SAP 10 Technical Paper
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SAP heating efficiency calculation for condensing boilers

Issue 1.2

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DOCUMENT REVISION LOG

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Executive summary

The heating efficiency of mains gas, LPG and oil condensing boilers, and the effect of compensating controls, is considered within the UK's National Calculation Methodology for energy rating of dwellings (SAP). Efficiency values are derived using a calculation method developed in 1998, known as SEDBUK (Seasonal performance of domestic boilers in the UK). The calculation method and its assumptions were examined in view of Ecodesign Regulations coming into force.

Boiler packages within the regulations consist of a condensing boiler and some form of "Temperature Control" and are labelled on a scale from A++ to G, in part based on laboratory test data. The complete details are noted within a supporting document available in the Official Journal of the European Union (EU). These were examined and it was concluded that the Ecodesign annual energy efficiency cannot be used in SAP because it:

- Includes the electricity consumption of the boiler package with a fixed primary energy factor of 2.5. In SAP, the efficiency is the ratio of the useful heat extracted and the fuel used. Electrical consumption is dealt with separately using a CO_2 factor for electricity
- Uses a different climate zone – One of three zones within the EU. No climate zone is particularly representative of the UK
- Relies too much on the measured heat efficiency at part load conditions, owing to inappropriate assumptions for heating load – the UK's typical heating load will exceed the assumptions within the Ecodesign regulations

There are eight classes of "temperature controls", termed Class I – VIII, specified by the Regulations. These were compared to the SAP definitions for Weather Compensation and Enhanced Load Compensation controls. It is recommended for SAP 10 (in terms of boiler efficiency adjustment only) that:

- Classes II to VIII, excluding IV, are separately identified and recognised

- Class I (a minimum requirement under the Building Regulations) and Class IV do not need identification for SAP assessments since they do not compensate
- Class VIII is recognised as being equivalent to Class V for the purposes of SAP

The efficiency of a condensing boiler varies seasonally, being lowest in the winter and highest in the late spring and early autumn. This variation is included implicitly in the SAP 2009 seasonal heating efficiency. An hourly calculation method was developed to explore the annual variation in boiler water return temperature and its effect upon heating efficiency. This method utilises the design flow temperature of the heat emitter system and is similar to the revised heat pump calculation method, which is based on prEN15316-4-2. The calculation method uses hourly weather data (East Pennines) to determine the hourly heat load and required flow temperature. The method is also influenced by prEN15316-4-1, which includes an allowance for on/off cycling losses[1].

Calculation results showed that heat emitters sized in accordance with common practice (design flow temperature of 80°C) may have inadequate heat output to produce sufficient heat over an 11-hour period (standard SAP heating hours) during the coldest days of the year. Therefore, for consistency with the annual efficiency calculation methods for Heat Pumps and Micro-cogeneration (also known as microCHP) in SAP, it is recommended that variable[2] heating hours are introduced to the boiler annual efficiency calculation[3] for SAP 10.

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[1] Basing the method entirely upon prEN15316-4-1 was considered, but it has several shortcomings, including the use of a standard tabular approach to efficiency variation with return temperature. This revised method calculates efficiency directly.

[2] Variable is an idealised control method for the purposes of the calculation method and uses specific controls that ensure that 16 hour operation or 24 hour operation is only required on certain days when the heat required cannot be met by operating for 9 hours/day or 16 hours/day respectively

[3] For the purposes of the seasonal efficiency calculation, this means that to satisfy the SAP heating delivery pattern requirement, the dwelling must be heated for 24 hours/day for three days of the year and 16 hours/day instead of 9 hours/day for nine days.

Utilising this calculation method for a range of condensing boilers currently entered in the SAP Product Characteristics Database (PCDB) has led to the recommendation (for SAP 10) that an amendment to the SAP/SEDBUK 2009 seasonal efficiency calculation is made, whereby the offset term is amended. The calculation is otherwise an average of both full and part load efficiency test results. Using the hourly calculation method for each new boiler entered into the PCDB was found to be unnecessary.

Additionally, a generic range of corrections should be applied to the calculated seasonal space heating efficiency. Determining a correction for individual boilers in the PCDB was also found to be unnecessary. This correction is based on the Ecodesign Control Class, the design flow temperature (80ºC, 70ºC, 55ºC, 45ºC, 35ºC), the fuel (mains gas, LPG and oil) and boiler firing control (modulating or on/off). Efficiency adjustments are calculated on the basis that they achieve almost ideal weather compensation, no compensation, or halfway in-between.

No changes are proposed for the treatment of non-condensing boilers in SAP 10.

The electricity consumption of boilers is measured as a requirement of the Ecodesign regulation; though circulation pump power is not. These measurements should be used for the purposes of SAP 10, replacing the annual electricity default assumption.

Water heating data is included in the Regulation’s requirements for combination boilers but this does not affect SAP, since this data can already be recognised (provision for EN13203 test data was introduced in SAP 2009, though only for Tapping Schedule M or Schedule M <u>and</u> S <u>or</u> L).

The Energy Balance Validation (EBV) method was introduced to improve the reliability of part load and full load test efficiency values, which are subsequently processed for entry in the PCDB. Boilers are entered in the PCDB if the direct measure is not more than 4 and 2 percentage points (net efficiency) higher, for part and full load test respectively, than an efficiency value derived from the Flue Loss Method. The EBV method has been extended to LPG and oil boilers, and the part load efficiency allowance is reduced to 2.5 percentage points.

CONTENTS

1. Introduction

Ecodesign energy labelling[4] and minimum performance[5] regulations were published in September 2013 and were supported by a European Commission Communication[6] published in July 2014. This report considers the annual performance of condensing gas and oil boilers, as determined in the National Calculation Method for energy rating of dwellings (SAP), and whether the current SEDBUK[7] 2009 method should be revised, in particular the treatment of low temperature heating systems and compensating controls.

The following heating controls are not considered:

1. Those that reduce boiler cycling by delaying boiler firing - since any benefit achieved is at the cost of reduced comfort
2. Delayed start controls - they are credited separately in SAP

An hourly calculation method was developed to explore the expected variation in annual emitter temperatures and hence variation in the space heating efficiency for condensing

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[4] *Commission Regulation (EU) no 811/2013 Supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of space heaters, combination heaters, packages of space heater, temperature control and solar device and packages of combination heater, temperature control and solar device, OJ L 239, 6.9.2013, p 1.*

[5] *Commission Delegated Regulation (EU) No 813/2013 implementing directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters, OJ L 239, 6.9.2013, p 136.*

[6] *Commission communication in the framework of the implementation of Commission Regulation (EU) No 813/2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters and of Commission Delegated Regulation (EU) No 811/2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of space heaters, combination heaters, packages of space heater, temperature control and solar device and packages of combination heater, temperature control and solar device, OJ (2014/C page 207/02), 3.7.2014.*

[7] *Seasonal Efficiency of Domestic Boilers in the UK, see SAP 2012 specification (Appendix D) at: www.bre.co.uk/sap2012*

boilers. Variation in efficiency by boiler firing options, emitter design flow temperature and the presence of weather compensation is also examined. The method replicates the approach used for heat pumps and is therefore influenced by prEN15316-4-2. It is also influenced by prEN15316-4-1.

The utilisation of electrical power measurements arising from Ecodesign requirements and means for improving the reliability of efficiency test measurements are also discussed.

2. SEDBUK history

The method for calculating the annual efficiency of domestic boilers in the UK (SEDBUK) was developed in 1998 and based on boiler signature data observed in the field for gas on/off regular boilers and gas modulating combination boilers. The signature data for on/off boilers was a series of gas on-times and off-times throughout the year. For modulating boilers the signature data also measured firing rate. Key parameters included boiler heat output at maximum and minimum rate compared to the dwelling's heating requirement. These parameters may have changed over time, particularly with the widespread adoption of modulating gas condensing boilers.

Historically, the SEDBUK method was an annual efficiency value that combined space and water heating annual efficiency, where a minimum standard was referenced in the Building Regulations.

The SEDBUK method[8] uses the simple unweighted numerical average of the heat efficiency measured at full load (100%) and part load (30%) as a starting point for the annual calculation. The method uses equal weighting factors to reduce the effect of measurement uncertainty. The simple average implies an average annual load of 65%. The offset in the SEDBUK formula adjusts the annual efficiency average to force agreement with performance implied by boiler signature data.

Changes introduced in SAP (SEDBUK) 2009 were:

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[8] Appendix D, SAP 2012

a) Splitting the annual efficiency into summer and winter efficiency values

b) Introduced deduction to account for the differences observed between units submitted for testing and production models

c) Rejecting boiler test results when either the declared full load or part load efficiency was higher by 2 and 4 percentage points respectively than that derived from the flue loss method.

d) Provision for acceptance of EN13203-2:2006 hot water production efficiency data for combination boilers

SAP provides a 3% efficiency credit to condensing gas boiler space heating efficiency (only) when controlled by either an Enhanced Load Compensator or Weather Compensator. A credit of 1.5% is applied for oil or LPG condensing boilers. These devices must be capable of reducing the flow water temperature at times when the heating load has reduced, but not when there is a high load.

The summer hot water efficiency in SAP for combination boilers not supported by EN13203-2 data and for all regular boilers is derived from boiler operational signature data during summer. The derivation assumes the boiler is 55K above the room temperature at the start of an off-period. The average return water temperature is implicitly assumed by taking the mean of the full and part load efficiency, giving a return (primary water) temperature of 45ºC.

Note provision (d) above provides an alternative method for estimating combination boiler hot water efficiency and is based on laboratory water heating efficiency measurements.

3. Ecodesign regulations

Ecodesign regulations concerning energy labelling (EU Regulation 811/2013)[4] and minimum performance (EU Regulation 813/2013)[5] of space and hot water heating boilers were published in September 2013. The energy label requires boiler packages to be labelled on a scale of A++ to G based on the energy efficiency of the boiler package.

The Regulations define the energy efficiency as the ratio of useful heat generated to the quantity of fuel required. Both are measured in a laboratory at the nominal heat output (the heat output quoted by manufacturers' literature) at high temperature (80/60°C) and at 30% part load at low temperatures (return water temperature of 30°C). These efficiencies are then averaged using weighting factors.

To derive the annual space heating energy efficiency of a boiler package (where a boiler is sold with a controller satisfying one of the temperature control class definitions – see Section 3.1), an addition is made depending on the temperature control class.

The annual space heating energy efficiency is used as a basis for the label rating class (an outline of the method to calculate an energy efficiency and consumption is given in Annex VII of Regulation No 811/2013).

In addition, information for combination boilers regarding hot water generation efficiency is added to the fiche and is derived from hot water heating tests (EN13203). It is also used for the energy label.

The regulation does not specify the exact test methods and standards, it instead states: *"For the purposes of compliance and verification of compliance with the requirements of this Regulation, measurements and calculations shall be made using harmonised standards the reference numbers of which have been published for this purpose in the Official Journal of the European Union, or using other reliable, accurate and reproducible methods that take into account the generally recognised state-of-the-art methods".* An official communication was published in the Official Journal of the European Union in July 2014 specifying the relevant harmonised standards[6].

The regulation requires that technical documentation should include the following parameters as indicated in Table 7 of Annex 5, EU Regulation 811/2013[4].

Table 7

Technical parameters for boiler space heaters, boiler combination heaters and cogeneration space heaters

Model(s): [information identifying the model(s) to which the information relates]

Condensing boiler: [yes/no]

Low-temperature (**) boiler: [yes/no]

B11 boiler: [yes/no]

Cogeneration space heater: [yes/no] If yes, equipped with a supplementary heater: [yes/no]

Combination heater: [yes/no]

Item	Symbol	Value	Unit	Item	Symbol	Value	Unit
Rated heat output	*Prated*	x	kW	**Seasonal space heating energy efficiency**	η_s	x	%
For boiler space heaters and boiler combination heaters: Useful heat output				For boiler space heaters and boiler combination heaters: Useful efficiency			
At rated heat output and high-temperature regime (*)	P_4	x,x	kW	At rated heat output and high-temperature regime (*)	η_4	x,x	%
At 30 % of rated heat output and low-temperature regime (**)	P_1	x,x	kW	At 30 % of rated heat output and low-temperature regime (**)	η_1	x,x	%
For cogeneration space heaters: Useful heat output				For cogeneration space heaters: Useful efficiency			
At rated heat output of cogeneration space heater with supplementary heater disabled	$P_{CHP100+Sup0}$	x,x	kW	At rated heat output of cogeneration space heater with supplementary heater disabled	$\eta_{CHP100+Sup0}$	x,x	%
At rated heat output of cogeneration space heater with supplementary heater enabled	$P_{CHP100+Sup100}$	x,x	kW	At rated heat output of cogeneration space heater with supplementary heater enabled	$\eta_{CHP100+Sup100}$	x,x	%
For cogeneration space heaters: Electrical efficiency				Supplementary heater			
At rated heat output of cogeneration space heater with supplementary heater disabled	$\eta_{el,CHP100+Sup0}$	x,x	%	Rated heat output	*Psup*	x,x	kW
At rated heat output of cogeneration space heater with supplementary heater enabled	$\eta_{el,CHP100+Sup100}$	x,x	%	Type of energy input			
Auxiliary electricity consumption				Other items			
At full load	*elmax*	x,x	kW	Standby heat loss	P_{stby}	x,x	kW
At part load	*elmin*	x,x	kW	Ignition burner power consumption	P_{ign}	x,x	kW
In standby mode	P_{SB}	x,xxx	kW	Annual energy consumption	Q_{HE}	x	kWh or GJ
				Sound power level, indoors	L_{WA}	x	dB

Figure 1 - Table 7, Annex 5 of EU Commission Regulation No 811/2013

The details of the efficiency calculations for the boiler energy label are not published in the Regulation but appear in supporting standards. The supporting publication states:

The annual space heating energy efficiency η_s *is defined as:*

$\eta_s = \eta_{son} - \Sigma F(i)$

where:

η_{son} *is the active efficiency defined as* $\eta_{son} = 0.85 \times \eta_1 + 0.15 \times \eta_4$

(η_1 *and* η_4 *is the measured efficiency at part load and full load).*

ΣF(i) is the summation of a series of adjustments in percentage points.

F(1) - accounts for a negative contribution[9] *to the annual space heating energy efficiency of heaters due to adjusted contributions of temperature controls to annual space heating energy efficiency of the package.*

F(2) accounts for a negative contribution to the annual space heating energy efficiency by auxiliary electricity consumption. For boilers this is

$$F(2) = 2.5 \times (0.15 \times elmax + 0.85 \times elmin + 1.3 \times P_{SB}) / (0.15 \times P_4 + 0.85 \times P_1)$$

(P_1*,* P_2 *and* P_{SB} *are measured useful heat output at part load and full load and the standby heat loss respectively, with elmax and elmin being the maximum and minimum auxiliary electricity consumption.*

F(3) accounts for a negative contribution to the annual space heating energy efficiency by standby heat loss and is given as follows:

[9] This negative value is specified as 3% and reflects the absence of temperature controls in the default case. The F(2), F(3) and F(4) definitions have erroneously omitted a “x100” term necessary for conversion to efficiency.

For boilers this is:

$F(3) = 0.5 \times P_{stby} / P_4$ P_{stby} *is the standby heat loss.*

F(4) accounts for a negative contribution to the annual space heating energy efficiency by ignition burner power consumption and is given as follows for boilers:

$F(4) = 0.5 \times P_{ign} / P_4$ P_{ign} *is the ignition power*

F(5) accounts for a positive contribution to the annual space heating energy efficiency by the electrical efficiency of co-generation space heater.

3.1 Temperature control classes

For recognition of temperature control class within the boiler package, the regulation requires the following to be specified:

- The temperature control class number
- The contribution of the temperature control to annual space heating energy efficiency in %

The definitions of the class types and efficiency correction defined by the regulation are:

Class I - On/off Room Thermostat: A room thermostat that controls the on/off operation of a heater. Performance parameters, including switching differential and room temperature control accuracy, are determined by the thermostat's mechanical construction.

Class II - Weather compensator control, for use with modulating heaters: A heater flow temperature control that varies the set point of the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. Control is achieved by modulating the output of the heater.

Class III - Weather compensator control, for use with on/off output heaters: A heater flow temperature control that varies the set point of the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather *compensation curve. Heater flow temperature is varied by controlling the on/off operation of the heater.*

Class IV - TPI[10] room thermostat, for use with on/off output heaters: An electronic room thermostat that controls both thermostat cycle rate and in-cycle on/off ratio of the heater proportional to room temperature. TPI control strategy reduces mean water temperature, improves room temperature control accuracy and enhances system efficiency.

Class V - Modulating room thermostat, for use with modulating heaters: An electronic room thermostat that varies the flow temperature of the water leaving the heater dependent upon measured room temperature deviation from room thermostat set point. Control is achieved by modulating the output of the heater.

Class VI - Weather compensator and room sensor, for use with modulating heaters: A heater flow temperature control that varies the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. A room temperature sensor monitors room temperature and adjusts the compensation curve parallel displacement to improve room comfort. Control is achieved by modulating the output of the heater.

Class VII - Weather compensator and room sensor, for use with on/off output heaters: A heater flow temperature control that varies the flow temperature of water leaving the heater dependent upon prevailing outside temperature and selected weather compensation curve. A room temperature sensor monitors room temperature and adjusts the compensation curve parallel displacement to improve room comfort. Heater flow temperature is varied by controlling the on/off operation of the heater.

Class VIII – Multi-sensor room temperature control, for use with modulating heaters: An electronic control, equipped with 3 or more room sensors that varies the flow temperature of the water leaving the heater dependent upon the aggregated measured room

[10] Time proportional and integral

temperature deviation from room sensor set points. Control is achieved by modulating the output of the heater.

Control Class Number	I	II	III	IV	V	VI	VII	VIII
Contribution to the annual space heating efficiency (percentage points)	1%	2%	1.5%	2%	3%	4%	3.5%	5%

Table 1 – Ecodesign regulation (811/2013) temperature control class efficiency corrections

The technical development of these values and hence reliability is not stated in any literature.

3.2 Relevance of Ecodesign regulations for SAP

The efficiency determined for Ecodesign regulations is not the same as the efficiency required for SAP and cannot be used directly for a number of reasons, including:

- The regulation is concerned with the energy performance of a boiler product, though in some cases (as chosen by the supplier) as a boiler package, whereas SAP is concerned with the energy efficiency of a dwelling heating system.

- The regulation includes the electricity consumption of the boiler package within the label and assumes a fixed primary energy factor of 2.5. Whereas the SAP space heating efficiency is the ratio of useful heat extracted to fuel input. Electrical consumption is dealt with separately and is based on SAP's CO_2 emission factors.

- The energy efficiency of a condensing boiler is affected by the characteristics of heating controls which may not form part of the boiler package as sold. The effect of any controls that are part of the package are added to the weighted average efficiency. The technical basis of these adjustments for controls (Table 1) is unclear.

- The regulation covers three climate zones within the EU and EEA. The northern and eastern parts of the UK correspond closest to the middle EU zone (Strasbourg) and southern and western parts of the UK correspond closest to southern EU zone. No zone is particularly representative of the UK average.

- The regulation applies a weighting factor of 85% to the active efficiency at 30% part load and 15% to the active efficiency at full load to derive a weighted average efficiency. This means the weighted average is heavily reliant on the part load measurement which has a larger measurement uncertainty than the full load measurement. These weighting factors effectively assume the average heating load is 40% and return water temperature is 34.5ºC. The consequences of the assumed weighting factors are discussed in chapter 6.

4. Annual space heating performance calculation description

4.1 General principles

To assess the performance of condensing boilers for a range of design emitter temperatures (also known as the mean water temperature) an hourly calculation method is developed that follows the main principles of the revised SAP heat pump calculation method – see: www.ncm-pcdb.org.uk/sap

The method uses an hourly efficiency that is estimated from the return water temperature and an efficiency-return water temperature curve. These vary on an hourly basis with reference to the space heating load, whereby the annual space heating efficiency is determined by the summation of the hourly heat energy requirements divided by the summation of the hourly fuel energy.

The efficiency-return water temperature curve is derived from validation by the Energy Balance (EBV) method and is adjusted to match the standard laboratory measurement of the efficiency at part and full load. It shows the efficiency curve for oil, LPG and mains gas. The curves differ between fuels primarily because of the different amounts of water produced by combustion.

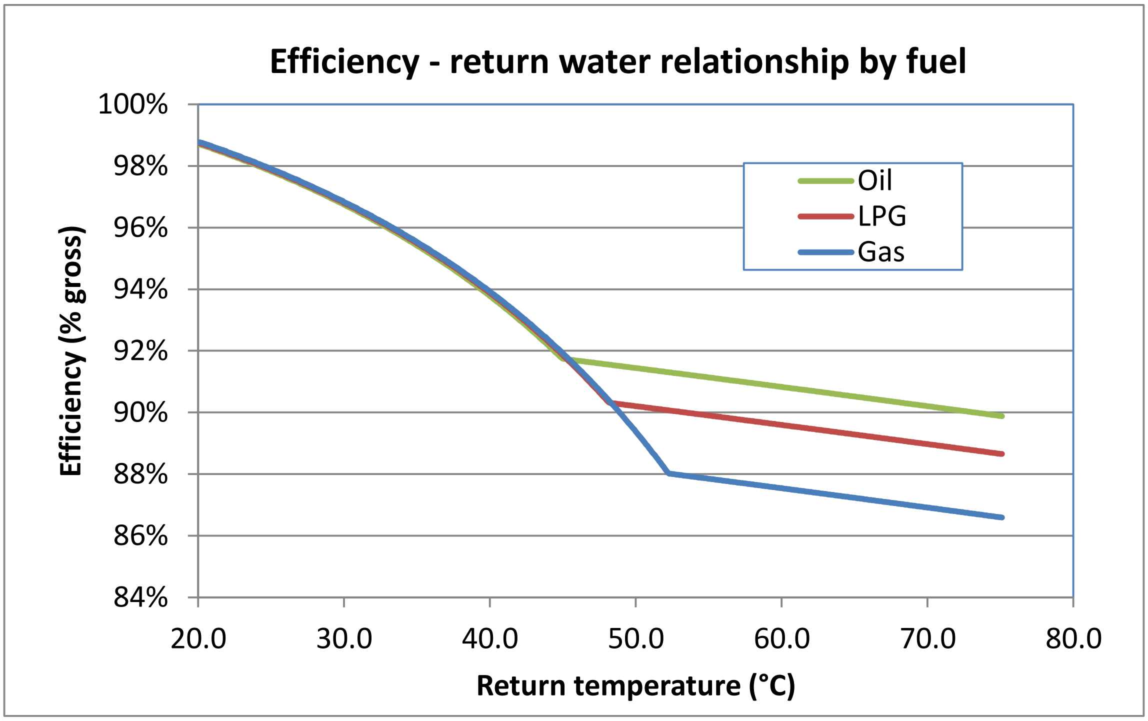

Figure 2 - Boiler efficiency - return water temperature relationship by fuel

The hourly return water temperature is analysed in the same way as that used for the revised SAP heat pump calculation method, but with the following variations depending on the control options selected:

a) Perfect weather and load compensator – the mean emitter temperature (and hence water return temperature) is that required to exactly match the dwelling heat losses after accounting for internal heat gains
b) No compensator – the return water temperature is taken as the design value throughout the heating season
c) Constant water flow rate throughout the heating season
d) Water flow rate controlled to maintain the same temperature difference across the boiler throughout the year

An adjustment to the hourly efficiency is introduced to account for the time when the boiler is cycling on/off at the minimum firing rate. For on/off boilers the minimum rate for firing continuously is 100% of the maximum (nominal) heat output.

To better account for intermittent heating the energy required to warm the emitters and primary water is supplied within the hour prior to the start of the heating period. This energy is then counted as useful heat gain during the heating period.

Note: the annual space heating efficiency is not numerically the same as the mean of hourly efficiencies because the calculation of the consumption involves the reciprocal of the efficiency and the heating load varies throughout the heating season.

4.2 Climate data

Hourly external temperatures ($T_{o,h}$) are sourced from CIBSE Guide J and are based on a Test Reference Year for Leeds (location close to the East Pennines Region, which is the region used for SAP calculations, see SAP 2012 - Table U1). The CIBSE values were normalised for consistency with SAP monthly average temperatures as:

$$T_{o,h} = T_{o,h}(Leeds) - (\bar{T}_o(Leeds) - \bar{T}_o(SAP)) \qquad ^{o}C \qquad (1)$$

The subscript "h" denotes hourly and the vinculum (over bar) denotes monthly average.

4.3 Heating load

The heating load depends principally on the required dwelling temperature, the outside air temperature, the rate of heat loss from the dwelling, the useful incidental internal heat gains (e.g. from the sun or electrical appliances) and the hours of heating.

The heat requirement of a dwelling is the net balance of the heat losses (Q_{loss}) offset by any useful heat gains (Q_{useful}).

$$Q_{H,gen,out} = Q_{loss} - Q_{useful} \qquad kWh \qquad (2)$$

The heat losses are proportional to the temperature difference between the inside (T_{in}) and the outside (T_o) of the dwelling $(T_{in} - T_o)$. Defining the heat loss coefficient of the dwelling (W/K) as 'H', the net heat balance becomes (t_{ci} is the calculation time interval – 1 hour):

$$Q_{H,gen,out} = (T_{in} - T_o) \times H \times t_{ci} - Q_{useful} \quad \text{kWh} \quad (3)$$

Making '*H*' a common factor gives:

$$Q_{H,gen,out} = (T_{in} - \frac{Q_{useful}}{H} - T_o) \times H \times t_{ci} \quad \text{kWh} \quad (4)$$

Note: $T_{in} - \frac{Q_{useful}}{H}$ is defined as the base temperature (T_b), making the energy balance equation:

$$Q_{H,gen,out} = (T_b - T_o) \times H \times t_{ci} \quad \text{kWh} \quad (5)$$

The Plant Size Ratio (PSR) is defined as the nominal boiler heat output, Q_{nom}, divided by the dwelling specific heat loss (*H*) multiplied by the design temperature difference between inside and outside of the dwelling. This can be used to eliminate the specific heat loss from the above equation to give:

$$Q_{H,gen,out} = \frac{(T_b - T_o) \times Q_{nom} \times t_{ci}}{PSR \times \Delta T_{d,d}} \quad \text{kWh} \quad (6)$$

Space heating can only be provided during the period of heating (h) and must be able to meet the balance of heat losses during both the on-period and the off-period (i.e. overnight), therefore the average heating load fraction due to this intermittency, F_{load_inter}, expressed as a fraction of the nominal heat output is:

$$F_{load\_inter} = \frac{24 \times (T_b - T_o)}{PSR \times h \times (\Delta T_{d,d})} \quad - \quad (7)$$

Where:

h is the hours of operation per day (24, 16, 11 or for variable hours see below). For SAP, the standard heating period is 16 hours at weekends and 9 hours in the week, giving an average of 11 hours/day

T_b is the <u>daily</u> 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 (see next section for details)

T_o is the daily average outside air (dry bulb) temperature (ºC)

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

4.4 Variable heating hours

There are some cold days when the heat emitter system may not be adequate to provide sufficient heat within the 11-hour heating period, even when sized to the usual guidelines (e.g. increasing the emitter size by a factor of 1.2 to allow for intermittent heating). In this case the hours of operation are extended to 16 or 24 hours/day, whichever is the lowest necessary to satisfy the heat requirement.

Boilers in practice usually have a plant size ratio of 1.8 or higher and as such it is expected that they can provide sufficient heat even on the very coldest days. However, the emitter's size will restrict this heat output. This means that for the purpose of calculating the number of days requiring extended heating, an effective plant size ratio of 1.2 is applicable.

For the Leeds test reference year, normalised to SAP 2012 monthly average temperatures, a 34-week heating season (238 days) will contain:

- 9 days when the heating period required is 16 hours/day, instead of 9 hours/day
- 2 days when the heating period is 24 hours/day, instead of 9 hours/day
- 1 day when the heating period is 24 hours/day of heating, instead of 16 hours/day

For reference, the hours of heating per day were determined using the following equation:

Calculate the lowest outside temperature (T_{oLi}) that can be met when operating for 24, 16 and 11 hours respectively without requiring system back-up heating.

$$T_{oLi} = T_b - h_i \times PSR \times \Delta T_{d,d} / 24 \quad \text{ºC} \qquad (8)$$

Where the subscript (i) is replaced by 24, 16 and 11 hours

Set the heating operational hours for calculation interval according to:

$h = 24$ when $T_o < T_{oL16}$

$h = 16$ when $T_{oL16} \leq T_o < T_{oL11}$

$h = 11$ when $T_o \geq T_{oL11}$

For consistency with Heat Pumps and Micro-cogeneration (also known as microCHP) applications, variable heating hours are introduced for boilers, with the number of days requiring extended heating hours noted above.

Using the temperature values derived in Table 2, Figure 3 illustrates how the heating load fraction (F_{load_inter}; based on nominal output) varies throughout the heating season when calculated on an hourly basis for:

a) Hourly outside temperatures in the CIBSE Leeds test reference year normalised to the external monthly temperatures used in SAP 2012
b) Plant Size Ratio of 1.8
c) Monthly base temperatures for a dwelling assessed by SAP and comprising a floor area of 100m^2, a medium level of insulation (heat loss parameter of 2.72 W/K per m^2) and a medium level of thermal mass (thermal mass parameter of 245.5 kJ/K per m^2).

	Outside temperature (ºC)	Base temperature (ºC)		
		Heating 11 hours/day	Heating 16 hours/day	Heating 24 hours/day
January	4.3	14.70	15.61	17.27
February	4.9	14.47	15.31	16.86
March	6.5	14.50	15.18	16.44
April	8.9	14.49	15.00	15.94
May	11.7	15.04	15.32	15.85
June	14.6	16.01	16.12	16.34
July	16.6	17.23	17.27	17.32
August	16.4	17.27	17.31	17.38
September	14.1	16.31	16.48	16.79
October	10.6	15.73	16.16	16.96
November	7.1	15.22	15.95	17.29
December	4.2	14.87	15.76	17.39

Table 2 - Monthly external and base temperatures

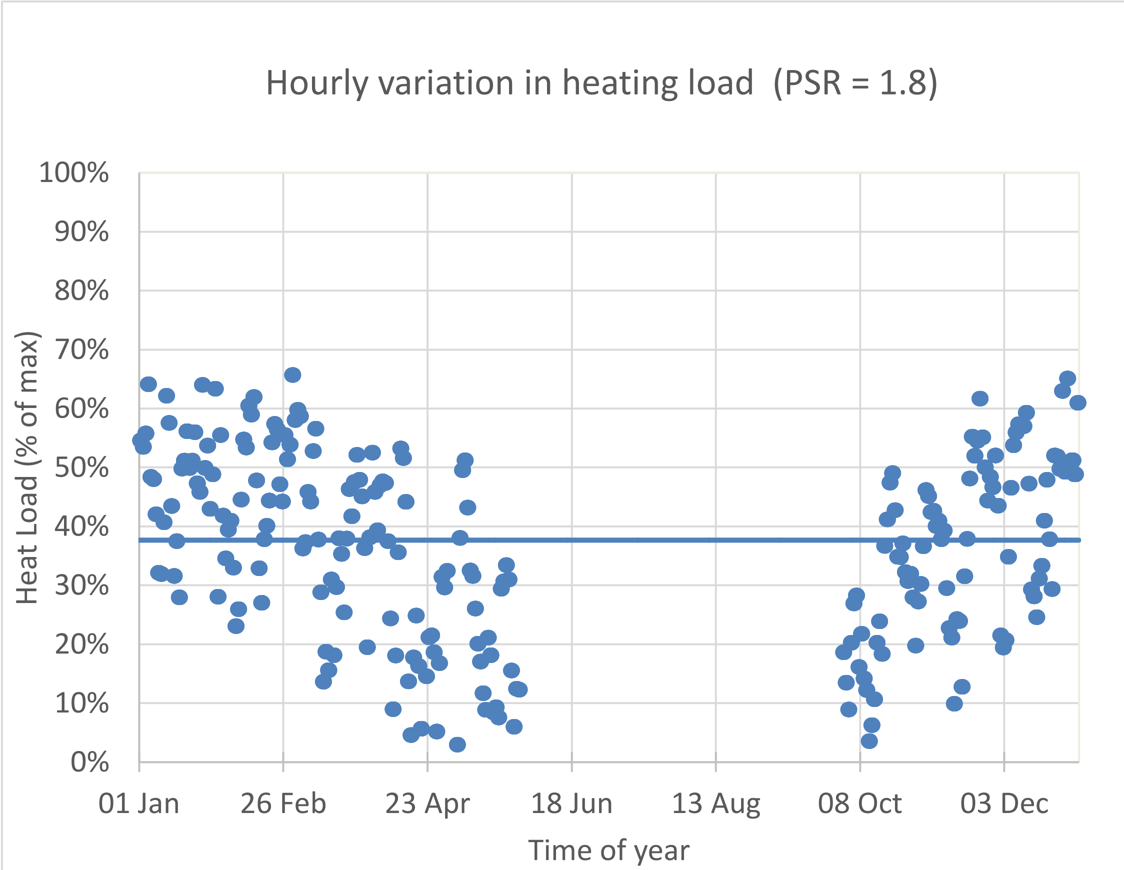

Figure 3 - Variation of heating load fraction (F_{load_inter})

The average space heating annual load is 38% and is denoted as the line in Figure 3. Interestingly, the Ecodesign regulation implies an average annual load of 40% (i.e. 0.85 x 30% + 0.15 x 100%).

4.5 Annual variation in boiler return water temperature

The temperature of water flowing though the boiler whilst firing is a key parameter affecting the efficiency of a condensing boiler. For example, the theoretical maximum gross efficiency of a gas condensing boiler operating at 36°C flow temperature (30°C return) is 97.3%, whereas the gross efficiency when operating at 80°C (60°C return) is 88.3%. The magnitude of the effect on a non-condensing boiler is much less, typically 1% or below.

4.6 Heat emitter temperature

This section analyses the annual variation in heat emitter temperature to derive an hourly return temperature profile.

Heat emitter temperature, often referred to as Mean Water Temperature (MWT), is the average of both flow and return temperatures. The heat emitter temperature will vary throughout the heating season. On cold days the heat emitter temperature required to maintain a room at its demand temperature will be higher than that required on a milder day. The heat emitter temperature depends on many factors, including:

- Emitter power law index
- Emitter design temperature
- Heating and emitter controls
- Boiler modulation and control, if any
- Outside temperature when sizing the heating load
- Intermittency factor applied when sizing the emitters

The simplest solution that can be derived mathematically assumes that a boiler can be perfectly controlled to match the exact instantaneous heating load throughout the year; this solution is derived below.

If the emitter heat output follows a power law, then the heat emitted (Q_E) with an index 'n' is given by:

$$Q_E = Q_{E,d} \frac{(\bar{T}_E - T_{rm,d})^n}{(\bar{T}_{E,d} - T_{rm,d})^n} \qquad \text{kW} \qquad (9)$$

Where:

n	is the power law index (n>0 and typically between 1 and 1.3)
$Q_{E,d}$	is the emitter power output under design conditions
$\bar{T}_E$	is the average of emitter temperature
$\bar{T}_{E,d}$	is the average emitter temperature under design conditions (e.g. 70°C)
$T_{rm,d}$	is the average demand temperature of the dwelling

Under design conditions for emitter sizing, the heat output required to achieve the demand temperature of the dwelling offsets the heat lost from the dwelling exactly[11], after accounting for the emitter intermittency factor, f. Therefore:

$$Q_E = H \times \Delta T_{d,d}/f \quad \text{kW} \quad (10)$$

Where:

H is the specific heat loss of the dwelling (W/K)

f is an emitter intermittency factor (typically 1/f = 1.20)

Substituting (8) into (7) to eliminate $Q_{E,d}$, the emitter heat output is given by:

$$Q_E = \frac{H \times \Delta T_{d,d}}{f} \times \frac{(\bar{T}_E - T_{rm,d})^n}{(\bar{T}_{E,d} - T_{rm,d})^n} \quad \text{kW} \quad (11)$$

From equation (5), the dwelling heat requirement can be expressed in terms of the base temperature (T_b) and the outside air temperature (T_o)

$$Q_{H,gen,out} = (T_b - T_o) \times H \times t_{ci} \quad \text{kWh} \quad (12)$$

The heat output (kW) emitted over 'h' hours of heating per day, must satisfy the heat energy requirement for that day, therefore equating (11) x h = (5) to give:

$$24 \times (T_b - T_o) \times H \times t = \frac{H \times h \times t_{ci} \times \Delta T_{d,d}}{f} \times \frac{(\bar{T}_E - T_{rm,d})^n}{(\bar{T}_{E,d} - T_{rm,d})^n} \quad \text{kWh} \quad (13)$$

Dividing both sides of the equation by H and t_{ci} and rearranging to give the mean emitter temperature ($\bar{T}_E$):

$$\bar{T}_E = T_{rm,d} + (\bar{T}_{E,d} - T_{rm,d})\left(\frac{24 \times f \times (T_b - T_o)}{h \times \Delta T_{d,d}}\right)^{1/n} \quad ^{\circ}\text{C} \quad (14)$$

---

[11] For sizing purposes internal heat gains are neglected

Equation (14) expresses the mean emitter temperature in terms of an outside air temperature, a base temperature and the design parameters of the heat emitter system. It is applied on an hourly basis.

When considering condensing boiler efficiency, the parameter of primary interest is the return water temperature and not necessarily the mean emitter temperature. The boiler return water temperature (T_r) is related to the mean emitter temperature and temperature drop across the emitter (ΔT_E) by: $\bar{T}_E = T_r + \Delta T_E/2$. Putting this expression into (7) and making T_r the subject gives:

$$T_r = T_{rm,d} + (\bar{T}_{E,d} - T_{rm,d})\left(\frac{24 \times f \times (T_b - T_o)}{h \times \Delta T_{d,d}}\right)^{1/n} - \frac{\Delta T_E}{2} \qquad ^{o}C \qquad (15)$$

To eliminate $\frac{\Delta T_E}{2}$ in (15), the only unknown, the water flow rate under design and general conditions is considered in equations (16) and (17).

Under design conditions, the power emitted ($Q_{E,d}$) is related to the temperature drop across the emitter, the mass flow rate ($\dot{m}_{prim\_design}$) of the circulating (primary) water and the specific heat loss of the dwelling by:

$$Q_{E,d} = \dot{m}_{prim\_design} \times \Delta T_{E,d} = \frac{H}{f} \times \Delta T_{d,d} \qquad kW \qquad (16)$$

Under general conditions the power emitted over ‘h’ hours required to satisfy the heat energy requirement is similarly related as:

$$hQ_E = h \times \dot{m}_{prim\_general} \times \Delta T_E = 24 \times H \times (T_b - T_o) \qquad kWh \qquad (17)$$

Where ‘$\dot{m}_{prim\_general}$’ is the mass flow rate of the water under general conditions.

Taking the water flow rate as constant throughout the year (i.e. $\dot{m}_{prim\_general} = \dot{m}_{prim\_design}$), dividing equation (16) by (17) and rearranging to make $\Delta T_E \div 2$ the subject gives:

$$\frac{\Delta T_E}{2} = \frac{\Delta T_{E,d}}{2} \times \frac{24f}{h} \times \frac{(T_b - T_o)}{\Delta T_{d,d}} \quad {}^{o}\mathrm{C} \qquad (18)$$

Finally, using (18) to eliminate $\Delta T_E \div 2$ then (15) becomes:

$$T_r = T_{rm,d} + (\bar{T}_{E,d} - T_{rm,d})\left(\frac{24f(T_b - T_o)}{h \times \Delta T_{d,d}}\right)^{1/n} - \frac{24f(T_b - T_o)}{h \times \Delta T_{d,d}} \frac{\Delta T_{E,d}}{2} \quad {}^{o}\mathrm{C} \qquad (19)$$

Where:

n	is the power law index (≥ 1)
$\bar{T}_{E,d}$	is the average emitter temperature under design conditions
$\Delta T_{E,d}$	is average water temperature difference across the boiler's and emitter's inlet and outlets under design conditions
T_f	is the temperature of water flowing from the boiler under design conditions
T_r	is the temperature of water returning to the boiler under design conditions
$T_{rm,d}$	is the temperature of the room under design conditions
$\Delta T_{d,d}$	is the temperature difference between the inside and outside of dwelling under design conditions
T_o	is the outside temperature
T_b	is the base temperature
f	is the emitter intermittency factor
h	is the hours of heating

Equation (19) shows the boiler return water temperature required to maintain the room at the demand temperature for 'h' hours per day for a given base temperature and outside temperature.

Similarly, the flow water temperature can be calculated from:

$$T_f = T_{rm,d} + (\bar{T}_{E,d} - T_{rm,d})\left(\frac{24f(T_b - T_o)}{h(T_{rm,d} - T_{o,d})}\right)^{\frac{1}{n}} + \frac{24f(T_b - T_o)}{h(T_{rm,d} - T_{o,d})}\frac{\Delta T_{E,d}}{2} \quad {}^{o}C \qquad (20)$$

Expressions (19) and (20) make three important assumptions:

a) The heat output of the emitter follows a power law of index n (n>1)

b) The flow rate of the circulating (primary) water is constant throughout the year. An alternative is to maintain a constant temperature drop across the emitters by adjusting the flow rate. In this case equation (21) applies.

$$T_f = T_{rm,d} + (\bar{T}_{E,d} - T_{rm,d})\left(\frac{24f(T_b - T_o)}{h \times \Delta T_{d,d}}\right)^{\frac{1}{n}} + \frac{\Delta T_{E,d}}{2} \quad {}^{o}C \qquad (21)$$

c) Controls can reduce the boiler thermal output to exactly match the hourly heating requirement

Assumption (a) is reasonable, whilst the sensitivity of (b) is examined in Section 5.3.3. Item (c) depends on the boiler type and controls.

4.7 Warm-up phase

Just prior to the heating period[12], primary water is warmed to the required emitter temperature. This energy will subsequently be released into the room when the emitters eventually cool.

The amount of energy required is the thermal mass of the emitter system (including water) multiplied by the temperature difference between the emitter and the room temperature. The thermal capacity of the emitter system (in kWh) is taken as:

[12] SAP heating hours strictly refer to the time when the dwelling is at the required temperature, rather than the programmed heating hours.

- Emitter water mass: 120 kg (24% of total weight)[13] x 4.18 KJ/kg/K / 3600
- Dry/metal emitter thermal capacity: 120 kg x (76%/24%) x 0.46 KJ/kg/K[14] /3600

SAP considers weekdays and weekends separately; during weekdays there are two heating periods (9 hours in total) and one period at weekends (16 hours). This calculation method represents all days within the heating season as having an 11-hour heating requirement via two heating periods seven days a week[15] (except during very cold weather where the hours of heating may vary – see Section 4.4). This means an adjustment is necessary to correctly represent the amount of energy for each warm-up period.

The number of SAP standard heating periods = 2 x 5 + 1 x 2 = 12 per week. For 11-hour heating the method has 14 periods per week, so an adjusted factor for each 11-hour heating period of 12/14 is introduced. For 16-hour heating no adjustment is necessary, whilst for 24-hour heating there is no warm-up period.

During the warm-up phase the water return temperature will be cooler and this is important to assess. Therefore, in the hour prior to the start of the heating period, the return water temperature is taken as that half-way between the room temperature and required return water temperature during the heating period.

The amount of energy required to warm-up the emitter system is treated like a useful gain and hence reduces the base temperature slightly. This reduced base temperature subsequently reduces the return water temperature.

4.8 Boiler cycling

During certain conditions, the heating requirement may be lower than the minimum produced by a boiler when firing continuously. For on/off boilers the minimum heat output

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[13] This is the average water content by weight of 12 radiators of varying size and type. The water content by weight varies from 21% to 28% of the total.

[14] The 120 kg x 0.76/0.24 is the dry weight of the emitter as 24% by weight is water.

[15] Representing the weekday and weekend profiles would require the calculation to be repeated for seven years, with each year starting on a different day of the week.

is 100%, so this will be true for all conditions. When the heat requirement is lower than the minimum boiler heat output, the boiler will cycle on/off at its minimum firing rate to produce the required output. Under this condition the heat loss during the off-part of the cycle reduces the hourly efficiency as follows.

The instantaneous efficiency (η_{min}) at minimum rate can expressed as a function of the thermal power produced ($P_{out,min}$), the rate of heat loss via the flue ($P_{fl,min}$) and case ($P_{cs,min}$).

$$\eta_{min} = \frac{(P_{out,min})}{(P_{out,min} + P_{fl,min} + P_{cs,min})} \qquad \text{kW/kW} \quad (22)$$

The efficiency when cycling at the minimum rate for time t_{on} and off for t_{off} is:

$$\eta_t = \frac{t_{on} \times P_{out,min}}{(P_{out,min} + P_{fl,min} + P_{cs,min}) \times t_{on} + P_{cs,min} \times t_{off}} \qquad \text{kWh/kWh} \quad (23)$$

This assumes that the heat lost via the flue products is small when the boiler is off, which is reasonable for condensing boilers as they have fan-assisted flues, which shut-down.

Combining (23) and (24) and rearranging gives:

$$\frac{1}{\eta_t} = \frac{1}{\eta_{min}} + \frac{P_{cs,min}}{P_{out,min}} \times \frac{t_{off}}{t_{on}} \qquad - \quad (24)$$

Making the reasonable assumption that $\frac{P_{cs,min}}{P_{out,min}}$ is the same as $\frac{P_{cs,max}}{P_{out,max}}$ when operated at the same mean water temperature and adopting the temperature correction noted in prEN15316-4-1, Section 6.9.4, equation 30 (October 2014 Draft) gives:

$$\frac{P_{cs,min}}{P_{out,min}} = \frac{P_{cs,ref}}{P_{out,ref}} \times \left(\frac{\bar{T}_E - T_{rm}}{\bar{T}_{E,ref} - T_{rm,ref}}\right)^{1,25} \qquad - \quad (25)$$

The subscript “ref” refers to some reference temperature, say, a mean water temperature of 70ºC (i.e. 80/60) – the full load test condition.

Incorporating the temperature correction from equation (25) in equation (24(26) makes the adjusted efficiency due to cycling:

$$\frac{1}{\eta_t} = \frac{1}{\eta_{min}} + \frac{P_{cs,ref}}{P_{out,ref}} \times \left(\frac{\bar{T}_E - T_{rm}}{\bar{T}_{E,ref} - T_{rm,ref}}\right)^{1,25} \times \frac{t_{off}}{t_{on}} \qquad - \qquad (26)$$

prEN15316-4-1: Equation (49) and Table B.3 — *Parameters for the calculation of stand-by heat losses* (October 2014 Draft) gives default values for case heat losses at a mean water temperature of 70ºC when expressed as a fraction of the nominal load:

a) 2.2% and 1.2% for condensing combination boilers with water volume less than 2L and between 2L and 10L respectively.
b) For regular condensing: 4.0 x $(Pn)^{-0.4}$ / 100 where (Pn is the nominal power in kW). For an 8.8 kW boiler this is 1.7% and for a 20kW boiler this is 1.2%; the loss gets smaller for larger boilers.

   For simplicity, and due to its small value (and range), a single default of 1.7% is applied within the calculation method for both regular and combination boilers.

$$\frac{1}{\eta_t} = \frac{1}{\eta_{min}} + 0.017 \times \left(\frac{\bar{T}_E - T_{rm}}{\bar{T}_{E,ref} - T_{rm,ref}}\right)^{1,25} \times \frac{t_{off}}{t_{on}} \qquad - \qquad (27)$$

The on-time is calculated for each hour during the heating period as follows:

If $Q_{req} < (P_{min} \times t_{ci})$ then the boiler cycles off and on at the minimum rate. The on-time is calculated from:

$$\mathrm{t}_{on} = \frac{Q_{req}}{P_{min}} \qquad \text{hours} \qquad (28)$$

The off-time is the total time (1 hour) minus the on-time. The default minimum output $P_{out,min}$ is taken as 20% of the nominal power. The sensitivity of this assumption is explored.

5. Calculation results

5.1 Summary

A number of scenarios were analysed for condensing mains gas, LPG and oil fuelled boilers. Table 1 displays results for mains gas boilers only, where modulating boilers must be capable of reducing nominal heat output to 20%; “perfect weather and load compensation” and “no compensation” is defined in section 4.1. All scenarios featured a boiler plant size ratio of 1.8.

Mains gas boiler scenarios	Annual space heating efficiency % gross Flow/Return design temperature ºC/ºC				
	80/60	**70/60**	**55/47.1**	**45/38.6**	**35/30**
Modulating boiler – ideal compensation	89.9%	89.9%	93.1%	94.9%	96.3%
On/off boiler – ideal compensation	88.9%	88.9%	92.1%	93.8%	95.1%
Modulating boiler – no compensation	87.1%	87.4%	89.3%	92.8%	95.3%
On/off boiler – no compensation	85.3%	85.6%	87.3%	90.6%	92.8%

Table 3 - Annual space heating efficiency for four mains gas boiler scenarios

5.2 Detailed results for mains gas modulating boilers

This section reviews calculation method results for mains gas boilers in detail to illustrate method features. The results are derived for a condensing boiler capable of modulating to 20% of nominal heat output with a plant size ratio of 1.8, design flow and return water temperature of 80ºC and 60ºC, an efficiency at full load and part load of 98.1% net and 108% net and perfect weather and load compensation (See section 4.1). The full and part load efficiency values selected are the average of the values held in the PCDB (as of October 2016), but their choice is not critical to the outcome (see 5.3.6)

Figure 4 plots hourly return water temperature with respect to outside temperature for an entire year (see section 4.2). It can be seen that the plot features three discrete data groups; these relate to the hours of heating (per day). The points near -5ºC are when 24-hour heating is required, the points near 0ºC are when 16-hour heating is required and the rest are when 11-hour heating is sufficient.

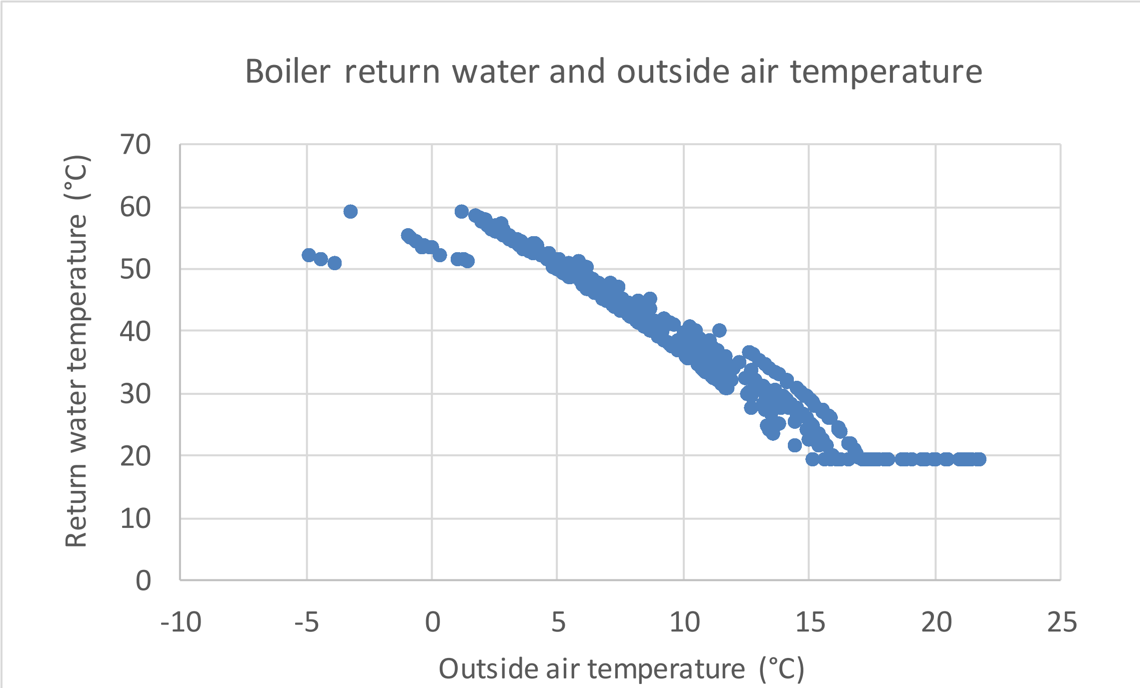

Figure 4 - Return water and outside air relationship

Figure 5 shows the efficiency versus the return water temperature relationship for a theoretical boiler. The curve is adjusted to match the average of the efficiency test results for an example boiler at full and part load. The points are actual example full and part load efficiency test results after the high value correction and capping in SAP 2012 Appendix D2.1 part 4 and 5 is applied. The adjusted curve (Figure 5) is used by the method to relate the efficiency to the calculated return water temperature (Figure 4).

As the two curves in Figure 5 are similar in shape, with a constant difference in efficiency across all return temperatures, it means the offset between the average of the part load and full load efficiency tests (corrected and capped as per SAP Appendix D) and the theoretical efficiency is constant. Therefore, the offset is insensitive to measured part load and full load efficiency values. This means that deriving standard efficiency corrections for a range of design flow temperature and compensation scenarios is reasonable.

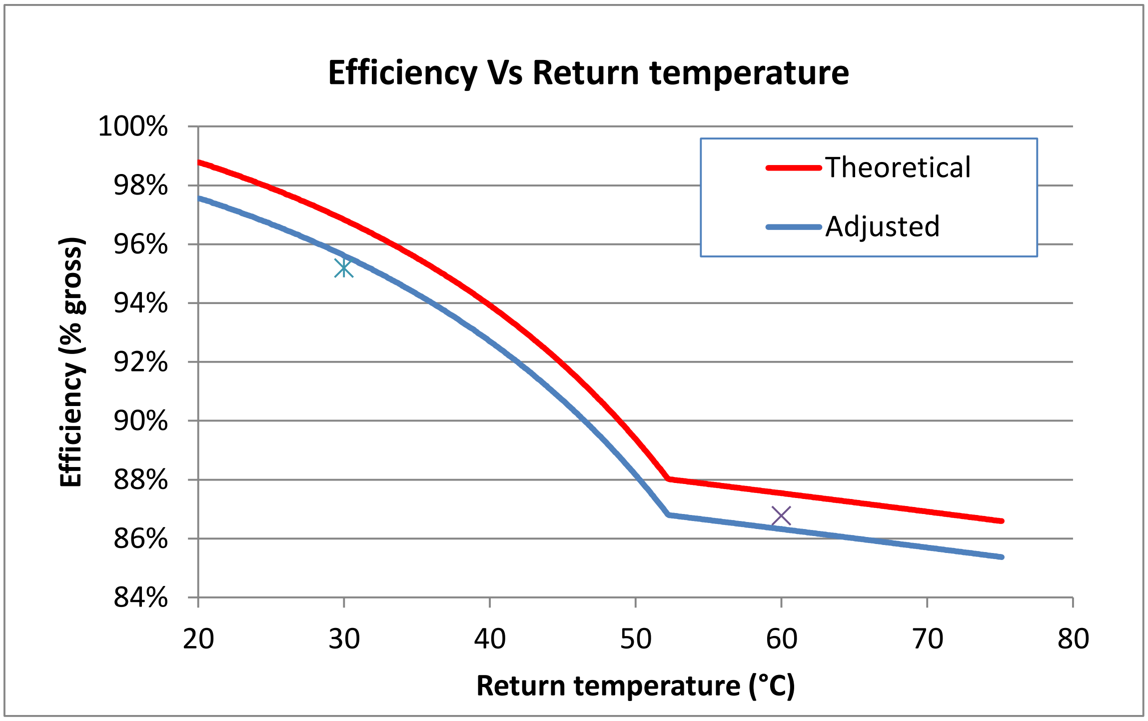

Figure 5 - Gas boiler efficiency relationship for theoretical and example boiler

Figure 6 shows how the return temperature varies with the boiler heat load. At 30% load the expected return temperature is 40ºC. Note: the heat load rises to nearly 70% and not 100% because the plant size ratio is 1.8.

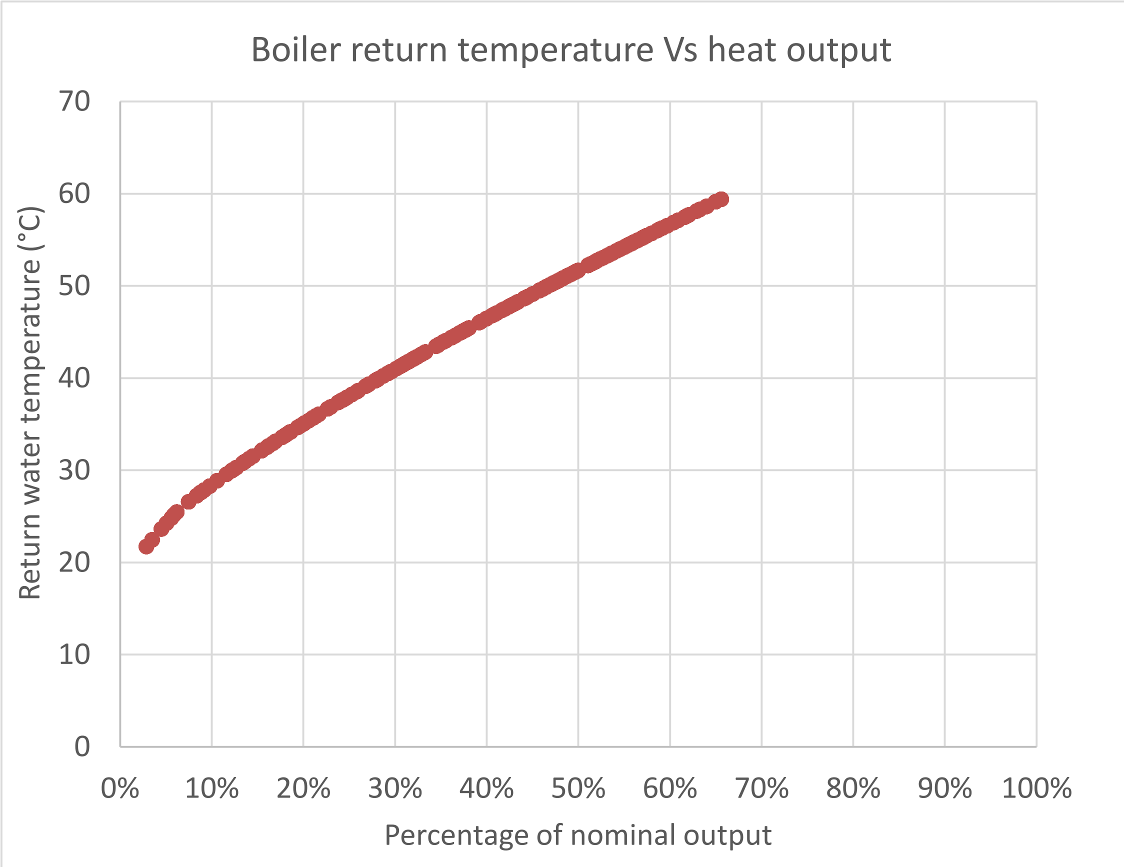

Figure 6 - Return water and load relationship

5.3 Sensitivity results

This section shows the annual space heating efficiency results from the analysis for a range of scenarios. For comparative purposes the scenarios are based on a boiler with a SAP winter efficiency of 90.0% for modulating boilers and 89.6% for on/off boilers, and an average of the full and part load efficiency of 91.0%[16]. All quoted values are gross efficiency unless specified otherwise.

[16] After the high value correction and capping. These are based on a boiler with part load and full load efficiencies of 98% (net) and 108.1% (net) respectively. This is the average of the all gas condensing boilers held in the PCDB at October 2016. See section 5.3.6 for more details.

5.3.1 Modulating boilers and plant size ratio variation

Table 4 illustrates the annual space heat efficiency variation with plant size ratio. Only for cases where the plant size ratio is very high is the efficiency significantly affected, i.e. when the plant size ratio exceeds 10 there is a 1.1 percentage point change.

	Annual space heating efficiency % gross Flow/Return design temperature ºC/ºC				
Plant size ratio	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
1.8	89.9%	89.9%	93.1%	94.9%	96.3%
2	89.9%	89.9%	93.1%	94.9%	96.3%
4	89.8%	89.8%	93.0%	94.8%	96.2%
6	89.5%	89.5%	92.7%	94.5%	95.8%
8	89.1%	89.1%	92.3%	94.0%	95.4%
10	88.8%	88.7%	91.9%	93.6%	94.9%
12	88.4%	88.4%	91.5%	93.1%	94.4%

Table 4 - Annual space heating efficiency variation with plant size ratio

5.3.2 Minimum modulation rate

Table 5 illustrates the variation in annual space heating efficiency due to different assumptions about the minimum heat load. The efficiency is relatively insensitive to the assumed minimum load, suggesting a value of 20% is reasonable.

	Annual space heating efficiency % gross Flow/Return design temperature ºC/ºC				
Plant size ratio/minimum load	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
2 / 10%	89.9%	89.9%	93.1%	94.9%	96.3%
2 / 20%	89.9%	89.9%	93.1%	94.9%	96.3%
2 / 30%	89.8%	89.8%	93.1%	94.9%	96.3%
2 / 40%	89.8%	89.8%	93.0%	94.8%	96.2%
4 / 10%	89.9%	89.9%	93.1%	94.9%	96.3%
4 / 20%	89.8%	89.8%	93.0%	94.8%	96.2%
4 / 30%	89.5%	89.5%	92.7%	94.5%	95.8%
4 / 40%	89.1%	89.1%	92.3%	94.0%	95.4%

Table 5 - Annual space heating efficiency variation minimum load

5.3.3 Water flow rate control

Table 4 shows the annual space heating efficiency assuming a constant water flow rate throughout the heating season. Table 6 shows the improvement in the annual space heating efficiency when this assumption is changed to a constant temperature drop across the heat emitters. To achieve this a system must be able to reduce the water flow rate as the boiler modulation reduces the firing rate. In the case of a system with a design mean emitter temperature of 70ºC (80/60), a drop of 20ºC and a room temperature of 20ºC, the water flow rate must reach 14% of the design flow rate, i.e. $[(30 – 20)/(70 – 20)]^{1.2}$.

The results suggest modulation of the flow rate can add 2 percentage points to the annual space heating efficiency, provided the flow rate can be reduced to 14% of the design flow rate.

	Annual space efficiency % gross Flow/Return design temperature ºC/ºC				
Plant size ratio	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
1.8	2.0%	1.0%	0.7%	0.5%	0.3%
2	2.0%	1.0%	0.7%	0.5%	0.3%
4	2.0%	1.1%	0.7%	0.5%	0.3%
6	2.0%	1.1%	0.7%	0.5%	0.4%
8	2.1%	1.1%	0.8%	0.6%	0.4%
10	2.1%	1.1%	0.8%	0.6%	0.5%
12	2.1%	1.1%	0.8%	0.6%	0.5%

Table 6 - Improvement in efficiency due to water flow rate modulation (compensator)

5.3.4 On/off boilers

Table 7 shows the results for on/off boilers. They were achieved by setting the minimum water flow rate to 100%. The table assumes flow and return temperatures are matched exactly to achieve the required mean emitter temperature.

	Annual space efficiency % gross Flow/Return design temperature ºC/ºC				
Plant size ratio	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
1.8	88.9%	88.9%	92.1%	93.8%	95.1%
2	88.8%	88.7%	91.9%	93.6%	94.9%
4	87.0%	86.9%	89.8%	91.4%	92.6%
6	85.2%	85.2%	87.9%	89.3%	90.4%
8	83.6%	83.5%	86.0%	87.3%	88.3%
10	82.0%	81.8%	84.2%	85.4%	86.3%
12	80.4%	80.3%	82.5%	83.6%	84.4%

Table 7 - Annual space heating efficiency on/off boilers (full compensation)

As expected there is a larger variation with PSR than modulating boilers, however, new on/off boilers of a combination type are rare[17], meaning the use of large PSR is an academic exercise.

On/off regular boilers are more common, but large PSRs is less relevant for these.

The effect of large plant size ratios only applies in practice to gas modulating combi boilers when installed in small or very well insulated properties. As noted in Section 5.3.1, the effect of PSR is not a significant issue for modulating boilers.

5.3.5 No compensation

The following two tables show the results for modulating and on/off boilers. They assume the design return temperature is constant throughout the year.

[17] The only mains gas on/off boiler that is understood to be in production and included in the PCDB was introduced in 2009.

	Annual space efficiency % gross Flow/Return design temperature ºC/ºC				
Plant size ratio	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
1.8	85.3%	85.6%	87.3%	90.6%	92.8%
2	85.0%	85.3%	87.0%	90.2%	92.4%
4	82.1%	82.4%	83.8%	86.6%	88.3%
6	79.4%	79.7%	80.8%	83.2%	84.6%
8	76.9%	77.2%	78.0%	80.1%	81.1%
10	74.5%	74.8%	75.4%	77.2%	78.0%
12	72.2%	72.6%	72.9%	74.5%	75.0%

Table 8 - Annual space heating efficiency for on/off boilers (no compensation)

	Annual space efficiency % gross Flow/Return design temperature ºC/ºC				
Plant size ratio	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
1.8	87.1%	87.4%	89.3%	92.8%	95.3%
2	87.1%	87.3%	89.2%	92.8%	95.3%
4	86.8%	87.1%	89.0%	92.5%	94.9%
6	86.3%	86.6%	88.4%	91.8%	94.2%
8	85.7%	85.9%	87.7%	91.0%	93.3%
10	85.0%	85.3%	87.0%	90.2%	92.4%
12	84.4%	84.7%	86.3%	89.5%	91.6%

Table 9 - Annual space heating efficiency for modulating boilers (no compensation)

These tables are shown for reference purposes; a room thermostat reduces the flow and return temperatures to some extent during milder weather.

5.3.6 Boiler test results

The following table shows the sensitivity of the offset to test efficiency measurements. The offset is the difference between the heating efficiency and the average of the full and part measurements after correction and capping. The measurements in the table span the expected range of results (i.e. from 90 to 100% net and 102% to 111% net for the full load and part load efficiency respectively).

			Space efficiency offset (% gross) Flow/return design temperature ºC/ºC				
Boiler control option	**Full load efficiency net**	**Part load efficiency net**	**80/60**	**70/60**	**55/47.1**	**45/38.6**	**35/30**
Modulating with perfect weather compensation	98.0%	108.1%	-1.1%	-1.1%	2.1%	3.9%	5.3%
	95.0%	106.0%	-1.1%	-1.1%	2.1%	3.9%	5.3%
	90.0%	102.0%	-1.1%	-1.1%	2.1%	3.9%	5.3%
	100.0%	111.0%	-1.1%	-1.1%	2.1%	3.9%	5.3%
Modulating with no compensation	98.0%	108.1%	-3.9%	-3.6%	-1.7%	1.8%	4.3%
	95.0%	106.0%	-3.9%	-3.6%	-1.7%	1.8%	4.3%
	90.0%	102.0%	-3.9%	-3.6%	-1.7%	1.8%	4.3%
	100.0%	111.0%	-3.9%	-3.6%	-1.7%	1.8%	4.3%
On/off with perfect weather compensation	98.0%	108.1%	-2.0%	-2.1%	1.1%	2.8%	4.1%
	95.0%	106.0%	-2.0%	-2.0%	1.1%	2.8%	4.2%
	90.0%	102.0%	-2.0%	-2.0%	1.2%	2.9%	4.2%
	100.0%	111.0%	-2.1%	-2.1%	1.1%	2.8%	4.1%
On/off with no compensation	98.0%	108.1%	-5.6%	-5.3%	-3.7%	-0.4%	1.8%
	95.0%	106.0%	-5.6%	-5.3%	-3.6%	-0.3%	1.9%
	90.0%	102.0%	-5.5%	-5.2%	-3.5%	-0.2%	2.0%
	100.0%	111.0%	-5.7%	-5.4%	-3.7%	-0.4%	1.8%

Table 10 - Space heating efficiency offsets

As expected for modulating boilers, irrespective of efficiency test measurement values, the offset is identical (within ±0.01 percentage points), see Figure 5, section 5.2)

For on/off boilers the above offsets are also within ±0.1 percentage points. The results are similar but not identical because of the boiler cycling on and off, which degrades efficiency. This effect also applies to modulating boilers during on/off operation at minimum power, but it is less significant as it occurs infrequently.

Overall the offset is relatively insensitive to the measured test efficiencies, which means a single offset can be applied to all condensing boilers without sacrificing accuracy. This means that deriving standard efficiency corrections for a range of design flow temperature and compensation scenarios is reasonable.

6. Weighting factors discussion

Both SEDBUK and Ecodesign apply weighting factors to the boiler efficiency measured at full load (100%) and part load (30%) to determine an annual space heating efficiency estimate for domestic installations. The Ecodesign regulation applies a weighting factor of 0.85 for part load and 0.15 for full load, which effectively implies an annual load of 40.5% and annual return temperature of 34.5ºC.

The current SEDBUK method applies equal factors of 0.5 to both as a starting point for the annual efficiency calculation. Offsets in the SEDBUK equation bring the calculated efficiency into line with the average load observed from boiler signature data.

The principal reasoning for the 50/50 approach was to reduce the effect of the measurement uncertainty of the part load (30%) measurement, since this is less accurate than that measured at full load for two main reasons:

a) For boilers that cannot modulate down to 30% part load, which were common at the time of the current SEDBUK method development, the efficiency at this load could be determined by one of two methods: a direct cyclic test[18] or indirect test. The indirect method measures standby heat loss to adjust a separately measured efficiency at a constant minimum firing rate. Boilers that can modulate down to 30% part load require only a steady test. Cyclic tests are generally less accurate and more variable than steady tests. The choice of methods introduces extra variability.

b) The temperature difference of water flowing through the boiler is only 30% of the temperature difference at full load (i.e. 6ºC at 30% load and 20ºC at 100% load) and will be less accurate in percentage terms to measure. For example, if a sensor was accurate to ±0.1ºC, the measurement uncertainty of temperature difference at full load will be ±0.5% (i.e. 0.1 in 20ºC) and at part load ±1.6% (i.e. 0.1 in 6ºC).

[18] For non-condensing boilers there is a choice between two direct methods

The annual space heating efficiency predicted by the hourly calculation method, when the boiler is controlled (ideally weather compensated) to satisfy the heating requirement precisely, is 89.9%. Using the efficiency curve equates to an equivalent average annual space heating water return temperature of 47.6ºC, which is significantly higher than the 34.5ºC implied by Ecodesign regulations (15%/85% weighting factors).

Although the annual average heating load implied by the 15%/85% weighting factor is near the annual heating average predicted by the hourly method, the implied average return temperature is much lower, meaning that annual space heating efficiency would be overestimated if Ecodesign weighting factors were used for SAP purposes.

7. Ecodesign control classes discussion

Chapter 5 shows the annual space heating efficiency for four system configurations due to seasonal variations in the emitter temperature and heating load.

a) Modulating boilers with ideal weather and load control (i.e. they are controlled perfectly to match the exact load by restricting the emitter temperature)
b) On/off boilers with ideal weather and load compensation
c) Modulating boilers with no compensation control (i.e. boilers with a constant water return temperature throughout the heating)
d) On/off boilers with no compensation control

7.1 Ecodesign class II, III, VI & VII (weather compensation)

For weather and load compensation control to be recognised by SAP, it must restrict the boiler water temperature by reducing the firing rate under mild conditions and not under cold conditions, which would sacrifice comfort.

Weather compensation, henceforth referred to as Ecodesign Class II or III, may be able to satisfy this requirement, since outside temperature is a major factor in determining heat load. However, other factors are also important, for instance building fabric heat loss, internal heat gains and thermal mass characteristics. Weather compensation that implements a single compensation curve will risk under heating during winter and overheating in milder weather. An example of a single compensation curve is one that restricts the boiler water flow temperature to a maximum of 80°C and 20°C for an outside temperature of -5°C and 20°C respectively, with linear interpolation in between.

The risk of under heating or overheating is particularly associated with weather compensation controls with intermittent heating. This has been recognised by control manufacturers, who have introduced manual settings that can adjust the compensation curve. These manual settings can reduce the effectiveness of weather compensation if permanently left in a cold weather setting during milder weather (higher flow temperature), thereby reducing boiler efficiency improvements.

More sophisticated weather compensation controls, henceforth referred to as Ecodesign Class VI or VII, that use information from room temperature sensors, in addition to external temperature sensors, are able to automatically and frequently adjust the weather compensation curve. This enables them to retain the benefits of weather compensation in milder weather without the risk of under heating in colder weather or overheating in milder conditions.

7.2 Ecodesign class IV

Since 2002, boiler installations (new or replacement) in the UK must comply with the Building Regulations[19] and consist of at least a single room thermostat (usually in a circulation space away from direct sunlight and other sources of heat), with thermostatic radiator values (TRVs) in the remaining rooms. If TPI control (Ecodesign Class IV) is installed without communication to TRVs, it will only reduce temperature fluctuations in the room/zone in which it is installed. Temperature fluctuations in other rooms are determined by the characteristics of the TRVs. If the TPI control communicates with TRVs (i.e. a communicating TRV) in rooms, the temperature fluctuations should reduce in these rooms.

[19] Central Heating System Specifications (CHeSS) Year 2002, General Information Leaflet 59, Housing Energy Efficiency, Best Practice Programme.

Whilst TPI may reduce temperature fluctuations around the set-point, it is unclear whether this will cause a reduction or increase in space heating energy consumption. For example, with a traditional room thermostat the temperature might fluctuate by 3°C between 19.5ºC and 22.5ºC and with a TPI control it might fluctuate by 1ºC. Householders might adjust the thermostat when they feel cold, which with TPI control might mean a variation from 19.5ºC to 20.5ºC. The energy savings in this case would be the energy required to maintain the room at 21ºC minus the energy required to maintain the room at 20ºC. However, householders might adjust the TPI control when they are too hot, meaning the room temperature will vary between 21.5ºC and 22.5ºC, requiring more energy than a traditional thermostat.

The Ecodesign Class IV definition for TPI controls only applies to on-off boilers. Certain TPI controls feature an eco-function which simply reduces the temperature setting by a certain amount and saves energy by reducing comfort. The TPI control strategy is similar to older anti-cycling devices that reduced boiler cycling by delaying the start of the next on-time. They are only likely to reduce energy consumption by reducing comfort. Therefore, these are treated in the same way as on/off thermostats.

7.3 Ecodesign class V (room temperature load compensation)

The full effectiveness of load compensation controls based on internal temperature (only) and defined as "Enhanced Load Compensation" in SAP 2009/2012, henceforth referred to as Ecodesign Class V, is more difficult to establish. Older versions of this control type used a fairly simple approach based on boiler flow[20] temperatures only; typically the firing rate is maintained at a high rate when the boiler flow water temperature is below a threshold, for example, 50°C. Above this threshold the firing rate is reduced; the higher the boiler flow water temperature the lower the firing rate. The operation of any room thermostat was an entirely separate control. This older type of compensators will reduce fluctuations in room temperature by reducing temperature overshoot (i.e. improve comfort), but will not necessarily reduce overall energy consumption because this is dependent on whether occupants adjust the room thermostat to the upper, middle or lower of the temperature fluctuations. This approach to compensation will produce similar

[20] Some also measure the boiler return temperature.

average return temperatures to on/off boilers when firing and controlled by the room thermostat. For example, when cycling on and off, the boiler starts off cold and rises until the room thermostat stops demanding heat. The average return temperature during firing will then be approximately near the mid-point and not too dissimilar to that produced by older compensators. However, it should be noted that at the start of a heating period or when the heating has been off for an hour or so, the on/off boiler may start to cycle on and off under control of the boiler thermostat before the room reaches the room thermostat set point. Under these circumstances the on/off boiler may result in higher average return temperatures when compared to modulating boilers.

Modern versions of room temperature load compensators (Ecodesign Class V) claim to use a variety of sophisticated approaches, but unless they have the means to restrict the flow temperatures when there is low demand (only), average boiler water return temperatures when firing will be similar to boilers without load compensators. It is important to distinguish the function of a room thermostat, which simply turns a boiler on or off when the room temperature drops or rises about a lower or higher threshold (respectively) and does not actually measure the room temperature (value). These are not Ecodesign Class V controls.

An Ecodesign Class V control measures room temperature and must be able to distinguish a high heat demand from a low demand in real-time. It is difficult to envisage how such a control can determine this in real time without an outside temperature sensor. One possible method may be to monitor dwelling cooling rate during the off-period of the room thermostat’s dead band range. A slower cooling rate would result in a reduced boiler flow temperature for the next on-period and so on. However, this creates a problem because the room temperature fluctuations would be substantially reduced, meaning that there is little or no opportunity to monitor a subsequent cooling period.

For intermittent heating only, a cooling rate could be measured at the end of the heating period and could be used to determine the required firing rate during the next heating period. This approach would be restricted to intermittent heating and may work provided that there are no sudden changes in weather or occupant behaviour and that the cooling rate is compared to the dwelling’s thermal characteristics.

Certain marketed Ecodesign Class V controls claim to adjust boiler flow temperature based on dwelling thermal characteristics and the cooling rate, but it must be clear whether this is to improve comfort (which would not improve boiler efficiency) or whether to restrict boiler temperatures (irrespective of comfort), or a compromise in-between.

7.4 Ecodesign class VIII

Ecodesign Class VIII is a multi-zonal control and is similar to the “Time and Temperature Zone Control” definition within SAP 2012, except that no timing facility is provided. Such a control is equivalent to Class V in terms of boiler efficiency adjustments.

7.5 Ecodesign class recommendations

It is recommended that four Ecodesign classes of boiler load compensation are recognised by SAP 10 for the purpose of awarding a boiler efficiency credit. Six classes are listed below with the first two being base cases, whereby no efficiency credit is awarded:

a) Ecodesign class I – This control type, which is considered the base case, does not directly control flow temperature, but the seasonal variation in heat load will nevertheless result in some degree of variation in return temperature. Therefore, based on calculation results for an idealised form of compensation control (see section 4.1 and 5.1), this control type should receive 25% of the predicted total boiler efficiency improvement

b) Ecodesign class IV – This control type will not be explicitly recognised by SAP, it will be considered equivalent to class I. The class definition only applies to on/off boilers

c) Ecodesign class II or III - These control boiler flow temperatures (and therefore output) by measuring outside temperature. They feature provision for manual adjustment of the weather compensation curves and thereby introduce a technical risk that optimal minimised flow temperatures are not always achieved, particularly because of the scope for manual override during cold weather. Based on calculation results for an idealised form of compensation control (see section 4.1

and 5.1), this control type should receive 50% of the predicted total boiler efficiency improvement

d) Ecodesign class V – These modulating room thermostats use an internal temperature sensor to control boiler flow temperature. Due to the issues discussed in Section 7.3, this control type should receive 50% of the predicted total boiler efficiency improvement determined by the calculation results for an idealised form of compensation control (see section 4.1 and 5.1),

e) Ecodesign class VI or VII - These weather compensators use an internal and an external temperature sensor to restrict boiler temperatures during low heat demand but not during high demand. The use of an internal temperature sensor avoids the risk of under heating, whilst still enabling energy savings. Based on calculation results for an idealised form of compensation control (see section 4.1 and 5.1), this control type should receive 90% of the predicted total boiler efficiency improvement

f) Ecodesign class VIII – Identical to Class V for boiler efficiency improvement

8. Measurement uncertainty and energy balance validation criteria

The full and part load efficiency of a boiler may be estimated from measurements in two ways:

a) From the measured heat input and the measured heat delivered to the circulating water, referred to as the “heat-to-water” method. This is the standard measure used to determine boiler thermal efficiency for Ecodesign regulations.
b) By subtracting from the heat content of the fuel, the heat loss in the combustion products and those from the envelope of the boiler, referred to as the “combustion product” method. The full details are described in: *“Energy Balance*

Validation: Investigation of the residual energy of thermal efficiency tests on gas and oil boilers'[21].

Typical measurement uncertainties for each individual measurement are:

- Gas or oil flow rate ±1%
- Carbon dioxide reading is ±0.25% points in 9% dry volume CO_2/dry volume air
- Combustion product temperature is ±2°C in 35°C (part-load) or in 65°C (full-load)
- Laboratory temperature is ±2°C in 20°C
- Laboratory humidity is ±10% points in a relative humidity of 70%
- Water temperature is ±0.1°C in 7°C (part-load) or 20°C (full-load)
- Standby loss is ±24W in 120W
- Electrical gains is ±10W in 80W
- Fuel flow rate is ±1%

8.1 Pooled uncertainties

The overall uncertainty in the efficiency of the two methods can be obtained by pooling the uncertainties. Provided the individual measurement uncertainties are independent and identically distributed[22], the pooled uncertainties are the square root of the sum of the squares of the individual uncertainties. Independence of each measurement uncertainty means that one measurement does not depend on another. This is reasonable, since each quantity is measured by different instruments. 'Identically distributed' requires knowledge of the uncertainty distribution of each instrument or source of uncertainty, but there is no obvious reason why these should differ.

The following table shows the uncertainty of the:

a) efficiency estimated from the heat-to-water method
b) efficiency estimated from the combustion products method
c) difference between the two methods

[21] www.bre.co.uk/filelibrary/SAP/2012/STP09-B02_Energy_balance_validation.pdf

[22] Identically distributed means each distribution of uncertainties follows the same probability function (e.g. a normal distribution).

	Full-load		Part-load	
	% change	% of input	% change	% of input
1. Boiler heat input (typical value)		100%		100%
gas flow rate	±1%		±1%	
gas temperature (0.5K in 293K)	±0.171%		±0.171%	
gas pressure (0.4mb in 1013mb)	±0.039%		±0.039%	
Calorific value (book value exact)				
Pooled uncertainty	±1.02%	±1.02%	±1.02%	±1.02%
2. Boiler heat output (typical value)		86.8%		96.3%
Water temperature is ±0.1K in 7K (part-load) or 20K (full-load)	±0.5%		±1.43%	
Mass flow rate	±0.6%		±0.6%	
Pooled uncertainty	±0.78%	±0.69%	±1.55%	±1.50
3. Flue loss/input (typical value)		11.93%		3.14%
CO_2 ±0.25% points in 9%	±0.33%		±2.32%	
Laboratory temperature ±2°C in 20°C	±0.91%		±4.92%	
Flue temperature ±2°C in 65°C/36°C	±0.76%		±14.80%	
Humidity ±10% points in 60%	±0%		±2.85%	
Pooled uncertainty	±1.23%	±0.15%	±16.02	±0.50%
4. Condensate heat loss/input (typical value)		0%		0.13%
CO_2 ±0.25% points in 9%		n/a	±0.8%	
Laboratory temperature ±2°C in 20°C		n/a	±19.2%	
Flue temperature ±2°C in 65°C/35°C		n/a	±5.19%	
Humidity ±10% points in 60%		n/a	±1.19%	
Pooled uncertainty	±0%	±0%	±19.96%	±0.03%
5. Casing loss/input (typical value)		0.45%		0.20%

	Laboratory temperature ±2°C in 20°C	±4.97%		±18.85	
	Standby loss is ±24W in 120W	±20.00%		±20.00%	
	Input	±1.02%		±1.02%	
	Pooled uncertainty	±20.6%	±0.09%	±27.52	±0.05%
6. Electrical gains/input (typical value)			0.27%		0.24%
	Electrical gains is ±10W in 80W	±12.5%		±15.13%	
	Input	±1.02%		±1.02%	
	Pooled uncertainty	±12.54%	±0.03%	±15.16	±0.04%
7. Overall efficiency					
Efficiency by heat-to-water method			±1.23%		±1.82%
Efficiency by product heat loss method			±0.18%		±0.63%
Difference in efficiency between methods[23]			±1.36%		±2.23%

Table 11 - Estimated experimental uncertainties

The measurement uncertainty in the heat-to-water method of the part load efficiency is only slightly higher than the full load efficiency and is under 2%.

The uncertainty in the efficiency of the combustion product method is more accurate than that of the heat-to-water method and therefore provides a useful check on the reliability of heat-to-water test results.

There are other uncertainties introduced by using different test rigs and operators, interpretation of standards and product to product variation. These uncertainties do not affect the uncertainty of the difference between the two methods and so are not of concern here.

[23] Uncertainties in item 5 and item 6 and the heat-to-water efficiency all depend on the same boiler input. So the uncertainty of the difference between the methods is the square root of uncertainties for (heat-to-water method + item 5+item 6)^2 +item 3^2 +item 4^2.

Considering the uncertainty in efficiency difference between the methods (last line of table), when the efficiency estimated by the combustion product method is greater than that estimated by the heat-to-water method by more than 1.8% this indicates that the heat-to-water figure is unreliable. This fact is the basis of the current Energy Balance Validation method[21], which is utilised for new PCDB entries when test results exceed the theoretical maximum[24]. When this limit is exceeded, additional data is required to check the efficiency against the combustion product method. If either the full or part load heat-to-water efficiency exceed the combustion product efficiency by 2% or 4% respectively, the submission is rejected.

A limit of 2% for full load efficiency was chosen. The limit of 4% for part load efficiency was to allow for some part load tests that may have been cyclic tests (i.e. when the boiler can't modulate the firing rate below 30%) and to provide a grace period (for when the method was introduced).

Figure 7 shows efficiency data for mains gas condensing regular or combination boilers on the PCDB in January 2016. These were introduced in 2006 or later and are still in production, a total of 1048 boilers. The bars represent the percentage of boilers (right hand axis) with an efficiency that lies within a 0.5% range (for example, a value of 97 on the horizontal scale means a range of 96.5 or more, but less than 97). The lines represent the percentage of boilers (left hand axis) with an efficiency higher than indicated by the horizontal scale. For example, approximately 30% of boilers have a part load efficiency greater than 108.5 (% net).

[24] The exact efficiency trigger threshold is confidential.

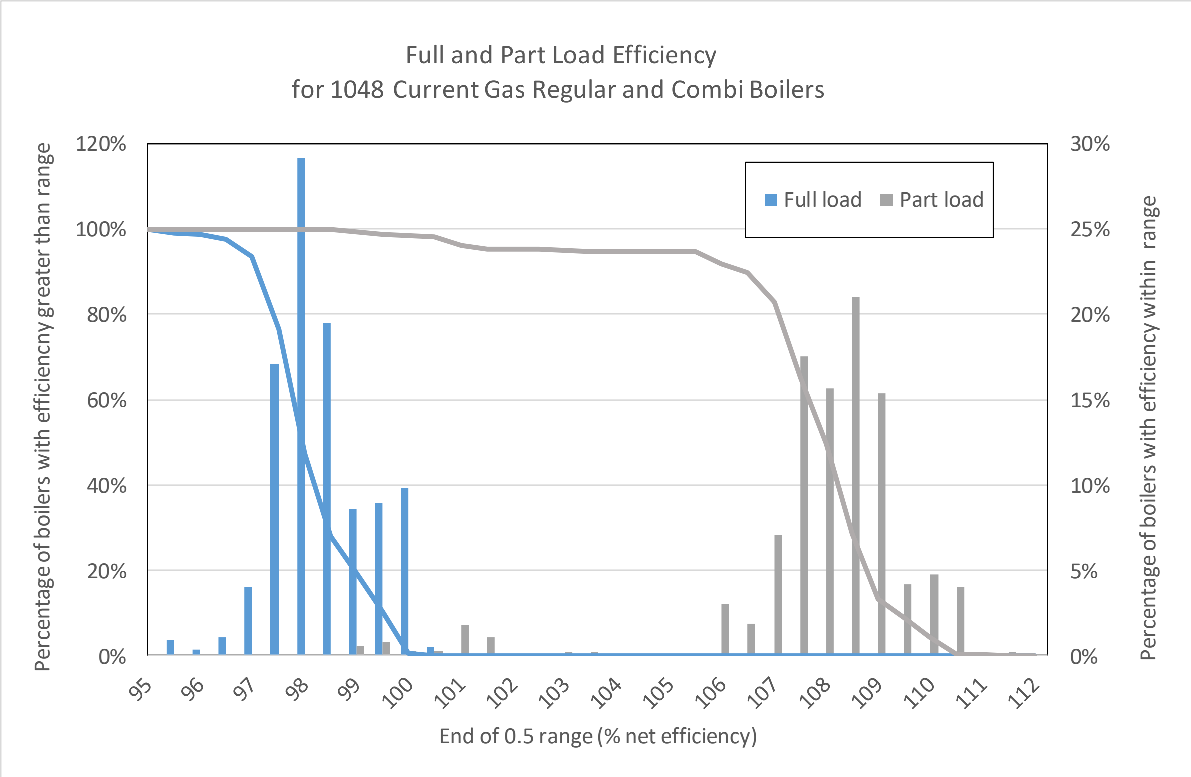

Figure 7 - Gas boiler efficiency data held in PCDB (January 2016)

Figure 7 also shows there are outliers: 5% of the boilers have part load figures between 99% and 103.5% and the next highest is between 105.5% and 106%. The standard deviation, a measure of the spread, is similar for the full load (0.84% net) and part load (1.0% net) results when the outliers are ignored, supporting the conclusion from the uncertainty table that the measurement uncertainty is slightly better for the full load figures.

Only 8 mains gas condensing boilers on the database introduced in 2006 or later and still in production are of the on/off type; the last one introduced was in 2009. Therefore, the vast bulk of new condensing boilers in 2016, if not all, will be a modulating type and capable of part load steady state testing. A much smaller efficiency difference (than say 4%) at part load between the two methods is now expected.

It is therefore recommended that the part load EBV efficiency deviation limit is reduced from 4% to 2.5%. The full load limit is unchanged, if the measured efficiency using the heat-to-water method deviates by more than 2% the PCDB application is rejected.

The next chart shows the plot for oil condensing boilers. If the oil boiler were to extract all the heat of combustion from the fuel the net efficiency would be 106.7%. Whilst accounting for heat losses (case and combustion) during the part load test, this maximum efficiency reduces to 104% net. Within the PCDB there are some extremely high test efficiency values, so it worthwhile introducing the EBV method for oil boilers. The efficiency trigger threshold will be determined in the same way as for mains gas condensing boilers.

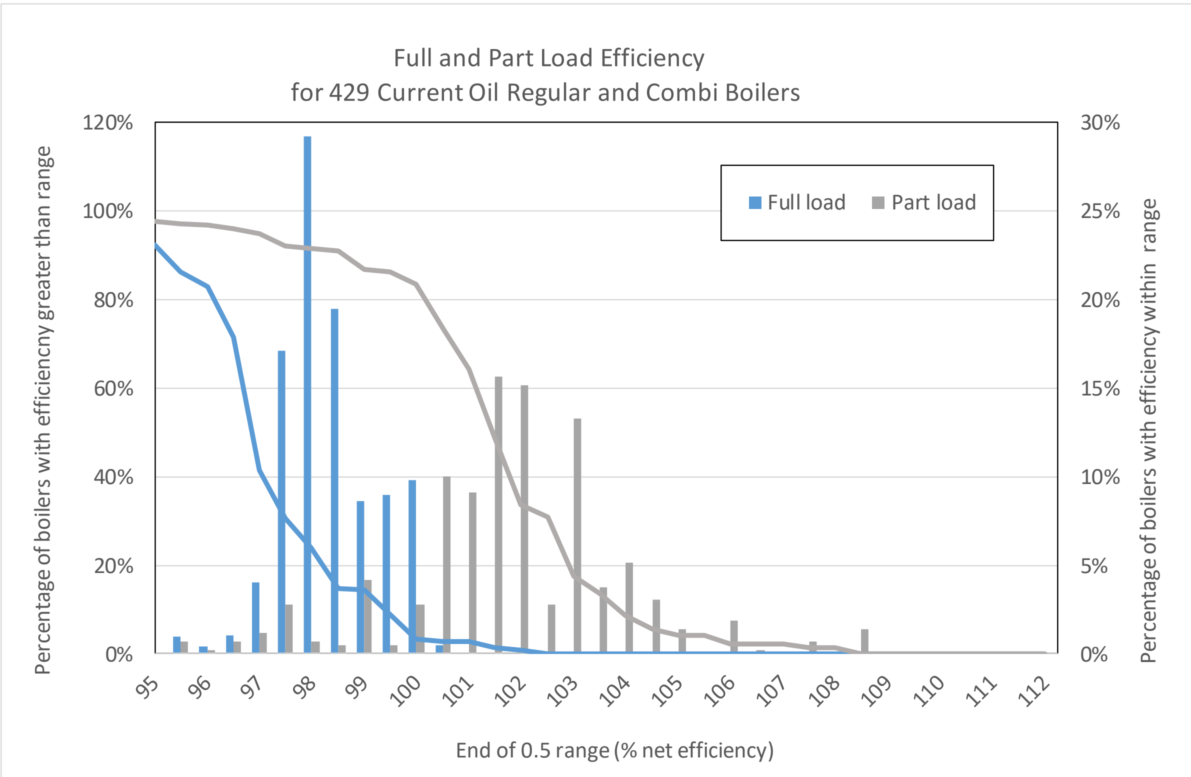

Figure 8 - Oil boiler efficiency data held in PCDB (JAN 2016)

Likewise, for LPG boilers it is recommended that the EBV method is introduced, similarly determining the efficiency trigger threshold as for mains gas condensing boilers.

9. Changes made in SAP 10

9.1 Modulating boiler definition

As the difference between modulating and on/off boiler space heating efficiency is bigger than previously represented, it is recommended that the SAP 10 definition for modulating boilers is strengthened to include a phase such as: “capability to vary the fuel burning rate, whilst maintaining continuous burner firing, to achieve a heat output no greater than 30% of nominal heat output”.

9.2 Heating hours

Analysis using the hourly calculation method demonstrates that there is insufficient time for the emitters to deliver the required daily heat within an 11-hour period during the coldest days. This is the case even when the emitters are sized according to standard practice (i.e. increasing the size by an intermittency factor of 1/0.83 = 1.2). To be consistent with Micro-cogeneration (also known as microCHP) and heat pumps and to prevent under heating, it recommended that variable hours of heating are also introduced into SAP for boilers. This would mean changing the number of days with heating running hours of 9 hours/day and 16 hours/day to those shown in the table below.

Days heating running hours are 16 hours instead of 9	Days heating running hours are 24 hours instead of 9	Days heating running hours are 24 hours instead of 16
9	2	1

Table 12 - Number of days heated for extended hours (boilers)

9.3 Space heating efficiency adjustment

Whilst the hourly calculation method derived within this document is considered reliable, it was not considered necessary to implement as a replacement for the existing SAP/SEDBUK equation format. Instead, this equation, specifically the offset, should be

modified on the basis of calculation results discussed earlier. The following four tables show the recommended adjustments to obtain the SAP winter efficiency.
Table 13 shows winter efficiency adjustments for condensing boilers only. These will be used within an updated SAP/SEDBUK winter efficiency calculation procedure (see existing procedure at: SAP 2012 Appendix D2.2) as:

$$\eta_{winter} = 0.5 \times (\eta_{full} + \eta_{part}) + \Delta\eta_{winter} \quad \text{\% gross} \qquad (29)$$

Where: $\Delta\eta_{winter}$ is the adjustment in Table 13

η_{full} and η_{part} are the test efficiency values at full and part load after the high value correction and capping in SAP Appendix D2.1 part 4 and 5.

The summer efficiency and the winter calculation for non-condensing boilers remain unaltered.

SAP Winter offset for condensing boiler firing options with Class I control for emitter flow and return design temperature of 80ºC/60 and 70ºC/60ºC.			
	Gas	LPG	Oil
On/Off boiler with Class I or IV control (Plain room thermostat or TPI)	-4.1%	-4.1%	-3.9%
Modulating boiler with Class I control (Plain room thermostat or modulating room thermostat)	-2.7%	-2.7	-2.4

Table 13 - SAP winter efficiency offset for condensing boilers

SAP 10 will require condensing boiler seasonal efficiency calculations for a range of situations that include[25]:

a) Modulating boilers without load or weather compensation (Ecodesign Class I)
b) On/off boilers without load or weather compensation (Ecodesign Class I or IV controls)
c) Modulating boilers with Ecodesign Class II, V or VIII controls
d) On/off boilers with Ecodesign Class III controls

[25] No changes to the calculation of non-condensing boiler efficiency are proposed for SAP 10.

e) Modulating boilers with Ecodesign Class VI controls

f) On/off boilers with Ecodesign Class VII controls

g) The above variations at five emitter design temperatures and for three fuels (90 combinations)

Table D1, D2 and D3 of the latest SAP 10 specification[26] displays efficiency corrections derived generically for on/off and modulating boilers. These are compared against an emitter system design return temperature of 60ºC.

The tables provide for four design flow temperatures categories. The design flow temperature can be designed and specified by a suitably qualified person, then recorded and reported to the SAP assessor via a design, installation and commissioning certificate in accordance with the requirements of SAP. For further details see: www.ncm-pcdb.org.uk/sap/lowtemperatureheating.

For design flow temperatures that are not categorised, SAP software will enable the entry of specific design flow temperatures, providing linear interpolation between categories. For design flow temperatures above 80°C, the efficiency correction for 80°C is used. For design flow temperatures below 35°C, the efficiency correction for 35°C is used.

[26] https://www.bregroup.com/sap/sap10/

9.4 Water heating efficiency

No changes to the SEDBUK calculation method for water heating efficiency were considered necessary. For combination boilers these are based on parameters derived from one or two hot water efficiency tests (EN13203), see SAP 2012 Appendix D.

9.5 Annual efficiency

For condensing boilers, a new annual space and water heating efficiency called SEDBUK 10 will be introduced. This is not used in the SAP calculations but provided as a useful comparator and is based on 91% of the winter and 9% of summer efficiency. These are the same weightings used for SEDBUK 2005 and SEDBUK 2009 annual efficiencies.

Fuel and boiler type	**Annual offset from the mean of the corrected full and part load efficiency**
Gas or LPG	
On/off regular	-5.3
Modulating regular	-4.0
On/off instantaneous combi	-5.3
Modulating instantaneous combi	-3.9
On/off storage combi	-5.2
Modulating storage combi	-3.8
On/off CPSU	-4.4
Modulating CPSU	-3.1
Oil	
On/off regular	-4.8
On/off Instantaneous combination	-4.7
On/off Storage combination	-4.6
Modulating regular	-3.3
Modulating instantaneous combination	-3.3
Modulating storage combination	-3.2

Table 14 - SEDBUK 10 Annual offsets

9.6 Permanent pilot

The Ecodesign regulation effectively includes a negative contribution due to permanent pilot burner power, P_{ign}, which is related to the output power at full load (P_4) by:

$50 \times P_{ign} \div P_4$

For example, a 100W pilot power in 12 kW output would give 0.4% reduction.

The current SAP/SEDBUK calculation method subtracts 4% from the seasonal efficiency if a permanent pilot is present. This correction is based on average pilot power relative to the dwelling heating load throughout the year.

Most modern boilers do not have permanent pilots and therefore any proposed changes in the 4% reduction would mainly apply to historical entries. The basis of the Ecodesign regulation assumes the pilot consumption is 50% efficient; presumably arguing that 50% of the time it is useful (the heating on-time) and 50% of the time it is not (heating off-time). This is clearly an overestimate for intermittent heating, since the boiler on-time would be far less than 50% in 24 hours. Considering this, it is recommended that no changes to the permanent pilot ignition subtraction are implemented within SAP/SEDBUK calculation method revisions.

9.7 Standby heat loss

The Ecodesign regulation effectively includes a negative contribution to account for standby heat losses. This contribution is calculated as $0.5 \times P_{stby} / P_4$, where P_4 is heat output at full load (W) and P_{stby} is the standby heat loss (W). This can only be measured via the indirect test method.

The proposed revisions to the SAP/SEDBUK method include defining a heat loss when a boiler cycles on and off. It uses a standby heat loss of 1.7% of the nominal heat output (average default value in prEN15316-4-1), which is adjusted for the hourly heat requirement and emitter temperature.

A standby heat loss is already incorporated within the constant offset term of the SEDBUK seasonal efficiency equations. Therefore, to prevent double counting (for condensing boilers), it is recommended that these offsets are removed and replaced with those in Table 13.

9.8 Electrical consumption

SAP currently considers boiler electrical consumption generically (SAP Table 4f), where a default value is applied to boilers with electrical combustion fans (and oil pumps for oil-fired boilers). The Ecodesign regulation requires electrical power measurements to be taken at part load, full load and standby mode, although this excludes circulation pump energy, which will always be added separately in SAP. For SAP 10, all electrical measurements arising from Ecodesign (which will exclude the water circulation pump) will be used to estimate annual electricity consumption.

Boiler running hours at full load and part load were analysed using a range of boilers and the hourly calculation method. This demonstrated that for a boiler with a plant size ratio of 1.8 and able to modulate to a minimum load of 20%, the typical total running hours is 2754 hours[27] at an average firing rate of 44.9%. This includes 219 hours of water heating at a firing rate of 100%.

For on/off boilers the typical running hours are 1236 hours at a firing rate of 100%.
The boiler's annual electrical energy consumption (kWh) for SAP should be calculated in accordance with the equations below. For modulating boilers use equation (30) and on/off boilers use (31).

$$P_{elec} = [(elmin \times 0.79 + elmax \times 0.21) \times 2754 + (P_{SB} \times 6006)] \div 1000 \quad \text{kWh} \qquad (30)$$

$$P_{elec} = [(elmax \times 1236) + (P_{SB} \times 7524)] \div 1000 \quad \text{kWh} \qquad (31)$$

Where:

$elmin$ is part load electrical power (W), but excludes circulator power

[27] These running hours will be used to assign revised default pump energy values within SAP 10 Table 4f. In SAP 2012 this value is 30 kWh/yr for the case *"Central heating pump (supplying hot water to radiators or underfloor system), 2013 or later"*, but will be amended to 41 kWh/yr (15 W x 2754 hr). For *"Central heating pump (supplying hot water to radiators or underfloor system), 2012 or earlier or unknown"*, this value is 120 kWh/yr, but will be amended to 165 kWh/yr (60 W x 2754 hr).

$elmax$ is full load electrical power (W), but excludes circulator power

p_{SB} is standby electrical power (W)

Note: the weighting factors of 0.79 for a 30% load and 0.21 for 100% load for modulating boilers, satisfying both space and hot water[28] loads, will achieve an average firing rate of 44.9%.

9.9 Energy balance validation criteria

The energy balance validation (EBV) method was introduced to improve the quality and robustness of full and part load efficiency test data entered into the PCDB. A direct measure of efficiency is compared to that estimated from flue product heat losses. The application for inclusion in the PCDB is currently rejected if the direct measure is respectively more than 4 and 2 percentage points higher than the part and full load test efficiency. It is recommended:

- That the part load allowance of 4 percentage points is reduced to 2.5 percentage points
- That the procedure is extended to LPG and oil fired boilers
- That high full load efficiencies can also trigger[29] application of the EBV method
- Since oil boilers are mostly the on/off type, the EBV method should feature an allowance trigger of 4 percentage points

[28] Based on the hot water demand profile defined in the revised SAP heat pump method.

[29] The efficiency for which the EBV method is triggered remains confidential