Energy and Buildings 60 (2013) 60–74

Contents lists available at SciVerse ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

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

Rajat Gupta*, Robert Irving

Low Carbon Building Group, Oxford Institute for Sustainable Development, School of Architecture, Oxford Brookes University, Oxford, United Kingdom

ARTICLE INFO

Article history:
Received 10 February 2012
Received in revised form 7 December 2012
Accepted 20 December 2012

Keywords:
Ground source heat pump
Seasonal performance factor
UK Renewable Heat Incentive
Heat pump energy model
BREDEM/SAP for heat pump systems
Energy consumption for additional heat and space cooling

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

* Corresponding author. Tel.: +44 1865 484049; fax: +44 1865 483298.
E-mail addresses: rgupta@brookes.ac.uk (R. Gupta), bob.irving@brookes.ac.uk (R. Irving).

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http://dx.doi.org/10.1016/j.enbuild.2012.12.037

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.