Modelling boilers within the Home Energy Model

A technical explanation of the methodology

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Contents

Background to the Home Energy Model

What is the Home Energy Model?

The Home Energy Model (HEM) is a calculation methodology designed to assess the energy performance of homes, which will replace the government's Standard Assessment Procedure (SAP).

The Home Energy Model is still under development and its first version will be implemented alongside the Future Homes Standard (FHS) in 2025. We are publishing information about the model while it is still at a formative stage to enable industry to participate in the ongoing development process.

Where can I find more information?

This document is part of a wider package of material relating to the Home Energy Model:

Home Energy Model technical documentation (e.g. this document)

What: This document is one of a suite of technical documents, which go into further detail on the methodology and the validation exercises that have been carried out. We intend to update and produce further technical documentation throughout the model development process.

Audience: The technical documentation will be of interest to those who want to understand the detail of how the Home Energy Model works and how different technologies are treated.

The Home Energy Model consultation

What: The Home Energy Model consultation, which explains the overhaul to the SAP methodology and seeks views on the approach taken by the new Home Energy Model.

Audience: The Home Energy Model consultation will be of interest to those who want to understand the proposed changes to the SAP methodology and wider SAP landscape.

The Home Energy Model reference code

What: The full Python source code for the Home Energy Model and the Home Energy Model: FHS assessment has been published as a Git repository. This code is identical to that sitting behind the consultation tool. We are currently considering whether the open-source code could serve as the approved methodology for regulatory uses of the Home Energy Model.

Audience: The reference code will be of interest to those who want to understand how the model has been implemented in code, and those wishing to fully clarify their understanding of the new methodology. It will also be of interest to any potential contributors to the Home Energy Model.

Related content

This paper sets out the methodology for modelling boilers within the Home Energy Model core engine. See below for other related documents and the relevant module in the reference code.

Related technical documents

Other relevant papers on the core engine include:

- HEM-TP-04 Space heating and cooling demand
- HEM-TP-11 Hot water storage tanks
- HEM-TP-16 Heat emitters
- HEM-TP-17 Controls

For further information on relevant assumptions made within the FHS assessment wrapper, please see:

- HEMFHS-TP-02 FHS space heating and cooling demand assumptions

Code implementation

To understand how this methodology has been implemented in computer code, please see:

src/core/heating_systems/boiler.py

Methodology

The method originates from the Energy Balance Validation (EBV) method and relies on part-load and full-load efficiency values obtained from EN 15502-1 tests. It also utilises EN 13203-2 test data to derive hot water performance when available.

An overview of the calculation steps to be performed is listed below. A flowchart can be seen in Figure 1.

1. The Home Energy Model (HEM) will provide the energy requirements for the required service and the required flow temperature during the operational hours. For space heating, this is calculated in the emitter module. For water heating with regular boilers, the tank module calls the boiler module. See section 1.
2. For combination boilers, the additional combi loss is calculated and added to the hot water demand. See section 1.1.
3. The current boiler power is calculated based on the boiler minimum modulation and energy demand.
4. The cycling and location adjustments are calculated. See section 2.
5. Calculate the Energy Balance Validation boiler efficiency. See section 3.
6. Calculate final boiler efficiency based on EBV efficiency, cycling adjustment and location adjustment. See section 4.
7. Calculate the energy delivered by the boiler and energy input to deliver that energy depending on energy requirements. See section 5.

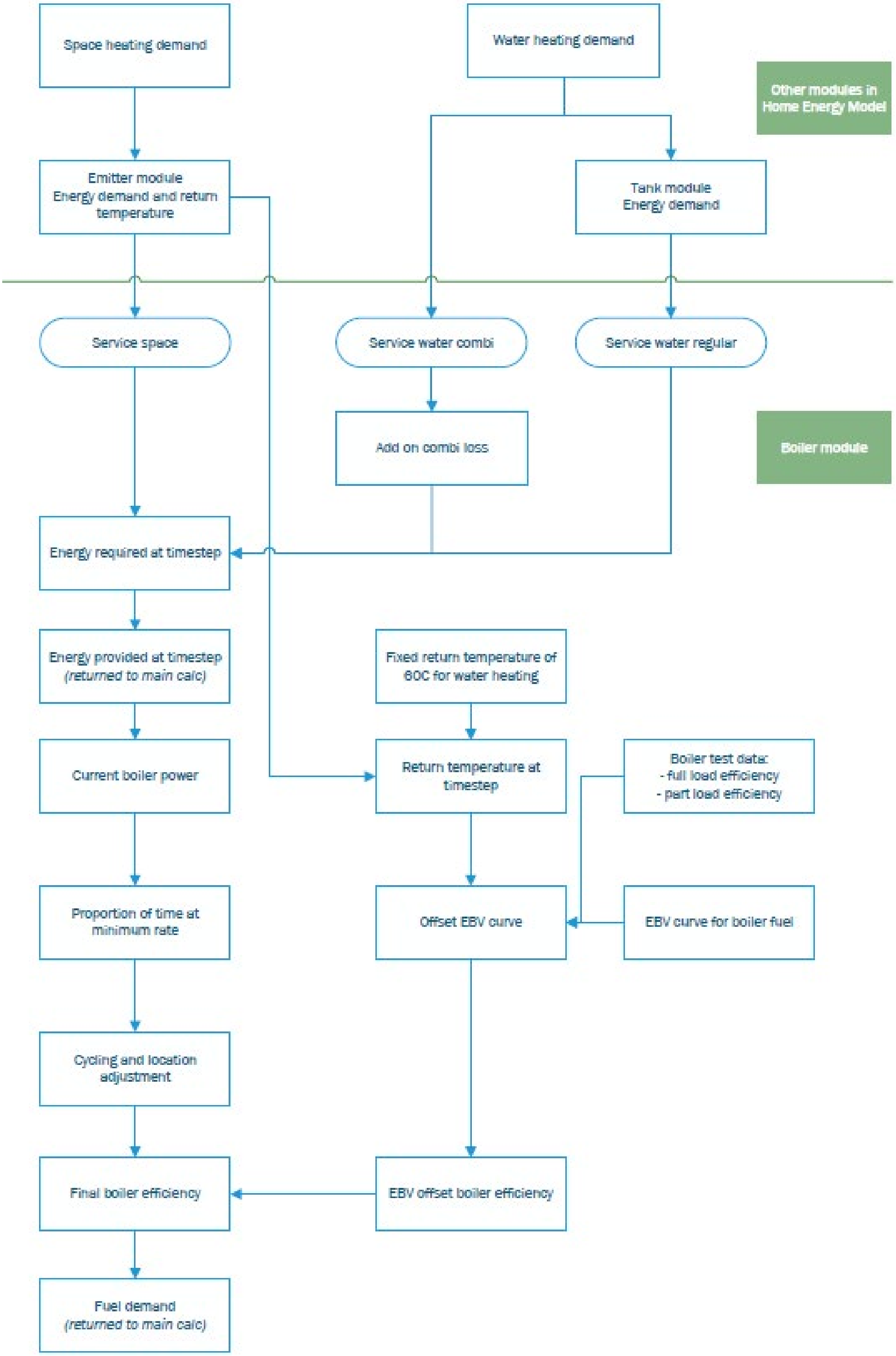

Figure 1 – Flowchart of calculation steps for gas boilers in the Home Energy Model

1. Energy requirement

1.1 Water heating

For water heating services with regular boilers, the energy demand and temperature of hot water is calculated by the storage tank module and is provided as an input to the boiler module.

For water heating services with combi boilers, the energy demand and temperature of hot water is from the hot water demand calculation is used directly (rather than being modified by the storage tank module).

The return temperature for water heating is currently fixed at 60°C.

1.1.1 Combi loss for no additional test results

When additional tests are unavailable, a combination loss of 600 kWh/year is assumed.

1.1.2 Combi loss for one additional test result (M only)

When test results submitted for a combination boiler are obtained in accordance with tapping cycle M (only) of EN 13203-2, the procedure to calculate the combi loss is as follows:

- Calculate the summer seasonal efficiency (η_{summer}) by retrieving the full load- efficiency from the space heating measurements (in %, gross calorific terms), converting from net to gross efficiency, if necessary applying the correction factor (Table 3) and any capping (Table 5).
- Calculate the proportion of rejected energy (r_1) by retrieving from water heating measurements the wasted volume of water in percentage terms and dividing by 200.
- Obtain the daily fuel consumption expressed in terms of the net calorific value in kWh/day. Convert it to gross calorific terms by dividing by the conversion factor, f, to obtain Q_{FLG}.
- Calculate the heat loss factor F_1 in kWh/day where:

$$F_1 = (\eta_{summer} \times Q_{FLG} \div 100) - 5.845 \times (1 + r_1)$$

- If the result is negative, set it to zero.
- These factors are then stored in the PCDB (or future equivalent)

The Home Energy Model calculates the combi loss using equation below:

$$Combi\ loss = [energy\ demand \times r_1 \times f_u] + [F_1 \times \frac{timestep}{hours\ per\ day}]$$

Where f_u is the daily hot water usage factor.

If daily hot water usage, $DHWU$ is less than 100L/day, f_u = $DHWU$ / 100L otherwise, f_u = 1.0.

1.1.3 Combi loss for two additional test results (M & S or M & L)

When test results are submitted for a combination boiler in accordance with tapping cycle M and S or M and L of EN 13203-2, a procedure to calculate combi loss is as follows:

- Estimate the proportion of rejected energy, r_1 and r_x by retrieving from test results the wasted volume of water, in percentage terms, respectively for cycle M and S or L and dividing each by 200.
- Retrieve from test results the daily fuel consumption in summer mode for profile M and for profile S or L expressed in terms of the net calorific value. Convert to gross calorific terms by dividing each by the conversion factor, f, Table 2 to obtain Q_{FLG} (for profile M) and $Q_{FLG,X}$ (for profile S or L).
- Calculate the summer seasonal efficiency (η_{summer}) in gross calorific terms:

$$\eta_{summer} = \frac{100 \times \left[\left(Q_{dhw} \times (1 + r_x)\right) - \left(5.845 \times (1 + r_1)\right)\right]}{\left[Q_{FLG,X} - Q_{FLG}\right]}$$

  where Q_{dhw} is 11.655 kWh/day for cycle L and 2.1 kWh/day for cycle S.

- Confirm whether the hot water tests included any active flue gas heat recovery system (FGHRS) and limit the result in step 3 (η_{summer}) to the maximum noted in Table 1.

Fuel type	Natural gas	LPG	Oil
Max. efficiency (%)	88.2	90.3	91.5

Table 1 - Maximum gross efficiency for summer hot water efficiency without FGHRS

- Calculate the heat loss factor F_2 in kWh/day from:

$$F_2 = (\eta_{summer} \times 0.98 \times Q_{FLG} \div 100) - 5.845 \times (1 + r_1)$$

  If the result is negative set it to zero.

- Calculate the heat loss factor $\mathrm{F_3}$ (change in wasted energy proportion per litre change in water usage) from:

$$\mathrm{F_3} = \frac{(\mathrm{r_1} - \mathrm{r_x})}{(\mathrm{V_U} - 100.2)}$$

  where $\mathrm{V_U}$ = volume of useful water = 199.8 or 36 for Profile L or S respectively.

- These factors are then stored in the PCDB (or future equivalent)
- HEM calculates the combi loss using equation below:

$$Combi\ loss = energy\ demand \times [r_1 + DVF * F_3] \times f_u + [F_2 \times \frac{timestep}{hours\ per\ day}]$$

Where DVF is the daily volume factor.

The daily volume factor DVF depends on the daily volume, $DHWU$, and the tapping profiles used for testing as follows:

Tapping profile M and S: if $DHWU$ < 36.0, DVF = 64.2

if $DHWU$ > 100.2, DVF = 0

otherwise DVF = 100.2 – $DHWU$

Tapping profile M and L: if $DHWU$ < 100.2, DVF = 0

if $DHWU$ > 199.8, DVF = -99.6

otherwise DVF = 100.2 – $DHWU$

1.2 Space heating

For space heating services, the energy demand and return temperature during each timestep are calculated by the emitter module and are provided as inputs to the boiler module.

2. Cycling and location adjustment

2.1 Cycling adjustment

During certain conditions, the heating requirement may be lower than the minimum heat produced by a boiler when firing continuously. For on/off boilers the minimum heat output 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 boiler heating efficiency is defined as the useful energy produced divided by the total of the useful and the energy wasted based on the losses method. Therefore, at the minimum firing rate under steady conditions the instantaneous efficiency can expressed as a function of the useful thermal power produced, the rate of heat loss in the flue products and from the case.

$$\eta_{min} = \frac{P_{out,min}}{(P_{out,min} + P_{fl,min} + P_{cs,min})} \tag{1}$$

Where:

η_{min}	Instantaneous efficiency
$P_{out,min}$	Useful thermal power produced at minimum firing rate
$P_{fl,min}$	Rate of heat loss in the flue products at minimum firing rate
$P_{cs,min}$	Power case losses at minimum firing rate

This assumes complete combustion which is reasonable because safety and environmental standards demand that only small amounts of CO can be produced.

Similarly, the efficiency when cycling at the minimum rate is:

$$\eta_t = \frac{t_{on} \times P_{out,min}}{(P_{out,min} + P_{fl,min} + P_{cs,min}) \times t_{on} + P_{cs,min} \times t_{off}} \tag{2}$$

Where:

η_t	Efficiency when cycling
t_{on}	proportion of timestep boiler is cycling at minimum rate
t_{off}	proportion of timestep boiler is not cycling at minimum rate

This assumes that the heat lost in 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 shortly after the boiler ceases to fire suppressing the natural convective heat losses.

Combining (2) and (3) and rearranging gives:

$$\frac{1}{\eta_t} = \frac{1}{\eta_{min}} + \frac{P_{cs,min}}{P_{out,min}} \times \frac{t_{off}}{t_{on}} \tag{3}$$

Making the assumption that proportion of heat losses from the case is the same at maximum and minimum power when operated at the same mean water temperature (that it, $\frac{P_{cs,min}}{P_{out,min}}$ is the same as $\frac{P_{cs,max}}{P_{out,max}}$) and adopting the temperature correction noted in EN 15316-4-1, Section 6.9.4, equation 30 gives:

$$\frac{P_{cs,min}}{P_{out,min}} = \frac{P_{cs,ref}}{P_{out,ref}} \times \left(\frac{\bar{T}_E - T_{rm}}{\bar{T}_{E,ref} - T_{rm,ref}}\right)^{1.25} \tag{4}$$

Where:

$P_{cs,min}$	Power case losses at minimum power
$P_{cs,max}$	Power case losses at maximum power
$P_{cs,ref}$	Power at reference temperature (a mean water temperature of 70ºC)
$P_{out,ref}$	Rate of heat loss produced at reference temperature
$\bar{T}_E$	Mean emitter temperature.
T_{rm}	Room temperature
$\bar{T}_{E,ref}$	Mean emitter temperature at reference temperature.
$T_{rm,ref}$	room temperature at reference temperature

1.25 is the boiler standby heat loss power law index

Incorporating the temperature correction from equation (4) in equation (3) makes the adjusted efficiency due to cycling:

$$\frac{1}{\eta_t} = \frac{1}{\eta_{min}} + \frac{P_{cs,ref}}{P_{out,ref}} \times \left(\frac{\bar{T}_E - T_{rm}}{\bar{T}_{E,ref} - T_{rm,ref}}\right)^{1,25} \times \frac{t_{off}}{t_{on}} \tag{5}$$

Table B.3 from EN 15316-4-1 2017 gives default values for case heat losses at a mean water temperature of 70ºC when expressed as a fraction of the nominal load.

$$standing\ loss = 4.0 \times (\mathrm{P})^{-0.4} \ / \ 100 \qquad (6)$$

Where:

P is the boiler power at the timestep

Note: This equation has been adjusted to use the current boiler power instead of the nominal power as in the standards to align with lab results.

When the boiler is firing continuously no adjustment is necessary so $\Delta cyc = 0$.

$$\Delta cyc = \frac{standing\ loss}{(30)^{1.25}} \times (T_{return\_temp} - T_{bloc,t})^{1.25} \times \frac{t_{off}}{t_{on}} \qquad (7)$$

Where:

Δcyc is the adjustment within the calculation timestep when cycling on/off at the minimum modulation rate

T_{return_temp} is the boiler return temperature.

$T_{bloc,t}$ is the boiler location temperature, which is room temperature when installed inside and outside temperature when outside

30 is the nominal temperature [K] difference between the boiler and test room during the standby loss test (EN 15502-1)

Note: The mean emitter temperature has been replaced by the return temperature as the emitter temperature in the HEM model is the final temperature in the timestep and is thus unlikely to be the temperature when the boiler is heating. Additionally, the majority of the water in the boiler is also likely to be the return temperature.

Note: the consultation version of the boiler module assumes the nominal temperature difference between the boiler and the test room is 30K as defined by the standby loss test (EN 15502-1). However, in the EN 15316-4-1-2017 says the average water temperature is 70C meaning a temperature difference of 50K.

2.2 Location adjustment

A boiler's efficiency reduces when installed outside due to an increase in case heat loss.

The following adjustment is made when the boiler is located outside (when installed inside no adjustment is necessary so $\Delta Loc = 0$)

$$\Delta Loc = \frac{standing\ loss}{(30)^{1.25}} \times \left[\left(T_{return\_temp} - T_{room}\right)^{1.25} - \left(T_{return\_temp} - T_{bloc,t}\right)^{1.25}\right] \quad (8)$$

Where:

ΔLoc is the efficiency adjustment

T_{room} is the room temperature

3. Energy Balance Validation boiler efficiency

1. Determine fuel for boiler type

The fuel for boiler type must be one of natural gas or LPG.

2. Obtain the boiler’s EN 15502-1 full load[1] and part load[2] gross efficiencies.

Retrieve the full-load efficiency, η_{FL} and 30% part-load efficiency, η_{PL} test results.

3. Convert net efficiencies to gross

Establish whether the efficiency test results are gross or net (i.e. calculated on the basis of gross or net calorific value for the fuel used in the tests). If gross proceed to step 4. If net, convert to gross using the following equation with the appropriate factor taken from the test report. For reference, indicative values (only) are reproduced in Table 2.

$$\eta_{gross} = f \times \eta_{net}$$

Fuel	**Net-to-gross conversion factor, f**
Natural gas	0.901
LPG (propane or butane)	0.921

Table 2 – Illustrative efficiency conversion factors

4. Apply correction to high test results

Apply an adjustment to full-load efficiency and to part-load efficiency to correct for observed bias in test results, according to Table 3 and Table 4. The figures are based on this boiler test report[3].

Fuel	**Full-load efficiency (η_{FL})**		
	Threshold value (%)	**Correction if η_{FL} > threshold**	**Correction if η_{FL} □ threshold**
Natural Gas	86.0455	- 0.673 (η_{FL} – 86.0455)	0
LPG	87.9555	- 0.673 (η_{FL} – 87.9555)	0

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[1] Test conducted with a return water temperature of 60°C

[2] Test conducted with a return water temperature of 30°C

[3] https://www.bre.co.uk/filelibrary/SAP/2012/STP09-B05_Meta-analysis_of_boiler_test__results.pdf

Table 3 - Efficiency correction term for full-load tests

Fuel	30% Part-load efficiency (η_{PL})		
	Threshold value (%)	Correction if η_{PL} > threshold	Correction if η_{PL} □ threshold
Natural Gas	87.0366	- 0.213 (η_{PL} – 87.0366)	0
LPG	88.9686	- 0.213 (η_{PL} – 88.9686)	0

Table 4 - Efficiency correction term for part-load tests

5. Reduce to maximum gross efficiency values

Table 5 gives the maximum values of gross efficiency for each fuel that may be used. Reduce any greater value (after adjustment according to Table 3 or Table 4) to the appropriate value given in Table 5.

	Condensing boilers			Non-condensing boilers		
	Natural gas	LPG	Oil	Natural gas	LPG	Oil
Full-load	88.298	90.258	91.826	82.892	84.732	86.204
Part-load	97.308	97.626	97.448	88.991	83.811	87.141

Table 5 - Maximum gross efficiency values (in %)

6. From the curve in Figure 2, obtain the average of the theoretical gross boiler efficiency for a return temperature of 60°C and 30°C, then subtract the average of the test results to obtain an offset value.

The resultant offset value is used to shift the theoretical curve, creating an adjusted gross efficiency curve for the boiler (with respect to return water temperature). The efficiency curves are based on fuel characteristics described in the EBV method developed in 2006[4]

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[4] https://www.bre.co.uk/filelibrary/SAP/2012/STP09-B02_Energy_balance_validation.pdf

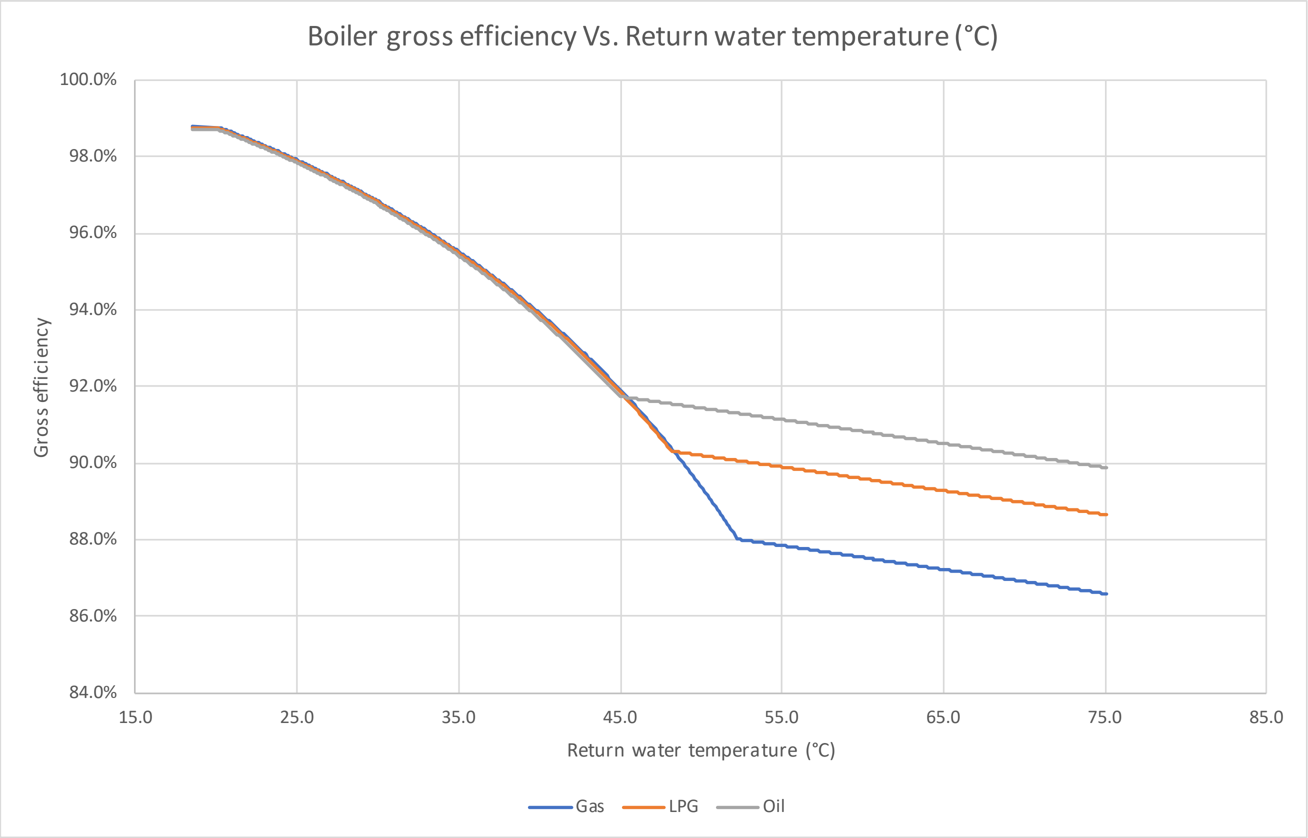

Figure 2 – Theoretical boiler efficiency vs return water temperature

4. Final boiler efficiency

1. For the timestep's return water temperature, obtain the boiler's gross efficiency from the adjusted gross efficiency curve.
2. If the boiler is located outside, calculate the location adjustment as specified in the location adjustment section.
3. Determine if the boiler cycles on/off during the timestep, which will occur if the heat energy requirement is less than the minimum boiler heat output multiplied by the timestep time. If so, calculate the cycling adjustment as specified in the cycling adjustment section. Otherwise, the boiler fires continuously and no adjustment applies. If boiler starts cycling use the corrected full load efficiency as the boiler efficiency before cycling adjustment is applied.
4. Calculate the final boiler efficiency after accounting for any adjustments for location and cycling using formula below.

$$\frac{1}{\eta_{final}} = \frac{1}{\eta_{EBV}} + \Delta Loc + \Delta cyc$$

Where:

η_{final}	is the final boiler efficiency used in HEM
η_{EBV}	is the boiler efficiency from the Energy Balance Validation method
ΔLoc	Location adjustment
Δcyc	Cycling adjustment

5. Electricity consumption

Where full-load efficiency and 30% part-load efficiency test results include electrical power measurements, the boiler's electrical energy consumption should be calculated in accordance with the equations below.

$$P_{elec} = circulation\,pump\,power + standby\,power + flue\,fan\ \,power$$

For on/off boilers:

$$P_{elec} = P_{circ} * running\ time + \ P_{SB} * standby\ time\ + \ el_{max} * running\ time$$

For modulating boilers:

$$P_{elec} = P_{circ} * running\ time + \ P_{SB} * standby\ time\ + \ el_{modulating\ flue} * running\ time$$

Where:

el_{min} is part-load electrical power (W)

el_{max} is full-load electrical power (W)

$el_{modulating\ flue}$ is electrical power interpolated between part-load and full-load electrical power (W)

P_{SB} is standby electrical power (W)

P_{circ} is the circulation pump power (W)

Future development

The following features are being considered for integration into the HEM boiler methodology:

- Further fuels (oil and solid fuel boilers)
- Non-condensing boilers
- Storage combination boilers
- Twin range cooker boilers
- Impact of permanent pilot

The consultation version of HEM assumes a 30% minimum modulation for all boilers while further testing and development is carried out.

The reformed PCDB may take advantage of additional data (e.g. on minimum modulation rates), and we will engage with industry on this in due course.

Further lab tests may be conducted to explore the effect of controls on boiler efficiency. This will include testing controllers that offer weather compensation, load compensation and both. The emitter module determines the flow and return temperatures in the radiator, the testing will also be used to validate the emitter module.

This publication is available from: https://www.gov.uk/government/publications/home-energy-model-technical-documentation