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Development and application of a domestic heat pump model for estimating CO2 emissions reductions from domestic space heating, hot water and potential cooling demand in the future

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ABSTRACT

This paper outlines the development and application of a domestic heat pump model for space heating and cooling energy. The model is intended to bridge the gap between the single coefficient of performance parameter currently used in the UK procedures for the assessment of the energy efficiency of dwellings and the dynamic simulation models frequently developed for the academic estimation of heat pump energy use. It is responsive to variations in source and sink temperatures whilst being simple enough to be embedded in a spreadsheet model.

The model was developed by: building a regression model, using heat pump performance test results, relating heat pump coefficient of performance to the differential between source and sink temperatures – "lift"; deriving estimating rules for monthly supply temperature estimates for commonly-used heat pump sources and for demand temperatures for normal wet central heating sinks to give a monthly estimate for the source/sink differential; embedding the regression model in the UK standard model for domestic energy estimation, with additional routines to estimate energy consumption for additional heat and for space cooling.

The model developed was validated by comparison with the existing BREDEM model. Compared with the standard BREDEM estimates, the resulting model showed correct response to changes in ambient temperatures, allowing correct estimating of consumption for additional heat under conditions of climate change. It showed variation of heat pump coefficient of performance across the year, allowing better estimation of winter peak load.

1. Introduction

1.1. UK Renewable Heat Incentive

With the impending implementation of the Renewable Heat Incentive (RHI) in the UK, some significant amount of attention has been focused recently on the energy performance of heat pump heating systems. For domestic systems, the Renewable Heat Incentive is aimed at encouraging the installation of ground source heat pumps, biomass boilers, and solar thermal hot water systems. 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 will be for solar thermal hot water, air source heat pumps, ground source heat pumps and biomass boilers. Eligibility for this payment will depend 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 will be aimed at dwellings without gas-fired central heating systems [1]. The main domestic RHI payments will commence later, possibly with per kilowatt-thermal payments being made for solar thermal, ground and air source heat pumps, and biomass boilers. Currently, the DECC proposal is that the output heat from these systems will be metered to calculate the payments due.

Currently (November 2012), no indication has been given what proportion of the 25,000 planned domestic RHI installations will 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 [2,3] and, in the longer term, to fulfil the legally binding requirement in the UK's Climate Change Act [4] 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

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Table 1
Heat pump source characteristics [32].

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

not known whether the installation scenarios proposed in the earlier background studies [5] made by NERA for the DECC "Heat and Energy Saving Strategy Consultation Document" [6] of the possible contributions that various technologies could make in reaching UK targets, are still under consideration.

The NERA background studies were largely 'top-down' in nature with [5] admitting in the "Further Work" section that 'better understanding of [heat pumps'] performance in different types of UK housing stock could be particularly useful'. This need for better understanding was presumably what triggered the Energy Savings Trust's year-long monitoring study of the energy use, over 2008–2009, of some 80 residential heat pumps, the published results of which, while alerting the public and the heating industry to the short-comings of some systems and their installation, have not, so far, added substantially to our knowledge of the issues surrounding heat pump performance [7,8]. For example, one of the key finding of the results was that performance of ground source heat pumps was, on average, poorer in the UK than in a similar trial in Europe, but no root cause was identified for this. The results of the trial also found a wide variation in performance between systems in the trial, but found that statistical analysis gave "only partial answers and unclear trends", with only consideration of individual installations giving "more insight" [7]. The more in-depth paper on the trial by Bradford et al. [8] reported a relationship showing that underfloor distribution system produced better heat pump performance and, on an individual system basis, found that a COP of 2.4 in the winter was reduced to 1.0 in the summer, indicating that loading also had a strong influence on efficiency. However, an overall relationship between efficiency and the other data measured was limited to that with system source and sink types and source temperature, explaining only about 50% of the variation in efficiency in the sample. To quote Bradford et al. [8], "The model is of limited practical value for making predictions regarding the performance of future systems". Because of these limitations, the trial has been continued into a second phase, with more detailed investigation of, and modifications to, heat pump systems from the first phase.

1.2. Heat pump heating systems

The basic function of a heat pump is to transfer heat from one body to another. A heat pump space-heating system takes low temperature heat energy from a large body and 'compresses' it into higher temperature heat in a smaller body, the 'large body' being any of the sources listed in Table 1 or any combination of these, and the smaller body being the distribution fluid in a hot water central heating system or the air in a house. The warmth in the large body is solar gain, and thus the heat pump is using as its source an inter-seasonal store, 'filled' in the summer by solar energy and 'emptied' during the winter by the heat pump [9] and on this basis, this type of heat pump system is judged to be utilising renewable energy. In addition, some sources may be re-charged by cooling the dwelling during the summer by means of a reversible heat pump. The performance of a heat pump system is normally measured by the ratio of heat energy output to the electrical energy input, known as its coefficient of performance (COP) when measured over a short period or seasonal performance factor (SPF) when measured over a longer period.

1.3. Energy saving and carbon dioxide emission reduction effects of heat pumps

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. Fig. 1 shows that, given a heat pump of a sufficiently high COP($\varepsilon = 3.0$), 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. Reduction of carbon dioxide emissions through the use of heat pumps is directly effected by the carbon intensity of generation, as per Fig. 2, which illustrates the effects of the recent change implemented to the parameter used in the UK Standard Assessment Procedure (SAP) [10,11] which was increased from 0.422 kg CO_2/kWh to 0.517 kg CO_2/kWh. The effect of this change is to require an increase of COP from about 2.1 to 2.6 to ensure that a heat pump system creates a reduction in carbon emissions in replacing a natural gas system. Settling on any carbon intensity value for use in estimation is highly problematic, since the actual value is constantly changing, as an energy company real-time display shows [12]. Fig. 2 also indicates the main benefit of heat pump systems, which is the potential to reduce carbon emissions both by taking advantage of reductions of the carbon intensity of generation and also by improvements in performance, while fuel burning systems are constrained by the carbon content of the fuel itself. Thus a reduction in carbon intensity from 0.422 kg CO_2/kWh to 0.3 kg CO_2/kWh brings about the same reduction as an increase in COP from 3 to 4.

At dwelling-level, the routines used to represent the energy characteristics of heat pump systems in the UK residential energy model, (BREDEM [13]), designed by the official built environment research organisation, BRE, do not allow for variations of system performance throughout the year or for energy use in different modes of operation. Similar deficiencies apply to the regulatory model for the energy performance of dwellings (SAP [14]) though this has recently been updated with a facility to specify the make and model of heat pump system installed, estimating its energy consumption using the methods in British Standard BS15316-4-2 [15]. The inadequacies of SAP in estimating the benefits of heat pumps and other non-traditional forms of heating and of sophisticated system controls were highlighted in the Pathways document by the Heat and Hot Water Task Force as barriers to the take-up of these technologies [16].

Recent academic researchers [17,18] in the UK have concentrated on dynamic simulation models which rely on the availability of detailed weather data and use performance data from specific heat pump units. Thus Jenkins et al. [18] in studying the cost and CO_2 savings of a GSHP used performance curves for a specific Viessman system and hourly thermal load data for a specific dwelling from Edinburgh in 2005, while Kelly and Cockroft [17] built an air source heat pump model based on laboratory test results which was integrated into a dynamic building simulation model (ESP-r [19]) with simulation performed at 1 min timesteps using a detailed weather dataset. Both of these models require detailed built form and weather data which is not available at housing stock level and, due to the complexity of the computer simulation, require run-times which would be unrealistic for large samples, hence the requirement for the type of model described in this paper.

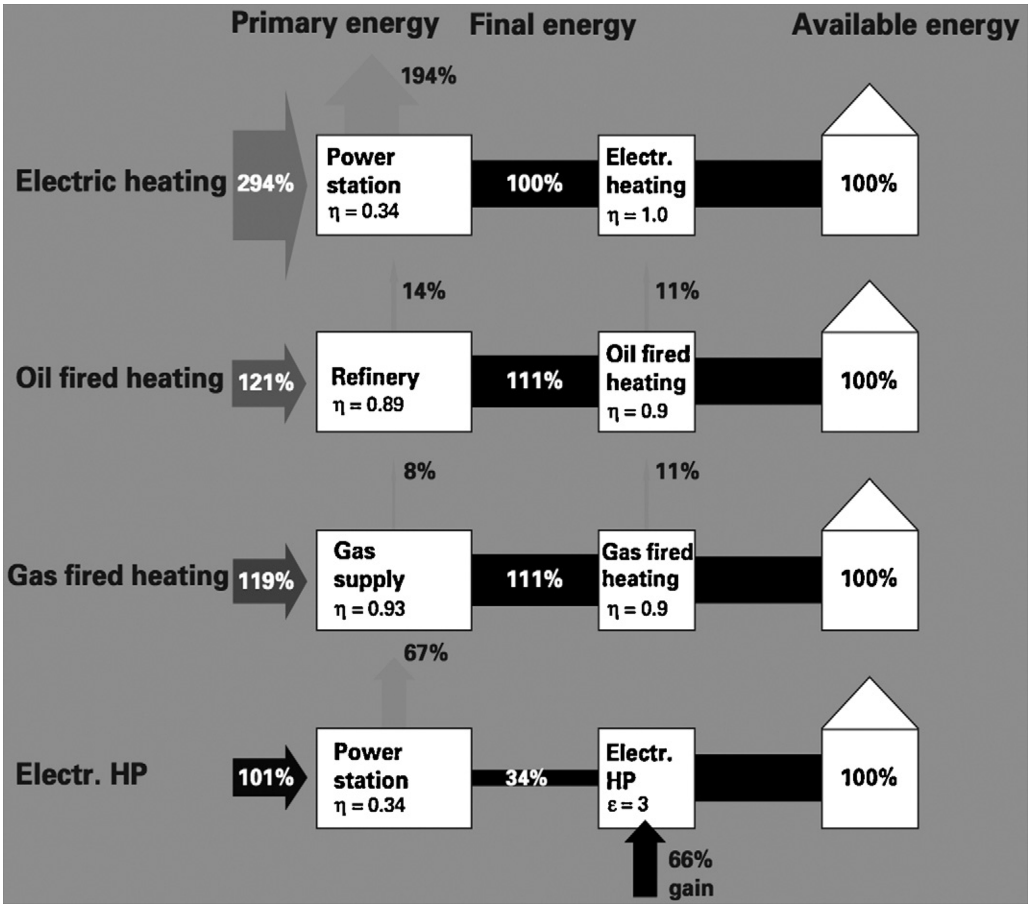

Fig. 1. Relative energy use of different heating systems.

1.4. Scope of this paper

This paper describes a model which is designed to estimate for a generic system, either air source or ground source, to function within the framework of a standard building energy model with weather information limited to monthly average temperatures. The process by which this model was developed involved the following activities:

(a) identification of the distinctive characteristics of heat pump heating systems which are to be incorporated into the model;
(b) the construction of a linear regression model for COP based on heat pump performance test results from the WärmePumpen Testzentrum (WPZ);
(c) for GSHPs, the calculation of the relationship between ground temperature and the input source temperature to the heat pump

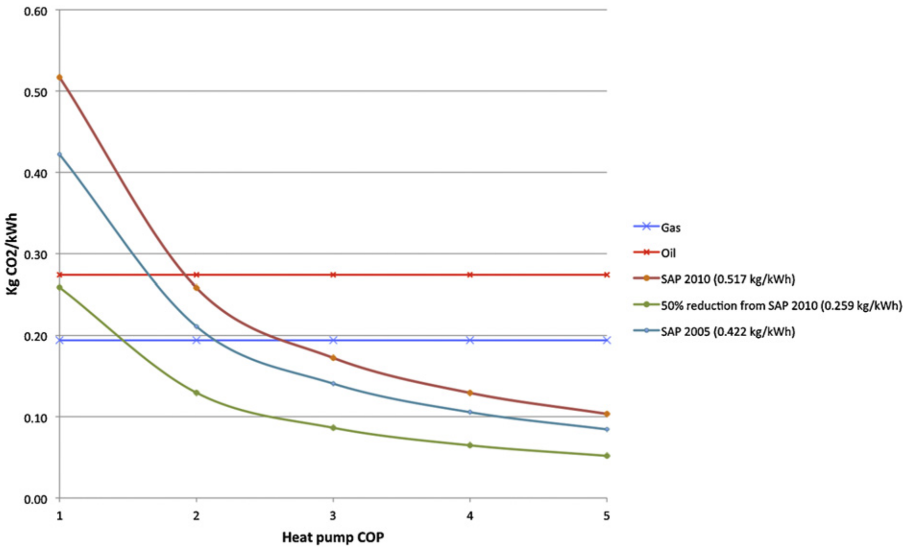

Fig. 2. Effect of carbon intensity of generation and COP on emissions from heat pump heating systems.

system, determining soil temperature using the sinusoidal relationship developed by Kusuda and Aschenbach [20]
(d) the construction of a generalised relationship linking external, ambient temperature and distribution system type with the heat pump system output temperature as determined by a weather-compensated control system;
(e) the incorporation of these relationships into a generalised heat pump model within the UK standard BREDEM-8 building energy model, with adaptation of BREDEM routines to estimate secondary system energy use in bivalent modes.
(f) validation of the model.

The paper reports on research carried out as part of a 3.5 year project funded by the Engineering and Physical Science Research Council (Grant no. CASE/CNA/06/82) to assess the potential of ground source heat pumps in reducing energy-related carbon emissions from UK housing in a changing climate.

2. Characterisation of heat pump heating systems

2.1. Distinctive characteristics of heat pump heating systems.

Compared with fuel-fired systems, heat pump heating systems have the following characteristics:

(a) significantly lower temperature output;
(b) reduction of performance due to the variation of source energy over the heating season because of the depletion of the ground as an inter-seasonable store, or because of 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 consumed, as noted in Section 1.3;
(d) the cost of installation of GSHP systems, especially that of the collector, is highly dependent on the capacity of the system;
(e) non-uniform increase in operating cost and CO_2 emissions when outside temperature falls below the system balance point temperature;
(f) capable of providing cooling as well as heating.

2.2. Lower temperature output

Without the use of auxiliary heaters, the current generation of heat pumps is restricted to generating heat at a maximum of 55–65 °C [9] compared with the 80 °C output from fuel-burning systems because of the thermodynamic limit of the vapour compression cycle heat pump.

The limit on heat pump performance is determined by a theoretical maximum, the Carnot coefficient of performance (Carnot COP) [21]. This COP is calculated by the formula:

$$\xi_{\text{carnot}} = \frac{T_h}{T_h - T_c} \tag{1}$$

where T_h and T_c are the sink (output) and source (input) temperatures for the system in degrees Kelvin. Thus a Carnot Engine heat pump raising the temperature of a source from 0 °C (273 K) to 50 °C (323 K) would be working at a Carnot COP of 6.46 [9, p. 14], while a lift from 0 °C (273 K) to 60 °C (333 K) reduces the Carnot COP value to 5.55, with the COP of an actual heat pump being in the region of 50% of the Carnot value [9]. In Eq. (1), as $(T_h - T_c)$ increases, the value of ξ_{Carnot} tends towards 1.0. Thus the greater the temperature rise or ‘lift’ required, the lower the coefficient of performance achievable and the greater the driving energy required to achieve that lift. This is most significant for the wet radiator central heating systems currently used in the UK, which have a comparatively small surface area and hence nominally require higher temperatures (~80–90 °C) to output sufficient heat. However, wet underfloor heating systems, having a much larger radiant area, provide sufficient output at the lower temperatures (~45 °C) at which heat pump systems operate more efficiently. Thus the heat distribution system installed determines the lift required further determining the possible COP and hence the efficiency of the system.

2.3. Variation of source energy over the heating season

Table 1 shows a list of the frequently used sources, their temperature range and collector type.

Apart from exhaust air, waste water and effluent, these sources all have one characteristic in common, viz. a fall in temperature and, hence, available heat, over the winter, the heating season. Thus a heat pump heating system is required to increase output at the same time as the energy available from its source is diminishing. This requirement to produce an increased lift over the heating season reduces the efficiency of a heat pump system in a similar way to the requirement to provide a higher temperature output for radiator distribution.

2.4. Installation cost of GSHP systems

Though the installation cost is highly significant to the purchaser of a GSHP system and implies that the sizing of the system warrants more care than that of a fuel-burning system, it is not relevant to an energy model and will not be addressed here.

2.5. Non-uniform increase in operating cost and CO_2 emissions with increase in output

A high proportion of heat pump heating systems are fitted with additional direct electric heating elements switched on by the heat pump controller when the main heat pump is unable to match the heating load required. As these effectively operate at a COP at or below 1.0, the overall COP of the heat pump system will be substantially reduced, with corresponding increases in costs and CO_2 emissions. Some retro-fit installations retain the existing boiler systems to take over the heating load at temperatures below the balance point with more radical variations in performance, cost and emissions at lower temperatures [9].

2.6. Capable of providing cooling as well as heating

Using additional valves in the refrigerant circuit, a heat pump system may be reversed to extract heat from the dwelling into the source to provide cooling, and, where the source is soil or a static body of water, recharge the source for the winter.

3. Building energy models and treatment of heat pumps

3.1. Selection of standard energy model

The BREDEM-8 [22] model was selected as the starting point for this model. The BREDEM series of models have been used by the UK Building Research Establishment (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 [23]. Since then, BREDEM has been developed through versions 2–12 and adopted as the basis of commercial energy assessment software, with BREDEM-9 being used as the basis for SAP [24]. Further, both BREDEM-8 and BREDEM-12 have been employed within the BREHOMES UK-wide domestic energy model [25] which provides analyses of energy consumption for the English House Condition Survey [26]. Results from BREDEM-8 and 12 were compared successfully against measurements in real

Table 2
Summary of heat pump system-related parameters extracted from BREDEM-8 specification [13].

	Source	Heat pump system parameters in BREDEM-8				
		Heat distribution by water	Efficiency/SPF	Responsiveness (from Table D4)		
				With radiators	UFH in insulated timber floor	UFH in screed or concrete slab
1	Table D1 Efficiency and responsiveness	Ground-to-water heat pump	320	1.0	1.0	0.25
		Ground-to-water heat pump with auxiliary heater	300			
		Water-to water heat pump	300			
		Air-to-water heat pump	250			
		Heat distribution by air				
		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	
		Fraction of heat supplied by secondary heating systems				
		Main heating system	Secondary system	Fraction		
2	Table D.7	Electric heat pump systems with heat storage or fan-assisted storage heaters	Gas fires	0.15		
			Coal fires	0.1		
			Electric heaters	0.05		

dwellings and also against the building energy simulation models of the time [27].

The main basis for the BREDEM models [22] is that of an analytical calculation 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, i.e. 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 zones, each of which has its own heating regime (or none) and heat loss coefficient, with allowance for the transmission of heat between zones by 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 – that required by the occupants, which is usually 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. Differing temperatures are calculated for the two zones depending on the demand temperatures and the level of sophistication of the controls in each zone.

The estimated space heating energy load is then calculated on a monthly basis from the heat loss coefficients, the average monthly external temperature for each month and the mean internal temperature and from this, the required input fuel or energy use is calculated based on the efficiency of the chosen heating system or systems according to the relative proportion of the dwelling heated by each system [22].

The BREDEM-8 model has two distinct advantages for enhancement by the addition of a heat pump system module. Firstly, it is partitioned into modules for different heating system types, which allows the addition of another system type without interference with the others. Secondly, the basing of space heating load calculations on monthly average external temperatures, rather than degree days used in BREDEM-12, provides the temperature data necessary for use in the estimation of source temperatures required as input parameters to the heat pump module.

3.2. *Heat pump parameters in BREDEM/SAP*

The parameters particular to the estimation of heat pump system energy consumption and output are quite limited in the SAP/BREDEM models. Their values are summarised in Tables 2 and 3. Table 2 contains parameter values that are used in both SAP and BREDEM, with some degree of variation, Table 3 those that are used in SAP only, for completeness.

3.2.1. *Single, annual SPF value*

The SPF values are used to calculate energy consumption from the energy load estimated for the dwelling. The responsiveness factor in Table 2 is used to adjust the Mean Internal Temperature according to the responsiveness of the distribution system.

Of the factors in Table 3, the 'adjustment to the efficiency of the main space heating system' factor is applied to the SPF in the energy consumption calculation. For estimating energy consumption in domestic hot water generation, the heat pump SPF is again used in calculations with the adjustment to the "efficiency of domestic hot water generation" applied according to the conditions in the table entries.

Thus the original BREDEM model uses a single SPF/COP value, invariant across the heating season, and rules out the use of manufacturers' or any other test values available. The use of energy for additional heating is allowed for by reducing this single SPF value, ignoring the fact that these heaters only operate when

Table 3
Summary of heat pump system-related parameters (additional to SPF tables) extracted from SAP 2005, 2008 update specification [14].

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 hp	0.7
		50% of DHW supplied by hp	1.0
		DHW Efficiency	
		If both a heat pump 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

temperatures are lower than the design limit or balance point for the heat pump system, as observed in Fig. 10. 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. This value is based on the performance of the system documented in the GIR 72 monitoring report produced by BRECSU [28]. With differing average temperatures in the various regions of the country, the reduction to SPF value will over-estimate energy consumption in warmer areas and under-estimate in cooler. Similarly, 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 database entries, and no attempt is made to generalise the calculation [29].

3.2.2. *Estimation of the effects of variation of output temperature*

The use of an adjustment value (Ref. 1 in Table 3) to allow for the lower efficiency of the heat pump system when connected to a radiator distribution system is not particularly satisfactory. The adjustment values were derived empirically from statistics of heat pump tests carried out by the WPZ [30] and are based on the ratio between the average COP of the systems tested at sink temperatures of 35 °C and 50 °C for both system types and source temperatures of 0 °C and 7 °C for GSHPs and ASHPs respectively as shown in the following Fig. 3 from experimental results in standard BS EN 13516-4-2:2008 [15]. The validity of the values derived by this graphical method can be confirmed by calculating the ratio between the Carnot COP (Eq. (1)) at 0 °C source/35 °C sink and that at 50 °C 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 7 °C which gives a value of 0.68. Since this latter calculation is based upon thermodynamic theory, it would appear to be a better basis for the SAP parameters and would avoid the use of a somewhat opaque adjustment parameter.

4. Requirements for heat pump modelling within a standard energy model

This process identifies the requirements for a heat pump model and to aid selection of a building energy model within which it can fit.

The previous Section 2.1 on characteristics leads to the following requirements for modelling the energy use of heat pump systems:

(a) an estimating method for heat pump COP that reflects the variation of performance due to the variation of available source

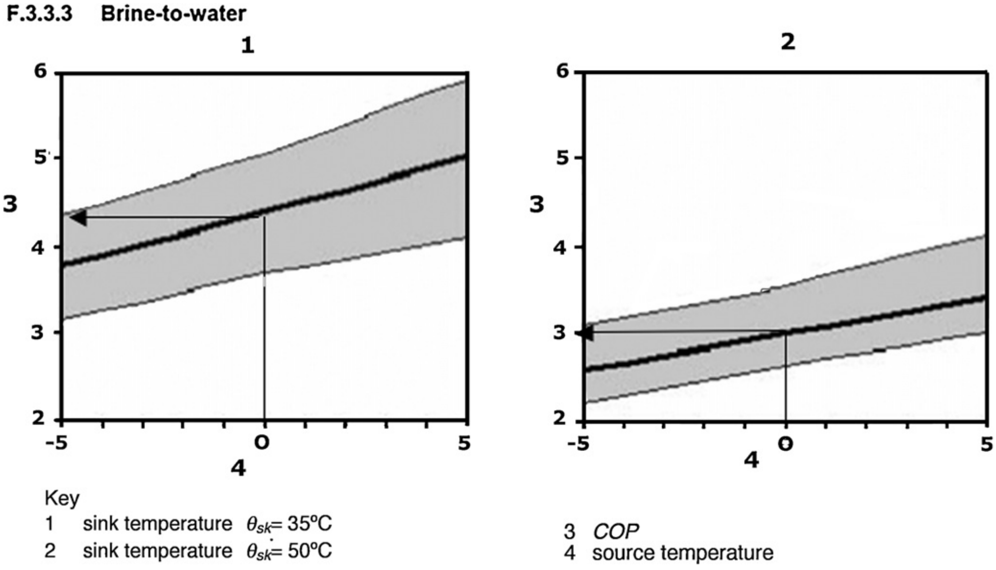

Fig. 3. Extract from EN 13516-2-4 which illustrates the relationship between CoP and source temperature.

Table 4
Differences between heat pump energy consumption estimates in BREDEM/SAP and enhanced model.

Ref	Parameter/variable	BREDEM/SAP version	Enhanced heat pump model
1	Space heating COP/SPF	Single annual value dependent on source type, reduced if system is fitted with auxiliary electric heaters.	Individual monthly values estimated using one of two regression models for either air or ground source systems, relating COP to "lift". Lift value calculated from source temperature estimates appropriate to system type and sink temperature estimates appropriate to system control. Individual monthly values.
2	Water heating COP/SPF	As above	Individual monthly values estimated using the same regression models as above with source value as above but constant value of 55 °C as sink value.
3	Additional heating	Allowed for in reduction in COP	Explicitly estimated based on a balance point temperature determined empirically from data monitoring results.
4	Cooling load	Not estimated in BREDEM. Single annual value for EER in SAP	Values estimated using the same regression models as above with source value = 20 °C and sink value = 18 °C.

temperatures and required sink temperatures across the year, matching characteristics 2.1 (a) and (b);

(b) an estimating method for the energy use of additional heating (bivalent operation) to meet a given balance temperature that reflects the bivalent mode required and that responds to changes in ambient temperature, matching characteristic 2.1 (e);
(c) an estimating method for cooling energy use, also responsive to source and sink temperatures, matching characteristic 2.1 (f).

Characteristic 2.1 (c) will be met by using the appropriate carbon intensity value for grid-supplied electricity in estimation, while 2.1 (d) is not relevant to an energy model.

5. Temperature data for heat pump systems

This was obtained from a monitoring study of ground source heat pump (GSHP) installations. This had two objectives: (1) to provide the industrial partner with independently-gathered data on the systems that they supply and (2) to inform the development of a generalised model for domestic heat pumps. It was carried out over one year (December 2008–November 2009) at three dwellings and involved the collection of energy and temperature data – both external and internal to the systems – throughout that period.

The systems monitored were installed in three dwellings chosen to form a cross-section of the built forms of UK housing. The heat pumps are manufactured by IVT in Sweden and are supplied by Ice Energy, the industrial partner in this research. A custom-built datalogger was used to acquire data via the heat pump controller i.e. temperatures for the ground loop and heat distribution system, the outflow from the heat pump compressor, the internal and external temperatures and the hot water tank temperature; status (operating/not operating) for the various sub-systems; heat output and electricity input. The temperature data is used to inform the development of the model described here.

6. Proposed enhancement of BREDEM for heat pump systems

Based on the deficiencies outlined above in Section 3.2, the replacements developed for the BREDEM parameters were as follows:

(a) a method of estimating COP based on the required lift. This in turn requires methods of determining the source and sink temperatures for the current application, i.e. space heating, space cooling, or domestic hot water (DHW) generation; such a method would allow the COP to vary from month to month;
(b) a method of estimating the energy use for secondary heating based on estimates of heating loads for periods when external temperatures fall below the balance point; such a method would be sensitive to changes in ambient temperatures;

In order to allow the heat pump model to be used within a domestic energy model for the UK housing stock, the above methods were applied to a generic heat pump model, with output sized to meet a given balance point temperature. The differences between SAP BREDEM and the model enhanced with the features from this study are summarised in Table 4.

6.1. Estimating method for variable COP

Estimating methods were required for source and sink temperatures and for COP based on lift.

6.1.1. Source temperatures

In practice, three source types are commonly used in the UK for domestic heat pumps – ambient air, closed vertical borehole ground loops and horizontal ground loops. Open loop systems, where the heat source is ground water, pumped through the heat pump evaporator then returned to the ground, are required to have an extraction license and the additional bureaucracy and expense are discouraging to domestic users. Information about water sources (river, lake or sea) is not usually available to a building stock level model.

For an ASHP, the source temperature is largely that of the ambient air around the dwelling. For a GSHP connected to a vertical bore hole source deeper than 10 m, it is accepted that the ground temperature is largely the same as the average annual air temperature [11,29,31]. For a GSHP with a horizontal ground loop as a source, a more complex relationship exists, since soil temperature above 10 m depth is still subject to the influence of air temperature, but with a lag dependent on depth and soil type. Kusuda and Aschenbach [20] found that the variation of the soil temperature over a period was sinusoidal in character and approximated to by the following equation:

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

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

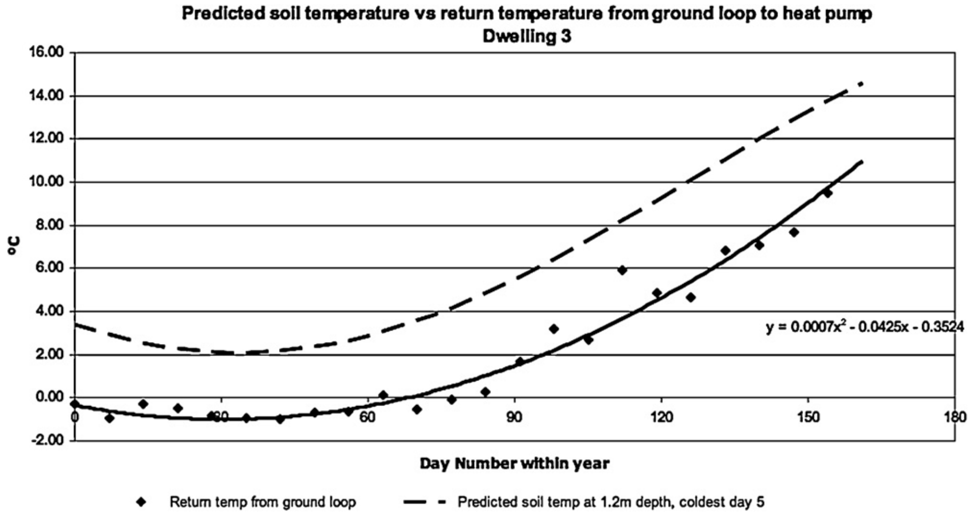

Fig. 4. Monitored dwelling 3. Comparison of predicted weekly soil temperatures at 1.2 m depth with day's average of return temperatures from ground loop to heat pump at seven day intervals.

temperature divided by 2), α is the soil thermal diffusivity in m^2/day. Jenkins et al. [18] compared the results of this equation using local data with actual ground temperature data from the Environmental Change Network site at Rothamsted, finding them to have 'reasonably close correlation'.

Values for the significant variables in Eq. (2), i.e. t_0, T_m, A_s and α as provided by Jenkins et al. [18] are $T_m = 10\,^\circ C$, $A_s = 8\,^\circ C$, $t_0 = 24$ days and $\alpha = 0.05\,m^2$/day. Using different values, $A_s = 13\,^\circ C$, $t_0 = 5$, which better match the exterior temperature data from the monitoring data, produces the following results, an example of which is in Fig. 4:

These indicate a plausible relationship between the soil temperature estimate and the temperature of the brine returning from the ground loop to the heat pump, which appear to be separated by between 2 and 4 °C. Unfortunately, little corroboration can be found for this value in literature. The IEA Heat Pump Centre Annex 25 programme showed [32] some 2 °C difference between borehole temperature and incoming brine, but the data is only for cooling mode for one day in the summer. Jenkins et al. [18] use an initial value of 6 °C in calculation, but allow this to vary according to the ratio between the heat pump capacity and heating demand, values which are not immediately available in BREDEM-8. In this study the 4 °C value will be used.

6.1.2. Sink temperature

Commonly used values for sink temperatures are 35 °C and 55 °C, corresponding to the requirements of UFH and of radiator distribution respectively, and these are the values utilised in EN14511 testing [33]. However, they are not easily reconciled with the datalogging results, as shown in Figs. 5–7, which show output flow temperatures over the heating season in the region of 47 °C and 37 °C average for dwellings 1 and 2 with distribution by radiators, and 42–47 °C average for dwelling 3 with UFH. Of these results, that for underfloor heating does not seem unusual, but those for the radiator systems seem comparatively low. It is claimed that radiator systems are frequently oversized, allowing lower temperatures, which would explain this anomaly. Since all three of the installations monitored have 'weather compensated' controls, which calculate a target distribution return temperature from the external temperature using a 'slope' equation, this will also cause the distribution temperature to vary. Where weather compensation control is present, then the following method is used to estimate a sink temperature.

6.1.3. Weather compensation control

These control mechanisms use an algorithm which takes as a starting point a family of 'curves' – in this case, straight line graphs – defining the relationship between external temperature and the target temperature for the heating system. The curve to be used by the controller for the particular installation is defined by a single value set by the user–higher values indicate a quicker target temperature ramp-up for the same change in external temperature. The controller manufacturer provides the following diagram, which shows the relationship between the curves and this value (Fig. 8) [34].

A set of linear equations can be derived from this diagram, the members of which correspond to the integer values of the controller setting ('curve slope' in the above), as follows:

$$T_{\text{Target}} = a_{0,n} + a_{1,n} T_{\text{Ext}} \tag{3}$$

where T_{Target} is the target temperature, T_{Ext} is the external temperature, $a_{0,n}$, is the intercept value for curve slope n, $a_{1,n}$ is the gradient value for curve slope n.

Using the intercepts $a_{0,n}$ and gradients $a_{1,n}$ from this equation set as observed variables and n as the dependent variable in two further linear regressions, a single equation is obtained for the relationship between T_{Target} and T_{Ext}, with n as a variable, viz.

$$T_{\text{Target}} = (a_{0,\text{grad}} + a_{1,\text{grad}} n) T_{\text{Ext}} + (a_{0,\text{intercept}} + a_{1,\text{intercept}} n) \tag{4}$$

where T_{Target}, T_{Ext} and n have meanings as before, a_0,$_{\text{grad}}$ and a_1,$_{\text{grad}}$ are the regression coefficients for the curve family gradient values against n, $a_{0,\text{intercept}}$ and a_1,$_{\text{intercept}}$ for the intercept values against n. The results of the regressions give the following equation relating the target temperature, T_{Target}, to n, the chosen curve and T_{Ext}, the external temperature:

$$T_{\text{Target}} = -(0.06 + 0.15n) T_{\text{Ext}} + (21.24 + 3.09n) \tag{5}$$

The values for n allocated within the heat pump system routine are 5.5, for radiator systems, 4 for underfloor heating systems. The former, higher value is that used in the two systems monitored where radiators were used, and the latter is that used for the single UFH system monitored and correspond to those suggested by the heat pump manufacturer's manual [34].

Because IVT heat pumps are configured such that the target value set is for the distribution system return temperature, a value is added for the distribution system heat loss to obtain an output temperature. Values for this are set at 10 °C for underfloor heating

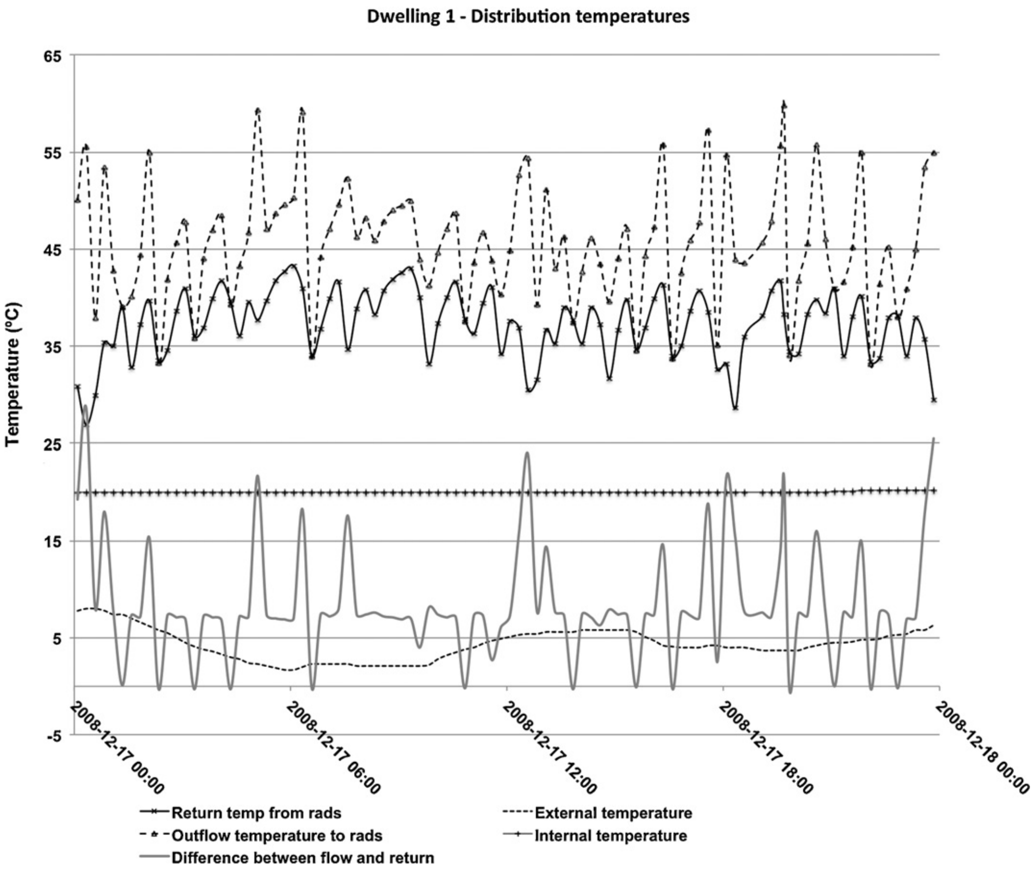

Fig. 5. Dwelling 1. Distribution supply and return temperature differential.

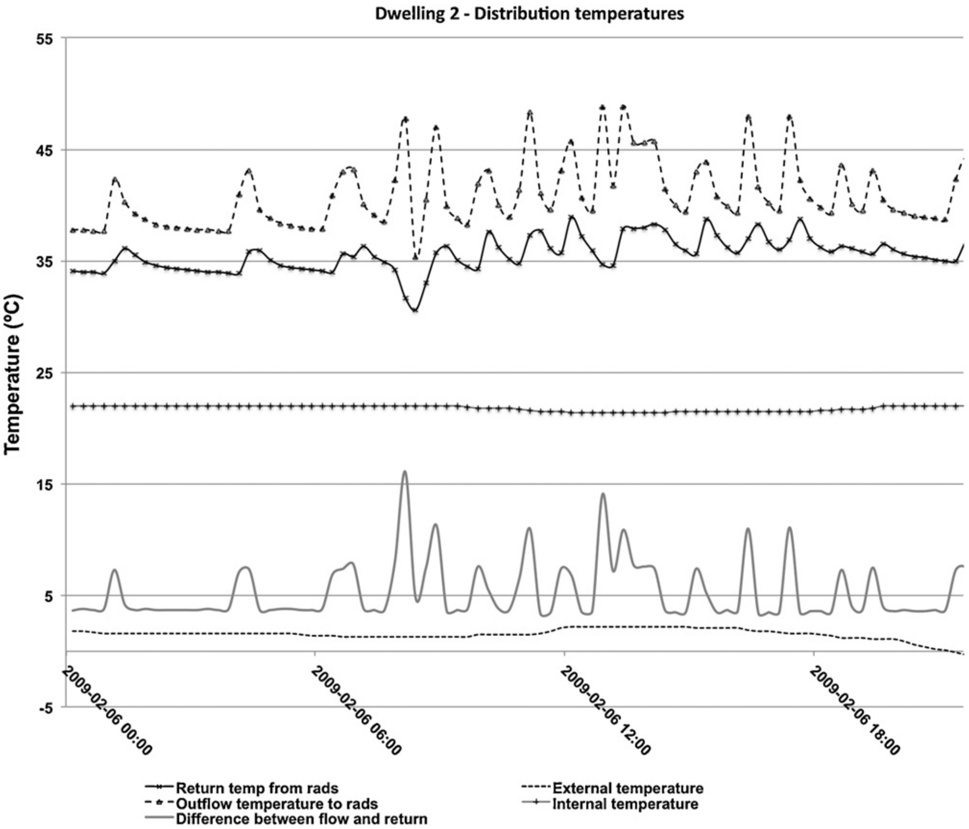

Fig. 6. Dwelling 2. Distribution supply and return temperature differential.

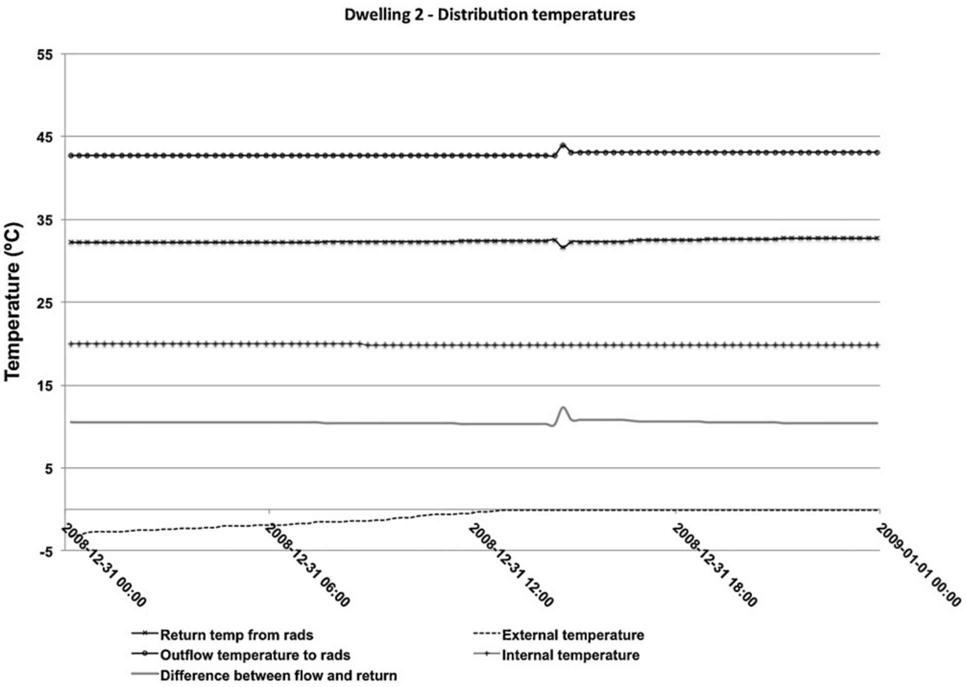

Fig. 7. Dwelling 3. Distribution supply and return temperature differential.

(UFH) and 7 °C for radiator systems, corresponding to the larger radiant area present in underfloor heating systems.

6.1.4. *Estimation of COP value*

Based on work by Staffel [35] and confirmed by some of the results by Bradford et al. [8], data to create a regression model for COP against 'lift' was acquired from test results available from the WPZ in Switzerland [30] which was converted into two spreadsheet files consisting of about 500 test results for 114 ASHP systems and 200 test results for 90 GSHPs giving the results in Fig. 9.

6.2. *COP calculation*

The model calculates three COP values as follows.

6.2.1. *Space heating COP*

A source temperature value is calculated based on the source type – air, ground loop, bore hole – and average monthly temperature.

A sink temperature value is calculated based on the monthly average external temperature, on distribution type – radiators, UFH – and on whether weather compensation controls are present.

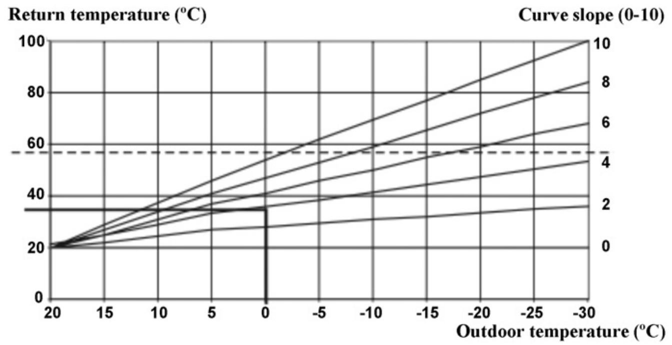

Fig. 8. Weather compensation temperature curves for Rego 600-series controller fitted to IVT heat pumps.

The source temperature is then subtracted from the sink to give a 'lift' value from which a COP value is calculated from the appropriate WPZ regression model for the heat pump type (air source or ground source).

6.2.2. *COP for DHW generation*

A lift value is calculated based on the same source temperature as the heat COP and a standard value of 55 °C for the sink. The COP is calculated as before.

6.2.3. *Cooling COP*

This calculation reflects the reversed direction of the heat flow, calculating a lift value based on the difference between a nominal sink value inside the dwelling of 18 °C [9] and the current source value.

6.3. *Estimating methods for secondary heating energy consumption–bivalent operation*

Bivalent operation – the switching-in of a secondary system when the heating load is high – overcomes the heat pump output temperature restrictions and allows the installation of a heat pump system that is smaller in capacity (and hence, cheaper) than is 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 to be balanced by the main system – the balance point – with auxiliary heating being switched in by the heat pump controller when the external temperature falls below this value, either as a boost to the heat pump which continues operating – 'bivalent parallel' mode – or to replace the heat pump, which is turned off – 'bivalent alternate' mode. If no secondary heating system is attached to the heat pump, then this is referred to as 'monovalent' mode. Given a predetermined balance point temperature, the energy consumption of additional heaters or a secondary system will be dependent on the number of heating degree days below that temperature [9, p. 40, 36]. The approach which was adopted was to calculate the frequency distribution of external temperatures recorded when the additional heaters were

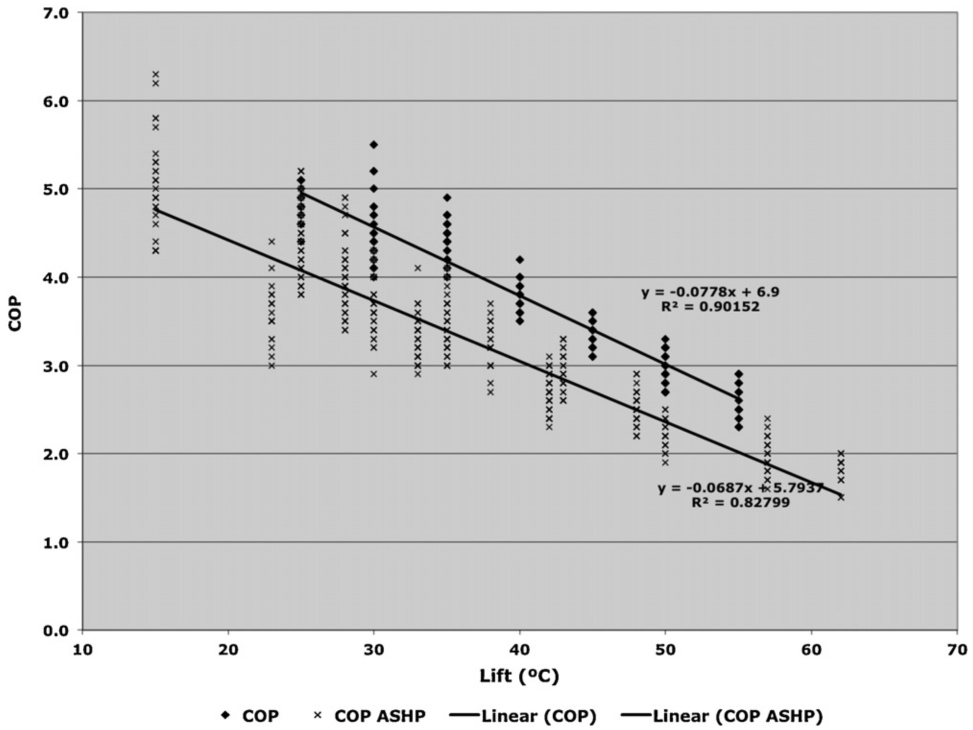

Fig. 9. Coefficient of performance against lift from ASHP and GSHP test results from WPZ.

switched on, resulting in Fig. 10, confirming a value of 3 °C as a balance point temperature.

6.3.1. *Heating degree days*

From Hitchin [37], the number of heating degree days in a month are estimated as follows:

$$\mathrm{DD}\{t_b\} = \frac{N(t_b - t_0)}{1 - \exp(-k(t_b - t_0))}, \quad t_b \neq t_0 \qquad (6)$$
$$= \frac{N}{K}, \quad t_b = 0$$

where t_b is the base temperature, t_0 is the monthly mean external temperature, N is the number of days in the month, $\mathrm{DD}\{t_b\}$ is the conventional notation for the number of heating degree days to the base t_b and k is a constant for which Hitchin 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 $\mathrm{DD}(t_b) = 0$, using an equation of the form:

$$Q_t = H.\mathrm{DD}\{t\} \qquad (7)$$

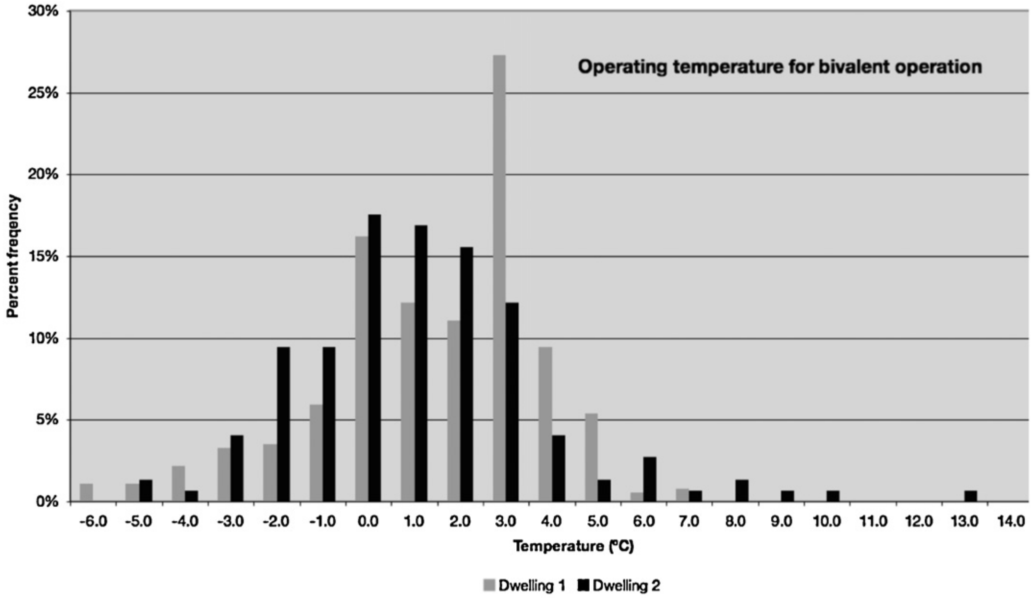

Fig. 10. Percentage frequencies of bivalent operating temperatures.

where Q_t is the heat required to maintain internal temperature t, H is the heat loss parameter for the building in W/°C, DD$\{t\}$ is the number of heating degree-days for a base temperature t.

6.3.2. *Choice of estimating methods*

For the purpose of this study it was decided that where possible any additional estimation methods should use methods the same as or similar to 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.

6.3.3. *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 the heat pump to maintain the internal temperature with both systems operating 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 supply by reheating the tank.

The steps in this method estimate, first, the quantity of heat that can be stored given the system’s 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, 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:

$$T_{\text{sat}} = \frac{H_1T_1 + H_2T_2 - G_1 - G_2 - C_{\text{max}}}{H_1 + H_2} \tag{8}$$

where H_1 and H_2 are the heat loss parameters, T_1 and T_2 are mean internal temperatures, G_2 and 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:

$$Q_{\text{on}} = 8.64 \times 10^{-5}(H_1 + H_2)\text{DD}\left\{T_{\text{sat}}\right\} \tag{9}$$

If the initial calculation of T_{sat} is omitted and replaced by a balance point temperature value of 3 °C as noted earlier, 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:

$$Q_{\text{on}} = H.\text{DD}\left\{T_{\text{bp}}\right\} \tag{10}$$

where H is the heat loss parameter in W/K, DD$\{T_{\text{bp}}\}$ 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.

$$Q_{\text{HP}} = Q_{\text{h}} - Q_{\text{on}} \tag{11}$$

where Q_{h} is the monthly space heating energy requirement as defined in the BREDEM-8 document, and Q_{on} is the additional heat requirement.

6.3.4. *Bivalent alternate operation*

As indicated above in Section 6.3, this mode is characterised by the secondary heating system cutting in to replace the heat pump system at the balance point temperature. 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. These routines are complicated by allowances for these systems’ characteristics 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:

$$Q_{\text{hpout}} = H(\text{DD}\{T_{\text{b}}\} - \text{DD}\{T_{\text{sat}}\}) \tag{12}$$

where Q_{hpout} is the 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 [38] is the 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 and 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 and 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}:

$$T_{\text{b1}} = T_{\text{d1}} - \frac{G_{\text{T1}} + (H_3/H_2 + H_3) \cdot G_{\text{b2}}}{H_1 + ((H_2H_3)/(H_2 + H_3))} \tag{13}$$

where T_{d1} is the demand temperature in zone 1 (°C), G_{T1} is the 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} is the 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 °C, 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:

$$Q_{\text{hpout}} = \frac{H_1 + ((H_2H_3)/(H_2 + H_3))}{d}\left[\text{DD}\{T_{\text{b1}}\} - \text{DD}\{T_{\text{sat}}\}\right] \tag{14}$$

where Q_{hpout} is the 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, $\mathrm{DD}\{T\}$ is the 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:

$$Q_{\mathrm{h1}} = 8.64 \times 10^{-5} d\{H_1(T_1 - T_{\mathrm{ext}}) + (H_3(T_1 - T_2) - G_1)\} \quad (\text{but if} < 0, \quad Q_{\mathrm{h1}} = 0) \tag{15}$$

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:

$$Q_{\mathrm{h}} = Q_{\mathrm{h1}} + Q_{\mathrm{h2}} - Q_{\mathrm{saved}} \quad (= 0, \quad \text{if} < 0) \tag{16}$$

(g) 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 (f) above. A second iteration is then performed replacing T_{d1} in Eqs. (13) and (14) to obtain a new value for Q_{hpout}.

(h) values for the main heat pump system (Q_{prim}) and the secondary system (Q_{sec}) energy in GJ are calculated as follows:

$$Q_{\mathrm{prim}} = \frac{8.64 \times 10^{-5} d Q_{\mathrm{hpout}}}{\varepsilon_{\mathrm{hp}}} \tag{17}$$

and

$$\begin{aligned} Q_{\mathrm{sec}} &= \frac{Q_{\mathrm{h}} - Q_{\mathrm{prim}}}{\varepsilon_{sec}} \qquad Q_{\mathrm{prim}} \geq Q_{\mathrm{h}} \\ &= 0, \qquad\qquad\quad Q_{\mathrm{prim}} < Q_{\mathrm{h}} \end{aligned} \tag{18}$$

where $\varepsilon_{\mathrm{hp}}$ and $\varepsilon_{\mathrm{sec}}$ are the COP of the heat pump and the efficiency of the secondary system, respectively.

7. Amendments to other sections of BREDEM-8

7.1. Energy requirement for space cooling

A routine based on that used in SAP version 9.90 [39,Tables 10, 10a, 10b] is used to estimate energy requirements for space cooling. This has the following parameters:

(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 (25 °C)
(d) cooling temperature (18 °C)
(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, Tables 10, 10a, 10b and 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 [40].

7.2. Carbon dioxide emissions

These are calculated for each fuel type using the kilogram per kilowatt hour values in SAP version 9.90 [39].

8. Validation

8.1. Comparison with standard BREDEM estimate for dwelling with heat pump

Fig. 11 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 shows that the enhanced model is much more responsive to the variations 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 i.e. 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. Similarly, the SPF value estimated by the model 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. With the reduction in the need for space heating, DHW energy requirements form a greater proportion of the energy load, causing a reduction in SPF due to the higher output temperature required. SPF peaks in the early autumn, when the soil temperature is highest and space heating requirements are only just starting to increase.

9. Discussion

9.1. Heat pump performance database

The regression model in this study uses a database built from data provided by the WPZ. Unfortunately, the format of this data requires substantial manual editing to create the database, which makes the process lengthy and prone to error. Though the use of this source limits the range of systems to those on sale in Switzerland, which is one of the smaller markets in Europe [41], one set of test results provided results for about 200 systems as opposed to the 30 systems currently documented in the BRE SAP Appendix Q heat pump database (April 2011) [42]

9.2. Use of Microsoft Excel

The model described above was developed in the Microsoft Excel environment. While this environment has many advantages, being widely available, flexible, with many methods of text, mathematical and database processing, and powerful, able to handle tables with over 100,000 rows and about 580 columns, it also has almost as many disadvantages, of which not least are the poor facilities for protecting formulae from being overwritten while the spreadsheet cells are being edited, the tendency of the environment to destroy cell range references in formulae when they are moved, and the difficulty of monitoring the progress of Excel programmes (except 'programs' in computers) while they are running.

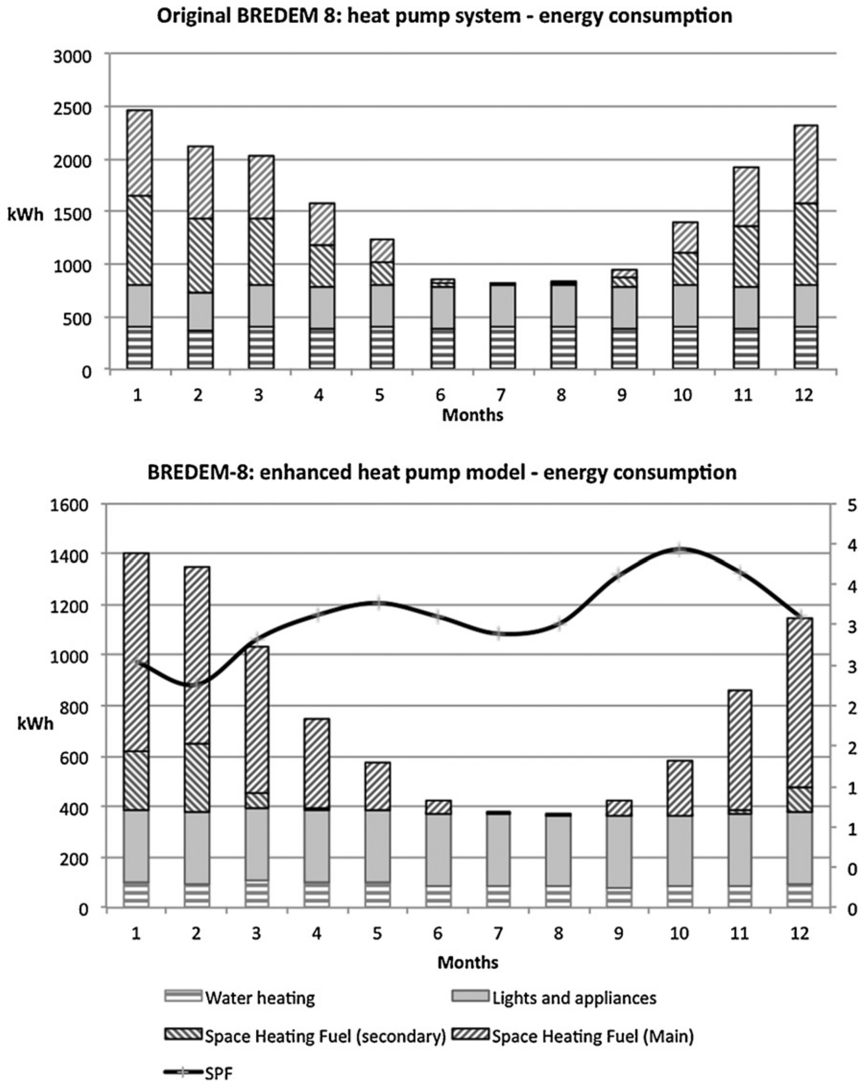

Fig. 11. Comparison between BREDEM-8 energy consumption estimates, original and enhanced.

The consequence of these characteristics is that the initial development of complex and feature-rich models is comparatively easy but it is difficult to maintain their integrity over further stages of their development.

10. Conclusions

Under the UK Renewable Heat Incentive, householders are to be incentivised to install heat pump systems and therefore it is highly desirable that modelling of heat pump heating systems in dwellings should reflect as closely as possible their actual performance, since these systems are seen as future low-carbon heating systems, both in zero-carbon new-build homes and for retro-fit to existing dwellings.

This study has identified the limitations in the current UK standard building energy models – particularly BREDEM-8 designed for housing stock modelling – in estimating for heat pump energy consumption. These consist of:

- a single annual value specified for the heat pump system COP, despite known effects of variable source temperature across the year;
- estimation of the effects on energy consumption of additional, direct electric heating and of different distribution and control systems are estimated by changes in this annual COP value, a method which is insensitive to ambient temperatures, for instance, under conditions of climate change;
- inability to estimate cooling loads, required to estimate the effects of climate change in the longer term.

Given these limitations, a combination of data monitoring, secondary data analysis and application of theory has been used to create a residential heat pump for use within the standard dwelling energy model, BREDEM-8. Data monitoring of ground source heat pumps in three dwellings has provided data on source, sink and balance point temperatures, while empirical studies have provided models for soil temperatures and for sink temperature requirements determined by weather-compensated temperature control systems. Analysis of the results from the standard testing of heat pump performance by the Swiss test facility, WPZ, provided a regression model linking heat pump coefficient of performance with source/sink temperature differential –“lift”. Development of the existing modelling routines for other heating system types within BREDEM has provided methods of estimating energy use for additional heating in bivalent operation.

These techniques have been combined to develop an estimating model for the energy consumption of a generic heat pump, using the minimum of parameter values, which has been embedded in an enhanced BREDEM-8 model for further use within a UK domestic energy model. The enhanced model includes: a regression model to estimate a monthly COP value based on 'lift', the difference between source and sink temperatures, with source temperatures based on the characteristics of the source and sink temperatures based on external temperature; estimation of energy use for bivalent operation based on an empirically-derived balance point temperature; and estimation of cooling energy consumption also based on the heat pump regression model. The model has been validated against a number of scenarios.

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