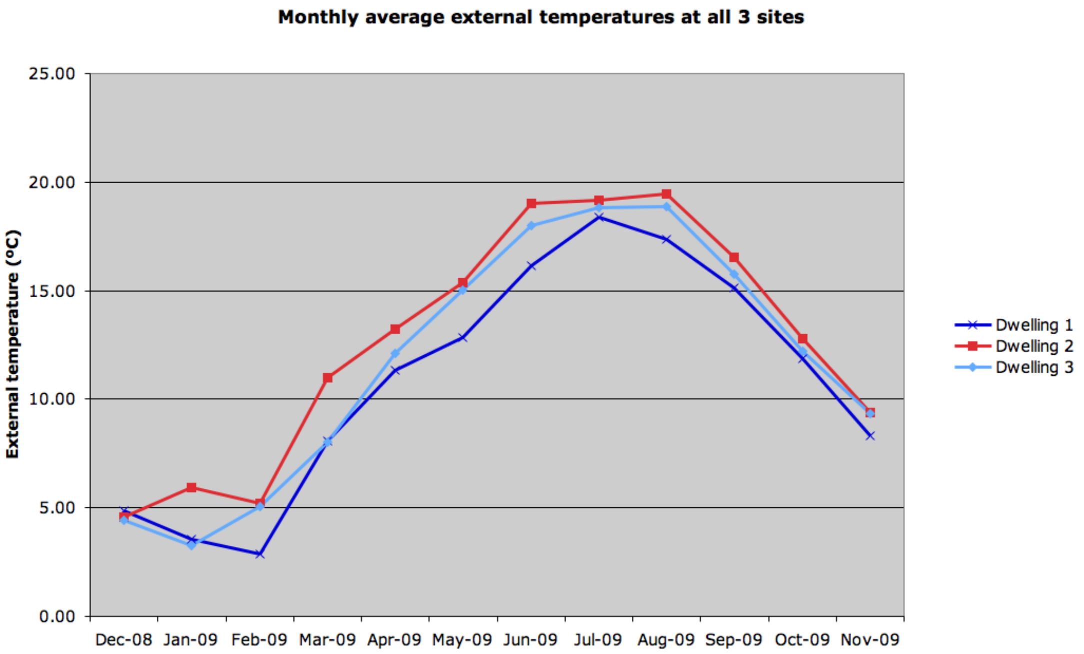


Figure 6.2 Monthly average external temperature at all 3 sites

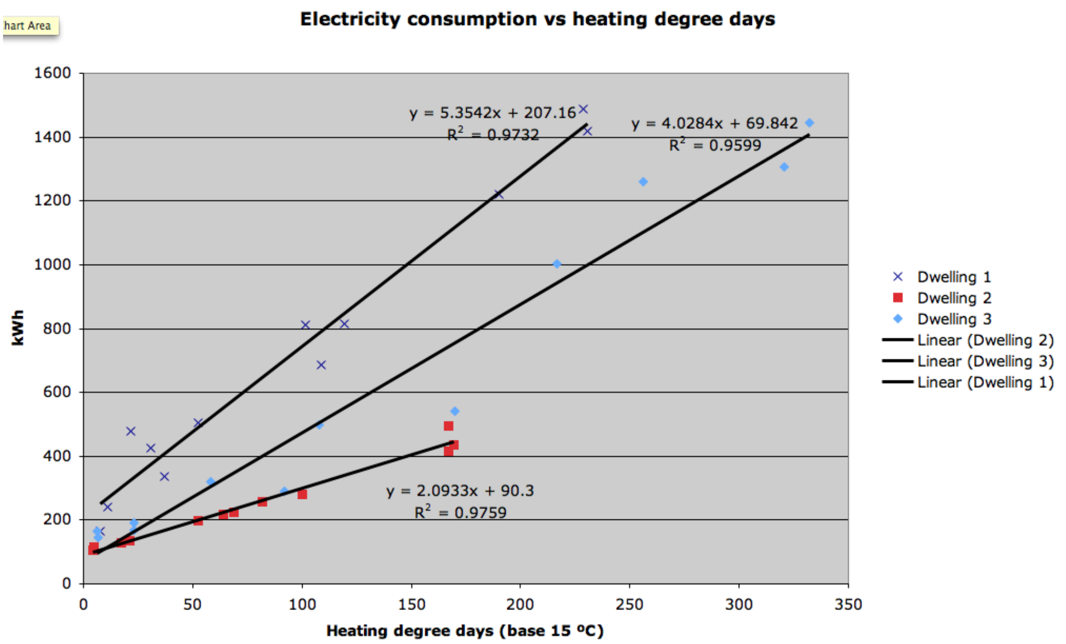


Figure 6.3 Electricity consumption vs heating degree days - all three sites

6.2.5 Results

6.2.5.1 General results

Energy and performance results for all three dwellings are summarised in the following Table 6.3. Apart from the collected data, an additional value is included for the heat load for each of the houses as estimated by the Apache dynamic simulation program within the IES Virtual Environment system (IES, 2012). This value was included for comparison because of the author's reduced confidence in the measurement of output by the heat meter installed. The two values for heat output, line 11 in Table 6.3, are, headed *'Heat meter'*, that measured by the afore-mentioned meter, and, headed '*From temp calculation',* that calculated using Equation 6.1.

Notable in these results are the following:

a) the exceedingly high space heating consumption per unit area of dwelling 1 compared with the other two;

b) the absence of direct electric heating in dwelling 3; possibly indicating that the system is over-sized;

c) the significantly higher consumption for distribution in dwelling 3 - more than twice either of the others as a percentage of electricity consumption; due to the second pump in the distribution system required for the upper floor;

d) the inconsistent results for dwelling 2, for which the SPF of the heat pump calculated on the data from the heat meter is implausibly high, but the heat load per unit area is comparable with dwelling 1;

e) the SPF of the heat pump in dwelling 3 is similar to that in dwelling 2 despite the use of underfloor heating for distribution which is claimed to improve performance by allowing a lower distribution temperature; this appears to be a consequence of the high consumption of the distribution pumps.

f) A general, fairly predictable, point that emerges from this table is that dwelling 3, being of more modern construction, has significantly lower energy use per unit area for space heating compared with the other two.

6.2.5.2 Monthly electricity consumption

Figure 6.4 provides a chart of the electricity consumption of all three systems. As indicated, it analyses consumption by the two functions of the heat pump, those of space heating and DHW generation and by circulation, the power used by the system pumps. Within the functions, a further separation is made into consumption by the compressor and that by the additional direct electric heaters for bivalent operation. Within the distribution electricity consumption, the separation is between the use of pumps when heat is being supplied to the house or the hot water reservoir, and that when the pumps are maintaining circulation to provide temperature feedback to the controller. A trend line indicates the heating degree days for each month - the values are based on the temperatures recorded at dwelling 3. The values for dwelling 1 and 2 have been adjusted for missing data as per section 6.2.4.8.

The significant points of these results, for this study, are as follows:

a) for dwellings 1 and 2, the proportion of consumption for bivalent operation for space heating is very small except in January and February; this implies that a significant rise in average temperatures or fabric improvements for energy efficiency might eliminate the requirement for bivalent operation; results for dwelling 3 contained almost no bivalent operation at all, raising a question as to whether the heat pump system is oversized.

b) reflecting the lower source temperatures in January and February, energy consumption for DHW generation rises in these months, despite the demand probably being similar throughout the year.

c) as noted in section 6.2.5.1, dwelling 3 has significantly higher energy consumption for distribution than the other two, of which a substantial proportion occurs during the summer months and consists largely of circulation for temperature monitoring.

Table 6.3 Summary results table for all dwellings

	Dwelling	**1**				**2**				**3**		
1)	*Floor area (m2)*	122				139				309		
2)	*Occupants*	4				4				2		
Annual energy consumption (kWh)												
Space heating												
3)	*Compressor*	*5,815*	*71.7%*			*3,275*	*68.1%*			*4,334*	*59.1%*	
4)	*Direct electric*	*188*	*2.3%*			*107*	*2.2%*			*11*	*0.1%*	
5) = (3)+(4)	**Total space heating**	**6,002**	**74.0%**			**3,382**	**70.3%**			**4,345**	**59.2%**	
	per unit area	49				24				14		
DWH generation												
6)	*Compressor*	*1,577*	*19.5%*			*854*	*17.8%*			*2,070*	*28.2%*	
7)	*Direct electric*	*62*	*0.8%*			*90*	*1.9%*			*48*	*0.6%*	
8)	**Total DHW**	**1,640**	**20.2%**			**945**	**19.6%**			**2,118**	**28.9%**	
	per occupant	*410*				*236*				*1,059*		
9)	**Heat distribution**	**230**	**2.8%**			**203**	**4.2%**			**255**	**3.5%**	
10)	**Circulation for control**	**235**	**2.9%**			**277**	**5.8%**			**616**	**8.4%**	
Total energy consumption	*11)=(10)+(9)+(8)+(5)*	**8,107**				**4,807**				**7,333**		
Annual heat load (kWh)		**Heat meter**		**From temp calculation**	**From dynamic simulation**	**Heat meter**		**From temp calculation**	**From dynamic simulation**	**From temp calculation**		**From dynamic simulation**
12)	*Annual heat load*	***16,809***	*77.1%*	***15,236***	***19,716***	***18,339***	*67.4%*	***11,509***	***13,550***	***14,686***	*70.0%*	***11,302***
13)	*per unit area*	*138*		*125*	*161*	*132*		*83*	*97*	*49*		*38*
Annual energy output from DHW usage (kWh)												
14)	*Total*	***4,989***	*22.9%*	***4,205***		***8,890***	*32.6%*	***8,787***		***6,304***	*30.0%*	
15)	*Per occupant*	*1,247*		*1,051*		*2,222*		*2,197*		*3,152*		
Total output	**(kWh)**											
16)=(12)+(14)		***21,798***		***19,441***		***27,228***		***20,296***		***20,991***		
17) = (12)/(5)	*SPF (Heating only)*	***2.80***		***2.54***		***5.42***		***3.40***		***3.38***		
18) = (16)/(11)	*SPF (Heating & DHW)*	***2.69***		***2.40***		***5.66***		***4.22***		***2.86***		
Estimated CO_2 emissions (kg)											*(assumed)*	
	Original system fuel	*Bottled LPG (0.234 kg/kWh)*				*Mains gas (0.194 kg / kWh)*				*Heating oil (0.265 kg / kWH)*		
19) from (16)	*Original system*	***5,101***		***4,549***		***5,282***		***3,937***		***5,563***		
20) from (11)	*Heat pump system (0.517 kg/kWh)*	***4,191***				***2,485***				***3,791***		
21)	***Emission reduction***	***18%***		***8%***		***53%***		***37%***		***32%***		

Figure 6.4 Electricity consumption for all three systems

6.2.5.3 Monthly output

The monthly output for all three systems, with systems 1 and 2 again adjusted for missing data is shown in Figure 6.5. A notable anomaly in these charts is the high value for bivalent energy output for dwelling 1 in month 2009/6. This was due to the failure of the compressor which caused the system to use the additional heaters to generate DHW for a substantial part of that month.

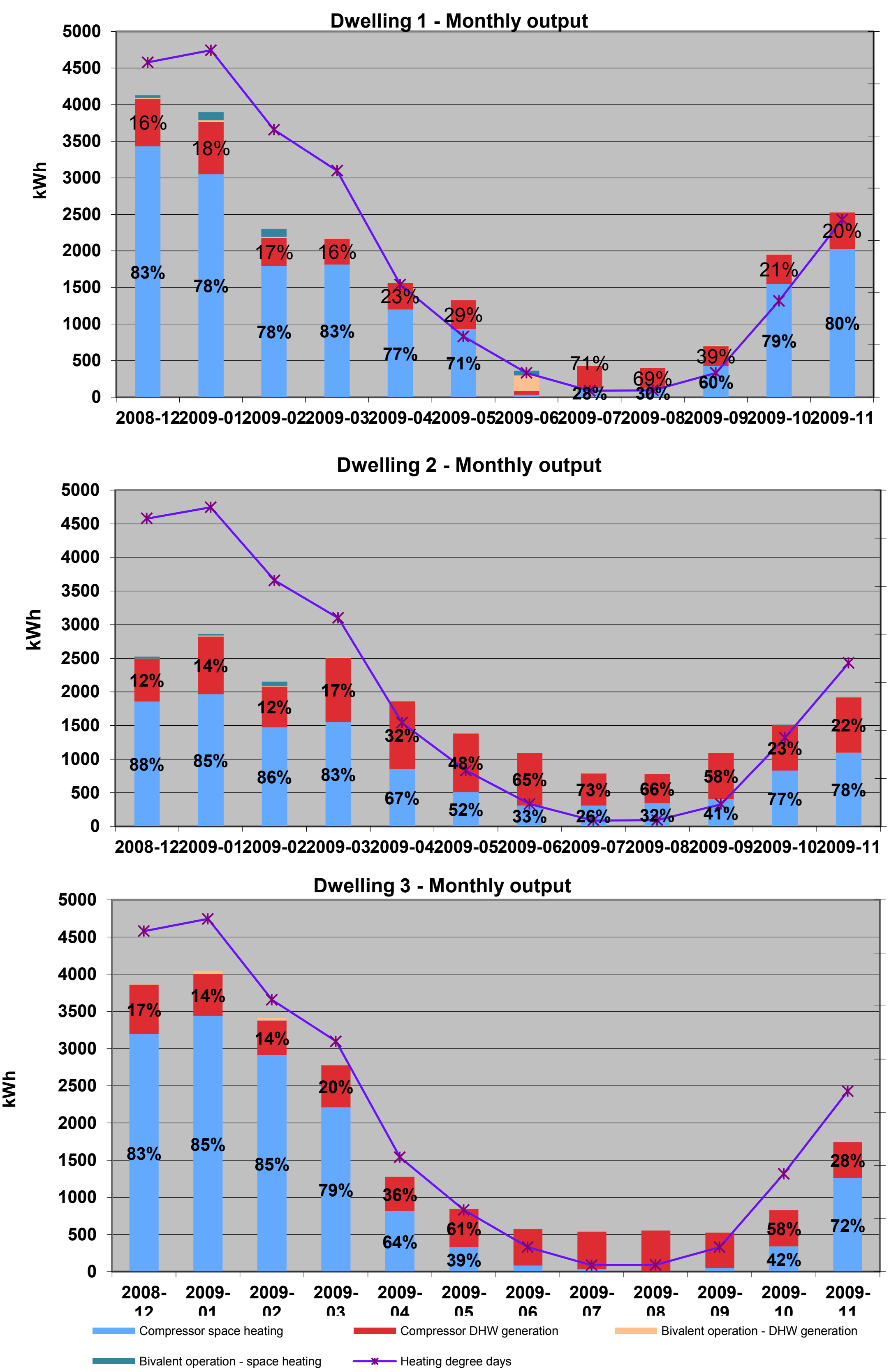


Figure 6.5 Monthly output from all three systems

6.2.5.4 Monthly SPF values

These are shown in Figure 6.6. Again, this figure shows a divergence between the performance of the two radiator/retro-fit systems and the UFH/new build system. Performance of the former two systems has twin peaks in early and late summer, falling off sharply at either end of the year, while the latter system varies only slightly throughout the year with a single peak in August. The former set of curves appears to reflect the improvement in performance due to the reduction in lift for heating required as both the ground temperature and the air temperature increase in spring / early summer, then, when heating is no longer required, a reduction in performance due to the requirement for DHW generation at a higher lift in mid-summer. The curve for the UFH system appears to reflect both its possible over-size, noted in 6.2.5.2 paragraph (a) and also the comparatively low demand for hot water, noted in 6.2.2.4.

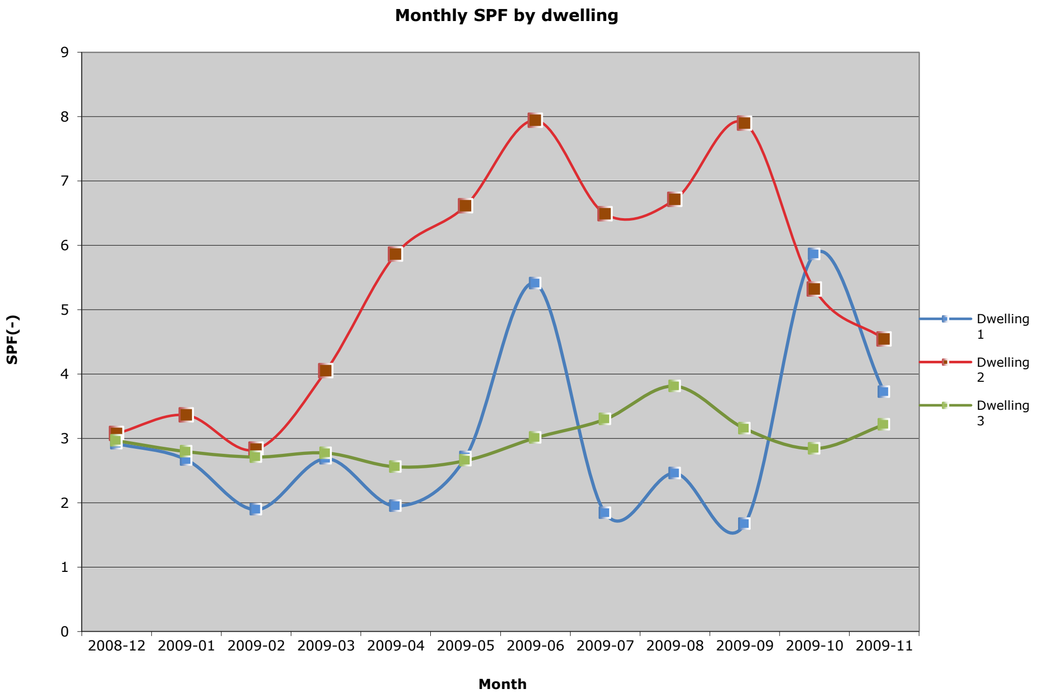


Figure 6.6 Monthly SPF by dwelling

6.2.5.5 Output temperatures to distribution (Sink temperature)

Table 6.4 shows that the distribution temperatures in the three dwellings differ substantially, in the same way as the SPF values. Distribution temperatures for the dwelling 2 system are considerably lower than the 55ºC that might be expected (Ochsner, 2007, p. 87), lower than those in the dwelling 3, yet the internal temperatures in dwelling 2 are maintained at or above 22 ºC. This reduction is presumably due to the effect of the weather compensation control (Cantor, 2011, p. 13), with distribution temperatures being reduced in response to higher external temperatures during the heating season.

Table 6.4 Distribution, internal and external temperatures for all three systems

Month	2008	2009										
All temps in ºC	12	1	2	3	4	5	6	7	8	9	10	11
Dwelling 1												
Distribution outflow	47.0	48.5	51.6	46.8	46.4	44.5	56.8	-	-	46.8	43.9	44.9
Hot water	54.9	54.7	55.4	55.3	55.2	55.3	52.2	52.1	52.5	52.3	52.5	52.4
Internal	19.9	19.7	19.7	20.2	20.5	20.6	21.7	22.9	22.2	21.1	20.6	20.0
External	4.9	3.6	2.8	8.1	11.3	12.8	16.1	18.4	17.4	15.1	11.9	8.3
Max distr	61.9	67.9	69.2	63.7	64.1	63.9	66.9	59.8	60.2	59.2	59.1	58.9
Dwelling 2												
Distribution outflow	37.8	36.8	37.5	37.1	38.6	41.6	45.0	-	44.7	43.1	38.2	36.7
Hot water	46.1	47.0	46.3	45.9	45.7	45.8	45.4	45.7	45.4	45.5	48.1	47.1
Internal	22.4	22.4	22.3	22.5	22.8	23.1	24.8	25.1	25.0	23.4	22.5	22.4
External	4.6	6.0	5.9	10.8	13.4	15.6	19.3	18.8	19.5	16.5	12.7	9.6
Max distr	49.1	66.7	49.0	47.8	49.0	49.3	49.4	50.3	49.9	49.0	48.4	49.3
Dwelling 3												
Distribution outflow	41.4	40.8	41.2	42.0	44.4	47.0	50.0	50.9	51.9	47.9	47.1	43.3
Hot water	47.5	47.4	46.9	46.9	46.7	46.5	46.6	46.9	46.9	43.0	44.4	45.9
Internal	21.1	20.3	21.4	20.9	21.1	21.6	23.1	23.1	23.0	21.7	20.5	19.6
External	4.4	3.3	5.0	8.0	12.1	15.0	18.0	18.8	18.9	15.8	12.2	9.3
Max distr	52.0	66.7	49.8	51.4	50.4	41.8	44.0	-	-	45.6	45.6	52.0

Further analysis of output temperatures and flow / return differentials was carried out to establish characteristics for estimating and these results are also presented in context in Chapter 7.

6.2.5.1 Temperatures returned from ground loop

An analysis was made to provide an estimate of the differential between soil temperature and the ground loop temperature. This is presented later in this document in Chapter 7 as being clearer in that context.

6.2.6 Discussion

6.2.6.1 Datalogging equipment

For datalogging, this research brought out two points. Firstly, the custom datalogging equipment, designed and built in a comparatively short time, was not a reliable solution to this problem and should have been avoided, with other solutions being explored such as the use of dedicated personal computers for data storage. Secondly, the heat meters employed for measuring the system output were too complex, requiring additional temperature sensors which were awkward to fit and which duplicated some already present in the heat pump system. Reference to the relevant data sheet (Sontex, 2004) shows that the flow meter within the Supercal 539 employs a magnetic sensor, which the author considers could have been disrupted by electro-magnetic interference within the heat pump, possibly from the compressor.

6.2.6.2 Heat pump systems and dwelling energy efficiency

The results of the data analysis confirm the relationship between output temperature and heat pump SPF, in that the average monthly distribution temperatures in the monitored systems form one progression from low (~ 37 ºC) to high (~ 45ºC), (Table 6.4) with the SPF values forming a second from high (~ 4.0) to low (~2.6) (Table 6.3) across the systems. However, the fact that the central pair of SPF and distribution temperature values is from Dwelling 3, a new-build house with a UFH distribution system, is anomalous in that UFH is deemed to require lower distribution temperatures to achieve the same heat output, allowing a higher SPF. Equally anomalous are the comparatively low distribution temperatures found in the Dwelling 2 system, thereby raising some queries about how much the energy efficiency of dwellings and their heat distribution systems should be regarded as barriers to the future take-up of heat pumps.

Because heat pump systems can achieve a higher COP whilst operating at lower temperatures, it is asserted that this necessitates both a low temperature distribution system and a high level of energy efficiency in a dwelling to provide an acceptable level of thermal comfort while still operating the system at a sufficiently high COP (Cantor, 2011; EST, 2011). The need to replace existing radiators with new, much larger ones and to upgrade insulation and draught-proofing is therefore seen as a barrier in the transition to heat pump systems, certainly by Fawcett (Fawcett, 2011). However, the degree to which the building fabric must be improved is unclear and there is some dispute - admittedly from some years previously (McMullan & Morgan, 1981, p108) - about the absolute necessity for replacing radiators on the basis that existing radiators are likely already to be oversized for fuel-fired systems. McMullan & Morgan contend that, in order to raise dwelling temperature quickly, it was the practise of heating engineers to install boilers and radiators which were as much as 250% larger than required which is in the region of the increase in size required to match the reduced temperature economically provided by a heat pump system. To some extent, the two retro-fit dwellings in the current study support McMullan & Morgan (1981), in that there was no change to the existing radiators when the heat pump systems were installed. In Dwelling 1, no additional efficiency measures were installed with the heat pump systems though double-glazing had been installed previously, but in Dwelling 2, double-glazing was installed and a substantial extension added at about the same time as the heat pump was installed, reducing the proportion of the external wall composed of the original single brick skin by about one third. The earlier improvements to Dwelling 1, though probably to a lower energy efficiency standard, have also somewhat improved that house but with a substantial increase in external surface area. With these improvements, the heating systems in both dwellings maintained an SPF sufficient to achieved some reductions in carbon emissions, as has been said above.

Given the above, found in what is, admittedly, a very small sample of dwellings, it would appear that double glazing and extensions to houses, made to contemporary standards, have the potential to improve the housing stock such that heat pump systems would be found to be viable for retro-fit, even without the additional improvement of larger radiators. Analysis of the relevant EHS file('shape') showed that about 13% of the English stock had been either refurbished completely, an extension added, or a loft extension built and approximately 82% had double glazing (Tables 6.5 & 6.6).

Table 6.5 Proportion of EHS stock sample having had substantial work (extension or refurbishment) by age of work.

	Sample total grossed-up	Percentage of stock
None	11499270	62.4%
Pre 1945	114769	0.6%
1945 - 1964	240564	1.3%
1965 - 1984	1703283	9.2%
1985 - 1990	1342562	7.3%
1991 - 1995	993906	5.4%
1996 - 2005	2243984	12.2%
Unknown	47492	0.3%
In progress	232350	1.3%
Since 1996		13.45%

Table 6.6 Analysis of window construction types from EHS

Construction	Grossed-up total	Percentage
double-glazed, UPVC	12663464	68.8%
single-glazed, wood sash	570848	3.1%
single-glazed, wood casement	1781376	9.7%
double-glazed, wood	1743240	9.5%
double-glazed, metal	797007	4.3%
single-glazed, UPVC	171448	0.9%
single-glazed, metal	280272	1.5%
mixed types	410525	2.2%

6.2.6.3 Monitoring of performance

Given a modest additional amount of computing capability and provided the problem identified in 6.2.6.1 can be solved, it would be possible to measure both the electricity consumption and heat output to provide real-time monitoring of a heat pump's performance, particularly of its COP, using the data from the heat and electricity meters used. In addition, though it is not immediately obvious from this study, the main indicators of the state of health of a heat pump system would appear to be the flow rate for the distribution system, indicating the proportion of the heat output that is reaching the distribution, and the relationship between the output temperature from the compressor and that to the distribution system, indicating the proportion of the compressor heat output that is being output via the condenser.

6.3 Secondary data acquisition

6.3.1 Heat pump performance data

As data for this study had been collected from only three installations of one type of heat pump, it was by no means possible to make any statistically-valid estimates of heat pump performance from this data. It was therefore necessary to acquire a larger volume of data for this purpose. Following on from Staffel (Staffel, 2009), test results from the Wärmenpumpen TestZentrum (WPZ) (WaermenPumpen Testzentrum, 2009) were employed for the purpose of this study.

6.3.1.1 Description

The WPZ tests used in this study are both air-to-water and soil-to-water systems, both to European Standard EN14511(British Standards Institution, 2007) and to EN255(British Standards Institution, 1997). Water-to-water heat pump test results are included with those for soil-to-water systems, and a separate set of results are included for water heating heat pump systems which are not required for this study. Samples of the test result documents are included as Appendix B & C of this thesis.

The data provided in the test results is as follows:

a) The system supplier

b) The supplier's model number for the system;

c) the test reference

d) the type and weight in kilogrammes of the refrigerant used in the system;

e) the performance test results in the form of energy input, energy output and COP for each source/sink temperature combination as specified in the test schedule for the Standard.

f) system flow rate used in testing (nominal - from manufacturer) in m^3/hour;

g) Temperature differential (K) between outflow and return from the heat pump sink;

Other data is present but is not deemed relevant to this study.

For the purpose of the current study, the substantive difference between the EN255 and the EN14511 standards is in the definition of the 'boundary' for a heat pump system, which, for EN14511, includes distribution pumps which are excluded from EN255 (British Standards Institution, 1997, 2007). The test values for each standard are summarised in Table 6.7. For each heat pump tested to EN14511, this means that 10 data points are available for a regression model for COP against 'lift', while for EN255, 10 data points are available for air / water heat pumps but only 6 for soil / water systems.

Table 6.7 Summary table for WPZ heat pump test conditions

Heat pump type : Air to water			
Standard: EN14511		Standard: EN255	
Source / sink temps	Lift	Source / sink temps	Lift
A10/W35	25	A20/W35	15
A7 /W30 - W35	28	A10/W35	25
A2/ W35	33	A7/W35	28
A2/W35-25	23	A2/W35	33
A-7/W35	42	A-7/W35	42
A-15/W35	50	A20/W50	30
A7/W45	38	A15/W50	35
A20/W55	35	A7/W50	43
A7/W55	48	A2/W50	48
A-7/W55	62	A-7/W50	57

Heat pump type : Soil to water			
Standard: EN14511		Standard: EN255	
Source / sink temps	Lift	Source / sink temps	Lift
B5/W35	25	B5/W35	30
B0/W35	35	B0/W35	35
B0/W35-25	25	B-5/W35	40
B5/W45	35	B5/W50	45
B0/W45	45	B0/W50	50
B-5/W45	55	B-5/W50	55
B5/W55	45		
B0/W55	55		

6.3.1.2 Development of database

The database of heat pump test results was created as follows:

The print format from WPZ was imported into an Excel spreadsheet, using "PDF2Office" (Recosoft, 2010) software which partially converted the data, leaving some items, particularly numeric values, to be formatted manually.

Further manual editing was performed to create: a) a table of all the heat pump suppliers present; a table of heat pump systems containing a row for each system; and two tables of heat pump test results, one for air/water systems, the other for soil/water systems, each containing one row for each test result, viz. source temperature, sink temperature, resultant lift , electricity input, heat output, resultant COP. For each heat pump row, a set of linear regression parameters were calculated, based on the lift and COP values from the test values for that system. A detailed list of the variables present in each table is shown in Table 6.8. An overall set of linear regression parameters are calculated for each of the two tables of test results.

Table 6.8 Variables in heat pump test results database

Table	Variable	Meaning / use
Supplier	Supplier ID	Unique identifier for supplier providing sample system for test
	Name	Allows selection of a list of systems by supplier
	Address	For confirmation of selection
Heat pump system	HP ID	Unique identifier for system
	Model number	Supplier's identification for system
	Supplier ID	Link to supplier entry
	Type	="AW" for air / water ="SW" for soil / water for choice of table for the location of test results.
	First entry	First row number of batch of test results data for current heat pump system.
	Count of following entries	Count of rows of test results for the current heat pump system.
	Regression parameters	Two parameters - results of linear regression of COP against lift value from the test results for the current heat pump system
	Date of test	
Test results	HP model number	Link to Heat Pump table entry
	Test ID	Unique identifier for test result entry
	Source temperature	Value prefixed by "A" in Test Conditions for air source systems or by "B" in those for ground source systems. (ºC)
	Sink temperature	Value prefixed by "W" in Test Conditions for both air source systems and ground source systems. (ºC).
	Input	Value in kW for electricity input during test
	Output	Value in kW for heat output during test
	COP	Output value ÷ input value.
	Lift	Sink temperature - source temperature (K)
	Date published	As stated.
	Carnot COP	= (Source temp + 273) / (Source - sink)
	Carnot efficiency	= actual COP / Carnot COP

6.3.1.3 Discussion

It should be noted from the above that a considerable amount of 'manual' manipulation of data was involved in the creating of this database rendering it somewhat impractical for regular usage. When last asked, WPZ responded that the information was not available in any other form (Nani, 2009), though recently the results files are being provided in English.

It would be useful if the test results data was available for the heat pump systems from UK suppliers so that this database was more applicable to this current study.

6.4 Summary and conclusions

This chapter described the primary and secondary data collection processes for this research, detailing the monitoring study of ground source heat pumps and analysis of its results, and the creation of a database of heat pump performance data from standard test results.

For the monitoring study of IVT ground source heat pumps, data for electricity input and heat output, system temperature values and statuses was collected from three installations using a custom datalogger over a period of 12 months starting in December 2008 and ending in November 2009. The monitoring study was hampered by lack of cases and by faults in the dataloggers, the root cause of which was a financial dispute between the industrial partner and the developer for the datalogger, which effectively prevented any more than three sets of equipment being built and faults in those three being cured.

The data was analysed to provide monthly totals for: electricity consumption by space heating, DHW generation and heat distribution, distinguishing where consumption was by the heat pump compressor or by the additional, direct electric heaters; heat output for space heating and DHW generation, again making the same distinction. Because of faults in the data loggers causing the loss of data samples, particularly for dwellings 1 and 2, it was necessary to adjust the results from the electricity input and heat output analysis to compensate for this loss, based on the heating degree days measured at Dwelling 3. An apparent failure of the heat meter on the system output for Dwelling 3 also made it necessary to base the heat output from that system on a calculated value. For comparison, values for heat output for dwellings 1 and 2 were calculated using the same method.

A monthly Seasonal Performance Factor (SPF) was calculated for each system to observe the pattern of its fluctuation. Return temperatures from the ground loop collector and output temperatures to the distribution system were analysed for use in the latter part of the study.

Results from the monitoring study indicated that:

while the heat pump systems in the two retro-fit installations appeared to be subject to more variable heating loads, it is still possible for such installations to reach a reasonably high Seasonable Performance Factor, albeit on the basis of a very small sample;

a penalty of using underfloor heating continues to be substantial consumption of electricity (~900 kWh annually, approx. 12%) by pumps for distribution, in particular for monitoring internal temperatures, as has been noted previously (BRECSU, 2000);

the distribution temperatures - both average and maximum - registered for one of the retro-fit installations, Dwelling 2, and for the new-build installation, Dwelling 3, did not differ substantially, with those from the retro-fit being considerably below the conventional value for radiator systems (average 38 ºC as opposed to 55 ºC) and those from the new-build similarly above that for underfloor heating (average 42 ºC as opposed to 35 ºC); distribution temperatures in Dwelling 1 were higher than in the others, but still lower than the conventional 55 ºC value. As the average internal temperature in all three dwellings is close to the required norm, this might indicate that the systems' weather compensation controls are effective in maintaining lower operating temperatures and that the heat transfer rate of the radiator distribution systems is adequate to maintain the required temperature, despite the lower operating temperatures.

One of the main points arising from the study was that the data collected did not provide an indication of the health and efficiency of the heat pump installations without considerable computation and that there is a need for research into diagnostic methods for this purpose.

To build a database of heat pump system performance data, the required data was extracted from print image files available from the Wärmenpumpen TestZentrum (WaermenPumpen Testzentrum, 2009) and formatted into separate spreadsheet tables for each of supplier details, heat pump system details and test result values.

The next chapter presents the details of a development of a simple regression model for heat pump energy use based on the data documented in the first two sections of this chapter, and its embedding in a building energy model.

CHAPTER 7 DEVELOPMENT OF AN ENHANCED STANDARD RESIDENTIAL BUILDING ENERGY MODEL

7.1 Introduction

This section contains details of the development of the building energy computer model in achieving Objective 4 of this study and consists of:

an analysis of the calculation methods used in the current UK standard procedures for assessing residential energy use, SAP/BREDEM, and the possible deficiencies of these methods in the handling of heat pump systems;

details of replacement methods for estimating the energy use of heat pump heating systems, including their theoretical basis, data sources and the equations required.

7.2 Objectives

The initial objective of this section is to detail the methods used to calculate the contribution made by the different types of heat pump systems to residential energy use in the BREDEM/SAP models used in the UK domestic energy model and standards for energy efficiency and for gaining Building Regulations approval under the Building Regulations Approved Documents: Part L1A applicable to new houses.

The second objective is to identify where these methods are substantially deficient in modelling the characteristics of heat pump systems.

A third objective is to identify more appropriate methods for characterizing heat pump systems, to provide an improved BREDEM-style model and to specify the equations and processing involved.

7.3 BREDEM/SAP estimation

The principles behind the BREDEM/SAP models have been described in Section 3.3.4.1. The BREDEM heat pump parameters are reproduced in Table 7.1, with those from SAP in Table 7.2.

Table 7.1 Heat pump system parameters in BREDEM-8

Ref.	Source	Heat pump system parameters in BREDEM-8				
1	Table D1 Efficiency & responsiveness		Efficiency / SPF	Responsiveness (from Table D4)		
		Heat distribution by water		With radiators	UFH in insulated timber floor	UFH in screed or concrete slab
		Ground-to-water heat pump	320			
		Ground-to-water heat pump with auxiliary heater	300	1.0	1.0	0.25
		Water-to-water heat pump	300			
		Air-to-water heat pump	250			
		Heat distribution by air		Responsiveness (from Table D1)		
		Ground-to-air heat pump	320		1.0	
		Ground-to-air heat pump with auxiliary heater	300		1.0	
		Water-to-air heat pump	300		1.0	
		Air-to-air heat pump	250		1.0	
2	From Table D.7	**Fraction of heat supplied by secondary systems**				
		Main heating system	**Secondary system**	**Fraction**		
		Central heating system with boiler and radiators, central warm-air system or other gas fired systems	gas fires	0.15		
			coal fires	0.10		
			electric heaters	0.05		
		Electric heat pump systems with heat storage or fan-assisted storage heaters	gas fires	0.15		
			coal fires	0.10		
			electric heaters	0.05		

Table 7.2. Summary of heat pump system-related parameters (additional to SPF tables) extracted from SAP 2005, 2008 update specification (BRE,2008)

Ref	Source	Additional heat pump system parameters in SAP 2005	
1	**Distribution type**	**Adjustment to Efficiency of main space heating system value for:**	Adjustment based on max. heat distribution temp. of 50°C.
		Underfloor heating	1.0
		With radiators and with load and weather compensation	0.75
		With radiators, without load or weather compensation	0.7
2	**Domestic Hot Water**	**Adjustment to Efficiency of domestic hot water generation value for percentage supplied**	Adjustment
		All DHW supplied by h p	0.7
		50% of DHW supplied by h p	1.0
		DHW Efficiency	
		If both a heat punp and immersion heater are present (assumes each contributes 50% of heating)	100 / (50 ÷ SPF) + 0.5
3	**Mean internal temperature**	Addition for where no time or thermostatic control fitted or programmer only	+0.3 °C
4	**Fraction of heat supplier by secondary heating system**	All heating system types	0.1

7.4 Comparison of heat pump characteristics with BREDEM / SAP heat pump-specific parameters

7.4.1 Heat pump system characteristics

These were identified in section 5.2, viz.

a) lower temperature output due to the characteristics of the vapour compression cycle heat pump;

b) variation of source energy over the heating season due to depletion of the ground as an inter-seasonable store or to the fall in air temperature;

c) CO_2 emissions from operating electric heat pumps are due to the carbon intensity of electricity generation rather than the fuel it consumes;

d) cost of installation of GSHP systems is highly dependent on the size of the system, especially of the collector;

e) Non-uniform increase in operating cost and CO_2 emissions with increase in indoor/outdoor temperature differential when outside temperature falls below the system balance point temperature; this being due to the use of additional heat at a COP < 1.0;

f) Heat pump systems are capable of providing cooling as well as heating.

In this section, each of these characteristics will be examined in turn as to whether or how they are dealt with by SAP / BREDEM.

7.4.2 Lower temperature output

The temperature of hot water output from fuel burning central heating systems is at least 80 °C. while the maximum from heat pump systems is around 55-65°C (McMullan & Morgan, 1981; Ochsner, 2007, p. p37). This characteristic of heat pump systems is reproduced in the factors dependent on Distribution Type (Ref. 1, Table 7.2) which reduce the efficiency value used in calculating energy use by a factor of 0.75 where distribution is by radiators with load and weather compensating controls and by 0.7 where radiators are used without these controls, basing these factors on a maximum distribution temperature of 50ºC. This implies that, in the first case, one third more and in the second, 43% more energy is necessary to maintain a given temperature with radiator distribution as against underfloor heating. According to Anderson (Anderson, 2009b) the factors were derived empirically from statistics of heat pump tests carried out by the Wärmpumpen Testzentrum (WPZ) (WaermenPumpen Testzentrum, 2011) and are based on the ratio between the average COP of the systems tested at sink temperatures of 35ºC and 50ºC for both system types and source temperatures of 0ºC and 7ºC for GSHPs and ASHPs respectively as shown in the following Figure 7.1, graphically, from experimental results in the British Standard EN 13516-2-4 (British Standards Institution, 2008a, p. p115).

The validity of the values derived by this graphical method can be confirmed by calculating the ratio between the Carnot COP of the perfect heat pump at 0ºC source/ 35ºC sink and that at 50ºC sink which gives a value of 0.734, fairly close to the SAP value; and the same calculation for an ASHP using a source temperature of 7ºC which gives a value of 0.68. Since this latter calculation is based upon thermodynamic theory, it could be a better basis for the SAP parameters.

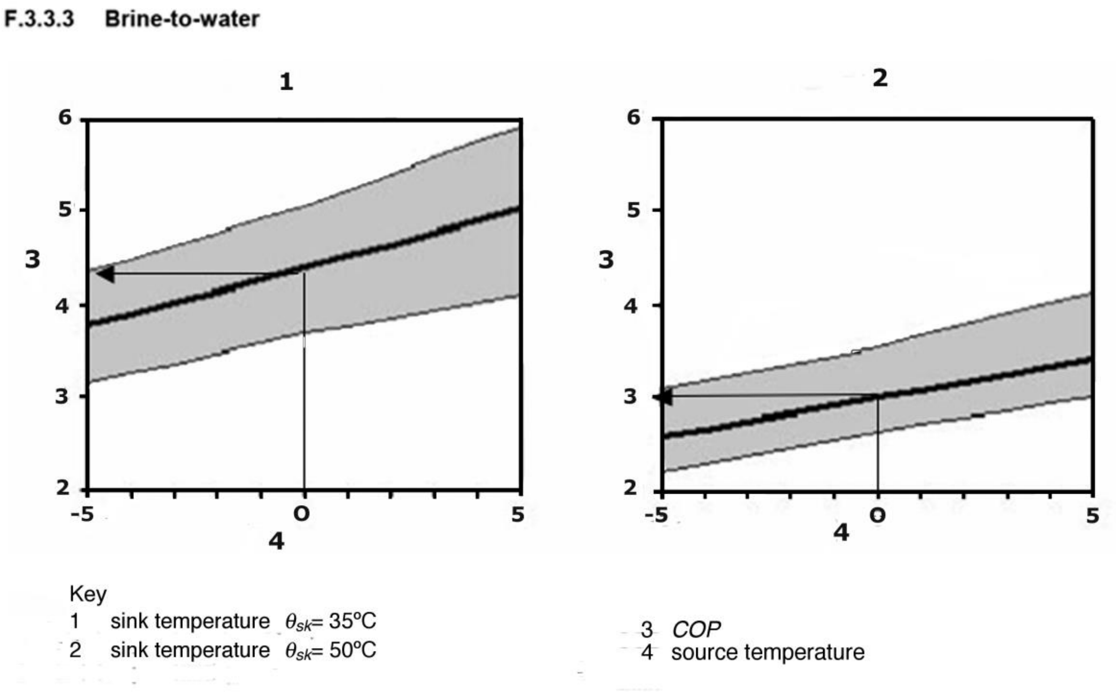


Figure 7.1 Extract from EN 13516-2-4 which illustrates the relationship between CoP and source/delivery temperature

7.4.3 Reduction of source energy over the heating season

The reduction of the energy available from the system source, either by the extraction of heat from the soil surrounding the collector of a GSHP over the course of a winter or the reduction of air temperature during the winter for an ASHP, represents a similar process to the calculations involved in estimating the fall in efficiency due to raising the sink temperature to that required by radiator distribution from that required by underfloor heating. They both represent a change in 'lift', since the heat pump has to cope with a fall in sink temperature while maintaining a similar or higher output temperature.

No attempt is made in BREDEM to estimate this effect since a single COP value is used throughout the year, despite the introduction of monthly calculations with SAP 2009. In SAP 2009, Appendix N (BRE, 2010a, p. p89), there is the following note *"In reality the space heating efficiency varies through the year according to the source temperature. The value used in this procedure is adjusted to the total annual space heating requirement so as to give the correct total fuel use but the monthly values of fuel use will not be correctly indicated".*

7.4.4 CO_2 emissions dependent on the method of electricity generation

Fixed values (Table 12 of SAP 2009) are used in SAP calculations for calculating the Dwelling and Target Emission Rates of carbon dioxide emissions based on the 'fuel' used by the heating system. Up until SAP 2009, the value for carbon emissions due to electricity generation had been unchanged since the SAP process was formulated and, at 0.422 $KgCO_2$/kWh, was considerably lower than that obtained from current official statistics, for which 0.53702 $KgCO_2$/kWh was quoted as a rolling average (DEFRA, 2008 Annex 3, p4). In this publication, a value of 0.43 $KgCO_2$/kWh is quoted as the marginal rate of emission to be used in calculating CO_2 savings. This rate corresponds to the savings due to the 'non-construction' of a combined-cycle gas-turbine power station and is the value used "*when appraising policies that reduce electricity consumption or encourage the use of renewable electricity*" to quote this document. As the calculations in SAP reflect additional electricity consumption in a new building, the use of a similar value in SAP does not seem particularly logical and it would be more appropriate to use the rolling average figure of 0.517 $KgCO_2$/kWh , which now appears to be used in SAP 2009.

7.4.5 Size-dependent cost of installation of GSHP systems

While this particular characteristic is highly significant to the purchaser of a GSHP system and implies that the sizing of the system warrants considerably more care than that of a fuel-burning system, it is not germane to an energy model and so is not included in either the original or the improved version.

7.4.6 Non-uniform increase in operating cost and CO_2 emissions with increase in load

To allow for the energy use of auxiliary electric heating in bivalent parallel operation, SAP/BREDEM reduces the fixed COP values used from 320% to 300%, i.e. by about 6.3%, for GSHPs, giving a corresponding increase in the energy use for the dwelling. This value is based on the performance of the system documented in the GIR 72 monitoring report produced by BRECSU (Anderson, 2009a; BRECSU, 2000). Since the additional heaters do not operate continuously, but only when the main heat pump is unable to balance the energy load below a design external temperature, this method of estimation does not reflect correctly the heat pump's change in energy consumption in response to an overall rise in ambient temperature. To allow SAP/BREDEM to be used under conditions of climate change, a calculation method is required for the energy contribution of the additional heating that relates directly to ambient temperature.

The above fixed parameters are improved upon by the SAP 2009 Appendix N/Q calculations, which derive a Secondary Heating Fraction value which relates to the Plant Size Ratio (ratio of the heat pump rated output to the dwelling design heat loss) but this is limited to those heat pumps for which there are data base entries, and no attempt is made to generalise the calculation.

7.4.7 Cooling energy consumption

Provision has been made in the latest version of SAP 2009 for the estimation of cooling loads and consequent energy consumption and costs. These are estimated according to the heat transfer coefficient, total gains, external temperature for the region and month concerned, based on a standard internal temperature of 25°C, reduced according to the fraction of the dwelling cooled and by an intermittency factor based on the Thermal Mass Parameter and Heat Loss Parameter for the dwelling. The cooling load equations used are detailed in Tables 10, 10a, 10b of the SAP 2009 document (BRE, 2010a) with the method for estimating energy consumption in Table 10c and the fuel cost, CO2 emission factor and primary emission factor values are those for electricity in Table 12 .

7.5 Replacement estimation methods

7.5.1 Objectives

In the previous section, the following deficiencies were identified in the BREDEM-8 estimation process and this study will endeavour to provide solutions for them:

a) use of a fixed value for system efficiency, thereby ignoring any variations between heat pump systems from different manufacturers and neglecting the variation in system efficiency over seasons due to variation in source temperatures;

b) the use of an empirically-estimated variation to this fixed system efficiency value to adjust for the different temperatures required for different distribution systems rather than basing the variation on thermodynamic theory; even this limited estimating process is absent from BREDEM-8, which ignores the distribution type altogether;

c) estimating the energy consumption of additional heaters in bivalent parallel operation by a reduction of the value of the fixed system efficiency; this would over-estimate the value of this reduction if there was a substantial overall rise in ambient temperature. The use of a single value for the year for the Secondary Heat Fraction has an identical disadvantage.

d) omission of an estimate of energy use for space cooling.

7.5.2 Approach

Rather than approach these in a piecemeal approach, it is considered by the author that it is better to document all the replacement methods together, then indicate which deficiencies have been addressed. It is thought that this provides a clearer exposition of the topic.

7.5.3 Determining heat pump system efficiency

In Section 2.4.2 of this study, the calculation of the Carnot COP for a heat pump was described in Equation 2.6. This relates the theoretical maximum COP of the heat pump to the temperature differential between the source temperature (external air or soil) and the sink temperature (the temperature output to the distribution). As this differential increases, the value of the Carnot COP falls towards unity, and, as a real heat pump system can achieve a COP of only a fraction of this ideal value, the COP of a real system will fall in the same way. Thus the COP of a heat pump system is heavily dependent on the source / sink temperature differential – commonly known as the ‘lift’ – required for the given heating load. Combining the objectives stated in paragraph 7.5.1 (a) and (b) of estimating the effect of variations of source temperature and of the different requirements of different distribution systems, the net effect of these variations is to change the lift required of the system. If the numerical relationship between the COP and the ‘lift’ is known, then a value for the COP may be estimated that reflects both changes in source and sink temperatures.

7.5.4 Numerical relationship between COP and ‘lift’

While, in theory, it would be possible to estimate parameters for this relationship using the data collected for this study, the resultant analysis showed only a small degree of correlation, of which Figure 7.2 below is typical. Analysis for the data from the Wärmpumpentestzentrum heat pump tests provided better results as per Figure 7.3.

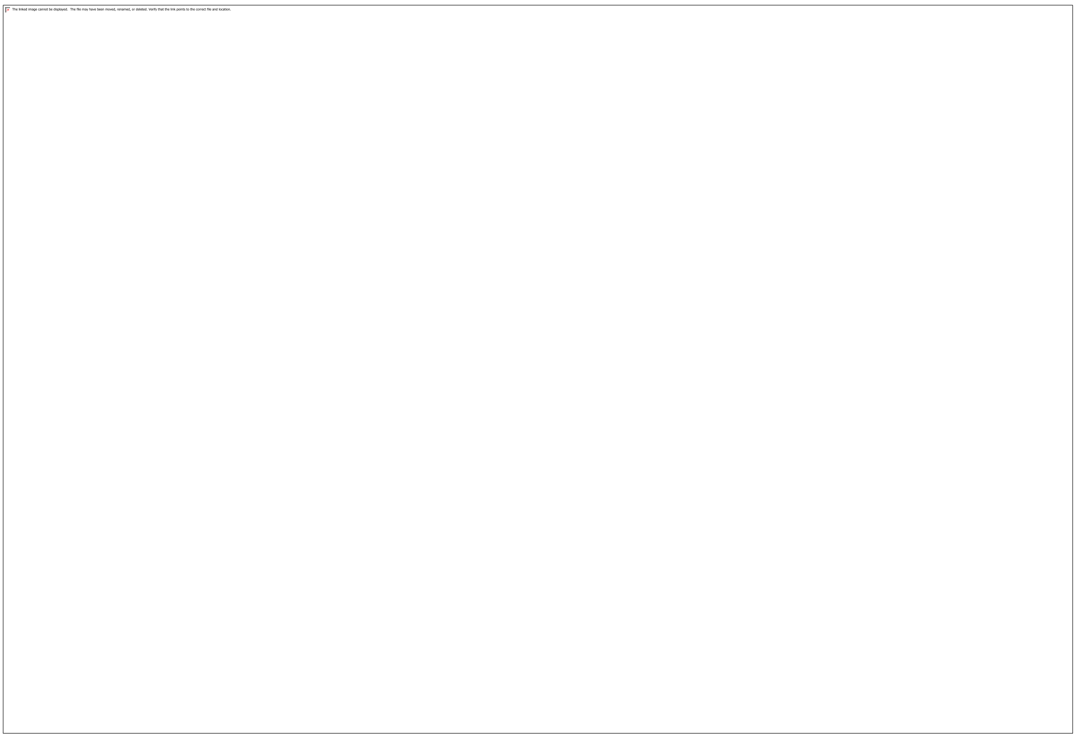


Figure 7.2. Dwelling 2: Coefficient of Performance against Lift

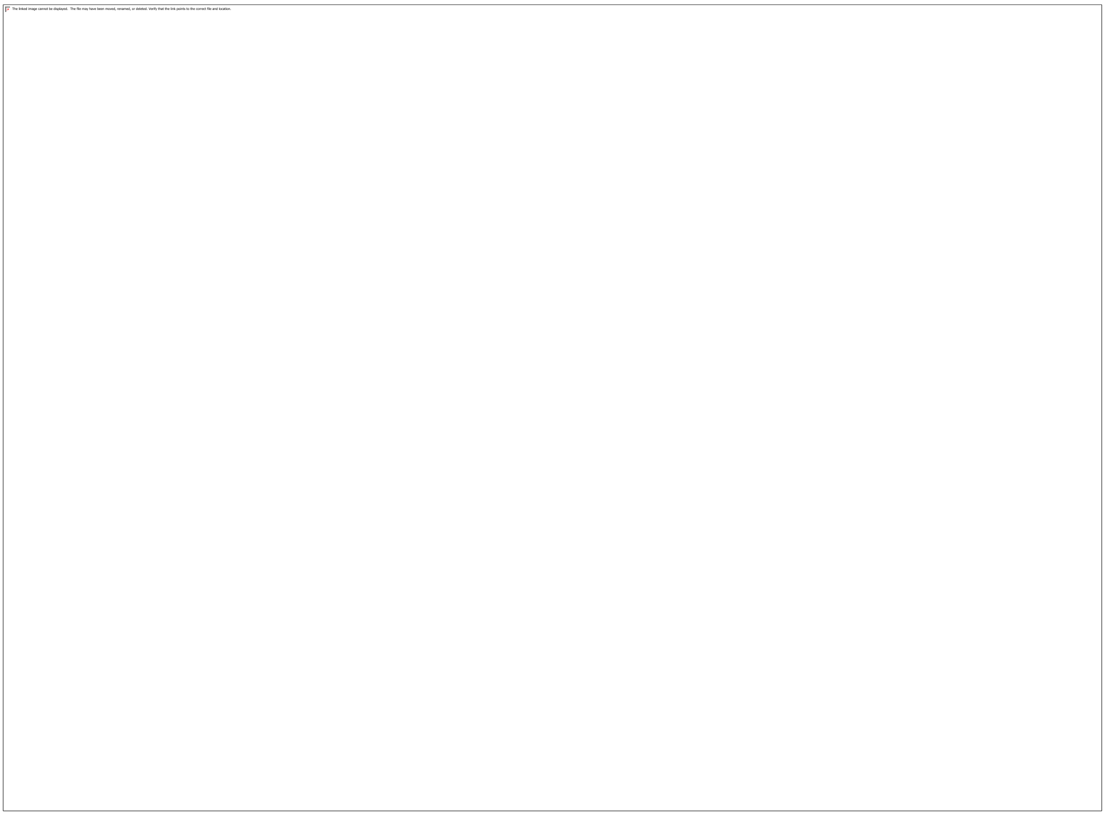


Figure 7.3. COP to 'lift' data points from one week's test results from WPZ for air source and ground source heat pump system, with trend lines

The results in the above graph come from 200 samples from 22 ground source heat pumps and 497 samples from 92 air source heat pumps. This data shows a reasonably high degree of negative correlation between ‘lift’ and COP as would be expected from theory. Thus, it would seem appropriate to use the equations derived from this data to estimate COP values from estimates of lift values.

7.5.5 Estimation methods for ‘lift’

7.5.5.1 Source and sink temperature estimation

Because of the different ways by which they are determined, different estimation methods are required for each of these temperature values. Further, different methods are required for the different source types.

For the purposes of this study, it is considered that estimation methods for three source types, air, borehole, and ground loop, are required. The various other sources in use – surface water (lake, river or sea), ground water, exhaust air - have been omitted as they are mostly used only in commercial buildings.

Two sink types will be allowed for, being wet radiators and wet underfloor heating. However, an equally significant determinant of sink temperature is the method used to control the system, in particular, the use of weather compensated control, by which the heating system temperature is set according to the external temperature.

7.5.6 Estimation methods for source temperature

For an ASHP, this temperature is largely that of the ambient air around the dwelling. For a GSHP connected to a vertical bore hole deeper than 10m, it is accepted that the ground temperature is largely the same as the average annual air temperature (Energy Saving Trust, 2007; Harris, 2006). For a GSHP connected to a horizontal ground loop, a more complex relationship exists, since above the 10m level, soil temperature is subject to several influences. For this, reference is made to the sinusoidal function from Equation 3.14, reproduced here as Equation 7.1, which provides a depth-dependent value for the soil temperature, as follows:

$$T(x_s,t) = T_m - A_s \exp\left\{-x_s\left(\frac{\pi}{365\alpha}\right)^{1/2}\right\}\cos\left\{\frac{2\pi}{365}\left[t - t_0 - \frac{x_s}{2}\left(\frac{365}{\pi\alpha}\right)^{1/2}\right]\right\} \qquad \textbf{(7.1)}$$

where $T(x_s, t)$ is the temperature at soil depth x_s on day t (in Julian day format, where 1st January = 0, 31st December = 364 in a non-leap year and t_0 is the day when the minimum soil surface temperature occurs), T_m is mean soil temperature, A_s is annual surface temperature amplitude (maximum temperature – minimum temperature divided by 2), α is the soil thermal diffusivity in m^2/day.

A discussion of the derivation of suitable values for these parameters follows.

7.5.6.1 Thermal diffusivity

Thermal diffusivity measures both the storage capacity and conductivity of soil or rock and is usually quoted in m^2/day, being a function of thermal conductivity (k, usually quoted in W/mK), density(ρ, in kg/m^3) and specific heat (C, in kJ/KgK) as follows:

$$'' = k / \# C \, [\qquad \textbf{(7.2)}$$

!

The above formula gives an answer in metres squared per second, which result is multiplied by 86,400 to give metres squared per day.

Rawlings (1999, p. 5) provides the following table of common soil characteristics (Table 7.3)

Table 7.3. Typical thermal properties of soils (Table 2.1 from Rawlings(1999) with addition)

Material	Conductivity W/(m K)	Specific heat kJ/(kg K)	Density kg/m^3	Diffusivity m^2/day	Average Diffusivity
Granite	2.1 to 4.5	0.84	2640	0.078 to 0.18	0.129
Limestone	1.4 to 5.2	0.88	2480	0.056 to 0.20	0.128
Marble	2.1 to 5.5	0.8	2560	0.084 to 0.23	0.157
Sandstone - Dry	1.4 to 5.2	0.71	2240	0.074 to 0.28	0.177
Sandstone - Wet	2.1 to 5.2			0.110 to 0.28	0.195
Clay - Damp	1.4 to 1.7	1.3 to 1.7		0.046 to 0.056	0.051
Clay - Wet	1.7 to 2.4	1.7 to 1.9	1,440 to 1,920	0.056 to 0.074	0.065
Sand - Damp	1.3 to 1.7			0.037 to 0.046	0.042
Sand - Wet	2.1 to 2.6	1.7 to 1.9	1,440 to 1,920	0.065 to 0.084	0.075

The data in this table, in which the first four rows are common UK rock types and the second four common soil types/states, shows that while there is a significant variation in diffusivity (a ratio of about 7.5:1) across soil and rock types, there is a much smaller variation within different kinds and states of soil where the ratio of the lowest value (damp sand) to the highest (wet sand) is about 2.27:1. Since horizontal collectors for GSHPs are installed in soil rather than rock, the lower variation in diffusivity is more applicable. The effect of variations in emissivity on soil temperature at 2 metres is illustrated by the following chart (Figure 7.4) again using Equation 7.1 from Labs (1979) :

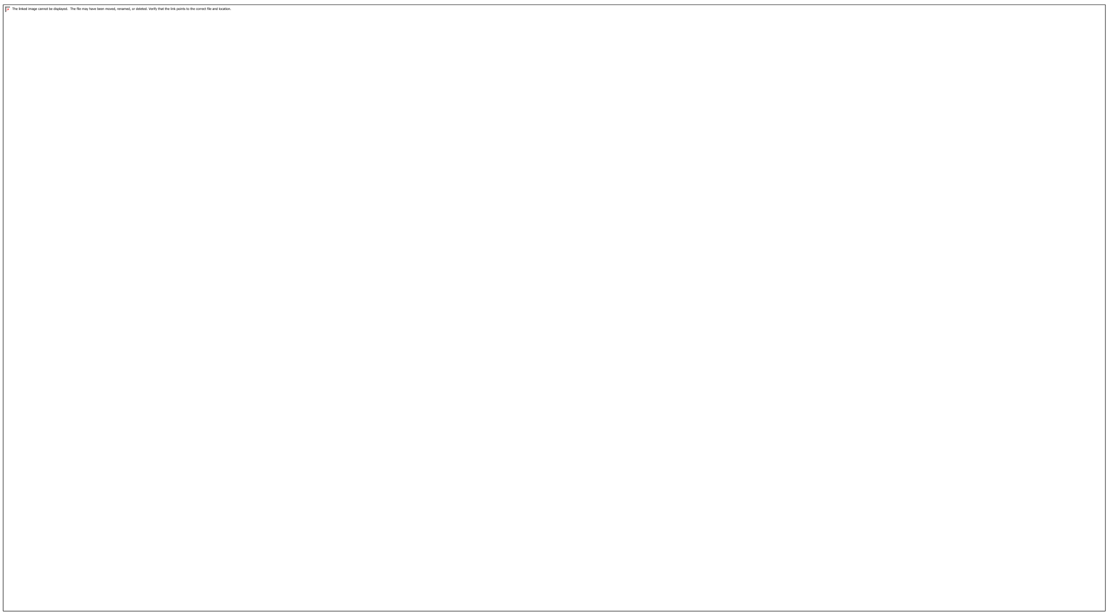


Figure 7.4. Soil temperature estimated from Equation 6.1 for different values of soil thermal diffusivity

The above curves are calculated using fairly typical values for the variables, viz. mean soil temperature = 10ºC, annual surface temperature amplitude of 13ºC, soil depth of 2m, Julian day of minimum soil surface temperature = 24. Jenkins et al (2009), in simulating the variations in soil diffusivity, found that '*changing the soil type only affects the system COP by 1 – 2%'*. This finding does not entirely gel with the approximately 2.5ºC difference between the estimates for the highest and lowest diffusivities in the above figure, particularly since these values coincide with the coldest and hottest parts of the year. Harris (2006) comments that "*soil types, and thermal properties, may vary with depth*" and that "*variation in soil type may lead to differences in the way moisture percolates through the layers"*. While such complexities may be included in models, the level of uncertainty in knowledge of soil properties means that this may not lead to any measurable improvement in accuracy. As can be seen from Table 7.3, thermal diffusivity also varies with soil moisture content, and it may differ radically for 'made ground' at brown field sites (Harris, 2006). Thus, it is probably necessary to make an arbitrary choice, the mean value, 0.058 m^2/day, from Table 7.3 being appropriate.

7.5.6.2 Mean soil temperature

This has been taken by other researchers (Zogou & Stamatelos, 1998) and practitioners (BSRIA, 2004; Rawlings, 1999; Viessmann UK, 2004) to be the so-called ‘far field’ temperature (that of the soil below the influence of air temperature – about 10m down) which again is equal to the mean air temperature - between 10 – 14 ºC, depending on location. Jenkins et al (2009) found the value to be 10 ºC at Rothamsted. Annual average soil temperature at 10 cm and 30 cm depths is available from the ten other sites in the Environmental Change Network (2009). Harris (2006) quotes Labs (1979) that the mean soil temperature can be calculated by adding 1.7 ºC to the mean air annual air temperature, but adds that this should be lower in the UK, failing to add how much lower.

7.5.6.3 Day number for minimum soil surface temperature

Values for this in the UK are obtainable from the Environmental Change Network summary data but only to the nearest month. Raw, daily data could be acquired to ascertain an exact Julian day, although interpolation between the monthly values might probably be accurate enough. From physical geography, Harris (2006) calculates a value of day 36, based on the 46 day lag of the surface temperature wave behind the solar radiation wave, which has its minimum at the winter solstice, Julian day 355. Jenkins et al (2009) use day 24 in their Rothamsted comparison.

7.5.6.4 Annual surface temperature amplitude

Values for this in the UK may be calculated from the Environmental Change Network summary data. Labs (1979) states that a suitable value can be estimated by dividing the difference between the July and January monthly average temperature and adding 1.1 ºC.

7.5.6.5 Soil – ground loop return temperature differential

While equation **(7.1** provides an estimate of soil temperature, for GSHPs, this does not equate to the temperature of the fluid return from the ground loop required to calculate the heat pump lift since the acquisition of heat can never be perfect.

In order to estimate a relationship between soil temperature and the return temperature from the ground loop, the following was carried out:

a) the day’s average of the return temperature from the ground loop to the heat pump was calculated at seven-day intervals for the each set of heat pump data for the monitored dwellings and plotted against Julian day within the year. A second order polynomial trend line was calculated by the software for the resultant plot.

b) a curve was plotted using Equation 7.1 using the same Julian day values for the variable t, with mean soil temperature, T_m = 10 ºC, A_s = 13ºC, α = 0.061 m^2/day and t_0 = 5.

For the three dwellings being monitored, this produced the following three figures (Figure 7.5, Figure 7.6 & Figure 7.7)

Figure 7.5. Monitored dwelling 1 - Comparison of predicted weekly soil temperatures at 1.2m depth with day's average of return temperatures from ground loop to heat pump at seven day intervals

Figure 7.6. Monitored dwelling 2 - Comparison of predicted weekly soil temperatures at 1.2m depth with day's average of return temperatures from ground loop to heat pump at seven day intervals

Figure 7.7. Monitored dwelling 3 - Comparison of predicted weekly soil temperatures at 1.2m depth with day's average of return temperatures from ground loop to heat pump at seven day intervals

This shows an average difference of about 3.5 ºC between estimated soil temperature and the trend values for the return temperature from the ground loop over much of the heating season, about the first 80 days of the year.

7.5.7 Estimating methods for sink temperature

The other value which must be estimated for the system 'lift' is the required output temperature to the system sink, that is, the dwelling distribution system. This value is determined by the type of distribution system and the type of control system installed.

7.5.7.1 Distribution systems

The main type of distribution system to be found in existing UK homes is a wet radiator system. With a fuel-fired boiler, this has a usual operating temperature of 80-90 ºC and the radiators will be sized to provide sufficient heat at this temperature. Thus if a heat pump system is retro-fitted to a radiator system, its operating temperature is deemed to be the highest economic for a heat pump, around 50 ºC. The alternative to wet radiators, wet underfloor heating, is judged to operate at the lower temperature of 35 ºC because of the much large surface area available. While this lower temperature is not explicitly stated in SAP, the effect of the relative temperatures is used to modify the value of the fixed value used for the system COP. See Table 7.2, Item 1.

7.5.7.2 Control system

In the SAP calculations, the presence or absence of load or weather compensation controls is also used in determining the value of any adjustment applied to the system COP, also without noting the relationship with operating temperature.

For the purposes of this study, the most relevant form of the control is that of weather compensation, the effect of which is to adjust the target temperature within the distribution system according to the external temperature. This adjustment is made according to a function within the controller which calculates a target temperature for the heat pump from the current external temperature based on a so-called heating curve, examples of which follow (Figures 7.8 & 7.9).

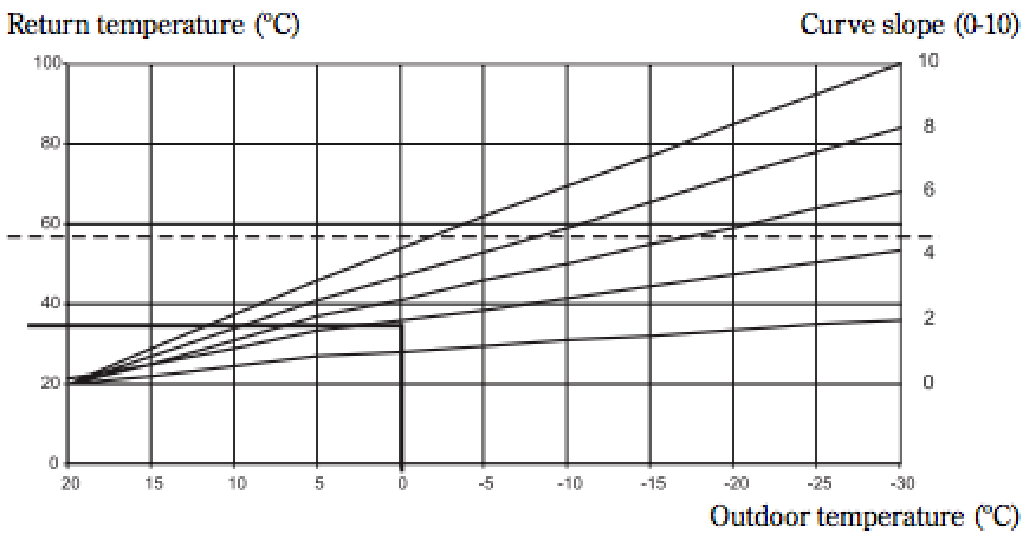


Figure 7.8 Weather compensation temperature curves for Rego 600-series controller fitted to IVT heat pumps.

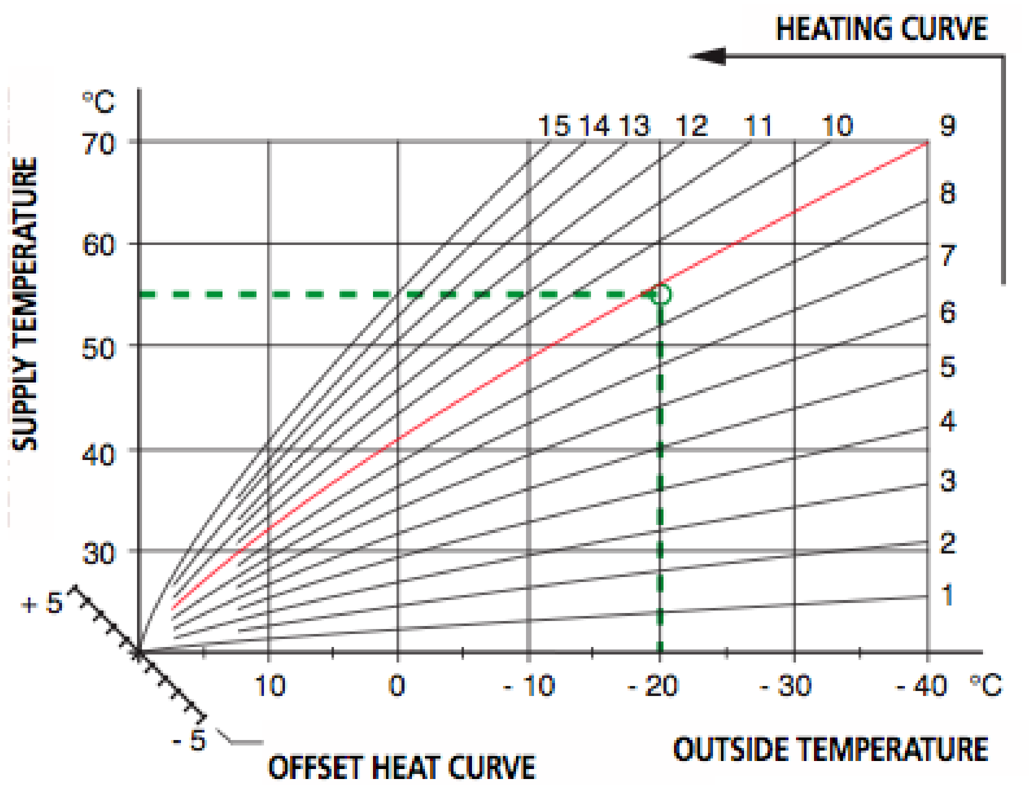


Figure 7.9 Weather compensation heat curves from NIBE Energy Systems SMO 10 system

The controller is set by the user choosing a curve by number, higher numbers responding with a higher system temperature for a given external temperature.

Higher curves are recommended for radiator systems, lower for UFH. Thus, if the function to calculate the target temperature for the heat pump output is known or can be determined, this can be used to estimate a value for the sink temperature from the external temperature. However, as might be expected, weather compensation functions are not uniform across heat pumps, either in their slopes or their configuration within the system. The two examples above differ in that the first is configured to use the return temperature from the distribution system as a target, the second to use the supply temperature, the first set of functions are simple linear relationships, the second slightly more complex curves. However, since, in practice, the effect of one weather compensation function set should be largely similar to any other, and greater variation in temperature conditions will be provided by the dwellings in which they are installed and by the usage of their inhabitants, the choice of an arbitrary but known set of functions would appear justifiable.

For the purposes of the current study, it is disadvantageous that the controller in the monitored IVT heat pumps tracks the distribution return temperature in comparison with the target output from the weather compensation algorithm, since the return temperature to the heat pump does not provide a particularly useful basis from which to estimate the supply temperature as indicated by the following figures (Figure 7.10, Figure 7.11 & Figure 7.12) which plot daily averages of these temperatures against external temperature:

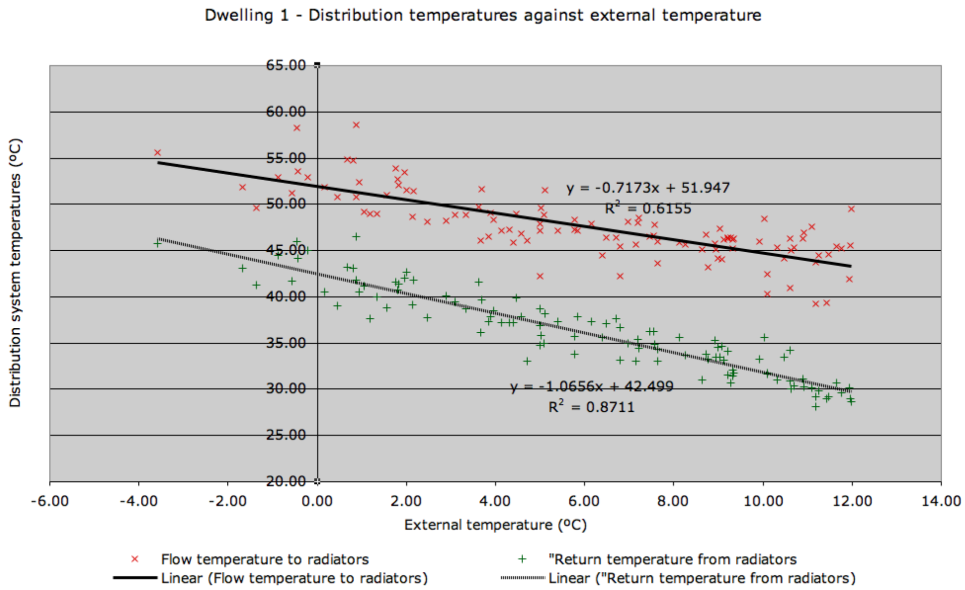


Figure 7.10. Dwelling 1 - Distribution system temperatures against external temperatures

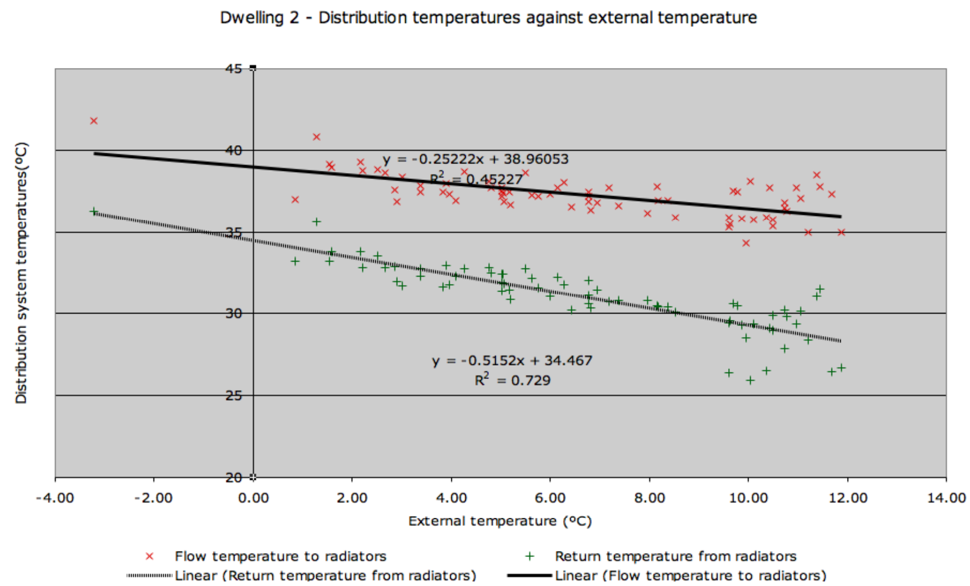


Figure 7.11. Dwelling 2 - Distribution system temperatures against external temperatures

Figure 7.12. Dwelling 3 - Distribution system temperatures against external temperatures

Applying a different analysis provides some clarification. By looking at a single day's worth of data, in particular one when the heat pump was in operation, if not the whole day, at least a very large proportion thereof, then the following set of graphs can be derived (Figures 7.13, 7.14 & 7.15):

Figure 7.13. Dwelling 1 - Distribution supply and return temperature differential

Figure 7.14. Dwelling 2 - Distribution supply and return temperature differential

Figure 7.15. Dwelling 3 - Distribution supply and return temperature differential

The figures all contain curves for five quantities: the supply and return temperatures to the distribution system (either UFH or radiators, depending on the dwelling) and the difference between these two; and the temperatures at the internal and external sensors. Where appropriate, other quantities are included: an estimate of the target temperature being applied by the weather compensation algorithm; an estimate of the energy use for additional heat to maintain the temperature when the heat pump cannot; an indication of when DHW was being generated.

Of these figures, Figure 7.15 is by the simplest and provides a value of 10ºC for the supply / return differential for an underfloor heating system. The other two are are more complex, since the supply temperature over the day selected is influenced by the operation of the additional heating in Figure 7.13 and by hot water generation in Figure 7.14. However, it would appear that, in a ‘steady state’, the value for the difference between supply and return temperatures is approximately 7 ºC in dwelling 1 and approximately 4ºC in dwelling 2.

7.5.8 Energy use for secondary heating – bivalent operation

7.5.8.1 General characteristics

Bivalent operation is employed to allow the installation of a heat pump system of smaller capacity than would be necessary to balance the heat load of the dwelling at the lowest occurring external temperature. A design decision is made as to the lowest external temperature which will be balanced by the main system – the balance point - with a form of auxiliary heating being switched in when the external temperature falls below this value, either as a boost to the heat pump which continues operating or as a replacement for the heat pump, which is turned off. Thus, the energy consumption of additional heaters or a secondary system is dependent on the the heating degree days of the periods during which the external temperature is below the balance point temperature (CIBSE, 2006).

7.5.8.2 Balance point temperature

A value for the balance point temperature was obtained empirically from the monitored data as follows:

a) selecting all those samples where i) the heat pump compressor was operating; ii) one or other of the additional heaters was switched on; iii) the three-way valve was directing the output to the distribution system, rather than the hot water tank.

b) creating a histogram of the percentage frequencies (Figure 7.16) of the external temperatures from each of these samples.

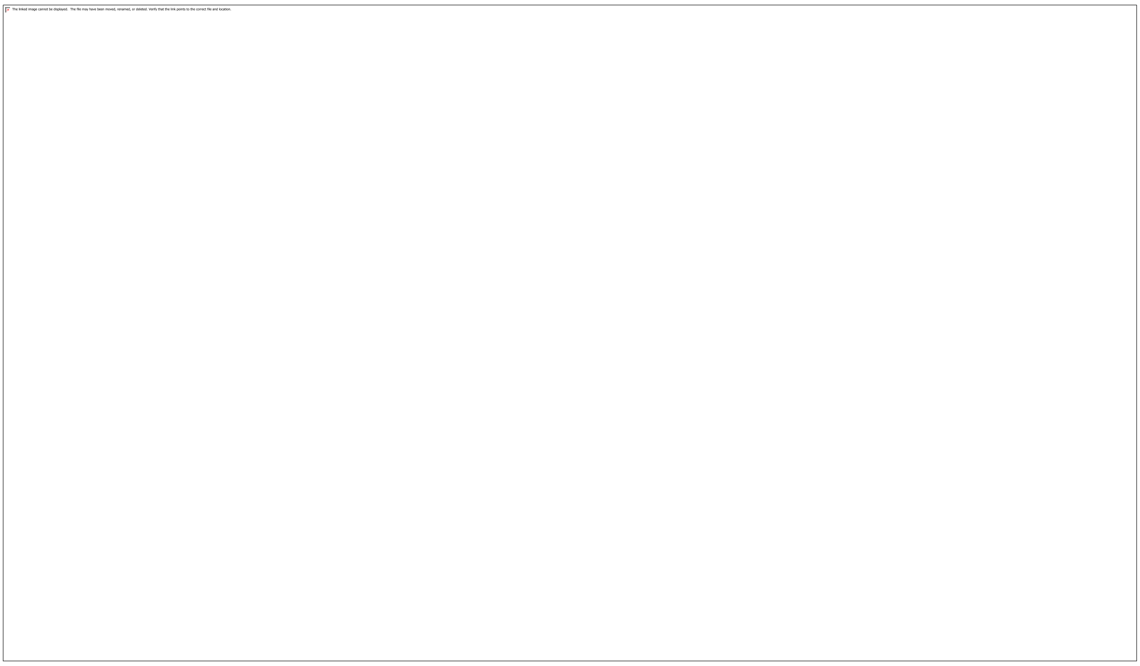


Figure 7.16. Percentage frequencies of bivalent operating temperatures

From Figure 7.16, it can be observed that the additional heaters are most likely to start operating at approximately 3ºC or below and this value has been used by the author in calculations.

7.5.8.3 Heating degree days

Hitchin (Hitchin, 1983, 1990) provides an equation which estimates the number of heating degree days which will occur in a month as follows:

$$\begin{aligned} DD(t_b) &= N(t_b - t_0)/\left(1 - \exp\left(-k\left(t_b - t_0\right)\right)\right), \quad t_b \neq t_0 \\ &= N/k, \quad t_b = t_0 \end{aligned} \tag{7.2}$$

where $\boldsymbol{t_b}$ = base temperature, $\boldsymbol{t_0}$ = monthly mean external temperature, ***N*** is the number of days in the month, $DD(t_b)$ is the conventional notation for the number of heating degree days to the base $\boldsymbol{t_b}$ and k is a constant for which Hitchen recommends a value of 0.71 although BREDEM-8 uses 1.1. This allows the calculation of both the heat output required at the balance point temperature and that required at the lowest temperature expected, given the average monthly temperature, which is the value of t_b for which $DD(t_b) = 0$, using an equation of the form:

$$Q_t = H.DD(t) \tag{7.3}$$

where Q_t is the heat required to maintain internal temperature t, H is the heat loss parameter for the building in W/ºC, $DD(t)$ is the number of heating degree-days for a base temperature t.

7.5.8.4 Choice of estimating methods

For the purpose of this study it was decided that where possible any additional estimation methods should use the same or similar methods as those already present in BREDEM-8. It was identified that a) the characteristics of the energy consumption of electric boiler systems are analogous to those of a heat pump system operating in bivalent parallel mode; b) those of heat storage radiators are analogous to those of bivalent alternate mode operation, so these methods were adapted for these purposes.

7.5.8.5 Bivalent parallel operation

The distinguishing characteristic of this mode of operation is that when the external temperature drops below the balance point temperature, the secondary heating system cuts in to 'top up' the output from heat pump to maintain the internal temperature and both systems will operate simultaneously. Section 11.2.5 of the BREDEM-8 document provides a method for estimating the energy use of an electric boiler system, operating using off-peak electricity to store heat in a buffer tank. It is assumed that if the capacity of the buffer tank is insufficient to balance the heating load for the external temperature during peak time, then on-peak electricity is used to maintain the demand by reheating the tank.

The steps in this method estimate, first, the quantity of heat that such a system can store given its rated energy output and the duration for which electricity is available at reduced, 'off-peak' rates, assuming that all the heat generated can be stored; secondly, an estimate is calculated for the 'saturation' temperature which is the lowest external temperature for which the stored heat can maintain the required indoor temperature.

From the value of the saturation temperature, the additional heat required to 'top up' the output from the stored heat may be calculated using the dwelling heat loss parameter and the degree-days value for the saturation temperature. T_{Sat} *is* calculated as follows:

$$T_{Sat} = \frac{H_1T_1 + H_2T_2 - G_1 - G_2 - C_{\mathbf{max}}}{H_1 + H_2} \qquad \textbf{(7.4)}$$

where H_1 & H_2 are the heat loss parameters, T_1 & T_2 are mean internal temperatures, G_2 & G_2 are the useful gains for the two zones defined in the BREDEM-8 model and C_{max} is the average heat output of the boiler. The next step in BREDEM-8 is to calculate the additional heat required to heat the house to T_{Sat}, which is given by the standard degree days formula:

$$Q_{on} = 8.64 \times 10^{-5} \left(H_1 + H_2\right) DD\left\{T_{sat}\right\} \qquad \textbf{(7.5)}$$

If the initial calculation of T_{sat} is omitted and replaced by a balance point temperature value of 3ºC as per para 7.5.8.2, then this method corresponds to that required to estimate the energy (Q_{on}) required to 'top up' the output of a heat pump system to maintain the demand temperatures at external temperatures below the balance point temperature as follows:

$$Q_{on} = H.DD\left\{T_{bp}\right\} \qquad \textbf{(7.6)}$$

where H is the heat loss parameter in W/K, $DD\{T_{bp}\}$ is the monthly degree-days for base temperature $T_{bp.}$ The portion of the heat output generated by the main heat pump system, Q_{HP}, is then estimated by simple subtraction from the total heating load on the dwelling, viz.

$$Q_{HP} = Q_h - Q_{on} \qquad \textbf{(7.7)}$$

where Q_h = monthly space heating energy requirement as defined in the BREDEM-8 document, and Q_{on} = the additional heat requirement.

7.5.8.6 Bivalent alternate operation

As indicated above in Section 7.5.8.1, this mode is characterised by the secondary heating system cutting in to replace the heat pump system at the balance point temperature. This is not a situation with which the BREDEM-8 routines cope explicitly. However, examination of the routines to estimate the energy use of storage heater systems shows that these systems have characteristics similar to bivalent alternate operation, in that once their relatively fixed heat capacity has been exhausted, further heat cannot be generated immediately and a second system must be brought into operation to maintain the demand temperature. The equations used in the routines for storage heaters are complicated by allowances for the characteristics of these devices and some of these can be removed for simplification. The most significant of these is the allowance for the lack of controllability of the storage heaters which allows heat to 'leak' out from them during the periods when the heating system would normally be switched off, contributing to the background temperature. For the purpose of this current routine, this assumption will be omitted.

The steps involved in this method in BREDEM again involve the calculation of a saturation temperature, T_{Sat} , with the same meaning as above. This is then used with the base temperature for the dwelling to calculate the average rate of off-peak electricity that is used for heat storage. This is the difference between the total heat (off-peak, and on-peak if required) to raise the living area temperature to the base temperature for the dwelling less the heat (on-peak), if required, to raise the living area temperature to the saturation temperature. The equation for this is of the form:

$$Q_{hpout} = H\left(DD\left\{T_b\right\} - DD\left\{T_{sat}\right\}\right) \tag{7.8}$$

where Q_{hpout} = maximum output of the heat pump system in watts required to maintain the demand temperature T_b given an external temperature of T_{sat}, , $DD[T]$ = heating degree days for temperature T, and H is the heat loss parameter as before.

A third complexity is that the average internal temperatures, T_1 & T_2, are unknown at the start of calculation, so the BREDEM-8 routine takes the demand temperature for Zone 1 as its starting value for T_1, calculates values for T_1 & T_2 and associated energy loads, then uses the latest value for T_1 as a fresh starting value to perform a second iteration of the calculations.

The calculations required are as follows:

a) background temperatures for both zones, labelled T_{c1} and T_{c2}, are calculated as per the main methods for other heating system types in section 9.2.1 of the BREDEM-8 document;

b) an initial estimation of the Zone 1 temperature, fully utilising gains, T_{b1}:

$$T_{b1} = T_{d1} - \frac{G_{T1} + \dfrac{H_3}{H_2 + H_3} \times G_{b2}}{H_1 + \dfrac{H_2 H_3}{H_2 + H_3}} \tag{7.9}$$

where T_{d1} is the demand temperature in zone 1 (ºC), G_{T1} = total gains in zone 1, H_1, H_2 are the specific loss coefficients for zones 1 and 2, H_3 is specific heat loss coefficient between Zones 1 and 2, G_{b2} = background useful gains in zone 2 ('useful' meaning that they occur while the external temperature is low enough such that the dwelling requires heating); if T_{b1} is less than or equal to the external temperature, T_{ext}, then no heating is required in the dwelling

c) in the standard BREDEM-8 routine, T_{sat} is calculated as the lowest temperature which can be maintained by the heating system, given its maximum heat storage capacity; in this current routine, T_{sat} is replaced by a constant, 3 ºC, as above.

d) a first value for the required output from heat pump, which corresponds to the stored heat energy generated using off-peak electricity in the original routine, is calculated as follows:

$$Q_{hpout} = \frac{\mathrm{H}_1 + \dfrac{H_2 H_3}{H_2 + H_3}}{d}\left[DD\{T_{b1}\} - DD\{T_{sat}\}\right] \qquad \textbf{(7.10)}$$

where Q_{hpout}= maximum output of the heat pump system in watts required to maintain the demand temperature T_{b1} given an external temperature of T_{sat}, d is the number of days in the current month, $DD\{T\}$ = heating degree days for temperature T, and H_1, H_2 and H_3 are as before;

e) the standard BREDEM routine next calculates a value for the rise in temperature in both zones due to the uncontrolled heat output from the storage heaters, which will be omitted from this routine, as detailed above,

f) mean internal temperatures, T_1 and T_2, are calculated using the standard BREDEM-8 methods in section 9.3 of the BREDEM document, from which heating loads (in GJ) for each month for both zones are calculated as follows:

$$Q_{h1} = 8.64 \times 10^{-5} d\left\{H_1(T_1 - T_{ext}) + \left(H_3(T_1 - T_2) - G_1\right)\right\}\ (but\ if < 0, Q_{h1} = 0) \qquad \textbf{(7.11)}$$

in which values are as before with the exception of G_1 and G_2 which are the average daily heat gains in zones 1 and 2 respectively; and the total monthly heating (also in GJ) allowing for savings due to a conservatory as follows;

$$Q_h = Q_{h1} + Q_{h2} - Q_{saved}\ (= 0, if < 0) \qquad \textbf{(7.12)}$$

f) the demand temperature for zone 1, T_{d1}, was used as starting value for the internal average temperature (normally T_1) in this zone. From this, a new, more accurate value for T_1 has been calculated as per paragraph (e) above. A second iteration is then performed replacing T_{d1} in Equations 13 and 14 to obtain a new value for Q_{hpout}.

g) values for the main heat pump system (Q_{prim}) and the secondary system (Q_{sec}) energy in GJ are calculated as follows:

$$Q_{prim} = \frac{8.64 \times 10^{-5} dQ_{hpout}}{\varepsilon_{hp}} \tag{7.13}$$

and

$$Q_{\sec} = \frac{Q_h - Q_{prim}}{\varepsilon_{\sec}} \quad Q_{prim} \geq Q_h$$
$$= 0, \quad Q_{prim} < Q_h \tag{7.14}$$

where ε_{hp} and ε_{sec} are the COP of the heat pump and the efficiency of the secondary system, respectively.

7.5.9 Estimation of cooling energy consumption

A routine based on that used in SAP version 9.90 (BRE, 2009a, Tables 10, 10a, 10b) is used to estimate energy requirements for space cooling. This has the following parameters, with the defaults used in parentheses:

a) type of cooling equipment (0 = none, 1 = reversible heat pump system, 2 = dedicated air conditioner)

b) thermal mass parameter for the dwelling (250 kJ/m^{2}K – median value from SAP 9.90 Table 1d)

c) internal temperature at which cooling starts (25ºC)

d) cooling temperature (18ºC)

e) fraction of total floor area cooled (100%)

f) Seasonal Energy Efficiency Ratio (SEER) for a dedicated air conditioning system (2.0 – assumed Energy Label class G from SAP 9.90, table 10c)

The routine follows SAP 9.90 (BRE, 2010a), tables 10, 10a, 10b & 10c. It returns the following values:

the annual cooling energy requirement (kWh);

the annual cooling energy use (kWh, GJ).

The SAP calculation is itself based on the similar calculation method in the BS EN ISO 13790 standard for estimating on a monthly basis (British Standards Institution, 2008b, pp. 64 - 68,).

7.6 Validation

7.6.1 Comparison with standard BREDEM estimate for dwelling with heat pump

Figure 7.17 shows the difference between energy consumption estimates using identical parameters for the built form of the dwelling, with the upper graph using the original BREDEM heat pump parameters and the lower using the enhanced BREDEM model, both with a GSHP using a soil collector. The lower figure indicates that the enhanced model is much more responsive to variation in ambient temperature since no energy is used by secondary space heating (additional heaters) outside the heating season, with heating coming from the main system only ie. relying totally on the heat pump compressor. The response to the change in ambient temperature throughout the year indicates that the model will respond correctly to the overall changes occurring under conditions of climate change.

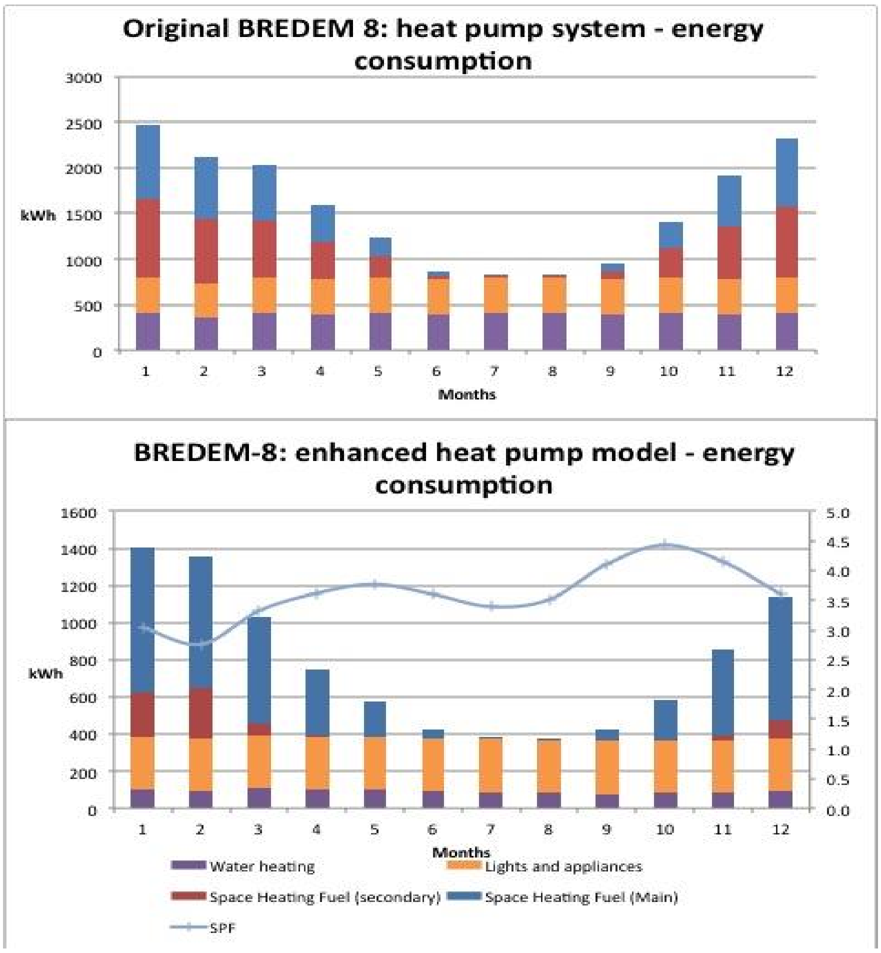


Figure 7.17 Comparison between BREDEM-8 energy consumption estimates, original & enhanced

7.6.2 Seasonal performance factor (SPF)

The heat pump model calculates Seasonal Performance Factor on a monthly basis, which is necessary to estimate peaks in electricity usage which cannot be identified by a yearly average. The SPF value estimated by the model, as shown in Figure 7.17 responds correctly to the change in source temperature throughout the year, initially falling due to the reduction in source temperature and increase in the required output temperature, then rising as both the source is recharged by solar gain and ambient temperature increases. As the need for space heating reduces, DHW energy requirements form a greater proportion of the energy load, and with the higher output temperature required for this, causes a reduction in SPF. The end of the summer causes space heating to increase as a proportion of the load and, with the recharge of solar gain in the soil, the corresponding reduction in the average distribution temperature indicates a peak in SPF, again falling away as the soil temperature reduces and the heating load increases. While in practice, the shape of this curve may vary, depending on the relative sizing of the heat pump system to the building loads, the curve in Figure 7.17 indicates that the model behaves as would be expected when the system is correctly sized.

The effect of space cooling must also be anticipated, since it is to be assumed for the purpose of this study that the heat pump systems involved will be reversible. Including this load is expected to cause the SPF value to rise significantly, since the load value is comparatively small, involving a small lift value between the required cooling temperature and the soil temperature. The results produced by the model are indicated by Figure 7.18, for which the space cooling load has been increased by 'morphing' the existing BREDEM-8 monthly average temperatures according to the UK Climate Projection (described in more detail in Section 8.3.4.2. These results appear to be consistent with what would be expected.

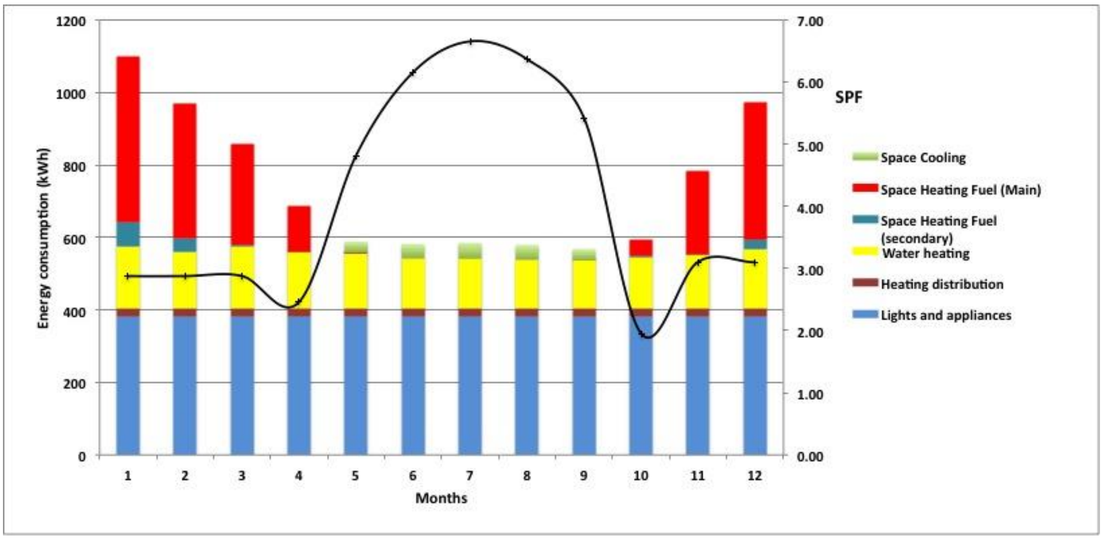


Figure 7.18 Effects of space cooling load on heat pump SPF, combined with external temperatures 'morphed' to 2050 values.

7.7 Discussion

7.7.1 Deficiencies of revised heat pump system energy model

a) Accuracy of temperature values:

The method used to estimate source and sink temperature could give rise to a degree of error, but this is considered to fall within acceptable limits. The values used in estimating the system source and sink temperatures in Sections 7.5.6 and 7.5.7 are taken from the heat pump monitoring study documented in Section 6.2 using the heat pump control sensors, which could not be calibrated for accuracy. The temperatures are recorded to one decimal place, relying for their output values being of the correct order of magnitude on their use in the control of the heat pump and its maintenance of comfort temperatures in the dwelling. The three installations in the monitoring study also constitute a very small data sample.

b) Use of arbitrary values and selections

The following arbitrary values and selections are utilised in this procedure:

Values of 35 and 55 ºC for sink temperatures for UFH and radiator system respectively where weather compensation controls are not used; these are 'accepted' values and it has not been possible to confirm or refute them;

Values of 10 ºC and 7 ºC for the difference between the supply and return temperatures across UFH and radiator systems, respectively; insufficient data has been gathered from dwellings of different built forms and heat distribution systems to confirm these values;

the utilisation of curves from IVT heat pumps to calculate target temperatures for weather compensation controlled operation; the target values that they return for a given external temperature will almost certainly differ from others installed in other heat pumps; this was compensated for by the substantial amount of data available from the monitoring process;

the selection of weather compensation curves for the estimation of UFH and radiator target temperatures; this was based on those set on the controllers in the appropriate dwellings and, as such, is drawn from a samples of only one and two, respectively;

choice of values for the variables in Equation 7.1: since BREDEM utilises a geographic division of the British Isles into only 21 different regions on the basis of average monthly temperature, it is unlikely that soil diffusivity will be similar across these regions; equally, those practitioners (Harris, 2006;

Jenkins, D. P., et al., 2009) who have attempted to validate Equation 7.1 have utilised various values for t_0, the 'coldest soil temperature' day, with only Harris (2006) selecting the day number on the basis of the theoretical lag between the surface temperature wave and the day of minimum solar radiation;

b) Omissions

In SAP, an adjustment of +0.3 ºC (DCLG, 2008b, p. 131,Tables) is made to the internal temperature for the dwelling in the estimation for heat pumps with no thermostat or other form of control. This has been omitted from the routine, since the author has not found such a system on sale.

7.8 Summary

7.8.1 Completion of Objective 4

This Chapter has documented the process of developing a heat pump energy model and an associated dwelling energy model to fulfill Objective 4 of this study. The chapter has summarised the available UK standard residential energy models and indicated that, out of those standard models which form the basis for the national modelling of domestic energy use, BREDEM-8 is deemed particularly suitable for this study because of its provision of monthly estimates. This is as opposed to the BREDEM-12 model, which creates estimates on a yearly basis, or the SAP model, which contains extra calculations for cooling energy consumption and for calculating SAP and environmental impact ratings based on energy consumption and carbon emissions respectively. The procedures and their parameters used for estimating heat pump energy consumption in the BREDEM / SAP models have been detailed, their deficiencies indicated and replacement estimating procedures defined.

7.8.2 Summary of BREDEM / SAP heat pump parameters and replacement estimation methods

Table 7.4 contains a list of these.

Table 7.4. Summary of changes to SAP / BREDEM for this study

Characteristic	**SAP / BREDEM**	**Proposed**
Efficiency / SPF values	Fixed values, possibly from previous studies	Regression model based on standard test results estimating SPF as a function of ‘lift’ - source minus sink temperature - on a monthly basis.
Effect of different source type	Fixed efficiency / SPF value for each source type (water, air, soil). Does not distinguish between horizontal ground loop and bore hole.	Source temperature estimation method for each source type on a monthly basis.
Effect of different sink (distribution) type	Adjusts SPF by a factor according to whether UFH or radiators in the system or whether the system has weather compensation controls. Factors range between 1.0 and 0.7. Affects the value of the ‘Responsiveness’ variable which represents the speed at which heating system cools after being turned off and hence determines the background temperature.	Explicitly sets sink temperature value according to distribution type, using default values for systems without weather compensation and calculating a value using a weather compensation algorithm from a known controller with monthly average external temperature as a parameter. Retains the 'responsiveness' calculation without change.
Energy use for DHW generation	Uses same Efficiency/SPF value as space heating estimate.	Recalculates SPF from regression model with ‘lift’ based on a sink temperature of 55 ºC.
Secondary space heating	Estimated as a fixed fraction of main space heating energy consumption	Two different estimation routines based on bivalent parallel and bivalent alternate modes of operation, with a third 'null' option of monovalent mode with all space heating provided by the heat pump system.
Space cooling energy consumption	Not present in BREDEM. In SAP 9-90, contains a single parameter for the SEER of the cooling system	Single SEER parameter is replaced monthly value calculated using heat pump model based on fixed sink temperature value and monthly average external temperature

CHAPTER 8 FUTURE ENERGY CONSUMPTION EFFECTS OF RESIDENTIAL HEAT PUMP DEPLOYMENT

8.1 Introduction

Objective 5 of this study is to examine the effects of potential future take-up of domestic heat pump equipment on the UK electricity supply and carbon emissions. This will involve the development of a disaggregated domestic energy model based on the English House Condition Survey data, using the enhanced BREDEM-8 model defined in Chapter 7.

To this end, this chapter contains the following:

For the English Housing Survey (EHS), a summary of its structure with a detailed description of the reasoning behind its choice and of the physical survey data which is incorporated into this study;

For the enhanced BREDEM-8 model, a description of its linkage to the EHS sample data with particular reference to the inference techniques used to provide the multiple parameters required for the estimation of building energy use in this type of model; a description of the methods developed to create sample-level energy and CO_2 (operational and embedded) estimates for the EHS extract table in building a Domestic Energy Model;

For the Domestic Energy Model, a description of the methods employed in creating scenarios for heat pump take-up to build energy mix and carbon estimates for the English housing stock for the period to 2020 and for 2050; a description and analysis of the resultant estimates.

The chapter also contains a discussion of the various issues and problems raised by the development process. and by the modelling results.

8.2 Initial processing of English House Condition Survey data

8.2.1 Extraction and building of sample data table

The variables relevant to this model occur in different EHS survey tables and, therefore, the initial stage in building the model was to extract the data for these variables from the database and amalgamate them into a single spreadsheet table to minimise the handling of irrelevant data and the processing overhead of cross-referencing between tables. The starting point for this process was the version of the survey data held in SPSS (SPSS Inc, 2010) format and initial edits were performed using SPSS. As noted in Section 5.6.7 the initial entry point for the extract was the derived dataset (file name 'physical.sav') for the physical survey, initially selecting by the variable 'housex' with value "house" cross-referencing by the Sample ID (variable name 'aacode') to perform extracts from tables as per the list in Table 8.1:

Table 8.1 EHS tables used in building main extract

File name	Description of file
around	Dwelling surroundings: dimensions of plot, relative location of plot
dimensions	Number of rooms, wall and floor areas
energy_performance	SAP ratings, energy efficiency ratings, light, water and space heating costs, energy upgrade costs
energydims	Area of ground and highest floor, ceiling heights, external wall and window areas.
firstimp	Key information on the first impressions of the dwelling and neighbourhood as recorded by interviewer
general	Tenure, dwelling condition, location, housing market in locality
physical	Built form, date of construction, construction details, heating system, SAP rating.
services	Details of heating systems
shape	Dwelling shape: external dimension of dwelling; material and construction of dwelling.

The variables extracted from each table are as follows:

Table 8.2 Variables extracted to build model

EHS SPSS dataset name	EHS SPSS variable name	Variable content	BREDEM parameter
general	goregx	Government office region	Used to assign BRE degree day region
general	aagcd67	Dwelling weight (core cases 2006-7 & 2007-8)	Used to gross up EHS sample values to English Housing stock
physical	dwtypenx	Dwelling type	Built form
physical	dwage9x	Dwelling age	In 9 bands - see Table 5.
physical	floorx	Useable floor area (m^2)	
physical	storeyx	Number of floors above ground	
physical	typewin	Predominant type of window	Frame material / single / double glazed
physical	heat7x	Main heating system	Used to assign BREDEM Heating System type
physical	fuelx	Main fuel type	Used to assign BREDEM Fuel type
physical	mainfuel	Main heating fuel	As above
physical	boiler	Type of boiler	Technical classification - "condensing, "combi" etc
physical	loftinsx	Loft insulation thickness	
physical	wallinsx	Type of wall and insulation	
physical	sap05	Energy efficiency (SAP05) rating	
interior	Finlivcl	Living room ceiling height (metres)	
shape	Fdhmwid1	Width	
services	Finohtyp	Other heating - type of	Secondary heating type

		system	
services	Finwhcpr	Boiler with Central heating - present	
services	Finwsipr	Single Immersion heater - present	Type of water heating
services	Finwsity	Single Immersion heater - type/fuel	Type of water heating
services	Finwdipr	Dual Immersion heater - present	Type of water heating
services	Finwdity	Dual Immersion heater - type/fuel	Type of water heating
services	Finwhcyl	Cylinder - present	Presence/absence of hot water storage cylinder.
services	Finwhsiz	Cylinder – size/volume	Size in litres of hot water cylinder
services	Finwhins	Hot water cylinder - insulation	Insulation by jacket or factory-installed foam
services	Finwhmms	Hot water cylinder - insulation thickness (mm)	Thickness of insulation
energydims	lowarea	Area of lowest floor in dwelling	
energydims	cheight0	Ceiling height of ground floor	
energydims	cheight1	Ceiling height of first floor	
energydims	cheight2	Ceiling height of second floor	
energydims	cheight3	Ceiling height of third floor	
energydims	exwirf	External window area : front	
energydims	exwirb	External window area : back	
energydims	exwirl	External window area : left	
energydims	exwirr	External window area : right	
energydims	exwarf	External wall area : front	
energydims	exwarb	External wall area : back	
energydims	exwarl	External wall area : left	
energydims	exwarr	External wall area : right	
dimensions	ebdpcpe	External back DPC (damp proof course) perimeter	
dimensions	efdpcpe	External front DPC perimeter	
around	Fexp1fdp	Front plot depth	Used to estimate plot areas for different
around	Fexwidth	Width of plot	heat pump collector types

This provides the built form and services data required either directly by the BREDEM-8 model or indirectly via the 'data reduction' tables based on built form or date of construction.

8.2.2 Additional variables created on the extract table

8.2.2.1 Plot dimensions

Useable plot area

The area of the dwelling plot useable for the burial of a ground source collector is calculated as the greater of the front or rear sections, assuming that either the rear or front, but not both, can be used. The plot width variable (EHCS variable name

'Fexwidth') can have a value of "Same as dwelling" in which case it is replaced by EHCS variable *Fdhmwid1* (from EHCS table *'shape'* with meaning *'MAIN 1ST LEVEL: Width'*, ie. the width of the main section of the first level of the dwelling above). The resultant value is multiplied by the greater of variables *'Fexp1fdp'* (Front plot depth) and *'Fexp2fdp'* (Rear plot depth) to obtain a final value to the useable plot area.

Rear plot area

Calculated from final plot width value (above) and EHCS variable *'Fexp2fdp'.*

8.2.2.2 Allocation of BRE heating degree days region

Monthly average temperatures are determined in the BREDEM-8 model according to the "heating degree day" region, for which BRE provide a table of 21 values covering the British Isles. Geographic locations within EHS are indicated by Government Office (GO) Regions which correspond only loosely to the BRE regions. The BRE Heating Degree regions and Government Office (GO) Regions consist of different sub-divisions of British counties. While they coincide to some degree, in general the GO regions are larger, in some cases occupying two or more BRE regions or, in others, containing parts of more than one BRE region. While it might have been simpler to ignore the inconsistencies and allocate to each sample the single BRE region which most coincides with the GO Region, the weather data for the BRE regions within one GO Region differ quite significantly, eg. BRE Regions 4, 5 and part of 3, which lie within the South West GO Region, contain monthly temperatures differing by ~1ºC and solar radiation differing by about 18% in some months. It was therefore deemed necessary to allocate BRE regions specifically to samples.

Housing stock statistics for each county (or other administrative unit) for each GO Region were obtained from the UK Dept. of Communities & Local Government (DCLG, 2010d). The BRE Regions and GO Regions were cross-referenced visually using map overlays as per Figure 8.1 which shows the counties within the regions of both types. From this visual cross-reference, a tabular version was constructed relating GO Regions to Districts (a sub-division of a county) to BRE Regions, since housing stock statistics are only available at district level. This was then summarised up to give with the housing stock totals for each GO Region/BRE Region combination.

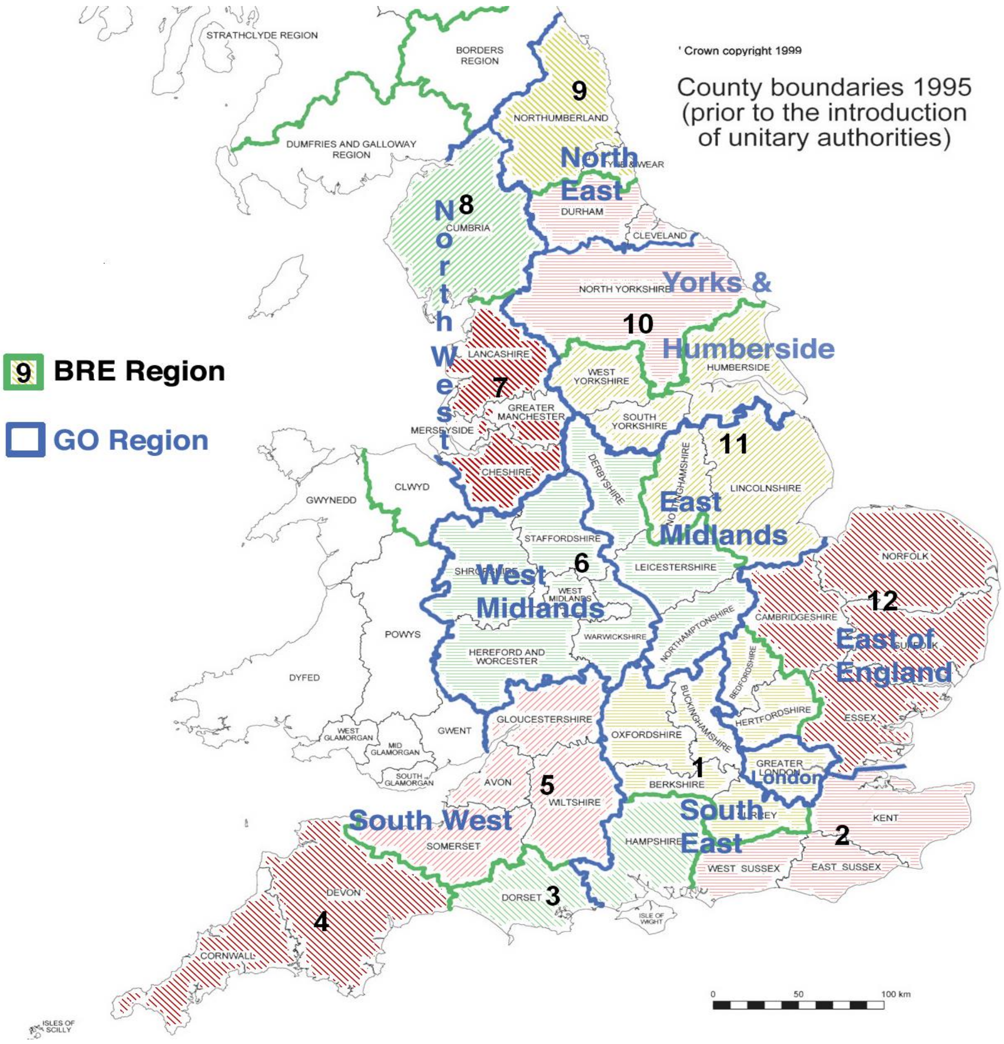


Figure 8.1 BRE HDD Regions and GO Regions

Table 8.3 GO to BRE Region cross-reference with allocations

Source: Table 100 Dwelling stock: Number of Dwellings by Tenure and district: England; 2008/09

GO Region	BRE Region	Total housing stock	Proportion in each BRE Region	Grossed-up stock values from EHS samples	Proportion as implemented in EHS samples	Cumulated proportion used in assignment routine
(1)	(2)	(3)	(4)	(5)	(6)	(7)
E	1	542906	0.22	476633	0.26	0.22
E	12	1943492	0.78	1362799	0.74	1.00
EM	6	1030521	0.53	886877	0.51	0.53
EM	11	906297	0.47	847214	0.49	1.00
L	1	3276108	1.00	1461089	1.00	1.00
NE	9	891553	0.77	992351	0.79	0.77
NE	10	264351	0.23	260255	0.21	1.00
NW	7	2858353	0.92	2787123	0.93	0.92
NW	8	234257	0.08	206371	0.07	1.00
SE	1	1438768	0.40	1160835	0.40	0.40
SE	2	1551930	0.43	1191397	0.41	0.82
SE	3	647954	0.18	520568	0.18	1.00
SW	3	342991	0.14	187125	0.11	0.14
SW	4	772675	0.33	536955	0.32	0.47
SW	5	1251899	0.53	955859	0.57	1.00
WM	6	2337863	1.00	1990184	1.00	1.00
YH	10	676648	0.30	793468	0.31	0.30
YH	11	1595676	0.70	1801077	0.69	1.00

Values in columns 5 and 7 were calculated from the values in column 3. The EHS samples were then processed to create a BRE Region from the GO Region as follows:

a) a random number in the range 0 - 0.99999 was generated for each sample;

b) the combination of GO Region from the sample and this random number was matched against columns 1 and 7 in Table 8.3 to select the first row where the combination of the columns was greater than the combination of GO Region / random value. The BRE Region code from this row was added to the output for the EHS sample output. As an example, if the GO Region from the sample was "SW" and the random number generated was 0.1, then the row selected would be 13 and the BRE Region set to 3. If the GO region was "L", then any random number would cause row 5 to be selected and the BRE region to be set to 1.

The resulting allocations to BRE Regions, in terms of grossed-up allocation of housing stock estimates and the proportions of the estimate in each GO Region allocated to the BRE Region segments, are shown in columns 5 and 6. These results differ somewhat from column 3, with some of the difference being accounted for by the exclusion of flats from the EHS data for this study. While it might have been more accurate for the BRE Region allocation to have been performed based on the grossed-up values rather than on just the samples, the benefits of the additional complexity are not obvious.

8.2.2.3 Embodied Carbon

Since one of the objectives of this analysis is to examine the effects of the installation of a substantial number of heat pumps on carbon emissions, it is necessary to provide estimates of the carbon dioxide and, more significantly, other green-house gases involved in the life-cycle of the equipment and compare them with the alternative systems. For GSHPs, Bennett (Bennett, 2007) puts forward an energy and carbon payback periods of 2.1 years and 6.0 years respectively compared with a gas-fuelled system, and embedded CO_2 of 500 kg CO_2(eq.). Johnson (Johnson, 2011), in estimating embedded carbon in ASHPs, found that electricity consumption contributed 80 − 83%, refrigerant and refrigerant leakage 15 − 18% and the material in the pump itself 2 − 4% of life-time carbon emissions. This provided a lifetime's embedded CO_2 value of between 4400 and 12000 kg CO_2(eq.) for heat pumps rated between 3.4 and 10.4 kw installed in the "Standard House Set" (Table 8.4), created by BRE for the Government consultation on the Renewable Heat Incentive (DECC, 2010g) to provide examples of possible payments under the scheme. Johnson's estimates are, however, based on a fluoro-carbon refrigerant, R-410A, which has a global warming potential (GWP) of 1725, whereas domestic heat pumps using carbon dioxide (GWP = 1) are already available in the UK (Sanyo, 2011). Making this refrigerant change would reduce the contribution from this source substantially and would be possible over the period to 2050, if not before, though for this study, the worst case scenario of the continued use of R-410A is assumed.

Table 8.4 "Standard set" of dwellings defined by BRE for RHI consultations, with additions by Johnson (DECC, 2010f; Johnson, 2011)

Property type	Bed - rooms	Floor area (m2)	Space heating (kWh/yr)		Hot water (kWh/yr)	Total heat demand (kWh/yr)	
			Cavity wall construction	Solid wall construction	All wall types	Cavity wall	Solid wall
Flat	1	42	3685	6244	3742	7427	9986
	2	61	4441	7525	3742	8183	11,267
	3	89	5365	9089	3742	9107	12,831
Mid-terrace house	2	63	4699	7961	3742	8441	11,703
	3	79	5262	8914	3742	9004	12,656
End-terrace house	2	63	8248	13,974	3742	11,990	17,716
	3	79	9236	15,648	3742	12,978	19,390
Semi-detached bungalow	2	64	6306	10,684	3742	10,048	14,426
	3	74	6808	11,534	3742	10,550	15,276
Detached bungalow	2	67	7786	13,192	3742	11,528	16,934
	3	78	8401	14,234	3742	12,143	17,976
	4	90	9024	15,289	3742	12,766	19,031
Semi-detached house	2	77	8998	15,245	3742	12,740	18,987
	3	89	9674	16,390	3742	13,416	20,132
	4	102	10,356	17,546	3742	14,098	21,288
Detached house	2	90	14,674	24,861	3742	18,416	28,603
	3	104	15,774	26,724	3742	19,516	30,466
	4	120	16,944	28,707	3742	20,686	32,449

The entries in Table 8.4 are based on one reference value for each property type / construction type, from which a linear relationship is used to calculate the entries for space heating energy consumption for the remaining entries (DECC, 2010f). From the entries in this table, Johnson estimates the heat pump capacities required for each dwelling / construction type and, hence, the operation, production, installation and disposal emissions, building Table 8.5 and

Table 8.6. From these, linear relationships between embedded carbon emissions and floor area, again by dwelling type and construction type, can be derived, of which Figure 8.2 is an example, allowing estimates for embedded carbon emissions for each sample to be calculated from its total floor area (EHS variable 'floorx'). Since the model in this study assumes that no change will be made to the distribution system in the sample dwellings and that CO_2 emissions will be estimated directly from energy estimates, the relationship coefficients are calculated including only the total of emissions from the refrigerant production and leakage, and the heat pump materials (column 13 in Table 8.5 and

Table 8.6). Per-sample values for embodied CO_2 calculated from these relationships are added as a new variable to the end of each extract table entry.

Table 8.5 Heat pump foot prints, cavity wall dwellings, 15 year lifetime - Johnson, 2011, additions by author

				Consumptions			Footprint						
							Production and disposal				Power	Lifetime	
Property		Heat pump definition		Power	Leakage		Refrigerant		Materials				
Type	Area	Capacity	R410A		Operat-ing	End of life	Leaks	Production	Heat Pump	Dist. System	All heating		Embedded
1	2	3	4	5	6	7	8	9	10	11	12	13	14
	m^2	kW	kg	kWh / lifetime	kg/ lifetime		kg CO_2e/ lifetime		kg CO_2e/ lifetime		kg CO_2e/ lifetime	kg CO_2e	kg CO_2e
Flat													
	42	3.7	1.1	37,827	1	0.6	3381	367	182	416	20,534	24,881	3,930
	61	4.1	1.2	40,859	1.1	0.7	3725	404	194	604	22,180	27,109	4,323
	89	4.6	1.4	44,565	1.2	0.8	4145	450	208	882	24,191	29,879	4,803
Mid-terrace-house													
	63	4.2	1.3	41,893	1.1	0.7	3842	417	198	624	22,741	27,825	4,457
	79	4.5	1.4	44,151	1.2	0.7	4098	445	206	783	23,967	29,502	4,749
End-terrace-house													
	63	6	1.8	56,127	1.6	1	5458	593	250	624	30,468	37,395	6,301
	79	6.5	2	60,090	1.8	1.1	5907	641	263	783	32,619	40,217	6,811
Semi-detached-bungalow													
	64	5	1.5	48,339	1.4	0.8	4574	497	222	634	26,240	32,169	5,293
	74	5.3	1.6	50,352	1.4	0.9	4802	521	229	733	27,333	33,622	5,552
Detached-bungalow													
	67	5.8	1.7	54,274	1.6	1	5247	570	243	664	29,462	36,189	6,060
	78	6.1	1.8	56,741	1.6	1	5527	600	252	773	30,801	37,956	6,379
	90	6.4	1.9	59,239	1.7	1.1	5811	631	260	892	32,158	39,754	6,702
Semi-detached-house													
	77	6.4	1.9	59,135	1.7	1.1	5799	630	260	763	32,101	39,555	6,689
	89	6.7	2	61,846	1.8	1.1	6107	663	269	882	33,573	41,496	7,039
	102	7.1	2.1	64,582	1.9	1.2	6417	697	278	1011	35,057	43,463	7,392
Detached-house													
	90	9.2	2.8	81,899	2.5	1.5	8,382	910	332	892	44,458	54,979	9,624
	104	9.8	2.9	86,311	2.6	1.6	8,883	964	345	1031	46,853	58,081	10,192
	120	10.4	3.1	91,003	2.8	1.7	9,416	1,022	359	1189	49,400	61,391	10,797

Table 8.6 Heat pump footprints, solid wall dwelling, 15 year lifetimes - Johnson, 2011, additions by author

				Consumptions			Footprint						
							Production and disposal				Power	Lifetime	
Property		Heat pump definition		Power	Leakage		Refrigerant		Materials				
Type	Area	Capacity	R410A		Operat-ing	End of life	Leaks	Production	Heat Pump	Dist. System	All heating		Embedded
1	2	3	4	5	6	7	8	9	10	11	12	13	14
	m^2	kW	kg	kWh / lifetime	kg/ lifetime		kg CO_2e/ lifetime		kg CO_2e/ lifetime		kg CO_2e/ lifetime	kg CO_2e	kg CO_2e
Flat													
	42	5	1.5	48,090	1.4	0.8	4545	493	221	416	26,105	31,784	5,259
	61	5.6	1.7	53,227	1.5	0.9	5128	557	240	604	28,894	35,426	5,925
	89	6.4	1.9	59,500	1.7	1.1	5840	634	261	882	32,299	39,920	6,735
Mid-terrace-house													
	63	5.9	1.8	54,976	1.6	1	5327	578	246	624	29,843	36,621	6,151
	79	6.3	1.9	58,798	1.7	1	5761	625	259	783	31,918	39,349	6,645
End-terrace-house													
	63	8.9	2.7	79,092	2.4	1.5	8064	875	324	624	42,934	52,826	9,263
	79	9.7	2.9	85,806	2.6	1.6	8826	958	344	783	46,579	57,494	10,128
Semi-detached-bungalow													
	64	7.2	2.2	65,897	2	1.2	6566	713	283	634	35,772	43,971	7,562
	74	7.7	2.3	69,306	2.1	1.3	6953	755	293	733	37,622	46,361	8,001
Detached-bungalow													
	67	8.5	2.5	75,956	2.3	1.4	7708	837	314	664	41,232	50,759	8,859
	78	9	2.7	80,135	2.4	1.5	8182	888	327	773	43,500	53,675	9,397
	90	9.5	2.9	84,366	2.6	1.6	8662	940	340	892	45,797	56,636	9,942
Semi-detached-house													
	77	9.5	2.9	84,189	2.6	1.6	8642	938	339	763	45,701	56,389	9,919
	89	10.1	3	88,782	2.7	1.7	9164	995	353	882	48,194	59,592	10,512
	102	10.7	3.2	93,418	2.9	1.8	9690	1,052	366	1011	50,711	62,835	11,108
Detached-house													
	90	14.3	4.3	122,755	3.9	2.4	13,019	1,413	446	892	66,637	82,414	14,878
	104	15.3	4.6	130,227	4.1	2.5	13,867	1,506	465	1031	70,693	87,568	15,838
	120	16.3	4.9	138,180	4.4	2.7	14,770	1,604	485	1189	75,010	93,065	16,859

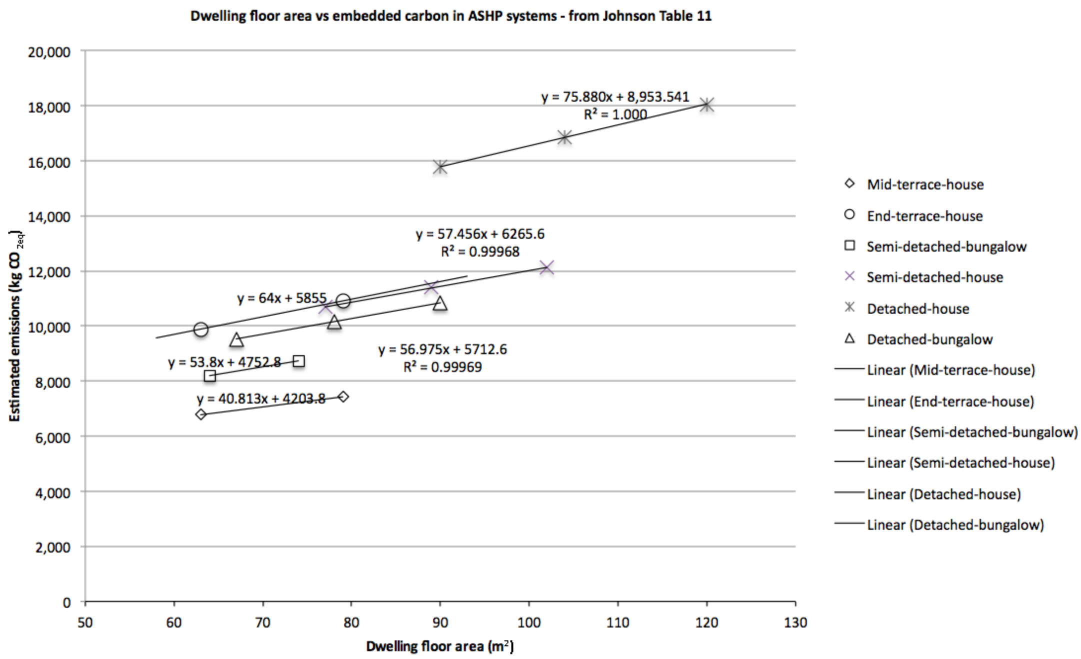


Figure 8.2 Plot of embodied carbon in ASHP systems against "Standard House Set" floor areas - from Johnson 2011 Table 11

8.2.3 Assignment of heat pump configurations to dwelling samples

The rules for determining the heat pump configuration for each sample according to the dwelling plot size, SAP rating and age are defined as follows:

the collector or source type is determined according to the following Table 8.7:

Table 8.7 Assignment rules for heat pump source

Dwelling plot size	Collector / source type	%age of sample
Plot size > 2 x total floor area(1)	Horizontal ground loop	32.5
Rear plot size > 4 m^2(2)	Air source collector	63.9
Otherwise	Vertical borehole ground loop	3.6

Sources: 1) (Nottingham Energy Partnership, 2006) 2) (Energy Saving Trust, 2011)

the operating mode is determined according to the following

Table 8.8:

Table 8.8 Assignment rules for heat pump operating mode

Characteristic	Operating mode	
SAP Rating > 51 and Source type = air source	Bivalent parallel	Main system continues operating while additional heaters are switched on
SAP SAP Rating > 51 and Source type=ground source (either type)	Monovalent	No additional heating required
Date of construction since 1965	Bivalent parallel	As above
Date of construction before 1965 and central heating system installed	Bivalent alternate	Additional heating replaces main system.
Otherwise	Heat pump system not suitable	

If no operating mode has been selected, then no heat pump energy estimates are created for the sample. The resultant split of weighted samples was as follows (Table 8.9):

Table 8.9 Percentage split of heat pump system operating mode

Operating Mode	Weighted percentage of installations
Bivalent alternate	55.6
Monovalent	0.1
Bivalent parallel	39.6
Heat pump system not suitable	4.7

8.2.4 Heating system and fuel type mappings

The BREDEM-8 (Anderson, et al., 2001) model requires a number of parameters to calculate energy consumption for space heating and hot water generation as follows:

a) For primary and secondary space heating systems:

   i) System type (Primary system only)

   ii) System efficiency

   iii) Responsiveness

   iv) Fuel type

b) Secondary system fraction - fraction of heating load provided by the secondary system

c) For the primary space heating system:

   Efficiency adjustments due to:

i) Low temperature distribution system

ii) Control system

d) Demand temperature adjustment due to control system

Of these, it was considered that there was insufficient information in the EHS data to provide values for the variables in (c) and (d), so these were set to default values.

8.2.4.1 Primary Heating System

System type, efficiency, response and fuel type for the primary space heating system is determined by a combination of four EHS variables (heat7x, fuelx, mainfuel, boiler in the following table):

Table 8.10 EHS variables and corresponding BREDEM-8 primary heating system characteristics

Variable	Content
heat7x	Type of system (gas or oil-fired boiler, electric storage radiators, solid fuel, electric boiler);
fuelx	Fuel type (eg. gas, electricity);
mainfuel	Fuel used (eg. mains gas, propane gas);
boiler	Type of boiler (eg. condensing, non-condensing)
System season efficiency	From BREDEM-8 table D.1, D.2
Responsiveness	From BREDEM-8 table D.1, D.2
BREDEM-8 heating system type	Values 1 = Boiler system, 2 = Storage heaters , 3 = Solid fuel systems, 4 = Electric boilers, 5 = Heat pump system
BREDEM-8 fuel type	Values as per SAP 2005 table

These variables reflect, to some extent, the structure of Tables D.1, D.2 and D.4 from the BREDEM-8 specification. Table D.1 has categories (capitalised headings) corresponding to the values in variable 'heat7x'. Sub-categories (in bold) approximate loosely to a combination of 'fuelx' and 'mainfuel', while individual entries have some sort of relationship with 'boiler' even if the closest value is "no boiler". Within the "Central heating with radiators" category, reference is made to Table D.2 which contains data on gas and oil boiler types which, again, approximate to the values in the 'boiler' variable, but also include an element of age in determining efficiency. The method adopted to build a cross-reference between the BREDEM-8 tables and the EHS variables was as follows:

a) a list (Table 1 in sheet 'EHS_htg_systems' in the 'EHS_2020_scenarios' workbook) was compiled from the EHS samples of all the unique combinations of the four variables in the data; this gave a list with 64 entries;

b) this was then cross-referenced manually to the BREDEM-8 D.1, D.2, D.4 tables and efficiency, responsiveness, heating type code and fuel type code assigned to each entry in the list.

Table D.1 has been annotated with line numbers for clarity in documenting these assignments - the annotated version is in Appendix E. Where two or more entries in the BREDEM-8 tables equated to a list entry, then the lower efficiency value was chosen to give a conservative energy estimate. For gas boilers, Table D.2 distinguishes three age-bands, "1998 or later", "Pre-1998, with fan-assisted flue" and "Pre-1998, with balanced or open flue". As flue details are not captured in the EHS and insufficient distinction is made in the values in the EHS 'boiler' variable to align them with those in the "1998 or later" band, the efficiency values chosen were those from the "Pre-1998, with fan-assisted flue" band, apart from the "Back boiler (to fire or stove)" value for which both pre-1998 and post-1998 values are the same, and the "Standard boiler (floor or wall)" value which was matched to the "Pre-1998, with balanced or open flue", "Wall mounted" efficiency value - this is the same as the "Floor mounted, 1979 - 1997" value as well.

8.2.4.2 Secondary heating system

Efficiency and Responsiveness

A smaller reference table (Table 2, located as Table 1 in Section 8.2.4.1) was created containing all the unique values of the EHS variable 'Finohtyp', each of which was assigned values of Efficiency and Responsiveness according to the equivalent types in BREDEM-8, Table D.1. Again, the reference table is documented with the line numbers from the annotated version of the BREDEM-8 table in Appendix E.

Secondary system fraction

The secondary system fraction, ie. the proportion of the heat load provided by the secondary system, to be assigned for each type of main system and secondary is defined in BREDEM-8 table D.7. Though small, this table is quite complex in its relationships between main and secondary heating system types, since it relates multiple fuel types and distribution system types for main systems to multiple fuel types for secondary systems. To implement these relationships, a table of all the unique combinations of heating system type (variable 'heat7x'), fuel type ('fuelx') and secondary heating system type ('Finohtyp') was created (Table 3, located as Table 1 in Section 8.2.4.1. A version of Table D.7 annotated with line numbers used to document Table 3 is also in Appendix F.

8.2.5 Dwelling orientation

The EHS survey does not record the orientation of the dwelling, so a value for this is generated from the row number of the dwelling sample in the EHS extract data table by calculating an index for a table of compass points, viz. "N", "NE/NW", "E/W", "SE/SW", "S" by taking the modulus of the row number to the base 5, plus 1, which generates a number in the range 1 to 5. The effect of this procedure is that the orientation of the sample dwellings is spread evenly over the 5 possible values. Even with current levels of knowledge of the advantages of correct solar orientation, there is no evidence that house builders do anything other than fit houses on to the available site (Peacock & Newborough, 2004, p. 8), so this allocation should not have any distorting effects.

8.2.6 Linkage of BREDEM model to EHS data

The details of the dwelling location, built form and dimensions, age of construction, window types, current heating and DHW generation from the each sample are passed to the enhanced BREDEM-8 model to estimate both the current energy consumption,

CO_2 emission and cost estimates and those for the generic heat pump system. If required, these may include estimates for cooling energy.

As noted in Section 5.6.8.4, the author opted to use the 'data reduction' techniques from DECoRuM (Gupta, 2005a, 2009a, 2009b), and earlier from Rylatt (Rylatt, et al., 2003a, 2003b).

Table 8.11 shows the relationship between built form and the proportion of the area of each building element assigned to each heating zone. Dwellings are assumed to have windows at the front and rear only. Zone 1, the main living area, is assumed to be situated on the ground floor only. For thermal bridging at corners, as each dwelling is assumed to be square in plan with all floors the same, a detached house will have four outside corners, semi-detached and end terrace houses 2 outside and 2 inside corners; and a mid-terrace 4 inside corners.

Table 8.11 Built form related parameters for BREDEM-8

	Built form	Detached	Semi detached	End terrace	Mid terrace	Bungalow
Roof area (proportion)	Zone 1	0.00	0.00	0.00	0.00	0.20
	Zone 2	1.00	1.00	1.00	1.00	0.80
GFA (proportion)	Zone 1	0.40	0.35	0.35	0.35	0.20
	Zone 2	0.60	0.65	0.65	0.65	0.80
	Zone 1	0.20	0.10	0.15	0.15	0.25
	Zone 2	0.80	0.90	0.85	0.85	0.75
Window area (proportion)	Zone 1 - Front	0.15	0.15	0.20	0.20	0.15
	Zone 2 - Front	0.35	0.35	0.30	0.30	0.35
	Zone 2 - rear	0.50	0.50	0.50	0.50	0.50
Thermal bridges (number)	Zone 1, Type 1 corners, ground floor	0	1	1	2	0
	Zone 1, Type 2 corners, ground floor	2	1	1	0	2
	Zone 2, Type 1 corners, ground floor	0	1	1	2	0
	Zone 2, Type 2 corners, ground floor	2	1	1	0	2
	Zone 2, Type 1 corners, upper floors	0	2	2	4	0
	Zone 2, Type 2 corners, upper floors	4	2	2	0	0

Table 8.12 below relates date of construction to u-value estimates for building elements, air-tightness parameters and hot water system characteristics for the current system.

Table 8.12 BREDEM-8 parameters related to date of construction

EHS Dwelling age bands	pre 1850	1850 to 1899	1900 to 1918	1919 to 1944	1945 to 1964	1965 to 1974	1975 to 1980	1981 to 1990	post 1990
Number of open fire places (open chimneys)	1.6	1.6	1.6	1.2	0.7	0.7	0	0	0
Efficiency of hot water system	0.702	0.702	0.702	0.703	0.706	0.704	0.738	0.738	0.738
Roof U-value (considering loft insulation)	0.67	0.67	0.67	0.53	0.44	0.44	0.44	0.35	0.25
Height of storeys	2.7	2.7	2.6	2.6	2.5	2.4	2.3	2.3	2.3
Thickness of wall construction (solid/cavity)	0.3	0.3	0.3	0.35	0.35	0.35	0.35	0.3	0.3
Wall U-value (unfilled cavity/solid)	2.12	2.12	2.12	1.6	1.6	1.5	1	0.6	0.45
Wall U-value (filled cavity)	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.35	0.45
Tightness of windows and doors	Loose	Loose	Loose	Loose	Loose	Loose	Loose	Tight	Tight
Draught stripping on doors	No	No	No	No	No	No	No	No	No
Tightness of doors	Loose	Loose	Loose	Loose	Loose	Loose	Loose	Tight	Tight
Ground Floor U-value	1.5	1.5	1.5	1.5	1.5	1.5	1	0.6	0.45
Roof U-value	2	2	2	2	1.5	1	0.6	0.35	0.25
Presence of hot water cylinder thermostat	No	No	No	No	No	No	No	Yes	Yes
Sealing of loft hatch	No	No	No	No	No	No	No	No	No
Number and type of fans	0	0	0	0	0	0	0	0	2

8.2.6.1 EHS Extract processing to create table of baseline estimates

The complete EHS Extract table is processed by an iterative routine which loads the values from each sample into the parameters for the enhanced BREDEM model, acquiring expansion values from Tables 8.9 and 8.10 to calculate the space heating load, the existing heating system parameters from the BREDEM-8 tables detailed in Section 8.2.6 configured according to Section 8.2.3 It then executes the BREDEM-8 processing, and extracts the estimates of energy use and CO_2 emissions created into a new table of results for use in the scenarios analysis. In the new table, the sample-level estimates are grossed-up by the sample weights to give the stock-level effect of each sample.

To implement the requirement to prepare a set of estimates under conditions of climate change, an suitably-amended table of monthly average temperatures (described in 8.3.4.2) is loaded over the original and the Excel process re-run to create a new output table.

8.2.7 DECC / BREDEM-8 variations

An initial comparison (Table 8.13) showed that the estimated consumption from the enhanced BREDEM-8 model for the individual fuel types exceeded the DECC values (DECC, 2010c) by approximately 30%, with only electricity consumption being less than the DECC value by about 82%. Since the DECC values included energy consumption for flats for which BREDEM-8 cannot provide estimates, this aspect was examined first. An analysis was made of the complete set of EHS data to calculate the total of the weighted total floor area by dwelling type and main type of space heating fuel. These values were then summarised into two dwelling type categories - simply “flat” and “house” - and the four main fuel types, electricity, gas, heating oil and solid fuel. From this, a ratio was calculated between total stock flat and house floor areas for each fuel type, giving column 1 of Table 8.14 which was used to calculate the proportion of total domestic energy consumption (column 2) due to flats (column 3), and that due to houses (column 4) which, when compared with the total stock energy consumption estimate for houses from the enhanced BREDEM-8 model (column 5), gave an adjustment factor in column 6 of Table 8.14.

Possible reasons for the necessity for this adjustment factor are that:

> Firstly, BREDEM-8 estimates are based on a demand temperature for the living space of 21ºC for all dwellings, a condition which is not necessarily true for all dwellings, since occupants’ thermal comfort requirements and behaviour have been found to be immensely variable (Gram-Hanssen, 2010; Gupta & Chandiwala, 2010; Steemers & Yun, 2009). Occupants of less efficient dwellings may not be able to afford the cost of heating either the whole or part of the dwelling to the BREDEM standard temperature. For Eire, an attempt was been made (Clinch, Healy, & King, 2001) to improve domestic energy modelling in this respect by including a relationship that reduced internal

temperature levels in dwellings with high energy costs, but acquiring sufficient data to construct this relationship for the UK would require a complete study of its own.

Secondly, the sample weights used in the grossing-up process for the housing stock estimates are related to the known housing stock by dwelling tenure within GO Region, a division which does not necessarily bear any relationship to dwelling energy consumption. However, as the EHS was designed and was used extensively for the energy efficiency analysis of the UK housing stock on meeting government targets for the reduction of "fuel poverty", under the previous definition as occupants' expenditure on space heating energy exceeding 10% of their income, then this would seem unlikely to be the cause.

Table 8.13 Comparison between grossed-up enhanced BREDEM estimates and Table 3.7 (DECC, 2010c)

All values in GWh (converted from PJ in Table 3.7)

	Table 3.7	Enhanced BREDEM	Variation
Solid fuel	7,678	12,144	163%
Gas	359,898	520,626	169%
Electricity	123,569	101,734	221%
Oil	35,631	39,558	190%
Total	526,775	674,061	178%

Table 8.14 Adjustment factors to be applied to EHS / Enhanced BREDEM-8 energy consumption estimates

	1 EHS Flat/house ratio by TFA	2 Table 3.7 values (Flats & houses) (GWh)	3 Estimated energy consumption - flats (GWh)	4 Estimated energy consumption - Houses (GWh)	5 B8 estimates (includes houses only) (GWh)	6 Adjustment factor
Solid fuel	0.05311	7,678	408	7,270	12,144	0.599
Gas	0.08792	359,898	31,644	328,254	520,626	0.630
Electricity	0.42789	123,569	52,873	70,695	101,734	0.695
Oil	0.00024	35,631	9	35,622	39,558	0.901
Total	0.10867	526,775	84,933	441,842	674,061	0.655

The differing energy consumption in the SAP / BREDEM comparison (Table 8.15) may be ascribed to the different calculation method used in the two routines. The SAP routine uses the same method for calculating energy consumption from all forms of heating, varying only the parameter values for the system type, while the BREDEM-8 uses a calculation method more characteristic of each system type. (Anderson, et al., 2001; BRE, 2005) This is especially marked with electricity consumption, and storage heaters in particular. The retention by BRE of both SAP and BREDEM methods which produce differing results seems somewhat illogical.

In view of the size of the discrepancies noted above, both original and adjusted energy consumption results are presented, but for carbon emissions, only one, unadjusted set of results in terms of changes are shown. This shows the BREDEM estimates for electric heating consumption to be about 60% lower than the SAP ones, with gas 5% lower and oil virtually identical.

Table 8.15 EHS SAP2005 vs enhanced BREDEM-8 estimated energy consumption for EHS samples

	SAP estimate	BREDEM-8	%age variation
	(MWh)	(MWh)	
other systems	494	161	67.5
boiler system with radiators	375,543	312,996	16.7
storage radiators	25,205	10,206	59.5
room heater	15,680	10,665	32.0
warm air system	3,462	2,764	20.2
communal	952	236	75.2
portable heaters only	587	288	50.9
Gas	346,746	288,220	16.9
Oil	31,319	26,465	15.5
Solid fuel	12,771	11,592	26.5
Electricity	30,136	12,301	59.2
Mains gas	343,879	285,752	16.9
Bulk LPG (propane or butane)	1,831	1,560	14.8
Bottled gas (propane)	1,036	909	12.3
Heating oil	31,319	26,465	15.5
House coal	4,540	3,513	22.6
Anthracite	1,586	1,402	11.6
Manufactured smokeless fuel	4,601	3,678	20.1
Wood logs	571	1,499	26.6
Bulk wood pellets	952	236	75.2
Wood chips	1,472	1,499	50.0
Dual fuel appliance	0	0	
Standard tariff	4,248	1,901	55.3
Off-peak 7-hour	23,968	9,673	59.6
Off-peak 10-hour	1,797	657	63.5
"24-hour"- heating Standard tariff	123	70	42.8

Finally, a primary energy conversion factor (as per Table 8.16) is applied to each energy consumption value to estimate the primary energy required. It should be noted that the fuel types in this table are from the earliest version of SAP 2005 in which the categories coincide best with those in the EHS 'mainfuel' variable.

Table 8.16 Costs. CO_2 emissions and primary energy conversion factors

Taken from SAP 2005, updated with values from SAP2009 (BRE, 2010a)

Fuel Type	Standing charge £	Cost p/kWh	CO2 emissions kg/kWh	Primary energy factor
01 mains gas	106	3.10	0.198	1.15
02 bulk LPG (propane or butane)	70	5.73	0.245	1.10
03 bottled gas (propane)		8.34	0.245	1.10
04 heating oil		4.06	0.274	1.19
05 house coal		2.97	0.301	1.07
06 anthracite		2.86	0.318	1.07
07 manufactured smokeless fuel		3.73	0.347	1.30
08 wood logs		3.42	0.008	1.10
10 bulk wood pellets		4.93	0.028	1.10
11 wood chips		2.49	0.009	1.10
12 dual fuel appliance		3.21	0.206	1.10
13 standard tariff		11.46	0.517	2.80
14 Off-peak 7-hour	27	4.78	0.517	2.80
15 Off-peak 10-hour	18	6.17	0.517	2.80
16 "24-hour"- heating tariff	57	4.64	0.517	2.80

8.3 Scenario creation

'Deployment scenarios' for short-term take-up for 2015 and 2020 of heat pump systems were taken from the background studies to the RHI proposals (NERA Economic Consulting, 2009), while a long-term take-up scenario was developed from the requirements of the UK Climate Change Act (UK Parliament, 2008a), with climate data taken from the UK Climate Projections 09 'Key Findings' data (DEFRA, 2009).

From the deployment scenario values, a second level of 'application scenarios' was built, reflecting the choices for selecting the dwellings for heat pump installations, by assigning heat pump installations to dwelling samples, totalling the weights of those samples until the total of the selected sample weights are equal to the deployment scenario values. Total estimates for each application scenario were calculated from the products of the sample weight and the sample estimates for the energy consumption and carbon dioxide emission reductions. For the most realistic and effective deployment scenarios, monthly energy consumption was estimated to provide an indication of effects on winter peak electricity loads.

The method used to create estimates for a scenario is a variation of the grossing-up process used to extend the sample estimates to the entire English housing stock. The grossing-up process uses the sample weights which are calculated by the EHS team to gross-up any values calculated for each sample to obtain the stock value. To calculate the effects of a scenario, each sample weight is replaced by the number of installations required (scenario weight value) for the given scenario. Thus, if the sample weight for the survey sample is 230, and the scenario weight value required for the scenario is 63, then the sample estimates are grossed up by a factor of 63 to obtain a result for the scenario, rather than 230. By definition, the maximum for a scenario weight value for a sample is limited to the sample weight.

8.3.1 Scenarios for 2020

8.3.1.1 Deployment scenarios

The base data for these scenarios was obtained from NERA/AEA studies for the UK Dept for Energy and Climate Change (NERA Economic Consulting, 2009), as part of that department's consultation on the proposed Renewable Heat Incentive. These are summarised in Table 8.17.

Table 8.17 NERA scenarios for heat pump installations 2015, 2020

Table C.5

Summary of ASHP Growth Scenarios

Year	Domestic sector Units thousand	Heat output TWh	Non-domestic sector Units thousand	Heat output TWh
Stretch growth scenario				
2015	81	1	9	3.1
2020	720	9.3	80	28
Central growth scenario				
2015	59	0.8	7	2.3
2020	270	3.5	30	11
Higher growth scenario				
2015	88	1.1	10	3.4
2020	410	5.3	46	16

Table C.8

Summary of GSHP Growth Scenarios

Year	Domestic sector Units thousand	Heat output TWh	Non-domestic sector Units thousand	Heat output TWh
Stretch growth scenario				
2015	140	1.7	15	5.3
2020	1,100	14	120	42
Central growth scenario				
2015	100	1.3	12	4.1
2020	290	3.7	32	11
Higher growth scenario				
2015	160	2	17	6.1
2020	440	5.6	48	17

The values for ASHPs and GSHPs were generated in two different ways by NERA, with those for ASHPs estimated by analogy with installation trends across Europe, while those for GSHPs by consulting with industry and academic bodies and with manufacturers. The higher values for GSHP installations (1.1 million by 2020 as against 720,000 ASHPs) would tend to indicate that the latter process contains an element of wishful thinking, since, for individual householders, the barriers to GSHP installation of higher cost and outside space requirement, and much greater inconvenience of installation, are far higher than those for ASHPs. Despite this caveat, these scenarios have been used in this study, as they have been recommended to the UK government as part of the decision to proceed with the Renewable Heat Incentive. An anomaly should be noted in that the installation values for the "2015 Stretch" are lower than those for the "2015 High" in the scenarios for ASHPs. Because of the closeness of the 2015 date to that of the current study, no scenario results have been generated for this date.

8.3.2 Application scenarios

8.3.2.1 Assumptions

Other than those actions allowed for explicitly in the scenarios themselves, it is assumed that there will be no concentrated programme of refurbishment of the English housing stock for energy efficiency over the period up to 2020, since there is no current target or strategy for this (Warren, Sunderland, & Croft, 2011). The most likely, current (February 2013) prospect for such a strategy stems only from the 'Green Deal' commencing operations in 2013 and the efficacy of this programme has yet to be shown. Future strategy on UK energy use appears to be providing for 120% increase in electricity demand by 2050 (DECC, 2010a).

It is assumed for the deployment scenarios for 2020 that there will be no reduction in the per-kilowatt hour emissions from electricity generation over the scenario period and the value of 0.517 kg/kWh used in SAP 2009 is used in calculating CO2 emissions. While the current targets for the carbon intensity of electricity generation for the UK are those shown in Table 8.18 (DECC, 2009b, 2010h; Fawcett, 2011), the main focus in the current White Paper on "Energy Market Reform" (DECC, 2011b) is on constraining new fossil-fueled generation to the Energy Performance Standard of 450 gCO_2/kWh, while providing some financial incentives for renewables and nuclear power. Considerable reliance is being placed on the construction of three new nuclear power stations in the period up to 2020, based on a lead time of 7 years, but of the two reactor types under consideration, the construction record of one type has been mixed, with those at Olkilouto in Finland and Flamanville in France meeting with considerable problems, though other, later-starting, examples are apparently on time and on budget (Thibault, 2010). Twelve units of the second type, on two sites, are under construction in the People's Republic of China, apparently without problem, though these were the first of this type to be built (World Nuclear Association, 2013). Thus a conservative value for emissions in 2020 seems appropriate.

Table 8.18 Predictions and targets for carbon intensity of electricity generation (Fawcett, 2011)

Date	Carbon intensity $kgCO_2/kWh$	Source
2008 (five year rolling average)	0.55	(Defra and DECC, 2010)
2020	0.30	(Committee on Climate Change 2010), to be achieved if current government ambitions on renewable energy and other low carbon sources are met.
2030	0.052	(Committee on Climate Change 2010). medium investment strategy (0.04 - 0.13 kgC02/kWh with high to low investment range)
2030 - 2050	Falls to around 0.01	Markal modelling on behalf of CCC, (Committee on Climate Change 2010)

A further assumption is that the heat pumps will not be using electricity at 'offpeak' rates, i.e. will operate continuously, depending on load requirements, throughout the day. This is current practise with the IVT heat pumps monitored in the earlier part of this study, and is deemed by their manufacturer to be required for weather compensation control, allowing the heat pump to respond to changes in external temperature as quickly as required (IVT Industrier AB, 2004). It is also perceived that weather compensation control allows lower distribution temperatures for which there is evidence in the data collected for this study (Table 8.19), which indicates that the monthly average distribution temperature in dwellings 1 and 2 is below the 55ºC deemed necessary for heating with radiators, thereby allowing the heat pump system to operate at a higher COP. The widespread occurrence of this practise is probably also due to the origin of a substantial proportion of heat pumps (particularly GSHP) in Sweden, where there are no off-peak periods in electricity supply. In contrast, the sole UK manufacturer of GSHPs, Kensa Engineering, recommend that their heat pumps utilise 'off-peak' electricity, particularly the "Economy 10 Off-Peak" charging system which allows three periods per day at a reduced rate (Kensa Engineering, 2007a).

Table 8.19 Outflow temperatures to distribution system for monitored heat pumps

System temperatures from dwellings monitored from Chapter 6 of this study

Dwelling	**1**			**2**			**3**		
	Average monthly temperatures			Average monthly temperatures			Average monthly temperatures		
Month	**Distr outflow**	**Hot water**	**Max distr temp (space heating only ºC)**	**Distr outflow**	**Hot water**	**Max distr temp (space heating only ºC)**	**Distr outflow**	**Hot water**	**Max distr temp (space heating only ºC)**
12	47.00	54.90	61.90	37.76	46.12	49.10	41.40	47.46	52.00
1	48.49	54.65	67.90	36.79	47.02	66.70	40.85	47.41	66.70
2	51.56	55.39	69.20	37.50	46.33	49.00	41.22	46.86	49.80
3	46.81	55.27	63.70	37.09	45.89	47.80	41.97	46.93	51.40
4	46.35	55.21	64.10	38.64	45.70	49.00	44.36	46.71	50.40
5	44.46	55.31	63.90	41.64	45.83	49.30	47.05	46.48	41.80
6	56.75	52.22	66.90	44.96	45.42	49.40	49.99	46.60	44.00
7		52.11	59.80		45.69	50.30	50.89	46.90	
8	-	52.52	60.20	44.66	45.44	49.90	51.92	46.86	
9	46.76	52.26	59.20	43.14	45.52	49.00	47.91	42.97	45.60
10	43.92	52.53	59.10	38.17	48.06	48.40	47.10	44.39	45.60
11	44.94	52.38	58.90	36.74	47.09	49.30	43.33	45.85	52.00

8.3.2.2 Application Scenario 1 - Heat pump deployment only

An initial set of results was created for a scenario reflecting the effect of the deployment of heat pump systems without the implementation of any other energy efficiency measures or constraints on the energy efficiency of the selected dwellings other than those detailed in

Table 8.8 above. Therefore, the scenario construction process made no assumptions about the dwellings, choosing samples randomly and within samples setting the scenario weight to a random proportion of the sample weight, up to the numbers required by the scenario.

8.3.2.3 Application scenario 2 - Energy mix and carbon emissions reductions based on current policy with insulation enhancements

A second scenario considered a policy enforcing limited improvements to insulation as a pre-condition for the subsidy. The improvements to be made were: increase of roof insulation to 300 mm, insulation of wall cavities (where possible), insulation of hot water storage with 80mm of foam. The estimates for this scenario were created by applying the improvements to the sample followed by re-executing the BREDEM-8 model for each sample selected for scenario 1. Table 8.20 indicates the grossed-up number of installations that were affected by these improvements.

Table 8.20 Sample sizes of dwellings affected by insulation improvements.

Scenario		*300 mm roof insulation*		*80 mm DHW tank insulation*		*Cavity wall insulation*	
		No of installations (000's)	*% of scenario*	*No of installations (000's)*	*% of scenario*	*No of installations (000's)*	*% of scenario*
2015	*Centre*	146	92%	115	72%	52	33%
	High	215	86%	167	67%	80	32%
	Stretch	207	94%	160	73%	79	36%
2020	*Centre*	520	93%	373	66%	188	34%
	High	781	92%	553	65%	291	34%
	Stretch	1710	94%	1192	66%	641	35%

8.3.2.4 Application scenario 3 - Maximising reduction of CO_2 emissions

A third scenario looked at maximising the carbon emission reduction by selecting those samples for which the estimated CO_2 savings were greatest, by sorting the sample table in descending order of total CO_2 emissions estimates for the grossed-up samples and assigning the entire sample to the heat pump system selection. This, in theory, should ensure the highest emissions reduction possible for the given number of installations in the scenario.

8.3.2.5 Application scenario 4 - Replacement of high CO_2 emitting technologies

The fourth scenario for the 2020 period considered technology replacement, i.e. selecting the highest CO_2 emitting heating systems for heat pump replacement by processing the sample table by heating system type within fuel CO_2 emissions rate. The effect of this scenario was to allocate heat pump installations first to dwellings with direct electric heating, followed by coal and similar solid fuels, followed by oil.

8.3.3 Scenario results

Table 8.21 summarises the results of assignments for all four application scenarios for 2020. Two main sets of results are presented. These are:

percentage reductions in CO_2 emissions for each fuel (mains or natural gas, propane, different forms of coal etc.) or energy (standard rate electricity, different forms of off-peak electricity) over all the scenarios;

percentage change in energy consumption for each of the above for each scenario;

electricity consumption for each scenario.

Table 8.21 Summary of application scenario / dwelling assignments

Summary of dwellings in scenarios

	2020 Centre	2020 High	2020 Stretch
No of ASHP installations (000's)	270	410	720
No of GSHP installations (000's)	290	440	1,100
Application scenarios 1 & 2: Heat pumps only and heat pumps plus insulation improvements			
Average floor area (m^2)	93	91	91
Average SAP rating	47	47	47
Tenure			
Private rented	7.8%	8.7%	7.9%
Housing association (RSL)	5.3%	5.4%	5.1%
Local authority	6.6%	6.8%	7.0%
Owner occupied	80.4%	79.4%	80.0%
Application scenario 3: Targetted on high CO2 emissions			
Average floor area (m^2)	202	182	154
Average SAP rating	38	38	39
Tenure			

Private rented	4.9%	4.3%	3.7%
Housing association (RSL)	0.4%	0.3%	0.2%
Local authority	0.2%	0.6%	0.3%
Owner occupied	94.5%	94.7%	95.8%
Application scenario 4: High CO_2 technology / fuel replacement			
Average floor area (m^2)	76	74	102
Average SAP rating	25	26	30
Tenure			
Private rented	15.4%	14.7%	12.6%
Housing association (RSL)	9.4%	11.0%	7.1%
Local authority	6.6%	7.7%	5.4%
Owner occupied	68.6%	66.6%	74.9%

For application scenarios 1 and 2, the characteristics of the dwellings selected are fairly close to the average SAP rating for the UK housing stock of 52 (Utley & Shorrock, 2008) and to the average total floor area for those in the EHS data, being 91 m^2. Those selected by application scenario 3, being those where the largest carbon emission savings are possible, and conversely, responsible for the largest emissions, are at the larger end of the size range and at the lower end of the SAP scale. Those selected by application scenario 4 appear to be much smaller than the average and have much lower than average SAP ratings because the heating systems selected first are lower rated by SAP (BRE, 2005).

The results for the four scenarios were recorded in individual worksheets and summarised to a fifth. Summary totals were calculated in four stages as follows:

a) Baseline total energy values for the whole housing stock were calculated for each fuel/energy type from the initial modelling process; these values were adjusted for according to the factors calculated in paragraph 8.2.7

b) for each policy scenario, totals were calculated for each installation scenario and fuel/energy type for original system and heat pump system for space heating (main and secondary) and DHW generation;

c) from (b), the difference between the original system value and the heat pump system value is calculated as a percentage of the total consumption from (a). This indicates which forms of heating had been affected by the change;

d) similarly, the effect of each installation scenario is calculated by adding the difference between the original system and heat pump system values to the total from (a).

For CO_2 emissions from operation, a baseline total estimate for the whole housing stock covered by EHS was calculated as per (a) above. Totals for emissions for application scenarios were calculated by summing the emissions for heat pumps and for original systems grossed up by the scenario weight for each sample included in the scenario.

The results are summarised in the following table:

Table 8.22 Summary of results for 2020 Scenarios

Deployment Scenario	2020 Scenarios	Change in net energy consumption	% change	Change in electricity consumption	% change	Reduction in CO_2 emissions	% reduction
		(GWh)		(GWh)		KTonnes	
1	Centre	6,031	1.0	5,228	2.6	1,217	0.94
	High	8,897	1.4	7,764	3.9	1,799	1.40
	Stretch	19,240	3.1	16,288	8.2	3,898	3.03
2	Centre	5,766	0.9	5,070	2.6	1,081	0.86
	High	8,486	1.4	7,515	3.8	1,594	1.27
	Stretch	18,365	2.9	15,738	8.0	3,413	2.73
3	Centre	16,767	2.7	8,441	4.3	4,789	3.27
	High	23,441	3.8	12,239	6.2	6,489	4.45
	Stretch	41,168	6.6	23,366	11.8	10,936	7.60
4	Centre	9.653	1.5	-3,661	-1.8	3,150	2.10
	High	15,555	2.5	245	0.1	5,048	3.41
	Stretch	34,864	5.6	12,702	6.4	9,824	6.82

For embodied CO_2, the grossed-up values for the heat pump system embodied energy are totalled, with a total value for original systems calculated using a single value for the embodied energy in a gas boiler, on the assumption that during the same 15-year period either an existing system would be replaced by gas or an existing gas boiler would be replaced.

8.3.3.1 Electricity consumption and energy mix

The following Figures 8.3 and Figure 8.4 indicate the overall estimated effect of the four scenarios on overall electricity consumption.

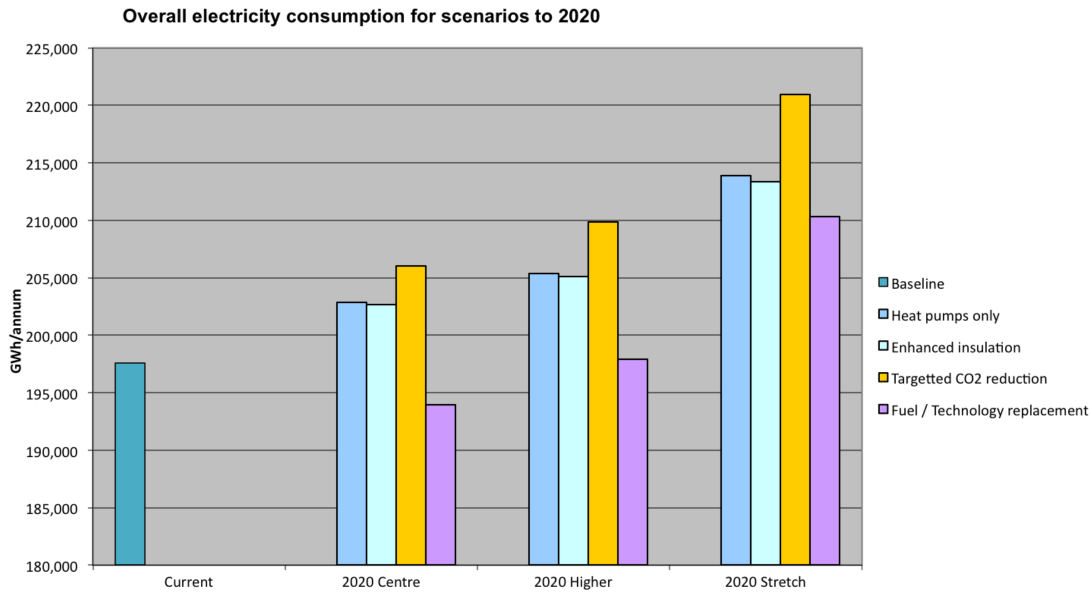


Figure 8.3 Overall electricity consumption to 2020

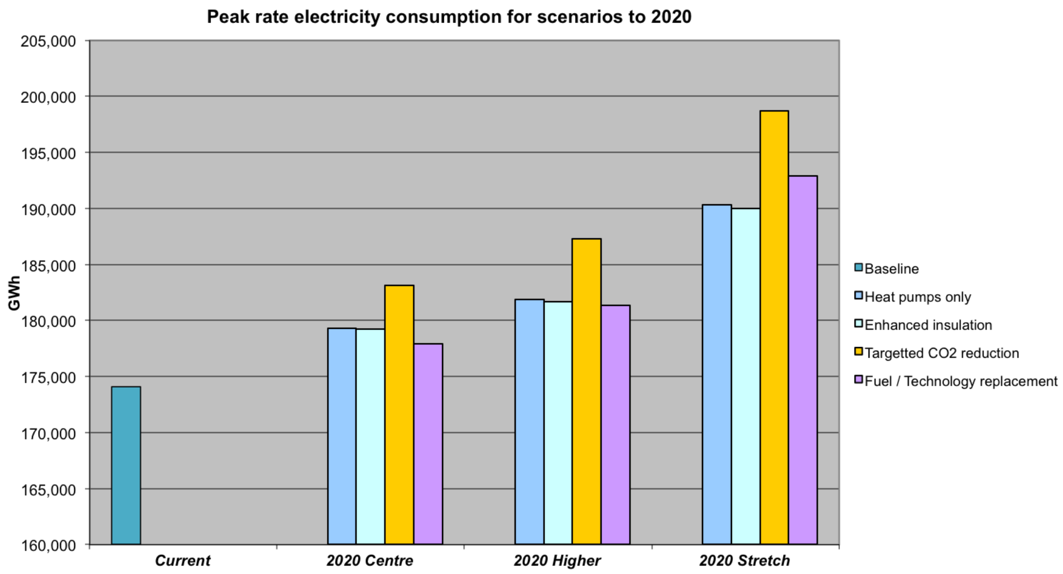


Figure 8.4 Peak rate electricity consumption to 2020

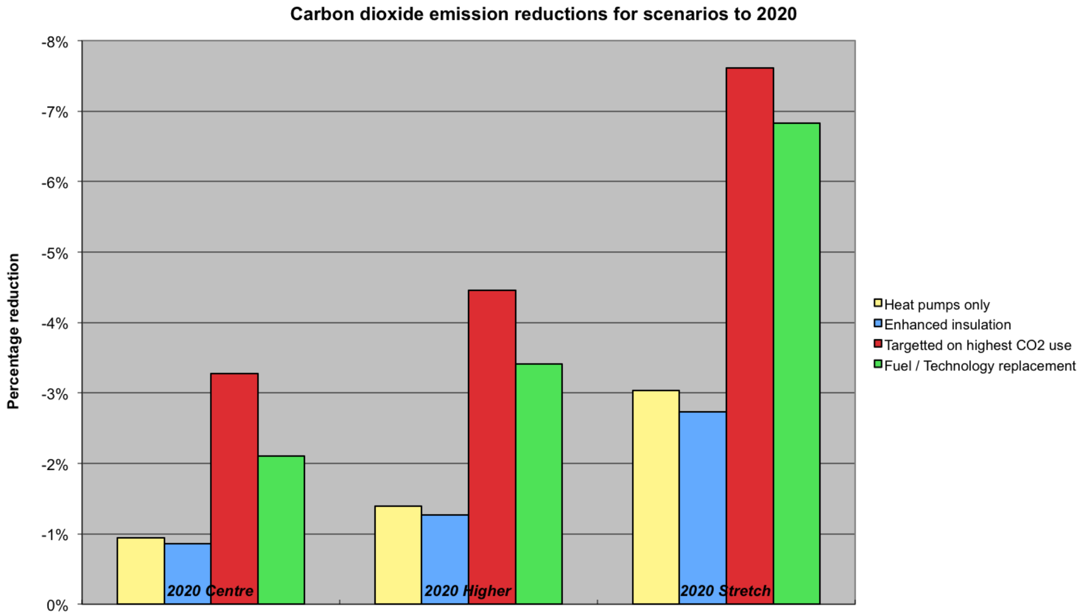


Figure 8.5 Carbon dioxide emission reductions for 2015 & 2020 policy scenarios

Figure 8.5 indicates that the most substantial reductions in CO2 - well over 7% for the “2020 Stretch” installation scenario - come from targeting the highest emitters, but these reductions come with a substantial penalty in additional electricity generation of some 23 TWh per annum as shown by Figure 8.3. Compared with the 'heat pumps only", Scenario 2 brings a slight increase in emissions, though only a fraction of a percentage more even in the “2020 Stretch” scenario, but with correspondingly reduced electricity consumption in all cases. Scenario 4, that of targeting dwellings where the heating system utilises the highest emitting fuels, is not as effective as Scenario 3 in reducing CO_2, but increases electricity consumption only by approximately 13 TWh annually in return for a reduction of just under 7% in carbon dioxide emissions.

Figure 8.6 indicates the changes which occur with greater numbers of heat pump installations under this scenario, with, initially, energy consumption being reduced with the replacement of systems burning fuel oil, then solid fuel systems burning coal, and storage heater systems using off-peak electricity. Because of the substantial load from lighting and appliances, the percentage change in electricity demand is only about 8%. Systems burning gas in all forms and biomass remain largely unaffected, though the dominance of mains (natural) gas-fired systems does mean that changes to energy consumed by other system types have a limited effect on overall energy consumption as indicated by Figure 8.7.

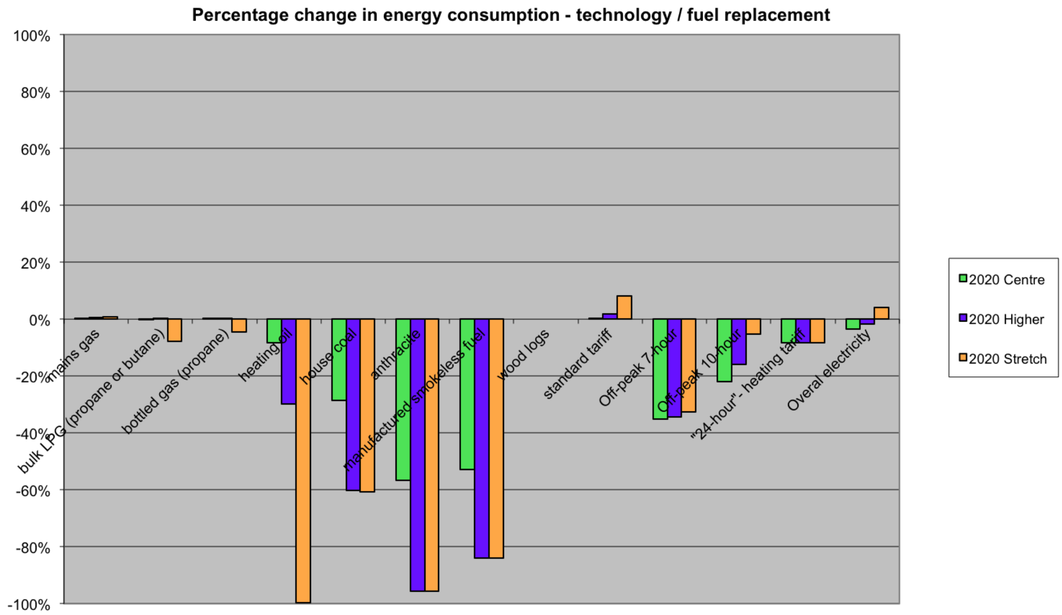


Figure 8.6 Percentage change in energy mix due to Policy Scenario 4

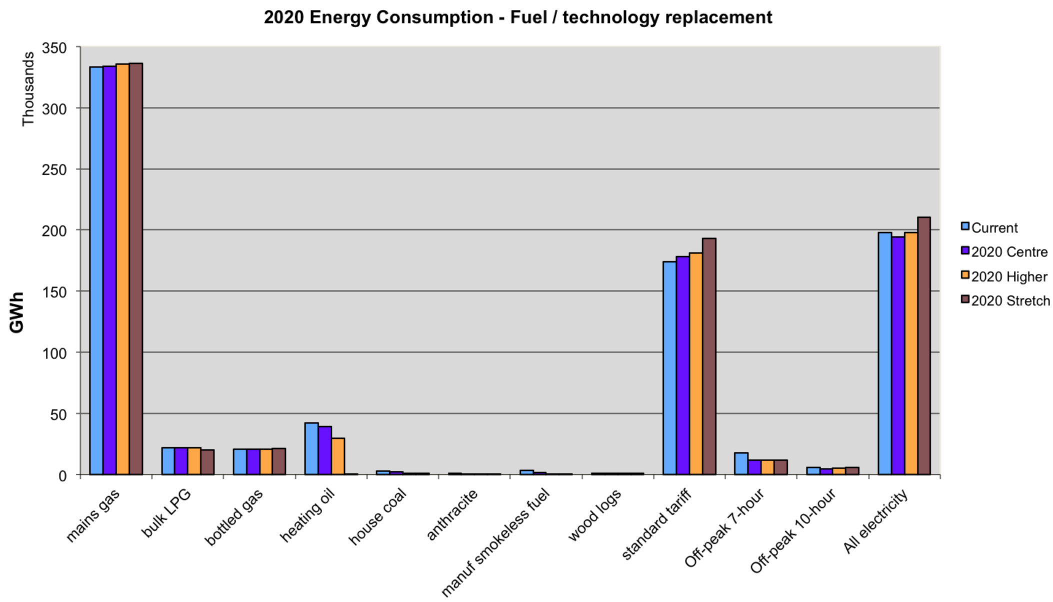


Figure 8.7 Energy consumption for Policy Scenario 4 - Fuel / technology replacement

8.3.3.2 Practicalities

In labelling the inner layer of scenarios as "application scenarios", there is an implication that these scenarios could be applied as the basis for government policy for the implementation of the Renewable Heat Incentive or a similar incentive scheme. However, for the rules governing these scenarios to function as policy, it is necessary either that they apply to all dwellings within the housing stock or that, if their success depends on applying the policy to a subset of the housing stock, then that subset should be identifiable. Of the four policy scenarios, Scenarios 1 and 2 were applied randomly across the whole housing stock. Policy Scenario 3, with the aim at an optimal assignment of installations to reduce carbon emissions, has no obvious method of implementation. While the individual dwellings surveyed for the EHS samples might be identifiable, those dwellings that are notionally grouped with each sample by the grossing weights are very likely not, having no obvious defining characteristics. However, Policy Scenario 4, which focuses on the type of heating system to be replaced, does provide a fairly precise basis for such a policy and so this type of scenario was used to examine monthly electricity loads for 2020. Policy Scenarios 1 and 2, which basically constitute a 'null' option and a minimal approach to improving energy efficiency, do not provide in these estimates any confidence that the current targets for the reduction of carbon dioxide emissions will be met.

8.3.3.3 Peak loading - 2020

The estimates for changes in the January loads for electricity are presented in Table 8.23 for the Heat pumps only, Improved insulation, and Fuel / Technology Replacement policy scenarios. The additional loads deriving from any of these scenarios are not of very great magnitude and all amount to less than 4% of the UK load of about 80 GW. As these scenarios cover a period when UK electricity supply will be decreasing unless further capacity is built, the small increase in load or consumption would be welcome. However, the use of heat pumps to replace off-peak storage heating comes with the penalty of added day-time load if the practice of operating the systems throughout the day is maintained, although the effect of large-scale heat pump installation using weather-compensated controls would be to avoid sudden peaking of load at the start of each low-charge period. That dwellings and their occupants vary considerably in their heat demands would also mitigate against a surge when external temperatures drop. Thus the emissions reduction of any heat pump installation programme must be balanced against the change in load profile for the electricity supply and, considering this, the "Fuel / technology replace" installation policy is advantageous.

Table 8.23 Effects of Scenarios 1, 2, & 4 on primary energy consumption and load for month of January

	Change in energy consumption 2020 Stretch			**Change in power loading 2020 Stretch**		
	Heat pumps only	+ improved insulation	Fuel / tech replace	Heat pumps only	+ improved insulation	Fuel / tech replace
	(GWh)	(GWh)	(GWh)	(GW)	(GW)	(GW)
Mains gas	-3,978	-3,738	484	**-4.65**	**-4.37**	**0.57**
Bulk LPG	269	-17	-252	0.33	-0.02	-0.31
Bottled gas	514	360	-135	0.63	0.44	-0.16
Heating oil	-1,084	-1,002	-3,466	-1.22	-1.13	-3.92
House coal	-26	-24	-151	-0.03	-0.03	-0.19
Anthracite	-12	-11	-86	-0.02	-0.01	-0.11
Manuf smokeless fuel	-40	-38	-272	-0.04	-0.04	-0.28
Wood logs	-35	-33	0	-0.04	-0.04	0.00
Electricity						
Std tariff	**2,385**	**2,361**	**1,684**	**3.21**	**3.17**	**2.26**
Off-peak 7-hour	-14	-20	-1,531	-0.02	-0.03	-2.06
Off-peak 10-hour	205	139	439	0.28	0.19	0.59
24-hour heating tariff	-1	-1	-14	0.00	0.00	-0.02
All electricity	**2,575**	**2,478**	**578**	**3.46**	**3.33**	**0.78**

8.3.4 Scenarios for 2050

These scenarios take as their basis the position outlined towards the end of the NERA document (NERA Economic Consulting, 2009) where an assumption is made that the number of heat pump installations, having reached 1.8 million for the 2020 'stretch' scenario, will reach a saturation point for this technology in 2030 (NERA Economic Consulting, 2009, p122).

This position leaves at least a further 16 million dwellings in England still using gas heating. Reductions in carbon emissions could be made through the replacement of older, less efficient gas systems, but if the intention is to take advantage of a 'decarbonized' electricity supply, this is best achieved by electrical systems in general and heat pump systems in particular as Figure 8.8 illustrates.

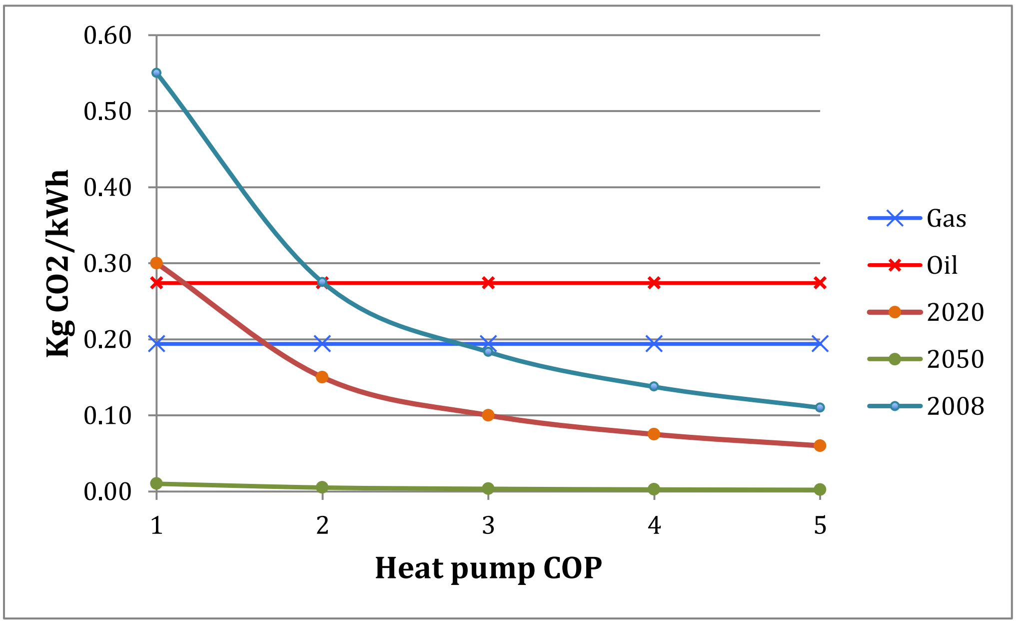


Figure 8.8 Relative emissions of heat pump systems at different carbon intensities of electricity generation compared with fuel-burning systems

8.3.4.1 Forecasts of heat pump take-up

To provide estimates for possible heat pump installations in 2050, the main precedent that exists in the UK is that of the current take-up of gas-fired central heating which has been installed in about 90% of dwellings up to 2006 (Utley & Shorrock, 2008) starting from almost 0% in 1964 (Utley & Shorrock, 2008). This would indicate the possibility of 80% take-up of heat pump systems in the slightly longer period up to 2050, equating to approximately 15.6 million installations for the

18 million dwellings for the EHS data in this study. If this value is taken as the “2050 Stretch” Deployment scenario and the proportions of “Stretch” to “Central” and of ASHPs to GSHPs in the 2020 Deployment scenario retained, this gives estimates for installations in 2050 as per Table 8.24. While the "2050 Stretch" level is within the values proposed by Boardman (2007, p. 101) of 25 million LZC installations by 2050, Boardman's proposals contain a mix of other low-carbon technologies, including 'green' - from anaerobic digestion - gas; solar thermal water heat heating; and community or micro combined heat & power, with ground and air source heat pumps as part of this mix. However, these proposals give no indication of the share of each technology in this mix, providing no indication of a possible number of heat pump installations. Mackay (2008) provides an estimate (Table 28.3, p229) for the cost of heat pumps of £6 billion at £1000 per person, which, with Mackay's allowance of two people per household, equates to 30 million systems, presumably one for every dwelling in the UK.

Table 8.24 Installation scenarios for 2050

	Year	GSHP Units (000s)	ASHP Units (000s)	Total Units (000s)
Stretch growth scenario	2050	5,550	10,000	15,550
Central growth scenario	2050	1,600	3,900	5,500

8.3.4.2 Future temperature forecasts

A replacement table of monthly average temperatures by BRE Heating Degree Day Region was created to allow for the effects of climate change. The adjustment values were taken from the UKCP09 data (DEFRA, 2011) for 2050, “high emission”, 90% probability data for GO Regions and further adjusted for the variations between the GO Regions and the BRE Heating Degree day regions, with a maximum adjustment of +5.2 ºC applied to the August temperature in the BRE Thames region and a minimum adjustment of +3.4 ºC applied to both W. Pennines, North West, and Borders regions throughout the first and last 4 months of the year. The average adjustment was 4.25 ºC.

In the context of the UKCP09 projections, "90% probability" implies that there is a 90% chance that the temperature increase will less than or equal to the temperature value. The selection of the "high emission", 90% probability data was made to provide an 'upper' bound for the estimates made.

The resultant temperature table is in the worksheet 'tables' in the 'EHS Processing 2050 scenarios' spreadsheet and reports of the UKCP09 web pages from which the adjustment values were obtained are in Appendix F.

8.3.4.3 Model assumptions

For these scenarios, the parameter was set in the model to require the estimation of energy use for space cooling. In these calculations, the SAP default value of 2 is set for the SEER (Seasonal Energy Efficiency Ratio) of the air conditioner. The model assumes that air conditioning uses only standard rate electricity, since the hottest part of any day is usually during peak hours. In calculating estimates for overall totals, it is assumed that there is no element of space-cooling in the baseline estimates.

A further, more radical, assumption made is that all the heat pumps installed are reversible, i.e. capable of both heating and cooling. In terms of the heat pump systems themselves, this assumption is plausible, with such systems currently available (ICS Renewable Energy ltd, 2011) and existing systems may be converted. However, in the retro-fit installations in this study, the existing radiator distribution systems are not recommended for cooling use. Ochsner (2007, p. 90) suggests that convection fans may be used for cooling and it is possible that these may be adopted over the 40 years to 2050, if cooling is found necessary.

In estimating the comparative energy use for space-cooling, the assumption made above that the baseline estimates exclude this value implies that the total effects of either separate air-conditioners or of heat pump systems are solely due to the values estimated by the enhanced BREDEM model from the samples included in the scenarios with estimates from the remainder excluded. This is deemed to be legitimate on the basis that energy for residential space-cooling is not analysed separately in UK statistics for energy consumption.

Output from roof-mounted photo-voltaic systems on each dwelling sample is also included in the scenario outputs, calculated as per Section 5.6.9 Since output from these systems is available directly for consumption in the dwelling, and is independent of the dwelling occupants' behaviour, estimates of their output are used unadjusted in calculations. Similarly, as minimal carbon dioxide emissions are attributable to their operation, estimates from the emissions calculation must be adjusted to reduce carbon dioxide emissions values by an amount equivalent to the photo-voltaic system output. As noted in Section 5.6.9, the putative systems are assumed to be as efficient as the best of those currently available, to allow for some degree of technological improvement in the period to 2050.

The value used for carbon dioxide emissions for electricity generation was reduced according to the current target for 80% reductions in carbon emissions by 2050, reducing from 0.517 $kgCO_{eq}$/kWh to 0.103 $kgCO_{eq}$/kWh.

8.3.4.4 Application scenario

Since the "Fuel / Technology Replace" application scenario produced the 'best' results for 2015 and 2020, this is used for 2050. The data from the "2020 Central" and "2020 Stretch" scenarios are also carried over into 2050 to illustrate the position if heat pump take-up remained at the level envisaged for the earlier year.

8.3.5 2050 Scenario results

8.3.5.1 Distribution of installations in dwellings

A summary of these are shown in

Table 8.25. This also shows the 2020 equivalent installation scenarios for comparison.

The effect of the de-carbonisation of the electricity supply is to complete the shift of solid fuel systems to heat pumps, while, in the "centre" scenario at least, the remaining direct electric systems remain in place. This is probably an anomaly, since these systems are likely to have been replaced in the years following 2020. The 2050 Stretch scenario finds all forms of heating virtually eliminated other than heat pumps (~85%) and gas central heating (~15%).

Table 8.25 Summary of dwelling / heat pump assignments for 2050 scenarios

Summary of dwellings in scenarios				
	2020 Centre	Stretch	2050 Centre	Stretch
No of ASHP installations (000's)	211	639	3,900	10,000
No of GSHP installations (000's)	190	960	1,600	5,550
Technology / fuel replacement				
Average floor area (m^2)	107	116	120	94
Average SAP rating	35	34	42	48
Tenure		Percentage of scenario total		
Private rented	15.4	12.6	5.7	8.4
Housing association (RSL)	9.4	7.1	1.9	3.4
Local authority	6.6	5.4	1.5	2.3
Owner occupied	68.6	75.0	90.8	85.8
Original fuel		Percentage of this fuel type in EHS weighted sample		
01 mains gas	87.8	86.9	68.3	15.2
02 bulk LPG (propane or butane)	0.4	0.0	0.0	0.0
03 bottled gas (propane)	0.3	0.0	0.0	0.0
04 heating oil	4.7	0.0	0.0	0.0
05 house coal	0.5	0.3	0.0	0.0
06 anthracite	0.1	0.0	0.0	0.0
07 manufactured smokeless fuel	0.4	0.1	0.0	0.0
08 wood logs	0.2	0.2	0.2	0.2
11 wood chips	0.0	0.0	0.1	0.1
13 standard tariff	3.0	9.9	29.9	84.6
14 Off-peak 7-hour	2.0	2.0	1.3	0.0
15 Off-peak 10-hour	0.1	0.1	0.3	0.0
16 "24-hour"- heating tariff	0.0	0.0	0.0	0.0
Total dwellings in scenario	560,000	1,820,000	5,500,000	15,550,000

8.3.5.2 Energy consumption

These results assume that, by 2050, space cooling will be required utilising conventional air condition equipment in estimating the "Business As Usual" values. Results for overall energy consumption and electricity consumption are shown in Figure 8.9 , Figure 8.10 and Figure 8.11 below.

These indicate that the substantial increase in heat pump installations, especially in the 2050 Stretch scenario, has a correspondingly significant effect on the consumption of mains gas, with a 40% decrease in gas consumption matching an increase by 40% in electricity consumption at "*Standard Tariff*", on-peak rates. All other forms of energy supplied to homes are substantially reduced while off-peak electricity supply is virtually eliminated. The increase in electricity is off-set over the course of a year by output from the photovoltaic systems resulting in net electricity consumption for the "2050 Central" scenario of approximately 13 TWh more than 'Business as usual', while that for the "Stretch" scenario is very slightly less.

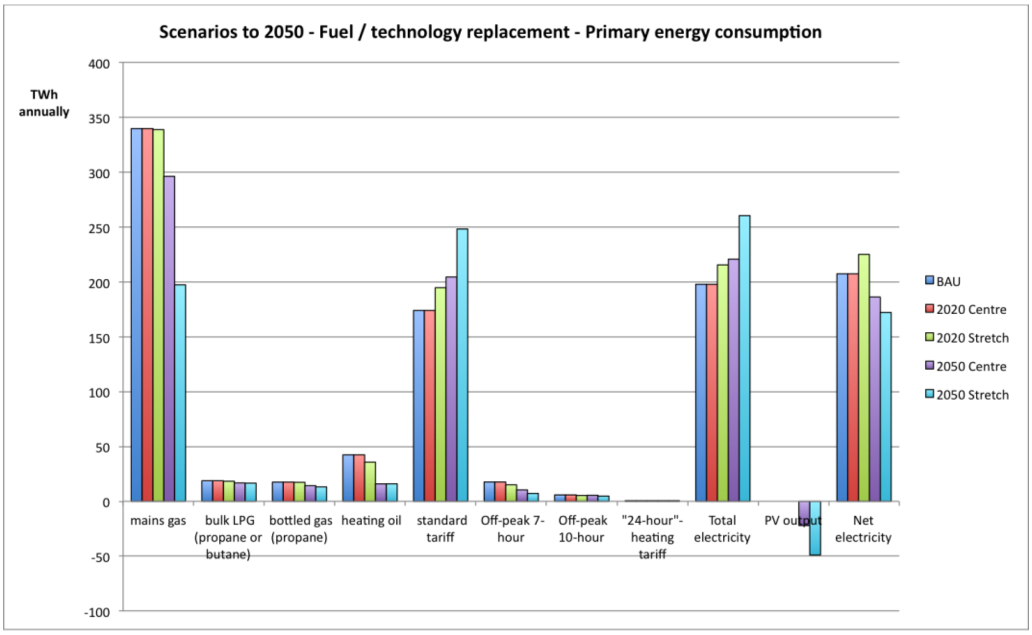


Figure 8.9 Primary energy consumption to 2050: Fuel / technology replace

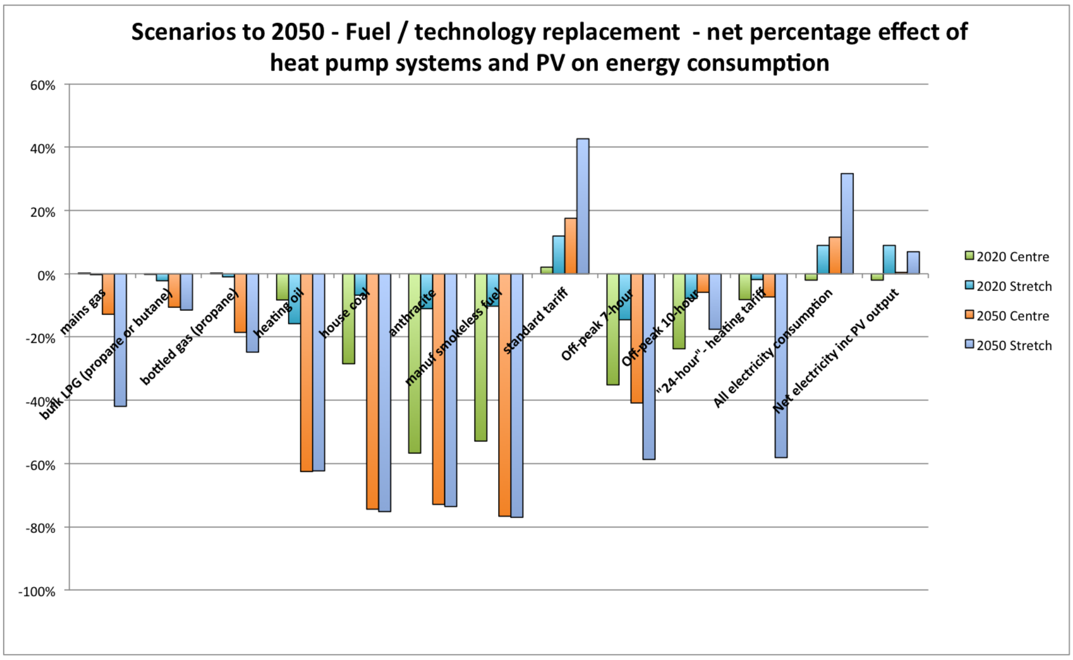


Figure 8.10 Up to 2050 - percentage change in energy consumption

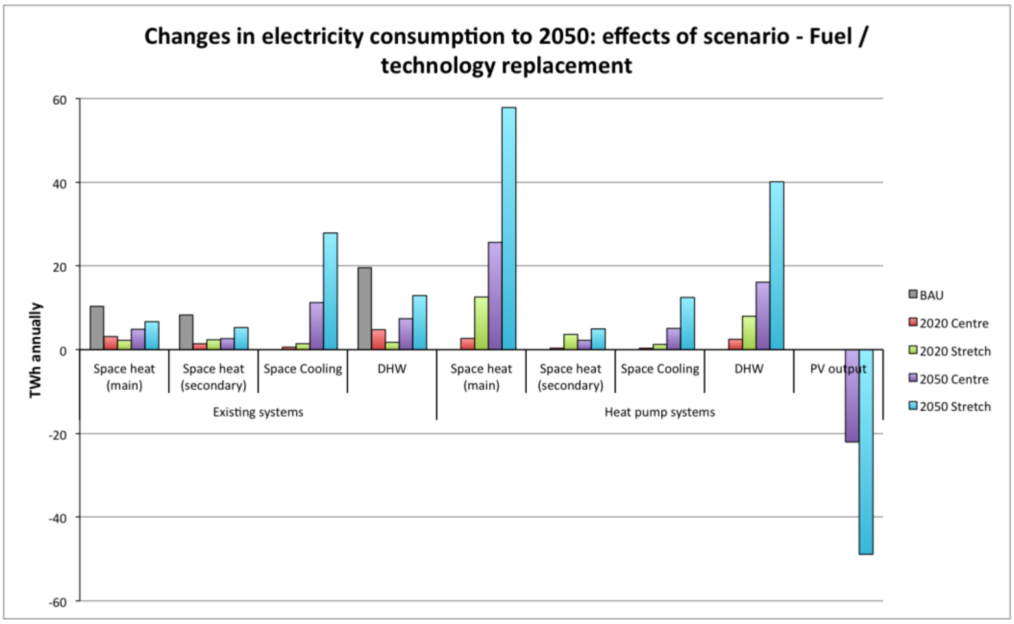


Figure 8.11 Primary energy consumption for electricity: scenarios up to 2050, including space cooling and output from photovoltaics

Of the estimated consumption for space cooling, the effect of heat pump installations is to reduce the estimated consumption for this purpose by some 5.4 TWh / annum (~19%) for the "2050 Stretch" scenario, and this, combined with the output from the photo-voltaic systems, compensates for the 73 TWh added by these installations.

These figures indicate the energy directly consumed by the installed heating and cooling systems in each dwelling and which are affected by the type of system installed. They do not include a value for the energy consumed by cooking, lighting and appliances, which, using the estimating method in BREDEM-8, was calculated to be 56.6 TWH annually for the dwelling samples in '2050 Centre' scenario and 134.4 TWh for the '2050 Stretch', which equates to a total for the whole English housing stock of 154 TWh which, if assumed to consist almost entirely of electricity, substantially exceeds the consumption by the heating and cooling systems.

8.3.5.3 Peak loading

Primary energy consumption and loads for the peak heating month of January and peak space cooling month of July are shown in

Table 8.26, along with monthly electricity supply values averaged over the years 1998 - 2011 and monthly natural gas production values for the years 1996 - 2011 obtained from the Digest of UK Energy Statistics (DECC, 2011a, 2011c)

Under the '2020 Stretch' scenario, the overall estimated effect of the heat pump installations on electricity consumption is minimal, with a rise in standard or peak rate electricity being matched by a fall of similar magnitude in 'off-peak - 7 hour' supplies. Mains gas consumption also falls substantially, though the major reduction is in the consumption of heating oil, which is to be expected due to its higher carbon emission.

Under the '2050 Stretch' scenario, in January, there is a substantial transfer from gas to electricity, particularly to standard rate, while in July, there is both a transfer from gas to electricity and also a reduction in electricity due to the replacement of stand-alone air conditioning. Thus in winter, electricity consumption rises by 31 - 34% of the UK's current generation, while in summer it falls by approximately 20%. Gas consumption falls by approximately 22% of current levels in winter and approximately 10% in summer.

Table 8.26 Estimated primary energy consumption and loads for January and July

	January				July			
	2020 Stretch		**2050 Stretch**		**2020 Stretch**		**2050 Stretch**	
(against 'business as usual')	Change in energy consumption (GWh)	Change in energy load (GW)	Change in energy consumption (GWh)	Change in energy load (GW)	Change in energy consumption (GWh)	Change in energy load (GW)	Change in energy consumption (GWh)	Change in energy load (GW)
Mains gas	-946	-1.27	**-23,018**	**-30.94**	**-88**	**-0.12**	**-4,056**	**-5.45**
Bulk LPG	-238	-0.32	708	0.95	-39	-0.05	-25	-0.03
Bottled gas	-112	-0.15	-508	-0.68	-21	-0.03	-15	-0.02
Heating oil	-3,169	-4.26	**-4,818**	**-6.48**	**-931**	**-1.25**	**-574**	**-0.77**
House coal	-238	-0.32	-295	-0.40	-82	-0.11	-132	-0.18
Anthracite	-154	-0.21	-121	-0.16	-53	-0.07	-52	-0.07
Manuf smokeless fuel	-335	-0.45	-311	-0.42	-142	-0.19	-156	-0.21
Electricity								
Std tariff	**-144**	**-0.19**	**11,387**	**15.31**	**-71**	**-0.10**	**-175**	**-0.24**
Off-peak 7-hour	-629	-0.85	-1,253	-1.68	-329	-0.44	-501	-0.67
Off-peak 10-hour	-228	-0.31	653	0.88	-21	-0.03	-32	-0.04
24-hour-heating tariff	-3	0.00	-20	-0.03	-2	0.00	-15	-0.02
Space cooling	0	0.00	0	0.00	0	0.00	2,862	3.85
All electricity	**-1,004**	**-1.35**	**11,013**	**14.80**	**-71**	**-0.10**	**2,385**	**3.21**

January	**% variation (2020 stretch)**	**% variation (2050 stretch)**	**July**	**% variation (2020 stretch)**	**% variation (2050 stretch)**
Actual electricity generation (1998-2011, TWh, from Dukes Table 5-4.)					
Average			**Average**		
32.5	-3.09%	33.92%	25.4	-1.66%	-9.39%
Maximum			**Maximum**		
34.9	-2.87%	31.51%	27.3	-1.55%	-8.74%
Natural gas production and supply (1996-2011, TWh, from Dukes Table 4.2.)					
Average			**Average**		
118.8	0.80%	-19.37%	**52.7**	-0.170%	-7.70%
Minimum			**Minimum**		
130.6	0.72%	-17.62%	**43.3**	-0.20%	-9.36%

8.3.5.4 System consumption by function

These estimates are shown in Figure 8.12 & Figure 8.13, below, which are scaled for comparision and indicate the following:

> that the output from the photo-voltaic systems comes close to balancing the energy consumption for heating, cooling and DHW generation between May and August in both scenarios;

an estimated 0.4 TWh monthly is consumed by heat distribution.

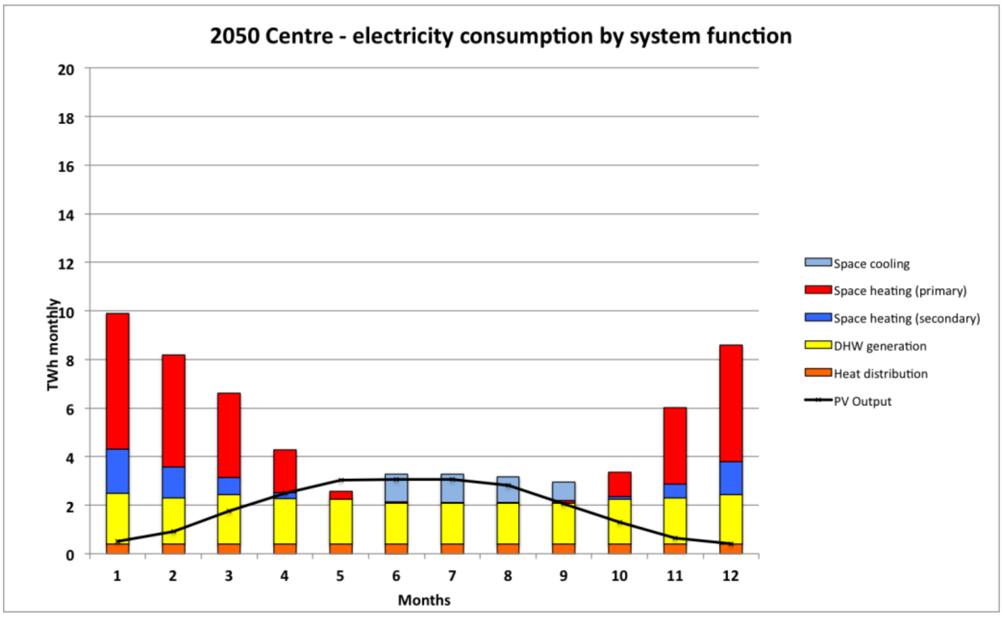


Figure 8.12 2050 Central - Monthly total effects of Fuel / Technology Change scenario

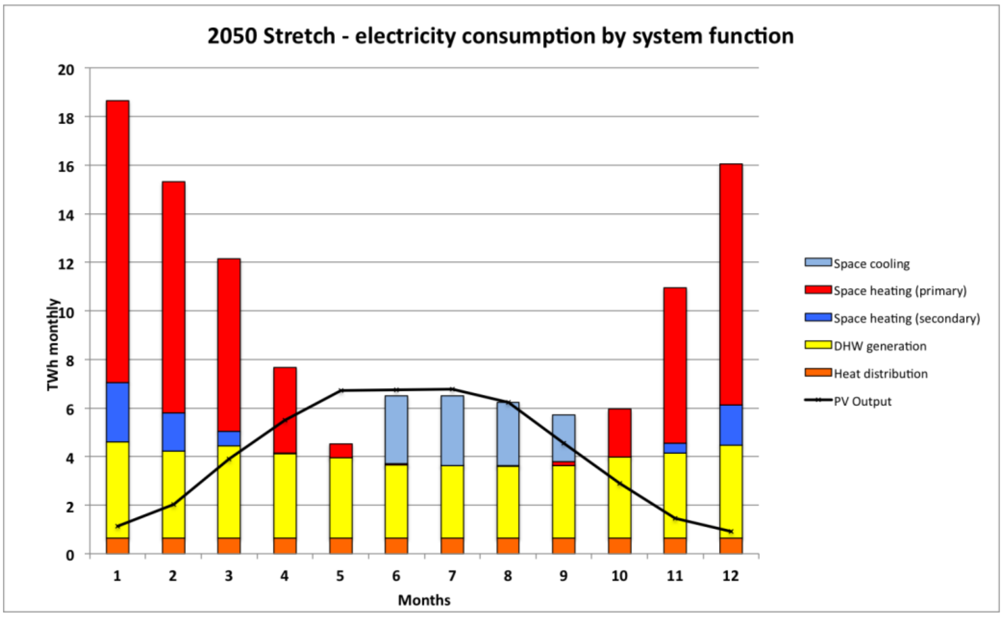


Figure 8.13 2050 Stretch - Monthly total effects of Fuel / Technology Change scenario

8.3.5.5 Carbon dioxide emissions

Embodied carbon dioxide estimates

These were estimated using the method described in section 8.2.2.3 and the results are summarised in Table 8.27, noting that if only one replacement gas boiler per household was necessary over the period to 2050, then there would be a net reduction in embodied carbon in heating systems with the higher numbers of installation. As the life of a gas boiler is put at 15 years (Energy Saving Trust, 2010), an ASHP at 15 years, and a GSHP at 20 − 25 years, then the actual reduction may exceed this estimate.

Table 8.27 Estimated carbon emissions to 2050

CO2 Emissions: embodied (Ktonnes)

	Effects to 2020		Effects to 2050	
	Centre	Stretch	Centre	Stretch
Gas boiler replacement	241	959	3,300	9,330
Heat pump + refrigerant	392	1,043	2,325	6,282
Net emissions	152	83	-975	-3,048

Carbon dioxide emissions from operation

These are summarised in

Table 8.28 and the detail of the reductions due to the change in fuel mix shown in Figure 8.14. The estimates in

Table 8.28 are compiled starting from a total value based on the BREDEM-8 estimates for the entire weighted EHS survey data using current emission estimates for electricity generation - line (1) in

Table 8.28. This total is then re-calculated for 2050 based on the emission estimated for the “de-carbonised” electricity supply and the changed energy requirements of the 2050 UKCP09 climate impacts as line (2), with the resulting reduction as line (3). The emissions reductions due to each application scenario is calculated (lines 6 and 10) from the estimated emissions with existing systems (lines 4 and 10) and with heat pumps (lines 5 and 11) and the overall reduction from 2006 to 2050 calculated in lines (6) and (12). These results show that for the target emissions reduction of 80% to be approached, the adoption of domestic heat pumps is not only required to reach the levels indicated in the “2050 Stretch” scenario but must be accompanied by a corresponding 80% reduction on the carbon intensity of electricity generation. Figure 8.14 indicates that the main difference between the two scenarios is the far greater reduction due to the replacement of natural gas systems.

Table 8.28 Carbon emissions from operation 2020, 2050

Installation Scenario			Total emissions (Ktonnes)	Emissions reduction (Ktonnes)	Percent change	Emissions reduction (Ktonnes)	Percent change
	1)	Total estimated CO2 emissions based on EHS survey - 2006 values	151,350				
	2)	Total estimated CO2 emissions based on EHS survey - 2050 values	74,856				
	3) (1) - (2)	Reduction due to lower emissions from electricity generation				76,494	50.5%
2050 Centre	4)	Effect of existing systems	30,060				
	5)	Effect of heat pumps	9,863				
	6) (4) - (5)	CO2 reduction due to scenario		20,197	27.0%	96,690	63.9%
	7)	Reduction due to PV output	2,278				
	8) (4)-(5)-(7)	Total reduction due to scenario		22,475	30.0%		
	9) (8) + (3)	Total CO2 reduction to 2050				98,968	65.4%
2050 Stretch	10)	Effect of existing systems	65,199				
	11)	Effect of heat pumps	22,210				
	12) (10)-(11)	CO2 reduction due to scenario		42,989	57.4%	119,483	78.9%
	13)	Reduction due to PV output	3,162				
	14) (12)-(13)	Total reduction due to scenario		48,042	64.2%		
	15) (12)+(13)	Total CO2 reduction to 2050				124,536	82.3%

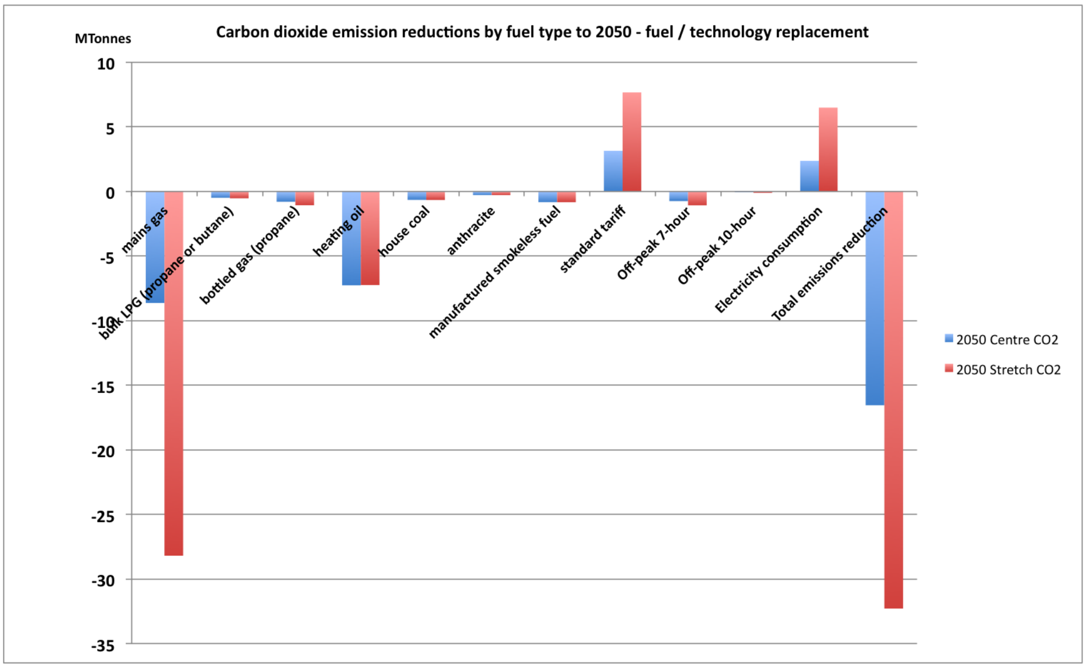


Figure 8.14 Change in CO2 emissions due to 2050 scenarios

However, while the '2050 Stretch' scenario apparently ensures that the UK reaches its target of 80% reduction in CO_2 emissions for the existing English housing stock, achieving this requires the installation of an extra 10 million heat pump systems than the '2050 Centre' scenario.

The substantial estimated cost of the CO_2 savings (Table 8.29) contributes to the anomalous position of heat pump heating systems, in that their status as low carbon technology is dependent on the availability of a low-carbon electricity supply and, in general, as the carbon intensity of the electricity supply reduces, the greater the effectiveness of these systems becomes at reducing carbon compared to a fossil fuel-fired system. However, as the carbon intensity of the electricity supply reduces, the difference in effectiveness in carbon emissions reduction between heat pump and direct electric systems reduces, even if the size of the heat pump COP is maintained. If a sufficiently large photovoltaic system is installed, ie. 3 kWp, the average size proposed here, the extra cost and complexity of installation of the heat pump system compared with, say, electric resistance radiators, becomes even more difficult to justify, since the value of the output from the photovoltaics will go some way to defray the extra running cost of direct electric heating. The cost of more substantial energy efficiency improvements to the building fabric than were considered earlier

Table 8.29 Annualised cost of carbon emissions reduction

System type	Cost per dwelling		Expected Life	Annualised cost		Number of systems / year	Total annualised cost		Annual savings
	Low	High		Low	High	(000's)	Low	High	(operating)
	£	£	Years	£	£		(£ millions)	(£ millions)	(£ millions)
ASHP	6,000	10000	15	400	667	6,100	2,440	4,067	764
GSHP	9,000	17000	25	360	680	3,950	1,422	2,686	648
					Net annual cost of heat pumps	(£millions)	2,450	5,340	
					Annual CO_2 reduction	(Ktonnes)	26,138		
					Cost of reduction	£/tonne CO_2	107	234	

Heat pump installation costs (EST, 2011)

in this study is likely to be similar to that of a heat pump system and this, too, would reduce running costs.

While direct electric systems lack the capability to provide space cooling, it is by no means clear that this would be an absolute requirement, given the range of possible outcomes in the UKCP09 forecasts, where estimates of summer temperature increases range from 1.2ºC to 7.6ºC under three different emissions scenarios (DEFRA, 2011). Temperature changes at the low end of this range would probably eliminate the necessity for space cooling.

8.4 Discussion

8.4.1 Sample weights

The use of sample weights to gross-up sample estimates to housing stock estimates is not supported well by the EHS documentation. The author has made extensive use of these to gross-up sample level results to housing stock estimates, bearing in mind the instructions in the EHS Technical Report (DCLG, 2010b), and the sample weights are employed in the analysis of EHS data to estimate the proportion of dwellings that meet the UK Government standard for thermal comfort - the "Decent Homes" standard. However, the weights are calculated on a basis of the probability of a given dwelling being selected for inclusion in the survey, with adjustment for non-response by householders and scaling according to the relative to separate control totals of the number of dwellings by tenure and region obtained from the last UK Census in 2001. To be valid in this context, the sample weight value should be the number of dwellings existing within the housing stock which are identical or very similar to the sample. This is not necessarily true of the sample weight values in the EHS data and it would not seem to be possible to estimate valid weights by the method outlined in the Technical Report.

8.4.2 Reliability of estimates

The estimates from the BREDEM model were found to over-estimate energy consumption, particularly of gas, as described in Section 8.2.7

The best explanation of this over-estimate is that a proportion of households are not heating their dwellings to the standard demand temperature of 21 ºC, either from personal requirements for thermal comfort or from finding the cost of heating the house to that temperature unaffordable. This could be confirmed and the adjustment process substantially refined if actual fuel expenditure and energy consumption data was collected by the EHS, replacing or as well as the values estimated using SAP. Actual income is already included in the EHS for assessment of household fuel poverty status and the extra information would allow the estimation of income available for expenditure on heating and, given the cost per kilowatt hour of the installed heat, the maximum annual energy consumption by the household.

8.4.3 Scenarios for domestic heat-pump take-up

This research does not attempt to describe the process by which the capacity is created to manufacture and finance the installation of the substantial number of heat pumps in the stretch scenario to 2050. Neither does it attempt to describe what motivation would bring about such a major change in heating systems.

The scale of heat pump take-up to 2050 (Table 8.24) is based approximately on the take-up of gas central heating over the period 1964 to the present day as being the closest and only precedent in the UK. Over this period, there was strong house price inflation - Figure 8.15 - which enabled house owners to finance improvements such as central heating by additional borrowing on mortgages at low interest rates - sometimes with the benefit of tax concessions on interest payments, with substantial deregulation of the mortgage industry in the 1980's also making this borrowing easier (Miles, 1992). Since the financial crash of 2008, mortgage lending has been more restricted and house prices have levelled out or fallen, as indicated by Figure 8.15. Without this, possibly unsustainable, inflation, householders may not be able to finance substantial purchases such as heat pumps. Moreover, the original motivation to make the change no longer exists. In 1964, UK housing still had, in general, very poor heating (Wright, 1964) and the installation of central heating of any kind brought about a vast improvement, not only in convenience, but also in making more rooms habitable. With some form of central heating already in place, its replacement by a heat pump system would only be maintenance of the status quo and would not provide the same degree of motivation. The UK government's financial incentives via the current (2011) Renewable Heat Payment Premium (RHPP) and Renewable Heat Incentive (RHI) (DECC, 2011d) which are documented in Chapter 1 do not yet fully support domestic systems and cover only the period up to 2020. Boardman (2007) suggests a combination of low-interest loans, house purchase tax ("Stamp Duty") rebates, and 'green' mortgages to enable and encourage householders to finance the improvements to make their properties more energy-efficient, "Low-carbon Zones" covering lowest-income households within which local authorities improve the energy efficiency of all houses. These measures are aimed at supporting the take-up of low-and-zero-carbon technologies, including heat pumps, at 600,000 units per year up to 2050.

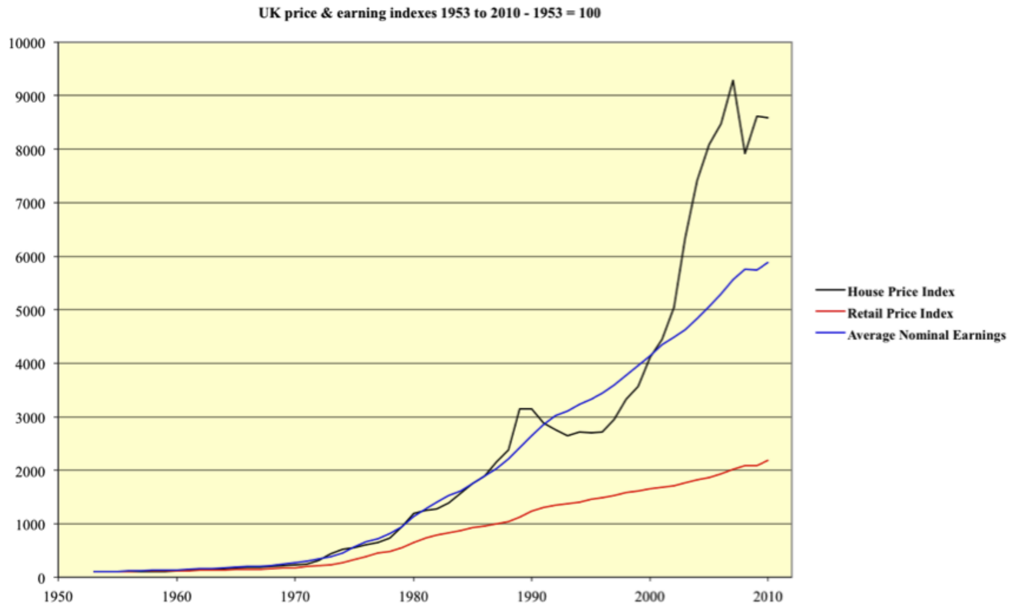


Figure 8.15 UK house prices, retail price index, earnings 1953 - 2010

((Nationwide Building Soc, 2011; Officer, 2011)

8.4.4 Openness, robustness and integrity of modelling

One of the subsidiary objectives of the development of this model (or models) was to endeavour to make sure that the input data and resultant software was both publicly available and as transparent as reasonably possible. This has only been achieved to a limited extent. Equally, it was hoped that the software could be developed to be reasonably robust, an aim which has been signally defeated by the software tool used.

The English Housing Survey was selected because it is freely available and is the most comprehensive survey of English housing. However, the only format in which this data is available, for which the appropriate software was also available to the author, was that of SPSS statistical software (SPSS Inc, 2010). This required extracts from the EHS SPSS tables to be made to create initial MS Excel input for thermal modelling. The choice of MS Excel was dictated by the provision by BRE of a basic spreadsheet version of the BREDEM-8 model implemented on that software platform and by the fact that the built-in 'Visual Basic for Applications' programming environment is well-known.

The major part of the software for the analysis was formed by two routines, one of which executes the BREDEM-8 model using the EHS extract as input and creates a output table of energy consumption and CO_2 estimates with one output entry for sample, the second of which assigns a scenario weight to each sample selected for the scenario. A third routine, a version of the first, calculates month-level estimates for energy consumption.

The processing time for the first and third routines is lengthy as it requires each of twelve thousand table entries to be processed. Moreover, there appeared to be a fault in Excel whereby the model formulae were not fully calculated and output table rows were created with the same values as the last. Coding was added to detect this condition and stop the routine, which then required to be restarted at the last correct entry.

To maintain the integrity of the central models, the author would have preferred to hold the BREDEM-8 and associated heat pump models in separate spreadsheets, but found that this was not possible because of the linkage methods in Excel which could not be maintained when creating new versions of the spreadsheets.

8.4.5 Allocation of heat pump sources and bivalent operating modes

The rules documented in Table 8.7 allow for a vertical borehole ground loop to be installed where the dwelling plot is too small to install an air source system. As the requirements for borehole installations include: specific geological conditions; that boreholes are not within 12 metres of each other, and a minimum ground area, this allowance might be better omitted.

In

Table 8.8, the rules allow for a bivalent alternate mode installation in older houses where there is an existing central heating system. As the combined systems would occupy considerable space, this configuration should possibly be restricted to dwellings with a minimum floor area.

8.5 Summary and conclusions

This chapter described the process of creating a Domestic Energy Model (DEM) from extracts from the EHS data sets, linked to the enhanced BREDEM-8 model described in Chapter 7 by employing 'data reduction' techniques. The base-line DEM estimates were compared with actual values from UK energy statistics and adjustment parameters calculated. Sets of scenarios for heat pump system installations were created based, for the shorter term to 2020, on consultation values for the current government ‘renewable heat’ incentive scheme and, for the longer term to 2050, on the historic take-up of existing gas central heating systems. From these scenarios, estimates were compiled of the energy mix changes, particularly of the increased electricity demand, and of carbon dioxide emissions reductions for these levels of heat pump take-up.

The main conclusions from this chapter are:

a domestic energy model for the English housing stock with the ability to generate monthly energy, CO_2 emissions and energy cost estimates can be created using a BREDEM-8 model implemented in MS Excel to analyse extracts from the English Housing Survey; this creates both existing system and heat pump system estimates at dwelling sample level which are grossed-up by survey sample weights to calculate stock-level estimates which form a baseline for the model; a process of "data reduction" is employed to provide multiple BREDEM-8 model parameters from the EHS samples by means of lookup tables keyed on one variable, built form or data of construction, from the sample.

Scenarios for future heat pump energy use can be created in terms of numbers of installations, by selection of samples under a application scenario, with or without modification to the configuration of the sample dwelling, by means of modified sample weighting. Stock level estimates for a scenario can be calculated by modifying the baseline estimates by the difference between the existing system and heat pump estimates for the scenario.

Existing government consultative reports can be analysed to provide three levels ("*centre", "high", "stretch"*) of installation numbers to build scenarios for the period to 2020, with application scenarios determined by the author, based on existing policy, limited energy efficiency improvements, dwellings with highest emissions, and dwellings with high emission heating systems (Policies 1, 2, 3 & 4) .

The results analysis of these application scenarios showed that, as the only scenario that had a substantial emissions reduction effect (~8% in "2020 Stretch'), the third scenario also caused a substantial increase in electricity consumption in all deployment scenarios. The fourth application scenario was the only one that caused a reduction in overall electricity consumption as well as in carbon dioxide emission. A further analysis of peak electricity loads was carried out on application scenarios 1, 2, and 4, dropping 3 on grounds of impracticality, and this showed that the average January peak load would increase negligibly in 2020 under scenario 4 with the other scenarios creating a circa 3 per cent increase in 2020. These results would indicate that if there are issues in maintaining the level of UK energy supply, then Application Scenario 4 would provide a slightly better solution than the other scenarios.

A second set of deployment / application scenarios were built for the years to 2050, with installation numbers based on the similar installations of gas-fired systems over the period from 1964, though the policy scenario was restricted to Policy 4 above.

Analyses were carried out with scenarios to 2050, re-calculating energy consumption and carbon emission estimates based on monthly average temperatures "morphed" to those estimated for the UK CP09 predictions, reduced emissions from electricity generation matching those required for 2050 by the UK Climate Change Act targets, and including space cooling. The effect of electricity output from the installation of photo-voltaic systems was also included in the estimates. Deployment scenarios for heat pump systems were based on the 80% adoption of gas central heating in dwellings between 1964 and 2010 and the application scenario used was that of scenario 4 above, resulting in the deployment of a total of 5.5 million systems in the 'Central' scenario and 15.5 million in the 'Stretch'. Analysis of electricity consumption showed an increase of approximately 50 TWh annually in electricity consumption for space heating for the "2050 Stretch" installation scenario, a substantial increase on the ~19 TWh of 'business as usual", but also showed a reduction from 28 TWh to 12.5 TWh in consumption for space cooling. Estimates of embedded carbon showed a substantial reduction - about 32% - from heat pump systems compared with gas boilers and estimates of carbon emissions from operation showed that the UK target of 80% reduction is approachable under the "2050 stretch" scenario, but is dependent on the parallel decarbonisation of the UK electricity supply. Estimates of the costs of these scenarios showed that, based on current fuel costs, they would result in substantial costs per kilogramme of CO_2 saved.

The next chapter presents reviews the main conclusions from the research and explains its original contribution to knowledge. It also suggests further research possibilities to improve knowledge of the factors influencing the performance of domestic heat pump performance.

CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Final conclusions

9.1.1 Fulfilment of objectives

In Chapter 2, in meeting the first part of Objective 1 of this study, a theoretical and physical review of the of heat pump heating systems identified the following characteristics as significant in estimating the energy use of heat pump heating systems:

their efficiency (COP) is inversely related to the increase in temperature required; dependence on external or ground temperatures for available energy rather than fuel supply; the magnitude of the temperature increase is dependent on the system source and sink, the characteristics of which are variable both with source and sink type, and temperature changes during the year;

balancing low temperatures with direct electric heating disproportionately increases energy use;

the status of heat pump systems as LZC technology is dependent on the carbon intensity of electricity generation;

cooling season energy may increase since some types of heat pump systems are capable of cooling as well as heating;

Other characteristics of heat pump systems which differ from fuel-fired systems are that the installation cost is highly dependent on output rating due to the collector size; uprating of a system is difficult and very expensive

In meeting the second part of Objective 1, Chapter 3 examined the modelling of heat pump heating systems, reviewing research studies, the relevant British/EU Standard and freely-available software. The research studies lacked generality in one aspect or another, particularly in climate data and the heat pump systems modelled. The model embedded in the British and European Standard was found to be very complex, requiring the estimation or defaulting of many parameters. Examples of freely-available software were found to be restricted to interactive use and hence not available for embedding in another model. Useful and validated routines for estimation of soil temperature (Jenkins, D. P., et al., 2009) and the generalised relationship between COP and 'lift' (Staffel, 2009) were found to be applicable to the current study.

In meeting Objective 2, Chapter 4, a review of availability and structure of a wide range of different domestic energy models found that their basic principles were naturally similar but their structure varied according to their studies' objectives and the software environment espoused by their developers.

The structure of models that were publicly available was found to be incompatible with the deployment scenarios for heat pump heating system installations, requiring allocation across the housing stock by percentage distribution and lacking the ability to filter by dwelling plot size or heat loss coefficient required for this study. This filtering requirement was found to be met by the methods used by the DECoRuM system and by data from the English Housing Survey.

9.1.2 Overview of research methodology - chapter 5

Since the two main objectives (4 and 5) of this research are to develop a detailed model of heat pump energy use and to study the effects of large scale installation of heat pumps as residential heating systems, the overall approach adopted was the 'bottom-up' approach required to model the effect of such a technological change. The monthly-based version of the BRE's dwelling energy model, BREDEM-8, combined with elements of the SAP model, was selected as the basis for the study model, with the heat pump model embedded therein. BREDEM-8 was chosen as a starting point because of its position as an accepted standard for dwelling energy modelling and for its provision of monthly estimates. It is also capable of being implemented on the chosen platform of MicroSoft Excel and allowed the use of existing work on parameter reduction techniques.

The approach adopted in the design of the heat pump model was :

- identification of those characteristics by which heat pump systems differ significantly from current UK heating system types;
- identification of the main components and determinants of heat pump energy use and the estimation of the theoretical relationships between them;
- a long-term detailed study was made of heat pump systems from which to estimate empirical relationships between the different determinants of the system's energy use where these are not determinable from theory;

- A secondary source of heat pump performance data was identified from which the central relationship between heat pump performance and 'lift' was built.

The English Housing Survey database was identified to be the most suitable basis for a disaggregated building energy model because of its completeness and public availability, being the definitive source of data for the English housing stock and the basis for reporting from BRE. This choice allowed the use of included sample weights to gross-up sample estimates to housing stock values.

9.1.3 Overview of heat pump energy data collection and analysis

9.1.3.1 Data collection and storage

To complete Objective 3 of the study, dataloggers were used to collect temperature, energy, and status data for a period of 12 months from ground source heat pump systems installed in three houses of different ages and built forms. The data was sampled at fifteen minute intervals and included: heat output and electricity input values; temperature values for the flow and return to the heat distribution system and to the ground loop, for output from the compressor; and for external air; and status values for the operation of the compressor, auxiliary heaters and hot water generation. Data was downloaded fortnightly from the dataloggers and stored in a spreadsheet for each dwelling with one entry for each 15-minute sample. Due to faults in the measurement sensors and the loggers, heat output for one of the systems had to be estimated from temperature and flow values and some samples were lost from the others, requiring energy values to be estimated based on heating degree days.

9.1.3.2 Data analysis

Data was summarised by day and month into total energy values and temperature averages, using status values to exclude values when the heat pump was not operating. Energy values were analysed according to function in terms of space heat, hot water generation, heat distribution and auxiliary heater operation to provide comparisons with SAP/BREDEM estimates. Monthly SPF values were calculated.

9.1.3.3 Conclusions from data monitoring

These were limited by the restricted number of systems in the study since this reduced the statistical significance of the results. The following was concluded from the results:

- the study indicated that the replacement of fossil-fuel-fired systems by heat pumps could provide significant CO_2 savings in existing houses, even if existing radiators were retained; the performance of the two heat pump systems in the retro-fit installations with radiation distribution reached a Seasonal Performance Factor of ~2.6 for one dwelling, ~4.6 for the other, despite being subject to more variable heating loads; compared with counterfactual systems, estimated CO_2 emission reductions were between 8 - 18% for dwelling 1 and between 37 - 53% for dwelling 2;
- the SPFs from the above give some indication that the fitting of replacement, double-glazed windows might be sufficient energy efficiency improvement to allow the adequate heating of existing houses with GSHPs using existing radiator distribution;
- a penalty of using underfloor heating continues to be substantial electricity consumption (~900 kWh annually, approx. 12%) by pumps for distribution, in particular for monitoring internal temperatures, as has been noted previously (BRECSU, 2000);
- distribution temperatures, both average and maximum, in Dwelling 2 were found to be considerably below the conventional value for radiator systems (average 38 ºC as opposed to 55 ºC); distribution temperatures in Dwelling 1 were higher than the other dwellings, but still lower than the conventional 55 ºC value. As the average internal temperature in both dwellings was close to

the required norm of 21ºC, this might indicate that the systems' weather compensation controls are effective in maintaining internal temperatures while allowing lower distribution temperatures and that the heat transfer rate of the radiator distribution systems is adequate.

- the proportion of electricity consumed by direct electric heating for bivalent operation was sensitive to ambient temperatures and not a fixed proportion of electricity consumption, being minimal outside the months of January and February.

9.1.4 Overview of secondary data acquisition

To create a database of heat pump performance values, an extract was created from standard performance test results performed by the Wärmenpumpen TestZentrum (WaermenPumpen Testzentrum, 2011). This consisted of tables of heat pump suppliers, air and ground source heat pump systems, and test results values. Each test result consisted of values for source temperature, sink temperature, and COP. The extraction process required considerable manual intervention and could not be recommended as a long term solution.

9.1.5 Overview of heat pump model and enhanced building energy model development

This section addresses Objective 4 of the study to develop a building energy computer model for heat pump heating systems in meeting heating and cooling demands for UK housing.

9.1.5.1 Development of heat pump model

The characterisation of heat pump heating systems in the current UK standard dwelling energy models, BREDEM and SAP was analysed and compared to the thermodynamic theory and physical characteristics of these systems in relation to their use in residential heating. This generated a list of requirements for new estimation methods and associated parameters to replace those in BREDEM to provide additional detail in the model estimates. It was identified that the BREDEM / SAP parameters that were most in need of replacement were the single annual value for Coefficient of Performance and the fixed parameter for the ratio between primary and secondary space heating energy consumption. Use of the former precluded the estimation of peak monthly loads that are sensitive to annual variations in source temperature and both the former and the latter are insensitive to overall variations in external temperature, due, for example, to climate change. It was also identified that, as heat pump systems largely operate with weather compensation control, this control system allows distribution system temperatures also to vary with external temperatures according to the control 'slope' set in the controller.

The resultant heat pump model contains the following:

- a routine to calculate a source temperature for each of the main source types: air, ground loop, vertical borehole; the value for air source is the monthly average external temperature, that for a vertical borehole is the annual average temperature, that for a ground loop is calculated from a sinusoidal function based on the annual amplitude of external temperature, soil thermal diffusivity, minimum soil temperature day number, mean soil temperature; a differential between the soil temperature and the return temperature from the ground loop or borehole was obtained empirically from the monitoring data;
- a routine to calculate the sink temperature based on whether weather compensation control is present, on the type of distribution system and the monthly external temperature; for weather compensation, a relationship based on manufacturer's curves calculates the sick temperature; otherwise fixed values are assumed;

the model then calculates a COP value based on the 'lift' value calculated from the temperatures resulting from the above using a regression parameters calculated from the performance test results database described in Section 9.1.4 The resultant heat pump model was then embedded in a BREDEM-8 model, in the form of a fifth heating system type module, with the addition of routines to estimate energy use for secondary heating, in either alternate or parallel mode. A module was added to estimate space cooling energy consumption, parameterised to indicate the use of standalone air-conditioning or reversible heat pump. The BREDEM-8 model was structured such that both the original system and the heat pump system estimates are available, displayed on a separate worksheet.

9.1.6 Overview of future energy mix and carbon emission reduction scenarios

This part of the research addressess Objective 5 of the study by utilising English Housing Survey data combine with the enhanced BREDEM-8 model to create estimates for housing stock energy use and carbon emissions under different scenarios for heat pump deployment for the periods to 2020 and to 2050. Estimates are also created for the embodied CO_2 of the heta pump systems and for the output of roof-mounted photovoltaic systems installed simultaneously with the heat pump systems.

9.1.6.1 Preprocessing of English Housing Survey data

The English Housing Survey was selected because it is the most comprehensive, publically available source of data for housing. It is the basis of the BREHOMES and other domestic energy models as detailed in Chapter 3. It contains data on households, on their composition and income, on dwellings, on their built form, services, surroundings, state of repair and valuation. The survey also contains derived data on energy efficiency derived from SAP modelling of the dwellings. For each sample, a weight has been calculated by means of which any survey variable can be grossed up to provide an estimate for the whole English housing stock.

For this study, extracts were made from the EHS tables and amalgamated into a single MicroSoft Excel table. The resultant table consisted of approximately 12,600 dwelling samples out of approximately 16,000 in the overall survey, the data having been filtered to omit data for flats or apartments, for which BREDEM-8 cannot calculate estimates. Variables were added and populated for: BRE heating degree day Region, based on the Government Office Region; for rear plot size, based on rear plot depth and width.

9.1.6.2 Overview of domestic energy model development

The development of the domestic energy model based on the EHS extract is based on a three part process. The initial stage is that of creating a linkage between the BREDEM-8 model and the EHS extract to provide the parameters required by that model. Since values for all the data variables required for BREDEM parameters are not available from the EHS data, it is necessary to infer these values from others. Values for the u-values (thermal conductivity) of the construction elements, number of fireplaces, storey height, thickness of walls, presence or absence of draught stripping, tightness of fit of doors have all been found by previous researchers to be related to the dwelling's date of construction, while the built form of dwelling has been found to determine the division of the floor, roof and window area between the two heating zones assumed by BREDEM-8 and the thermal bridging characteristics. In setting the built form parameters, the simplifying assumptions were made that the dwelling has a rectangular plan and that windows and doors were only located on the front and rear walls.

Further parameters for heating system characteristics were determined from look-up tables relating the heating systems defined within the EHS samples to system efficiency, responsiveness and secondary system fraction values.

The next stage was to create a baseline energy, emissions and costs estimates table by processing the EHS extract table samples, generating an output results row for each entry in the extract. Results were calculated for both existing and replacement heat pump systems. Additional variables were added to this baseline table to provide estimates of embodied carbon dioxide for heat pump systems. The overall total energy consumption obtained for the existing systems was compared with actual annual consumption over the period of the survey, adjusting for the exclusion of flats from the model, from which adjustment factors ere calculated for each main domestic fuel/energy type (natural gas, fuel oil, solid fuel, electricity). These adjustment factors were applied throughout the consequent energy analyses.

9.1.6.3 Scenario creation and results for period up to 2020

For this period, the following assumptions were made:

- that there would be no concentrated programme of refurbishment of the UK housing stock;
- that there would be no reduction in carbon emissions from electricity generation in the UK;
- that heat pump installations will operate using electricity at peak rates taking advantage of weather compensation control, rather than using off-peak rates for cost savings.

Estimates were created for each of the deployment/application scenarios by firstly, selecting samples according to the application rule, secondly, allocating weight values to the selected samples to meet the number of installations to be deployed in the scenario. The exact method by which these steps were carried out was dependent on the definition of each scenario.

The installation scenarios to 2020 were taken from the background studies to the Renewable Heat Incentive proposals (NERA Economic Consulting, 2009) with values as per the following Table 9.1.

Table 9.1 NERA Scenarios for residential heat pump installations 2015, 2020 (taken from Tables C.5 & C.8)

Summary of Growth Scenarios

Year	ASHP Units thousand	Heat output TWh	GSHP Units thousand	Heat output TWh
Stretch growth scenario				
2015	81	1	140	1.7
2020	720	9.3	1,100	14
Central growth scenario				
2015	59	0.8	100	1.3
2020	270	3.5	290	3.7
Higher growth scenario				
2015	88	1.1	160	2
2020	410	5.3	440	5.6

The policy scenarios for which estimates were created were as follows:

- **Scenario 1 (Heat pumps only)**: installation of heat pump systems without any pre-conditions or dwelling enhancements and consisting of the random selection of samples from the initial results table, followed by the allocation of a random weight (less than or equal to the sample weight) to the selected samples.

- **Scenario 2 (Enhanced insulation)**: An alternative version of Scenario 1 where energy use is re-estimated after implementing low-cost energy efficiency measures applied to same samples selected and weighted as in Scenario 1.
- **Scenario 3 (Targetted on maximum CO reduction)**: to observe the effects of selecting those dwellings having the highest carbon emissions over the weighted sample. Samples are selected from the highest emissions downward allocating the whole sample weight to the scenario.
- **Scenario 4 (Fuel / technology replacement)**: to observe the effects of selecting dwellings with the highest emitting fuel or technology. Samples are selected from the highest emitting fuel downwards allocating the whole sample weight to the scenario.

For each of these Application scenarios, estimates are calculated for a set of three deployment scenarios for each period, using the terminology from the NERA report, as Centre, Higher, and Stretch, in order of increasing numbers of installations as per Table 9.1. The results are summarised in Table 8.21, reproduced here as Table 9.2.

Table 9.2 Summary of results for 2020 Scenarios

Deployment Scenario	**2020 Scenarios**	**Change in net energy consumption** (GWh)	**% change**	**Change in electricity consumption** (GWh)	**% change**	**Reduction in CO_2 emissions** KTonnes	**% reduction**
1	Centre	6,031	1.0	5,228	2.6	1,217	0.94
	High	8,897	1.4	7,764	3.9	1,799	1.40
	Stretch	19,240	3.1	16,288	8.2	3,898	3.03
2	Centre	5,766	0.9	5,070	2.6	1,081	0.86
	High	8,486	1.4	7,515	3.8	1,594	1.27
	Stretch	18,365	2.9	15,738	8.0	3,413	2.73
3	Centre	16,767	2.7	8,441	4.3	4,789	3.27
	High	23,441	3.8	12,239	6.2	6,489	4.45
	Stretch	41,168	6.6	23,366	11.8	10,936	7.60
4	Centre	9.653	1.5	-3,661	-1.8	3,150	2.10
	High	15,555	2.5	245	0.1	5,048	3.41
	Stretch	34,864	5.6	12,702	6.4	9,824	6.82

The scenario results indicate that Scenario 4 would be most appropriate policy to apply for the period up to 2020, given the current forecasts for a reduction in UK electricity generation capacity due to the closure of nuclear power stations (DECC, 2010e) and older conventional stations due to pollution concerns (EU Environment Commission, 2001), along with the requirements to reduce carbon emissions under the Climate Change Act (UK Parliament, 2008a).

Over the four scenarios, for this period to 2020, Scenario 3 generates the highest CO_2 reductions, at 7.6%. However, this is accompanied by an increase of just under 12% in electricity consumption. Scenario 4 generates around 7% CO_2 reductions accompanied by a increase of approximately 6% in electricity consumption. The effect of Scenario 3 on the consumption of existing fuels is to displace some 27% of each of heating oil and anthracite, and 17% of each of house coal and manufactured smokeless fuel, while Scenario 4 displaces 41% of manufactured smokeless fuel and 16% of direct, off-peak electricity consumption. The latter combination makes the application in this scenario preferable. Moreover, a 'real world' attempt to implement Scenario 3 within energy policy for carbon emissions reduction would be hampered by the lack of obvious features by which to identify the required 'highest emissions' dwellings.

9.1.6.4 Scenario creation and results for 2050

A second set of analyses were carried out to model possible scenarios for the period to 2050, allowing a much higher take-up of heat pump systems and including the temperature effects of climate change in determining space heating and space cooling.

Assumptions in the modelling were as follows:

- as before, there would be no concentrated programme of refurbishment of the UK housing stock; however it was assumed that any improvements in the energy efficiency of the stock would be counterbalanced by the increase in stock over the period; additions to the stock are assumed to be considerably more efficient than the existing stock;
- that there would be an 80% reduction in CO_2 emissions from electricity generation; this being consistent with the requirements of the Climate Change Act;

- again, heat pump systems will operate using peak rate electricity;
- where necessary, given external temperatures, space cooling will operate using reversible heat pumps and stand-alone air-conditioners with existing heating systems;
- external temperatures were 'morphed' for the effects of climate change with adjustment values from the UKCP09 data (DEFRA, 2011).
- estimated values were also included for output from roof-mounted photo-voltaic systems for each sample; these were assumed to be primary energy and carbon-emission free.

The basis for the Deployment Scenarios for 2050 was much more speculative and was based on the 90% uptake of gas central heating systems between 1964 and 2010, being the only previous residential heating upgrade of this magnitude. For the scenario, the uptake was restricted to 80%, with numbers of ASHP and GSHP systems split in the same proportion as that in the "2020 Stretch" scenarios and the "2050 Central" and "2050 Stretch" scenario values in the same proportion as the equivalent values for 2020.

Table 9.3 Installation scenarios for 2050 (also Table 8.25)

	Year	GSHP Units (000s)	ASHP Units (000s)	Total Units (000s)
Stretch growth scenario	2050	5,550	10,000	15,550
Central growth scenario	2050	1,600	3,900	5,500

Choices for the selection/filtering for application scenarios were limited by the high proportion of the housing stock in the '2050 Stretch' Installation scenario, and therefore a single Application Scenario was used, limited to the same criteria as Scenario 4 from the 2015/2020 analyses.

Results for these analyses show that:

- carbon emission reductions, at 79%, through the '2050 Stretch' scenario, approach the UK target of 80% reduction; the overall reduction is dependent on the 43% reduction arising from the parallel 'decarbonisation' of the UK electricity supply;

- including the effect of the output from photo-voltaic systems, carbon emissions reductions reach 82%;
- an increase in electricity consumption of 40% is matched by a reduction of gas consumption by 40%, the extra electricity consumption being substantially reduced by generation from photovoltaic systems;
- the use of reversible heat pumps for space cooling reduces energy consumption for this purpose by about 12 TWH over the 'Business as usual' position without heat pump systems;
- replacement of gas boilers by heat pump systems gives estimated savings of embodied CO_2 of ~970 KTonnes and ~3000 KTonnes for the "2050 Centre" and "2050 Stretch" scenarios respectively.

The above constitute the results required to address Objective 5 of this study.

9.2 Contributions to the field

9.2.1 Heat pump and dwelling energy models

In the field of dwelling energy modelling, the heat pump model as defined in this study represents what is thought to be the most detailed modelling of a generic heat pump system, being based on a regression model relating COP to source temperature and sink temperature, with source and sink temperatures based only on the type of source, external temperature and the type of distribution used as sink. It also models the effects of weather compensation control and the energy consumption due to bivalent operation, in both parallel and alternate modes. The capability of the embedded heat pump model of relating COP to the source sink differential also allows the dwelling energy model to use a different system efficiency for DHW generation and for space cooling.

9.2.2 Domestic energy model

The main contribution of this part of the study is that it provides the estimates for electricity consumption and carbon emissions for the installation of a single form of heating system across the English housing stock for the periods to 2020 and 2050. While these results are limited in the range of heating equipment to which they apply, their significance lies in the fact that, of all the heating systems currently available, heat pump systems in their various forms are the only type that can be installed in nearly every dwelling without major modifications and without additional storage or extra space requirement. The previous studies reviewed for this thesis have included a range of different measures to reduce carbon emissions in their modelling, including a variety of heating systems and energy efficiency improvements. However, the sole precedent for the upgrade of heating systems in UK dwellings has resulted in a 'monoculture' with some 90% of dwellings being heated by gas central heating. This study has envisaged this process being repeated with heat pump systems, which are currently the most efficient type of heating that reproduces the convenience of the gas system, while utilising the existing wet distribution systems and taking advantage of the de-carbonisation of the electricity supply.

A second contribution of the domestic energy model in this study is that it indicates that a significant domestic energy model can be developed using publicly-available data and a comparatively simple dwelling energy model, to create useful estimates for the English housing stock energy consumption. The creation of such model is facilitated by using a proportion of the EHS sample weight to define the application of heat pump installation scenarios to dwelling samples, a method which has, as far the author knows, not been used in any other studies. This method provides a simple way of allocating any required measure to a subset of the EHS samples.

The model is also significant in that it actively considers the plot size for the EHS sample dwellings when making assigning heat pump types to the sample dwelling. In the previous models reviewed in Section 4.5, this level of detail is omitted, with at best an assumption made that the installation of GSHP systems, as a low carbon measure, is confined to rural properties in the UKDCM model (Hinnells, Boardman, Darby, Killip, & Layberry, 2007) .

The model also considers the effect of combining photovoltaic systems - most effective during the summer months - with the use of space-cooling by means of reversible heat pumps.

9.3 Scope and limitations of the research

The BREDEM-8 model in this study is restricted to preparing estimates for single family houses and cannot produce estimate for flats, either purpose-built or converted. Modifying the model to accommodate these would not be easy as the EHS database does not contain a sample for each dwelling in a block of flats.

The models were developed in Microsoft Excel, which, while it enabled them to be created fairly quickly, did not prove to be resilient or easy to maintain. In some routines, it appeared to be failing to complete the processing of tables and the routines had to be re-run to ensure processing was completed.

Because of the structure chosen for the domestic energy model, it was necessary to reprocess the EHS sample table either to create another scenario or correct a fault in an existing one. This required a run time of about 12 hours and was prone to error. A revised structure in which the main BREDEM-8 model was implemented in a Visual Basic function could have been constructed, avoiding the reprocessing, but it is possible that the recalculation time for this version of the spreadsheet would have been too long to be useable.

The BREDEM-8 model, both in general and in this thesis, assumes that the main living areas in dwellings are heated to the standard 21ºC. As quoted in the appropriate section, this is very far from being the case, particularly in older harder-to-heat homes. A more complex algorithm is required for the setting of this internal temperature, possible related to the cost of heating as was defined by Clinch, Healy, & King (2001).

The linking of the BREDEM-8 model to the EHS data extract made many assumptions about the built form of the dwelling in each sample, eg. a rectangular floor plan, windows and doors at front and back only, and some omissions which were due to lack of data, viz. dimensions of built-in or attached garages or other unheated spaces, and attached conservatories. The floor plan assumption, in particular, could cause inaccuracies, and especially, underestimation, of the dwelling heat loss due to thermal bridging at the corner of house extensions.

In defining scenarios for take-up of heat pump system, this thesis does not describe either the process by which householders and social or private landlords might be motivated to make the change to heat pump systems or how the capacity to manufacture and finance the substantial numbers of systems to fulfill these scenarios might be created.

The model does not address future electricity consumption for cooking, lights and appliances, where future changes are most probably dependent upon technology that currently does not exist.

9.4 Recommendations for further research

9.4.1 Coefficient of performance / Season Performance Factor measurement

It was observed during the data monitoring phase of this study that the COP of the heat pump system (and longer term, the SPF) can be calculated fairly simply from the data available from the loggers, though this information was not available from the heat pump controller itself. It is proposed that research be carried out into the feasibility of creating a stand-alone device to provide this information for heat pump systems. Particular areas of research would be methods of acquiring flow rate and temperature data from the distribution system and algorithms for maintaining the volumes and currency of the performance data.

9.4.2 Heat pump performance

A further observation made during the monitoring phase was that it was not immediately obvious which of the systems in the study was performing better than the others or even performing satisfactorily.

Some further research is required into immediate symptoms of poor heat pump performance, which it is considered might be evidenced by distribution system flow rate, data which was not collected separately in this study. The heat pump trials by the Energy Saving Trust (Dunbabin, Charlick, & Green, 2013; Dunbabin & Wickins, 2012) into the variation of performance between systems measured performance over a substantial period of monitoring before making a judgement as to their efficiency and taking action to improve it. Since this implies that a householder may suffer some months of poor heating or unexpectedly receive an excessive bill before realising that their heating is performing badly, it is considered that this is not a satisfactory situation and some form of immediate reporting is necessary to overcome it.

9.4.3 Take-up of heat pump heating systems

In order to support the large numbers of installations envisaged in these scenarios, research and development is required as follows:

- the creation of an independently-funded heat pump system performance test facility, with publicly-available results database;
- incorporation of this database into SAP in the same manner as the existing gas and oil boiler database.

9.4.4 Heat pump performance testing

Currently the specification of gas and oil boilers in the UK Standard Assessment Procedure for dwellings is supported by the SEBUK (BRECSU, 2011) database of boiler test results. No such database exists for heat pump systems, which are handled by the SAP Appendix Q procedure, the deficiencies of which are documented in chapters 2 and 7. It is unrealistic to expect the mass installation of such equipment in the UK to succeed without such a facility

In order to provide a similar database for heat pump systems, it is recommended that the performance results from the testing for certification under the Microgeneration Certification Scheme (MCS, 2011) are made available in an online database similar to that of SEDBUK. Currently, heat pump systems which are eligible for support payments under the UK Renewable Heat Incentive are required to be certified under the MCS and, once certified, are visible on its database, but without performance data in the entries for each system. As this data relates to certification required for subsidies or grant awards made by a public body, the Dept of Energy and Climate Change, it is considered that the original performance test results should be made publicly available.

9.4.5 Heat pump module and associated database in SAP

It is suggested that the heat pump module as defined in this thesis should be added to the SAP routine, including the facility to select a heat pump model and rating from the database, including the regression model based on SPF and source / sink temperature differential to replace the "Appendix Q" procedure.

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