Predicting the performance of domestic electrical heat pumps in UK homes

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Abstract

To reduce CO2 emissions, the electrification of space and hot water heating via electrical heat pumps is a widely pursued policy aim. Unfortunately, the UK's experience of domestic electrical heat pumps has been mixed, with field trials demonstrating poorer performance than anticipated. A widespread understanding of performance drivers is lacking, and a robust and dependable method for estimating annual efficiency is required.

Initially in support of SAP assessments, a calculation method was developed based on prEN15316-4-2 and using EN14825 test data (arising from Ecodesign regulations). This incorporates a combined hourly space and hot water heating duty cycle, based on typical UK conditions derived from field evidence.

Method validation compared field trial results and demonstrated the method's superiority to Ecodesign performance estimates, whilst providing greater functionality.

Keywords Heat Pumps, Efficiency, Prediction, Calculation, Ecodesign

1 Introduction

The UK's National Calculation Methodology for energy rating of dwellings, known as SAP, has incorporated heat pump performance data since 2010. This was achieved via the Product Characteristics Database (PCDB) using EN14511:2007 test data at defined test conditions and a modified version of the calculation method EN15316-4-2:2008 – a bin method.

Whilst this calculation method enabled the reflection of Plant Size Ratio on performance (PSR: heat pump design capacity divided by design load), it was not possible to recognise the effect of the following critical areas, which as a result of BRE's experience with field monitoring had proven highly important to the estimation of annual performance. These include:

- Plant Size Ratio: whilst this was reflected within the original method, a bin method did not reflect the dynamics of heat pump and emitter system energy status variation over time, whereas an hourly time-step approach is more accurate[1]
- The effect of hot water load and the time and temperature of any hot water draw-offs, specifically when a simultaneous space heating demand exists
- The facility to modulate (using inverter-driven heat pumps) and the minimum level of modulation achievable, which affects on/off losses, particularly at higher PSRs
- Heat pump operating hours and their annual variation

Ecodesign regulations now require all heat pumps to be tested in accordance with the standard EN14825; SAP's previous test data requirements have become obsolete. The EN14825 standard estimates annual performance via a Seasonal COP (SCOP), using a simple bin method, which means the issues discussed above are not resolved. Additionally, because SAP requires annual efficiency for the heat generator system, not the product alone, the SCOP is unsuitable. Nevertheless, the required heat pump product test conditions and data arising from the EN14825 standard are highly useful.

An annual combined space and hot water heating duty cycle was developed by BRE that incorporates hourly heat load and temperature assumptions for a typical UK domestic system. This includes hot water draw-off times based on a scaled version of EN16147 Profile M, with energy requirements derived from field trials (1,2). The combined duty cycle is used to estimate annual efficiency using UK average (Leeds) weather conditions. The calculation method is based on a modified version of the draft standard prEN15316-4-2 and uses EN14825 test data.

[1] A dynamic simulation is not considered appropriate because it cannot be used by SAP, which is a simple static energy model.

2 The method

The heat pump calculation method is based on the hourly method within prEN15316-4-2 [*Energy performance of buildings — Method for calculation of system energy requirements and system efficiencies — Part 4-2: Space heating generation systems, heat pump systems, Module M3-8-2, M8-8-2*]. An hourly time-step approach was selected owing to the issues discussed above, but with considerable customisation and specification of UK dwelling-specific variables. The calculation method is entitled: "Calculation Method: CALCM:01 - SAP Revised Heat Pump Performance Method - Issue 1.0"[2].

The method performs hourly COP (Coefficient of Performance) calculations for each hour, or fraction of it, depending upon the heating service being delivered (space or hot water), the required flow (sink) temperature and source (air or ground) temperature. The Seasonal Performance Factor (SPF) is calculated by dividing total energy outputs by total energy inputs – see Section 2.3. It is multiplied by 100 to provide annual efficiency (%).

The following calculation method variables and assumptions are highlighted due to their significance:

- *Plant Size Ratio (PSR)*[3]*:* Unlike other methods, including the EN14825 SCOP calculation used for Ecodesign regulations, the calculation method considers the impact of the heat load of the dwelling in which the heat pump is installed – it determines a system efficiency, as opposed to product efficiency.

- *Back-up heating:* If a heating service demand exists and the heat pump has inadequate capacity to satisfy that heat requirement, then direct-electric heating satisfies any deficit. This includes times when satisfying a hot water load results in inadequate capacity to satisfy a simultaneous space heating demand

- *Variable operating hours:* Based on a presumption that homeowners will adjust heat pump operating hours during periods of colder weather, i.e. to keep warm, or an intelligent control exists to provide the same function, the method varies the heat pump operating times in order to satisfy the heat requirement. This idealised control method, known as "Variable", means that 16-hour operation or 24-hour operation is only required on certain cold days when the heat requirement cannot be met by operating for 11 hours/day. During mild weather the heat pump operates for the SAP

[2] http://www.ncm-pcdb.org.uk/sap/filelibrary/pdf/Calculation_Methodology/SAP_2012/CALCM-01---SAP-REVISED-HEAT-PUMP-PERFORMANCE-METHOD---V1.0.pdf
[3] Heat pump design capacity divided by dwelling design heat load

standard heating times[4]. It should be noted that whilst continuous operation will result in improved heat pump annual efficiency, it will increase energy consumption, since heat demand is increased. It is standard practice to intermittently heat homes in the UK.

- *Flow temperature for space heating* is calculated on an hourly basis and is affected by heat emitter characteristics, external conditions, and the heat pump operating hours, which are Variable. Smaller heat pumps, relative to dwelling design heat load, will require longer or continuous operation to satisfy heat loads, meaning that flow temperatures will be lower. If weather compensation control is disabled, then the flow temperature will be fixed at the design flow temperature.

- *Flow temperature for hot water heating* is assumed fixed at 55°C based on various EN16147 tests[5] (unpublished) conducted by BRE on air-source heat pumps connected to hot water cylinders. This was based on the observation that the set-point hot water temperature tends to match the average flow temperature during the cylinder recharging process.

- *External and source temperature assumptions:* As discussed in footnote 1, since the method is not dynamic, the hourly heating load is based on the daily outside temperature, and not the hourly temperature, because the dwelling's thermal mass dampens the response. Heat losses and useful heat gains are sourced from an example SAP calculation for a dwelling with a medium level of insulation and medium thermal mass[6]. External hourly temperatures are sourced from CIBSE Guide J, with the City of Leeds being selected as representative of UK average conditions.

- *Hot water heating operating times[4]* are determined by considering the hot water vessel at one uniform temperature. It is assumed that the vessel only demands heat when 1/3rd or more of the total heat that can be stored is depleted due to hot water draw-offs and vessel heat losses. A value of 1/3rd was chosen because cylinder thermostats are typically fitted approximately 1/3rd of the distance between the base and top of the

[4] Actual SAP standard heating operational hours are:
- 07:00-09:00 and 16:00-23:00 on weekdays for Zone 1
- 07:00-09:00 and 18:00-23:00 on weekdays for Zone 2
- 07:00-23:00 on weekends for Zone 1
- 07:00-09:00 and 14:00-23:00 on weekends for Zone 2

The method takes the standard SAP operating hours (16 hours at weekends and 9 hours on weekdays for Zone 1) as occurring from 07:00-09:00 and 14:00-23:00 seven days a week, which is 11 hours/day. The 16 hour/day operating option is defined as 07:00-23:00. There is no space heating from June to September. The operational hours for water heating (i.e. times when any hot water vessel can be heated) are the same as for space heating, but continue in the summer months.

[5] EN16147: Heat pumps with electrically driven compressors - Testing, performance rating and requirements for marking of domestic hot water units

[6] A detached house (100m^2) with a heat loss parameter of 2.72 W/K per m² and a thermal mass parameter of 245.5 kJ/K per m²

cylinder. The worse-case cylinder standing heat loss (kWh/day) and volume are specified by the heat pump manufacturer when making applications to the PCDB. Daily hot water draw-off times are based on EN16147 tapping schedule "M", but with the energy content of each draw-off proportionally scaled, as discussed in the next point. Hot water cylinder charging occurs during standard SAP heating hours.

- *Hot water energy requirement* is determined with reference to English Housing Survey data (see Figure 1). The method derives the space heating load from the heat pump design capacity (@ -4.7°C) and the PSR for the installation and uses this to infer hot water energy demand.

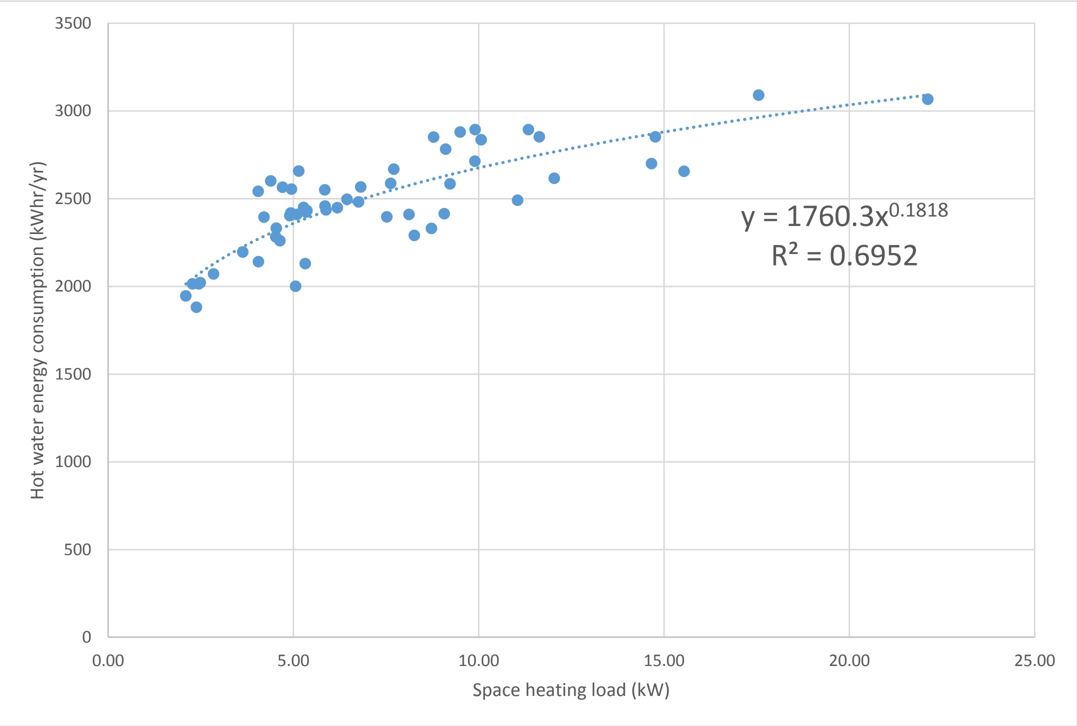

Figure 1 – Hot water energy consumption Vs space heating load

2.1 *Space heating energy demand*

The following equation is reproduced from the calculation method and shows how hourly space heating energy demand is calculated:

$$Q_{H,\text{gen,out}} = \frac{24 \times (T_b - T_o) \times \phi_{dgn} \times t_{ci}}{h \times PSR \times \Delta T_{d,d}} \quad \text{(kWh)}$$

Where:

h is the hours of operation per day (24, 16, 11, which is determined by "Variable" control logic from the SAP 2012 specification (3))

T_b is the daily mean internal temperature of the dwelling minus the ratio of useful heat gains to heat losses. A monthly gains/loss ratio value is used for this purpose since it varies throughout the year and according to heating operation hours. The daily mean internal temperature is taken as the monthly value calculated by SAP. Heat losses and useful heat gains are sourced from an example SAP calculation for a dwelling with a medium level of insulation and medium thermal mass[7].

t_{ci} is the calculation interval in hours (1 hour)

T_0 is the daily average outside air (dry bulb) temperature (°C)

$\Delta T_{d,d}$ is the temperature difference between the inside and outside of the dwelling under design conditions.

ϕ_{dgn} is the heat output under design conditions [at -4.7°C]

2.2 Flow temperature

Heat pump performance is affected by the flow temperature, often referred to as the sink temperature; within the method this varies for each hourly interval during space heating service. It is fixed at 55°C for hot water service. The following equation is reproduced from the calculation method and shows how hourly space heating flow temperature is calculated:

$$\vartheta_{gen,out}(t) = T_{d,d} + \left(\overline{T_{E,d}} - T_{d,d}\right)\left[\frac{24f(T_b - T_o)}{h\Delta T_{d,d}}\right]^{1/n} + \frac{24f(T_b - T_o)}{h\Delta T_{d,d}}\frac{\Delta T_{E,d}}{2} \qquad (°C)$$

Where:

n is the power law index

$T_{d,d}$ is the temperature of the dwelling under design conditions[8]

$\overline{T}_{E,d}$ is the average emitter temperature[9] under design conditions

[7] A detached house (100m²) with a heat loss parameter of 2.72 W/K per m² and a thermal mass parameter of 245.5 kJ/K per m²
[8] Derived using SAP as 19.5°C (24hr/day)
[9] Also referred to as Mean Water Temperature

$\Delta T_{E,d}$ is the water temperature difference across the emitter's inlet and outlet under design conditions

$\vartheta_{gen,out}$ is the heat pump flow (outlet water) temperature

f is the emitter intermittency factor

h is the number of hours of heating per day

2.3 SEPEMO system boundaries

Figure 3 displays system boundaries for the determination of heat pump annual performance. The boundaries (and the image) were created during the SEPEMO-Build project (4).

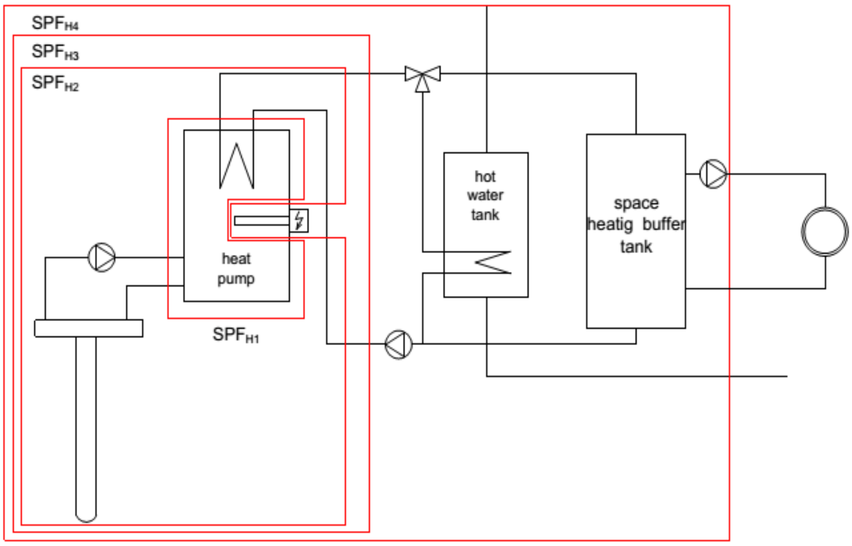

Figure 2 – SEPEMO system boundaries

The system boundaries used within this calculation method are identical to the SEPEMO SPF H4 definition, except that the standard case for space heating SPF excludes a buffer vessel; these are not common for UK heat pump installations. The calculation method ignores heat pump buffer vessels, even if installed outside the heated envelope. It is assumed that the specification of a buffer vessel, in order to reduce on/off cycling and improve annual efficiency, will only occur if vessel heat losses do not negate this improvement.

The SEPEMO SPF H4 definition for hot water heating includes all heat supplied to the hot water vessel, including subsequent heat losses, within the numerator, as does the SAP heat pump calculation method. However, it should be noted that the SAP calculation itself considers these vessel heat losses as useful heat. The SAP calculation applies a monthly utilisation factor to the internal heat gains from hot water vessels.

2.4 Implementation

Heat pump manufacturers submit an EN14825 test dataset for a given heat pump and it is subsequently processed into a range of annual efficiency values held in the PCDB for use by SAP software. These efficiencies are selected by SAP software depending upon:

- Heating service (space heating or hot water)
- Design flow temperature
- Plant Size Ratio
- Presence of weather compensation

EN14825 test data is entered by manufacturers using an application web portal, developed for the purpose, with program logic dictating the data entry combinations and a manual audit process for Quality Assurance purposes. Data is subsequently processed by a calculation engine implementing the calculation method.

The calculation engine is written in the Python scripting language (approximately 2,000 lines of code) and is arranged into modules reflecting the different stages of the calculation. The calculation is run at nine different plant size ratios and, depending on the test data provided, up to four different design flow temperatures, all with and without weather compensation. This level of iteration (up to 630,720 hourly calculations) incurs a time penalty and required significant optimisation of the code structure. Processing a single heat pump takes approximately 80 seconds if all possible combinations of plant size ratio, design flow temperature and weather compensation are calculated.

The results from each of the hourly calculations are aggregated as appropriate and output to a results database, which is used to generate entries in the PCDB. Each application can result in the addition of up to eight PCDB data records, covering each combination of design flow temperature and presence of weather compensation. In addition, each record will contain efficiency results for up to nine different plant size ratios.

3 Example calculation results

This section illustrates the effect that PSR and operating hours have upon annual efficiency, which are two of the most significant installation variables for a given heat pump, after design flow temperature. The design flow temperature was 55°C in the below examples.

The ability to interrogate hourly calculation method results using the developed calculation engine is a useful facility that could be utilised for numerous purposes,

3.1 Effect of PSR

Figure 3 and Figure 4 display results for the same heat pump, where the PSR differs with values of 0.5 and 1.5 respectively. These figures show that:

- The hot water energy requirement increases with a lower PSR
- The hot water energy requirement increases in winter due to colder inlet water temperatures
- The heat pump requires more direct-electric back-up to satisfy the space heating load when the PSR is lower

There is an optimal PSR, providing the highest annual efficiency (presented as SPF), and this is explored in Figure 10.

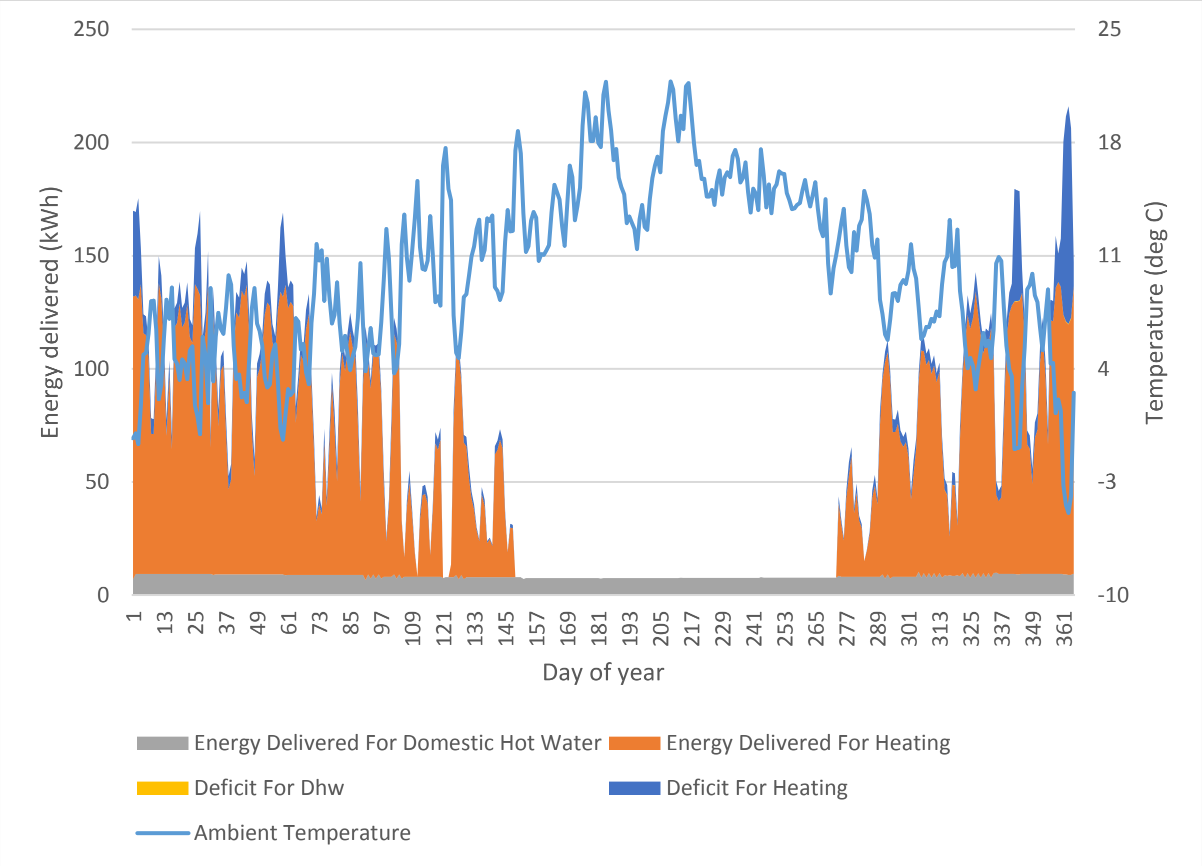

Figure 3 – Example heat pump - Daily energy delivered and external temperature when PSR = 0.5

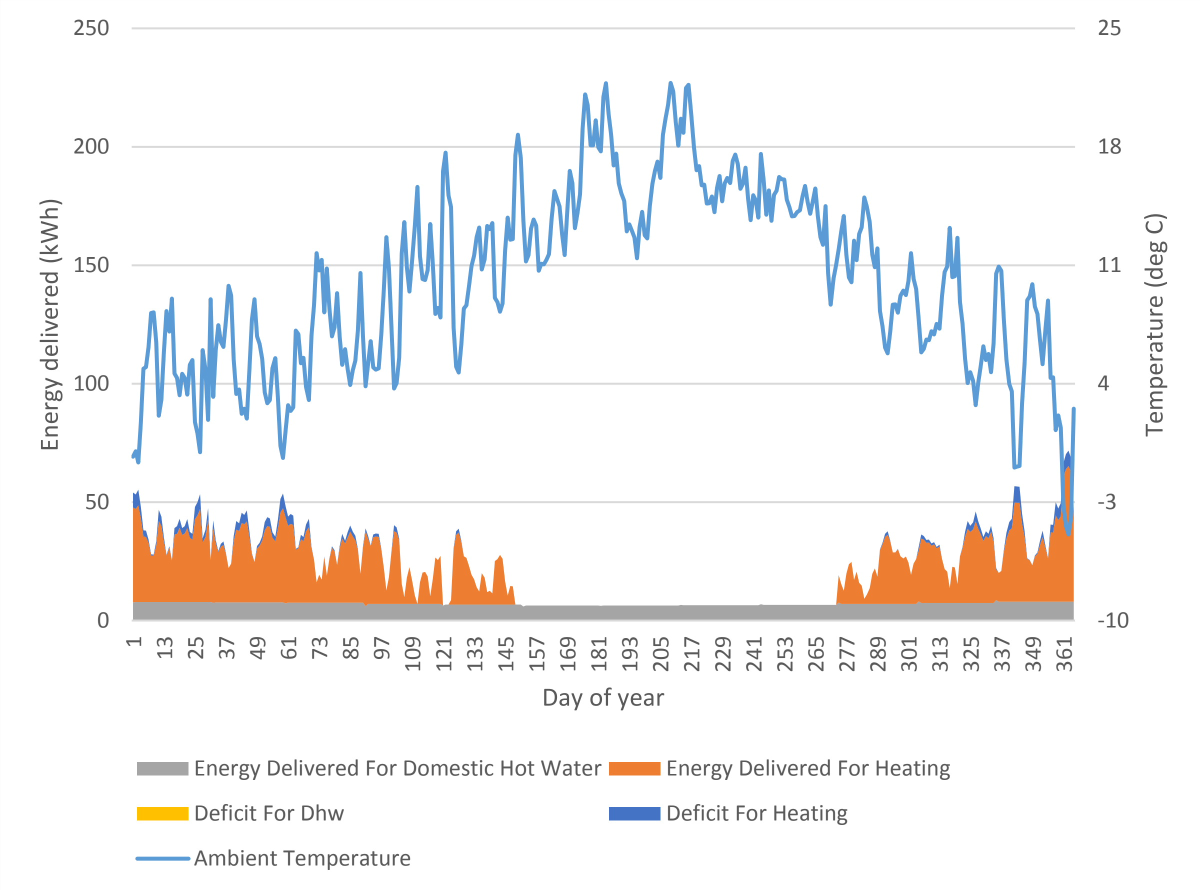

Figure 4 - Example heat pump - Daily energy delivered and external temperature when PSR = 1.5

3.2 Effect of operating hours

Figure 5, Figure 6 and Figure 7 display results for the same heat pump, with a PSR of 0.8, where the operating hours vary from 24 hours/day for the coldest day of the year to 16 and 11 hours on the coldest days that can be supported by these reduced operating hours. These figures show that:

- Where a hot water demand exists, for these days some or all of the space heating demand must be satisfied by direct-electric heating
- Operating hot water heating at times of peak space heating demand is not optimal. Whilst this may not occur in some or many installations in practice, it is still commonplace.
- Unsurprisingly, the heat pump is able to deliver a larger amount of energy in hours when the ambient (source) temperature is higher (Figure 5).

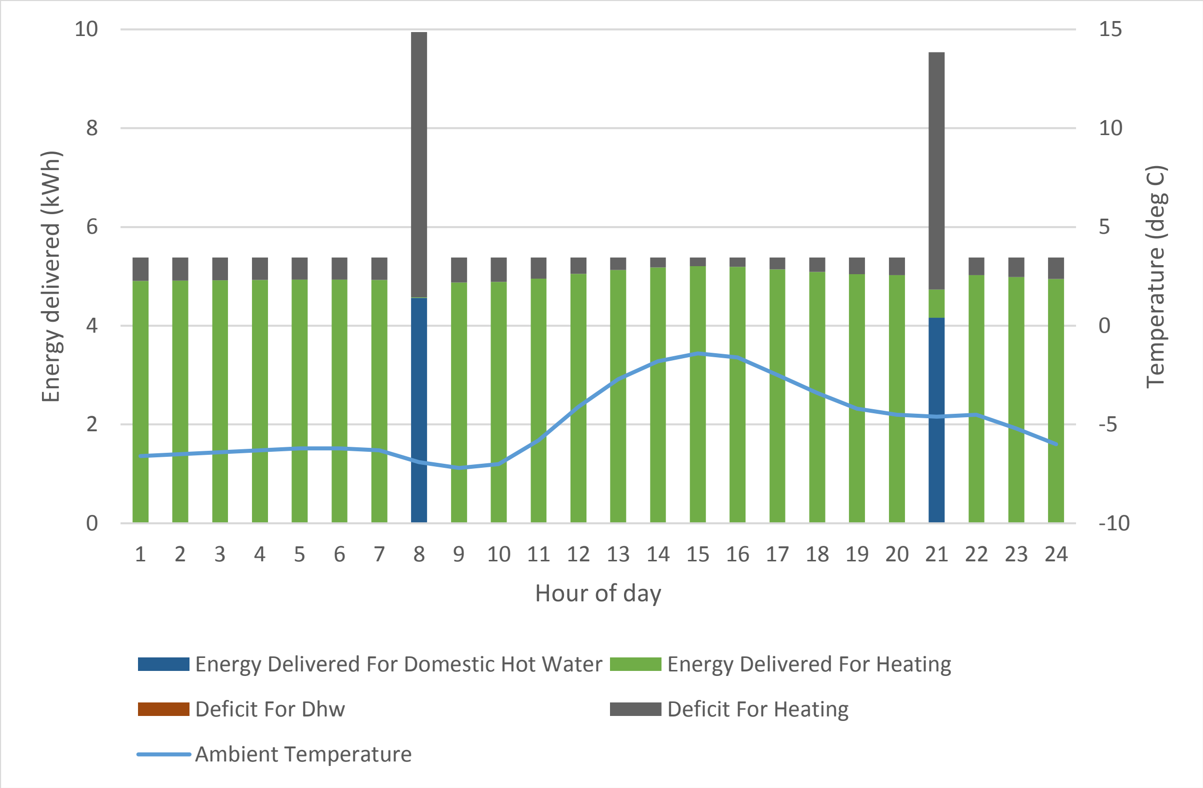

Figure 5 – Example heat pump – Energy delivered on the coldest day of the year (24hr heating), with PSR = 0.8

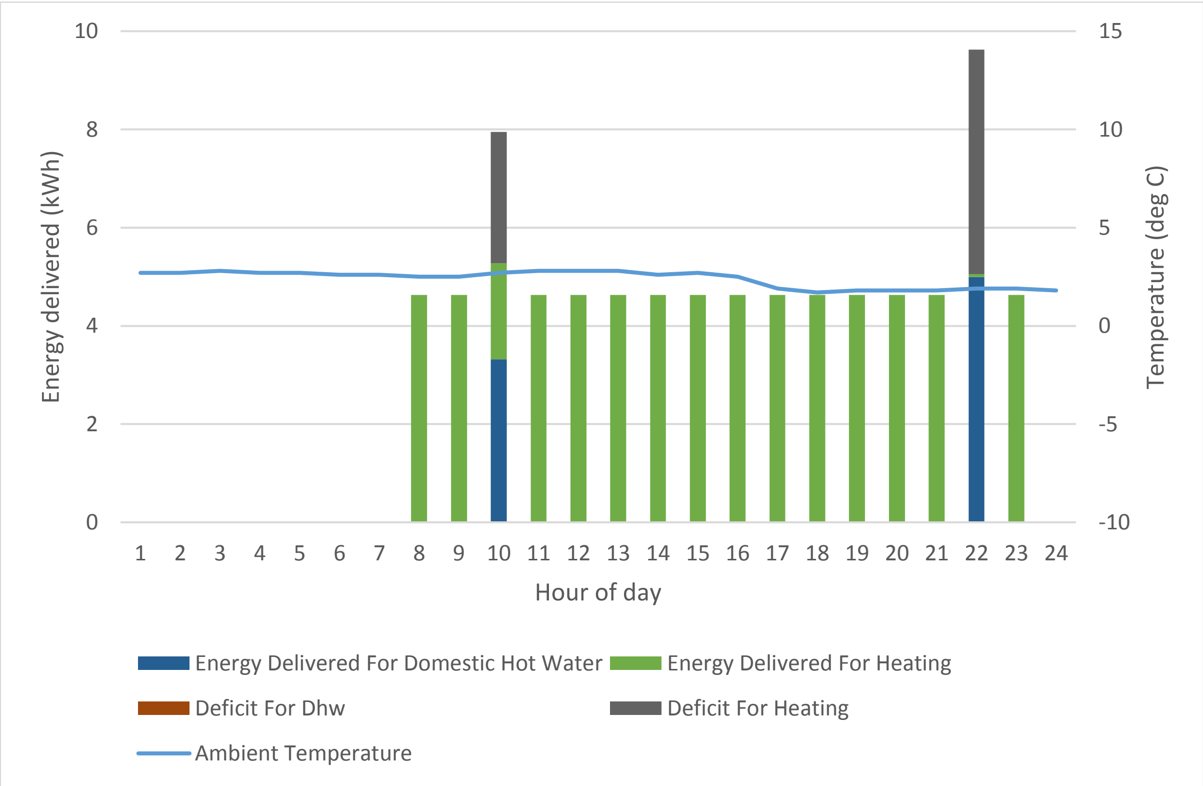

Figure 6 - Example heat pump – Energy delivered on the coldest day of the year on which 16-hour heating is supported, with PSR = 0.8

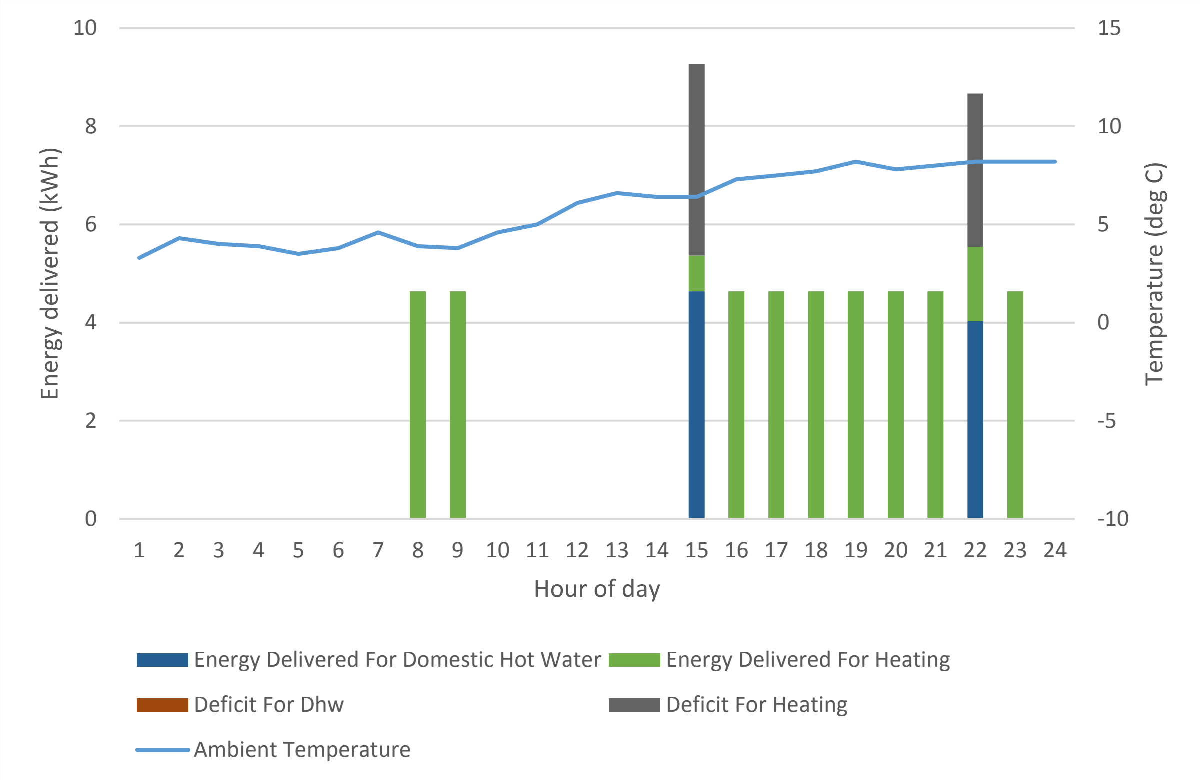

Figure 7 - Example heat pump – Energy delivered on the coldest day of the year on which 11-hour heating is supported, with PSR = 0.8

4 Calculation method validation

In order to determine if the development of the annual combined space and hot water heating duty cycle, in combination with implementing prEN15316-4-2, enables a reasonably accurate estimate of heat pump system annual efficiency, it was necessary to validate the method.

The Department for Business, Energy and Industry Strategy's Renewable Heat Premium Payment (RHPP) heat pump metering programme has involved a number of organisations, including BRE. The analysis of data has been undertaken by University College London (UCL) and unpublished data was supplied to BRE for the purpose of validating calculation method results. This data had been extensively filtered to ensure only sites with suitably robust meter readings were used.

The RHPP monitoring programme featured twenty-two RHPP installation sites with a particular model of air-source heat pump (8.5 kW). Figure 8 displays SPF (H4) estimates calculated using the calculation method for this example heat pump at a range of Plant Size Ratios. The calculation assumes that Weather Compensation has been enabled. The SPF values are multiplied by an in-use factor (IUF) of 0.95 to allow for uncertainties in the calculation method.

Figure 8 features measured SPF (H4) values from sixteen of the twenty-two relevant RHPP sites. The process for including these was:

- SPF (H4) measured values are plotted against a design flow temperature (taken at -4.7°C) as per the SAP calculation method. The design flow temperature was processed and corrected during the RHPP field trial analysis process, then extrapolated to a design flow temperature of -4.7°C.
- Weather compensation was observed as being active from flow temperature measurements

Though considerable measurement uncertainty clearly exists, and no design heat load information for RHPP installation sites is available (to derive PSR), the calculation method still provides reasonable agreement with measured results. It is also clear that Ecodesign SCOP values appear to over-predict performance.

From the RHPP data, it is also clear that lowering the design flow temperature does not always result in higher SPF. For five sites the SPF is considerably lower than predicted, which is counter-intuitive. It is hypothesised that this reduced performance is caused by excessive on/off cycling, which wastes energy and is likely caused by poor controls. Analysing such site-specific behaviour within a calculation method is unlikely to be practical.

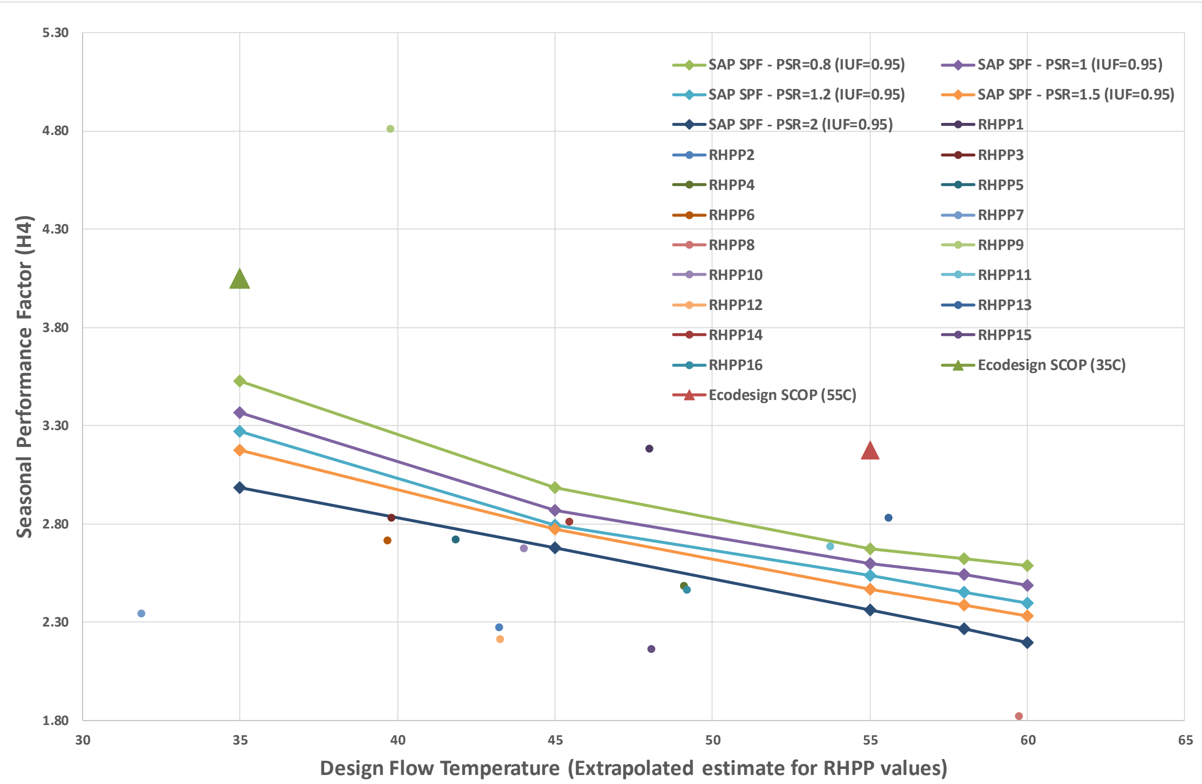

Figure 8 - Example 8.5kW ASHP with Weather Compensation - Extrapolated estimate of Design Flow Temperature Vs RHPP Measured and Predicted SPF

Figure 9 displays measured SPF (H4) values for the remaining six RHPP sites, which were observed to have weather compensation disabled. It compares these to SPF H4 estimates using the calculation method. Similar conclusions regarding calculation method accuracy can be drawn. Note that Ecodesign SCOP always assumes weather compensation is present and enabled, so in cases where it is not, the accuracy of the SCOP performance estimate is further reduced.

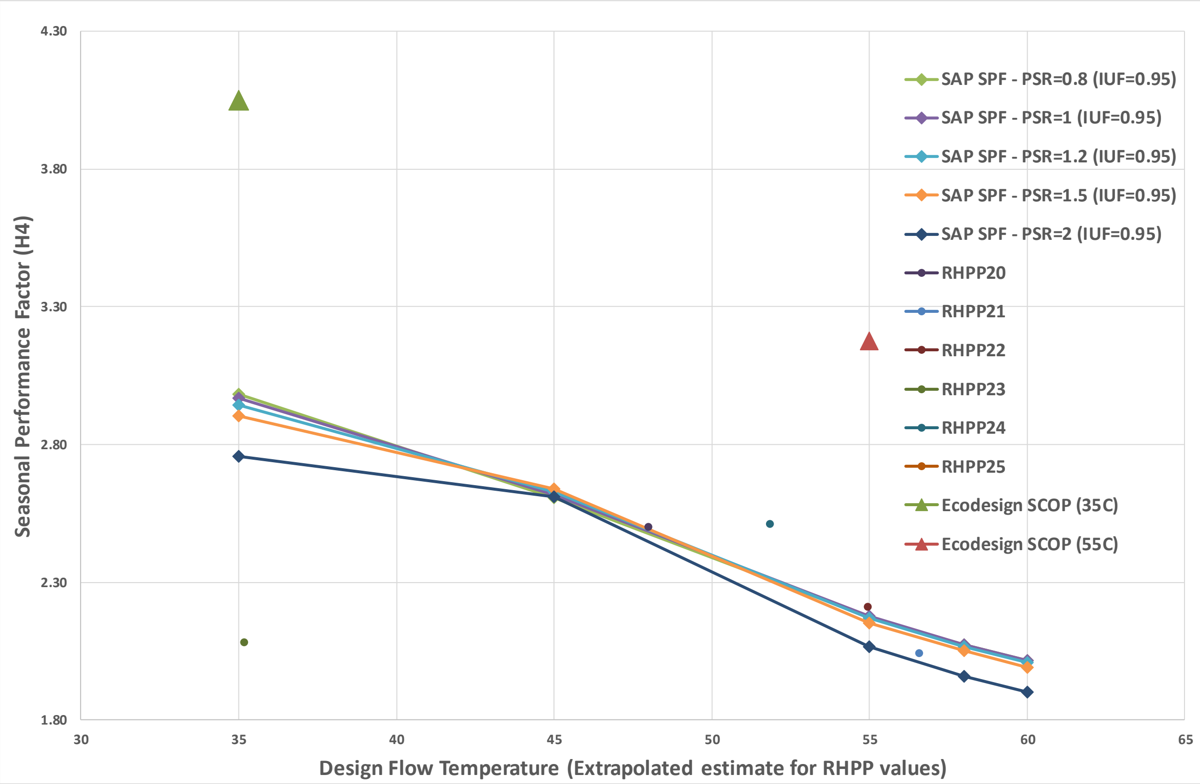

Figure 9 - Example 8.5kW ASHP with No Compensation - Extrapolated Estimate of Design Flow Temperature Vs RHPP Measured and Predicted SPF

Figure 10 displays SPF (H4) values calculated using the calculation method (with no in-use factor applied) to demonstrate the scope of the method. It displays the effect of:

- Design flow temperature
- Presence of weather compensation
- Plant Size Ratio

It is interesting to note that installations with no weather compensation are much less sensitive to PSR.

It is generally recognised that highest annual efficiencies occur at PSRs of 0.5 to 0.8. Figure 10 agrees with this conclusion, though it should be noted that the effect of larger PSRs is lessened with modern variable capacity (inverter) heat pumps, where the minimum modulation is typically around 40%. Nevertheless, the Microgeneration Certification Scheme (MCS), specifically the standard MIS3001, requires that the PSR is at least 1.

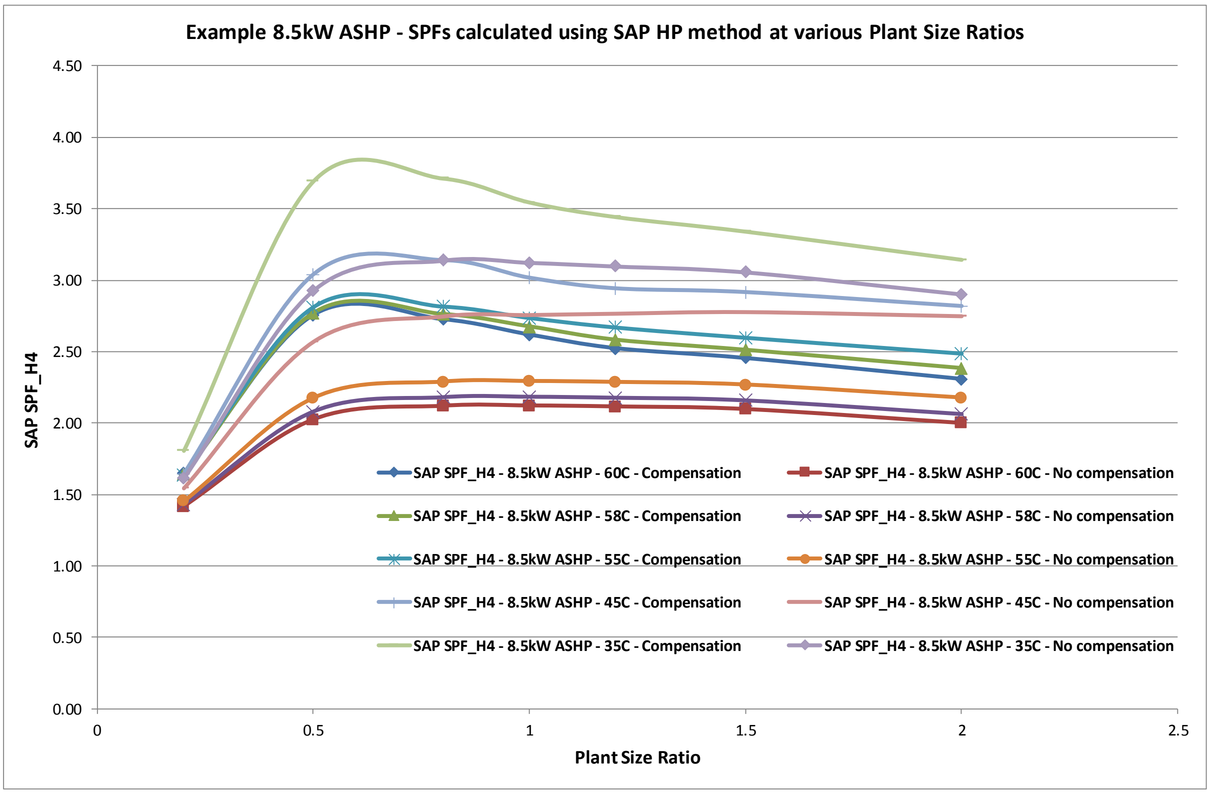

Figure 10 - Example 8.5kW ASHP - SPFs calculated using SAP HP method at various Plant Size Ratios

5 Conclusion

The calculation method demonstrates a reasonable approach to predicting domestic heat pump annual performance whilst accounting for a significant number of influencing variables. The development of a combined space and hot water heating duty cycle enables a rigorous assessment of annual performance, whilst the development of a PCDB application portal website, calculation engine, and the publicly-available PCDB file itself means that calculation outputs could be a useful resource for policy purposes other than SAP in future.

Example calculation method results highlight the hypothesis that poor controls can have a negative effect upon annual efficiency, due to excessive on/off cycling. The method provides a suitable indication of the efficiency that could otherwise be expected, which could be used to interrogate performance expectations for an installation site.

In principle, annual efficiency calculations could be performed on an installation site specific basis, which could include amending the duty cycle assumptions for that purpose. Such calculations could be used for informing performance expectations for housing developments.

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