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Measurement of the in-situ performance of solid biomass boilers

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Full technical report

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Measurement of the in-situ performance of solid biomass boilers

Full technical report

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Preface

This report is the full technical findings of work carried out for BEIS from 2015 to 2018 where the real-life efficiencies and pollutant emissions of a range of biomass boilers were measured.

The work was carried out by a consortium of Kiwa Gastec, Ricardo Energy and Environment, Energy Saving Trust, HETAS, and Optimum Consultancy.

A summary report is provided separately.

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1 Introduction

The Renewable Heat Incentive in England, Scotland and Wales (the RHI) was the world's first long-term financial support programme for renewable heat. Since its launch, the RHI has supported many solid biomass boilers, with biomass boilers comprising 89% of total non-domestic installations and 21% of domestic installations [1, 2]. Financial support is provided for 7 years for boilers on the domestic RHI and 20 years for the non-domestic RHI scheme. In March 2014, the Department of Energy & Climate Change (DECC) – now the Department for Business, Energy & Industrial Strategy (BEIS)[1], began an evaluation of the RHI, focussed on the delivery of the scheme against its objectives and lessons for the future. Work evaluating technologies incentivised by the RHI (and its predecessor Renewable Heat Premium Payment scheme) has also been on-going, most notably air, water and ground source heat pumps in the domestic and non-domestic sectors. DECC wished to extend its evaluation of technologies to solid biomass heating systems and commissioned a desk-based study to examine the performance and installation practices for biomass boilers [3].

The report presented an assessment of the performance standards and installation practices in the biomass heating sector, using existing data and a desk-based assessment of current industry practice both in the UK and abroad. It identified that many biomass boilers were not performing as well as expected. Varying levels of underperformance were indicated in the analysis; however, the data was of poor and variable quality and not sufficiently robust to draw clear conclusions. Further investigative work was recommended to clarify the level of performance in biomass boilers under the RHI. In response, DECC explored the possibility of carrying out a field trial of a sample of boilers.

In preparation for the field trial, further work was carried out in 2015 to establish a robust and cost-effective methodology for measuring the performance of biomass boilers in the field. The resulting report [4] concluded that an indirect method of efficiency measurement would enable accurate short- and long-term assessment of boiler efficiencies. It also discussed methods to assess gaseous emissions in the field and the difficulties of doing so along with associated risks.

In late 2015, DECC commissioned a field trial to gather further data on the performance and emissions of a selection of boilers over a minimum of 12 months, in order to gain a greater understanding of the performance of the population of boilers installed in England, Scotland and Wales under the RHI and the reasons for good and poor performance. The work was carried out by a consortium of organisations, led by Kiwa Gastec and including Ricardo Energy & Environment, Energy Saving Trust, HETAS and Optimum Consultancy.

Remote monitoring equipment was installed on 67 boilers in early 2016 and data was gathered from February 2016 until July 2017 (and for selected sites, until July 2018). The field trial data was augmented by laboratory scale test work particularly related to atmospheric emissions, and a programme of social research which examined boiler operators' perceptions and experiences. Interventions were made at selected sites and their impact was assessed by continued monitoring and analysis of data. Guidance documents on best practice ways to improve biomass boiler performance were also produced. This report presents the results and conclusions of the programme.

[1] In July 2016, the Department of Energy & Climate Change (DECC) became part of the Department for Business, Energy & Industrial Strategy (BEIS). Where we refer to actions taken before this date, we refer to DECC. After this date, we refer to BEIS.

1.1 Reasons for research

Government supported technologies are tested in laboratories to assess performance based on British and European standards, however it is unclear how they perform outside the laboratory i.e. in-situ and in use. This work was commissioned by DECC in order to answer two key questions:

- What affects performance of these systems?
- Are DECC (BEIS) assumptions for modelling correct?

DECC's overarching requirement of this study was that it should inform policy development. Key questions for policy development were:

- Overall is biomass contributing as predicted to renewable heat production?
- Overall is biomass use achieving the requirements for greenhouse gas emissions reduction?
- How are individual fuel, technology and rating segments of the RHI registered biomass boiler population contributing to renewable heat generation and air quality emissions production?

The research questions of the field trial focussed on three areas: energy efficiency, fuel, and air quality/emissions (see Table 1).

Table 1: Key research questions

Area	Questions

Energy efficiency	• How efficient are solid biomass boilers in the field throughout their operation in comparison to their rated efficiency?
	• How efficient are biomass heating systems when the whole hydraulic design is taken in to account (e.g. accumulator tanks, domestic hot water demand, process heating etc.)?
	• How efficient are biomass systems during different cycles of operation?
	   o Boiler warm-up
	   o Constant load
	   o Frequent cycling
	   o Summer DHW efficiency
	   o Base load led
	   o Peak load led
	• What are the reasons for good and poor performance?
	• What is the impact of user operation on efficiency?
	• How does the sizing of the boiler to the load impact on efficiency (e.g. oversizing/under sizing plant)?
	• How does the efficiency of a boiler change over different timescales?
	• What best practice guidance can be offered to operators to identify poor performance and improve efficiency?

Fuel	• How much variation is there in fuel quality at different times of the year and what impact does that have on boiler operation? • How much does parasitic energy consumption affect overall system efficiency? • How does fuel storage type and duration affect fuel quality and efficiency? • What best practice guidance can be offered to operators to identify poor fuel?

Air quality/emissions	• Quantify in-situ emissions from biomass boilers via in-situ measurements of efficiency and laboratory replication of operation (pollutants (PM, NO_x and SO_x) and overall GHG emissions)? • How does operation impact on emissions (to be quantified) • What are the reasons for good and poor emissions (fuel type, fuel moisture content, boiler type, way boiler operated)? • To reduce biomass boiler emissions, what are the issues that should be focused on? • How do in-situ emissions compare to emissions certificates? • How do emissions compare to the counterfactual (oil for domestic boilers, oil and gas for non-domestic boilers)? • What best practice guidance can be offered to operators to identify poor performance and improve air quality/reduce pollutant emissions? • What is the likely fate of heavy metals present in the fuel – are they emitted to atmosphere or retained in the ash?

1.2 Project objectives

The objectives of the project were:

- To assess RHI biomass boiler population performance, both in terms of efficiency (taking into account all energy inputs and outputs) and emissions[2] (CO_2, PM, NO_x, SO_x and heavy metals).
- To identify the key causes of good and poor performance and quantify their impact.
- To understand how different uses of boilers and user interaction affect their overall performance, and whether this can be improved through operator guidance.

1.3 Summary of work carried out

The work carried out under this contract is summarised below:

- Characterised population of biomass boilers installed under the RHI
  - Data from DECC and Ofgem supplemented with data from stakeholder contact
  - Data analysed and used to categorise the type of biomass installations
- Examined possible reasons for good and poor performance of biomass boilers
  - Identified measurements required to evaluate performance along with measurement techniques
- Field trial
  - 67 boilers monitored across 60 sites for 12 months
  - Efficiency and fuel input calculated by 'indirect method'
  - Experimental obscuration measurements at 6 sites (for indicative dust)
- Lab trials
  - 25kW wood pellet boiler
  - 800kW wood chip boiler
  - Analysis of fuel and ash samples for heavy metals
- Social research
- Interventions at selected sites
  - 22 boilers (16 with interventions, 6 for control), across 21 sites
  - Additional monitoring for 12 months
  - Guidance documentation for commercial and domestic sites
- Data analysis & case studies

[2] To assess the performance of the biomass boilers during the field trial, pollutant emissions have been compared with literature values and against the RHI air quality requirements. The impact on the local environment by the pollutant emissions generated by the boilers has not been assessed as part of this work and this was not included in the project scope.

2 Background

This section provides some general background information which will help in understanding findings from this report. It also provides a summary of the main factors known to affect biomass boiler performance. This existing knowledge was used when developing the methodology of the field trial, laboratory trials and social research.

2.1 Glossary

Accumulator	A thermal water-storage tank which is integrated into the heating system. It collects and stores heat energy from the system to allow its flexible use at all times and to smooth out daily demand profiles. See also *buffer vessel* and *thermal store.*
Ash	During combustion, not all the fuel is burned. The unburned material is generally referred to as *ash* and can be left behind (in or under the grate or combustion region) or carried out of the boiler (usually as very small particles, that may be caught by flue gas clean-up systems, or lost with the flue gases). This material is comprised of non-combustible mineral matter and non-combusted material (mainly carbon) from the fuel. Material left under the grate is called *bottom (or bed) ash*, and material carried away is called *fly ash*. Ash that melts or fuses can cause the formation of slag or clinker. See *Sections 2.5.1 and 2.6.* N.B. The term *ash content* is also often used to describe the non-combustible mineral matter itself in the fuel.
Auger	An Archimedean screw used to transfer material (typically to move fuel from a store to the combustion chamber or to remove ash).
Bi-modal heating	Heating pattern where the heating system operates twice in a day (generally morning and evening). See *Section 2.5.1.*
Boiler efficiency	The ratio of delivered useful energy relative to the input potential fuel energy determined over a time period. See *Section 2.2.*
Buffer vessel	A tank of water used to improve biomass system efficiency by capturing residual heat from a biomass boiler on shutdown, and to provide this heat to the system during start-up. See also *accumulator* and *thermal store.*
Burn back	Combustion of fuel in the feed screw; this can easily lead to damage to the feed system and possibly a hopper fire, hence modern boilers are fitted with burn back protection systems.
Calorific value (CV)	The amount of energy released during the combustion of a specified amount of fuel. Two values are used; the Gross or Higher heating value and Net or Lower heating value. This report employs both Net and Gross values Net values. Net efficiencies report numerically larger efficiencies. The units are kJ/kg. See *Section 2.2.*
Clinker	A hard deposit material which is produced through ash melting, and forming a mass of sticky material that hardens as it cools. See *Section 2.6.*
Coefficient of determination, r^2	When fitting a straight line to a plot of data, it is the proportion of variation of one variable in a data set that is accounted for by variation of the other variable. The closer to 1 the r^2 value the better the data converges to a straight line.
Continuous heating	The heating system operates 24 hours per day. See *Section 2.5.1.*
Cycle	During normal operation, a biomass boiler will go through four stages: ignition, burn mode, shutdown and off. All four of these stages in sequence form one complete cycle of the boiler. All biomass boilers follow this general sequence however the lengths of each stage may vary. See *Section 4.2.4*

Degree day heating (DDH)	A measure of the heating requirement based on the difference between the ambient temperature and a base temperature (which is normally taken as 15.5°C in the UK). The higher the number of degree days, the colder the outside temperature was on average. Degree day analysis is used to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different.
Direct efficiency (%)	Heat output of boiler divided by the energy input. See *Section 2.3.*
Dust	See *particulate matter.*
Energy balance validation (EBV)	A technique for assessing the validity and robustness of performance measurements. See *Section 2.3.1.*
Feedstock	The raw biomass material subsequently used as a fuel.
Fuel balance closure	Comparison between the monthly predicted fuel usage (calculated using the indirect method) with the fuel usage reported by the site operators. The closer to 100% the fuel balance closure is, the higher the confidence in the data.
Heating season	Generally, the winter period from October to March when heating is required, however some sites have different heating patterns. It is customarily 235 days/year.
Heavy metals	Generally higher density metals, many of which are biologically active. The effects of metals can vary greatly depending on their concentrations and the compounds in which they occur. Metals in living organisms can be categorised as nutrients, secondary nutrients, trace nutrients and potentially toxic elements . Some metals are necessary for living organisms (e.g. potassium, calcium, magnesium). Others are generally considered toxic in biological systems (e.g. lead, mercury, chromium, copper) but may be considered harmless in low concentrations, and even be trace nutrients (copper).
Indirect efficiency (%)	100% efficiency minus the energy lost in flue gas, boiler case loss and any un-burnt fuel loss (all expressed as percentages). See *Section 2.3.*
kW	Kilowatts, a measurement of power (energy per unit time).
kWh	Kilowatt-hours, a measurement of energy. 1 kWh = 3.6 MJ (Megajoules).
Load factor	The amount of heat provided by the biomass boiler in a time period compared to the maximum amount of heat that could have been provided during that period. For example, a load factor of 100% means the boiler was running at its rated output for the entire period. A load factor of 50% means the boiler was either: • running at its rated output for half the period and was off for the other half, or • was running at 50% of its rated output for the entire period, or • some other similar combination of outputs and operating times The higher the load factor, the harder the boiler is working. In this report: • The heat supplied was measured by the heat meter on the boiler (kWh) • The heat that could be supplied (kWh) was calculated by multiplying the maximum rated output (kW) from the boiler nameplate by the time period (h). A load factor greater than 100% indicates the rated output of the boiler is incorrect, or that boiler is being over-driven. See also *utilisation factor.*
Modulation	The ability of a boiler to maintain stable operation at an output lower than its rated (or maximum) output. See also *turndown ratio.*
NO_x	Oxides of nitrogen that contribute to air pollution. These are nitrogen dioxide (NO_2) and nitric oxide (NO). The sum of these is usually reported as an equivalent amount of NO_2. See *Sections 2.4.1* and *2.4.*

Particulate matter (PM)	Small particles of solid or liquid suspended in a gas. Also referred to as particulates or dust. Specific sizes of particulate matter are often measured as they have a bearing on local air quality. These are often the number of particles that are <10 µm in size, known as PM_{10}, and the number of particles <2.5 µm in size, known is $PM_{2.5}$. See *Sections 2.4.1* and *2.4.*
Slumber mode	Operation mode of a biomass plant when fuel is still lit, but not generating a significant amount of heat.
Thermal store	See also *accumulator* and *buffer vessel.*
Turndown ratio	The ratio of the minimum stable output of a boiler to its maximum output. See also *modulation.*
Uni-modal heating	Heating pattern where the heating system operates throughout the day, but is switched off during the night. See *Section 2.5.1.*
Utilisation factor	The amount of time that the biomass boiler operated for (i.e. was burning fuel) in a time period compared to the maximum amount of time that it could have operated for. For example, a utilisation factor of 100% means the boiler was firing for the entire period. It may have been firing at any output, i.e. rated output or modulated output. This means its load factor may be lower. See also *load factor.*
Volatile organic compounds (VOCs)	Carbon-based compounds that have high enough vapour pressures under normal conditions to vaporise into the atmosphere. See *Sections 2.4.1* and *2.4.*

2.2 Introduction to biomass combustion

The combustion of biomass comprises a range of processes which are summarised in Figure 1. The mix of these processes in any particular scenario (combustion system, fuel, operating conditions) leads to the outcome of combustion.

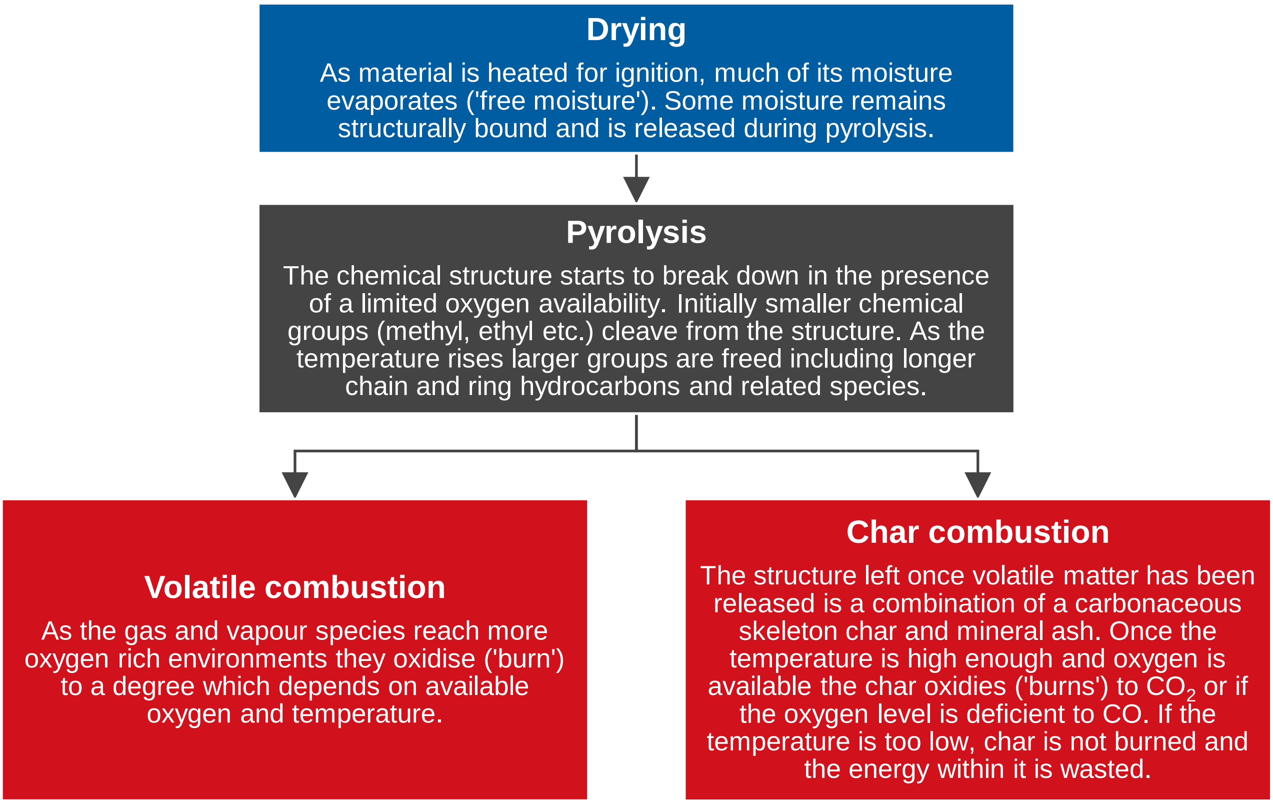


Figure 1: Summary of biomass combustion processes

2.2.1 The grate

The grate in a solid fuel combustion appliance is the device which presents the fuel to the combustion air and facilitates sustained combustion and separation/removal of residual ash. Many types of grate have been developed for combustion of solid fuels. Generally, each design is suited to combustion of one or more types of fuel. There are various constraints on designs such as the size of the fuel particles to be burned.

The combination of the grate design and operating conditions have a direct effect on the combustion process. Where fuels that deviate from the design specification are burned this can lead to a variety of issues. In particular, if fuels with higher ash contents or with lower ash melting points are used deposits of ash can be formed, restricting flows of combustion air causing a degradation of combustion performance.

The following grate types were installed in the boilers included in the field trial:

For pellets:

- Underfeed
- Overfeed

For chips:

- Underfeed
- Stepped or moving grate
- Overfeed

For logs:

- Gasification
- Moving grate

For the laboratory work in this research project measurements were made on two boilers, a 25kW overfeed pellet burner and an 800kW underfeed chip burner, the designs of which are shown below.

Overfeed grate

Fuel is dropped from the screw feeder into the combustion pot. Primary combustion air is supplied through holes distributed around the combustion pot. The fuel is ignited and combustion processes take place within and above the fuel bed. Residual ash drops from the bottom of the pot. When the boiler shuts down, the bed is dumped into the ash collection tray through a flap at the bottom of the combustion pot. Some incompletely burnt fuel is lost each time the boiler cycles.

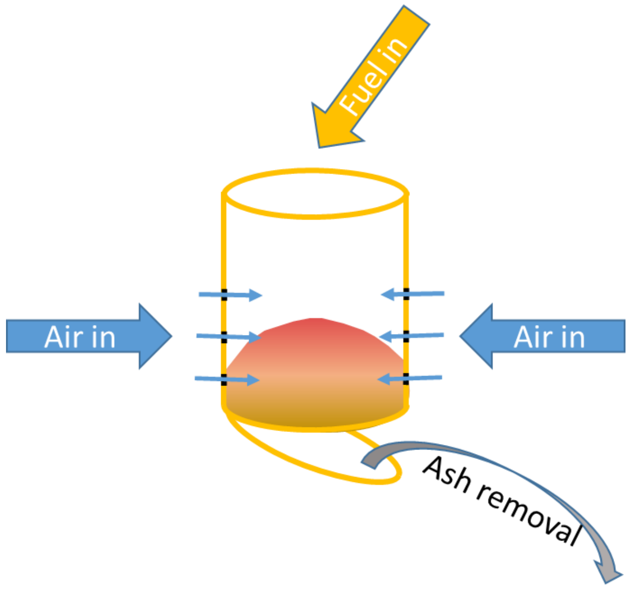


Figure 2: Overfeed grate

Underfeed grate

Fuel is forced into the bottom of the combustion pot by the feed screw. Primary combustion air is supplied through slots distributed along all four sides of the rectangular combustion pot. The fuel is ignited and the various stages of combustion taken place within the fuel bed. As combustion is completed the residual ash is gradually pushed towards the ash removal point.

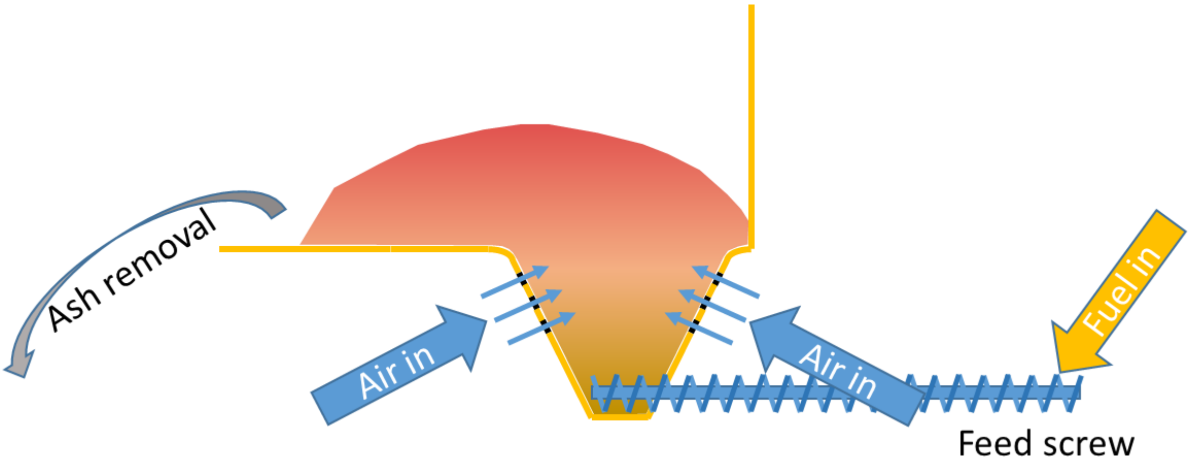


Figure 3: Underfeed stoker grate

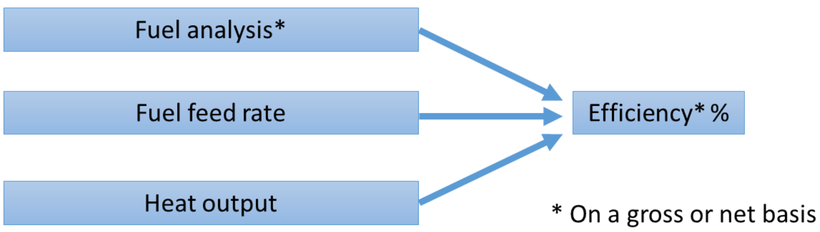
2.3 Methods of calculating efficiency

Boiler efficiency can be quoted either on a net or gross basis. When efficiency is quoted on a net basis, it is assumed that the energy contained in the water vapour which is formed as a product of combustion is recovered. When efficiency is quoted on a gross basis, it is assumed that the energy contained in the water vapour is not recovered. Typically, the difference between the value of net boiler efficiency and the value of gross boiler efficiency for a biomass fuelled boiler is around 9% with the net value being higher than the gross value [5].

There are two methods for determining the efficiency of a boiler:

- The **direct method**:

$$\text{Efficiency} = \frac{\text{Energy out}}{\text{Energy in}}$$



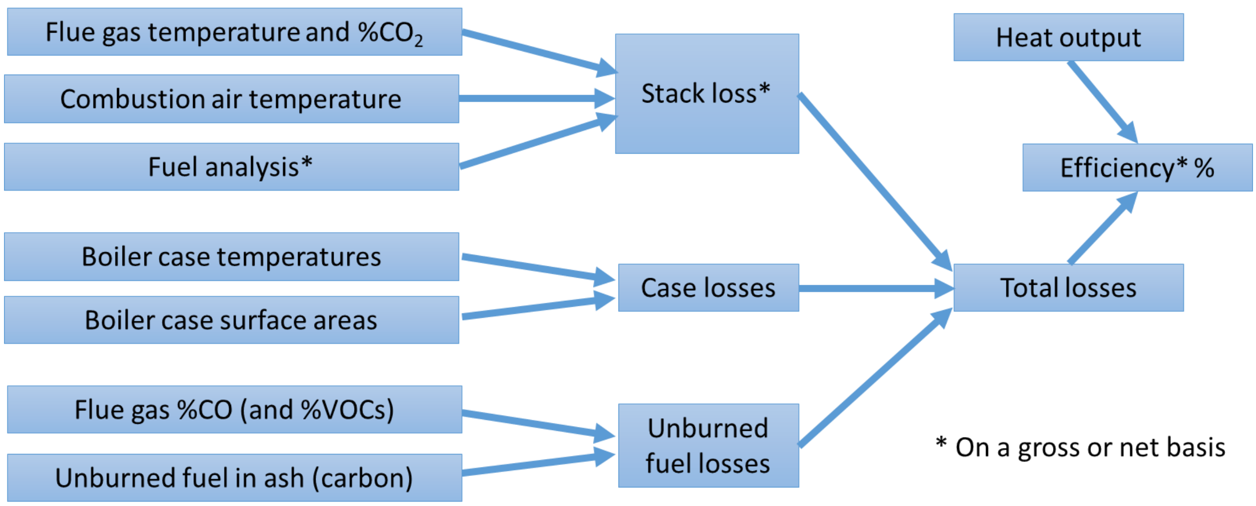
This is very difficult to achieve in the field, because it is difficult to measure the fuel feed rate accurately. Errors in the fuel feed rate can then have a large impact on the calculated efficiency, including leading to efficiencies greater than 100%, which is not physically possible.

- The **losses/indirect method**:

$$\text{Efficiency} = \frac{\text{Energy in} - \text{Losses}}{\text{Energy in}}$$

or:

$$\text{Efficiency} = \frac{\text{Energy out}}{\text{Energy out} + \text{Losses}}$$



In the field, the indirect method using heat output is generally more accurate overall. This is because errors in the losses have a smaller relative impact on the overall calculated efficiency.

Losses usually[3] consist of:

- flue gas losses – often around 10 to 15%
- case losses – usually 1 to 2%
- unburned fuel, in the ash and as carbon and in flue gas (generally as CO) – varies

$$\text{Total losses} = \text{Flue losses} + \text{Case losses} + \text{Unburned fuel losses}$$

In some analyses, 'energy in' includes the electrical energy used to power augers, fans, and drives. Due to the range of installation complexities encountered in the field trial, the system boundary of electrical input is variable. This is because, at some sites it was not possible to break into the boiler room's electrical distribution system without significant additional effort. This resulted in parasitic loads such as system distribution pumps being included at some sites but not at others. Therefore, in this report, electrical energy is excluded[4] from the reported efficiencies and the 'energy in' term is purely the energy input in the fuel (i.e. the mass of fuel fed multiplied by its calorific value). However, the measured electrical consumptions recorded in the field trail and laboratory trials are reported in their respective annexes.

[3] These can be readily confirmed by carrying out a sensitivity analysis of the equations in BS 845 [24].
[4] Electrical energy input was measured during the field trial and laboratory trials, but to make it easier to interpret the analysis, it is not included in the quoted efficiencies.

2.3.1 Energy balance validation (EBV)

Energy balance validation (EBV) is a technique for assessing the validity of performance measurements for heat appliances such as boilers and mCHP. In an EBV, a system boundary is drawn around the appliance and all the energy going into and coming out of the system (including losses) is accounted for. The EBV 'closure' is calculated from the equation:

$$\text{EBV closure} = \frac{\text{Sum of all energy outputs (including losses)}}{\text{Sum of all energy inputs}}$$

$$= \frac{\left(\begin{array}{c}\text{Useful heat out} + \text{Flue losses} + \text{Case losses} \\ + \text{Unburned fuel losses} + \text{Heat added to boiler}^{5}\end{array}\right)}{\text{Energy supplied by fuel} + \text{Electricity supplied}}$$

In essence, this is a comparison of the efficiency calculated by the direct method, with the efficiency calculated by the indirect method.

In an ideal situation, these should match exactly and the EBV closure should be close to 100%[6]. Practically, achieving close to balance from measurements is most likely to be achieved where operation is at steady state, in which case the energy content of the test item can be assumed to be constant. For the field trial and laboratory trials carried out in this project, the appliances were not in steady state, so a wider band of EBVs was expected.

Where a tight closure of the balance is achieved, this increases confidence in the performance measurements and conversely where the balance deviates from closure, this reduces confidence in the measurements. For the measurements made in this research project, specific thresholds for acceptability cannot be set. However, EBV still provides an important check and helps to identify the likely sources of uncertainty e.g. assumptions about the adjustments required to account for non-steady state operation.

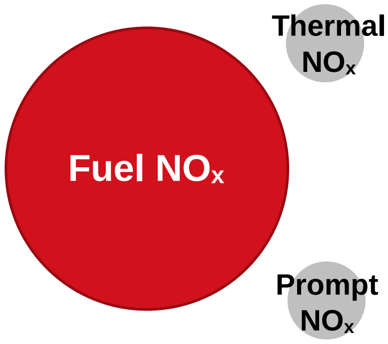
[5] In the laboratory trials of the small boiler, an additional term was included in the EBV to account for the fact that the start and end conditions of the tests were not identical (there was a difference between initial and final boiler water flow temperatures).

[6] With gas boilers and CHP, it is common for the EBV to be slightly less than 100%, due to some losses being unaccounted for [41].

2.4 Sources of pollutant emissions

Potential sources of pollutant emissions are summarised in Table 2.

Table 2: Sources of pollutant emissions from biomass combustion

Pollutant	Source
Particulates	• Partially burned pyrolysis product – fine char particles • Ash particles • Incompletely burned char particles • Pyrolysis products condensed on the surfaces of other solid particles
NO_x	• **Fuel NO_x** – nitrogen in the fuel is converted to NO_x during the combustion process. During biomass combustion, this is the primary source of NO_x. • **Thermal NO_x** – direct combination of oxygen and nitrogen in the combustion air and becomes significant above about 1,300°C. Normally not significant during biomass combustion. • **Prompt NO_x** – indirect route where air nitrogen first combines with fuel and then behaves as fuel nitrogen, when there is very high excess air. Not significant during biomass combustion. 
Hydrocarbons (VOCs)	• Pyrolysis products
SO_x	• Biomass contains very low levels of sulphur (less than 0.03% from sites on the trial). When oxidised it is emitted as sulphur dioxide (SO_2) and sometimes as sulphur trioxide (SO_3), which can combine with water and fall as acid rain.
Heavy metals	• Metals present in the fuel may be emitted in the flue gases or may remain bound up in the ash. • Metals in the flue gases may be associated with particulates and be collected in abatement technologies (e.g. collected as a part of the grit or dust). • The proportion of metal that remains in the bottom ash is difficult to predict and is dependent on many factors, including the species in which the metal is present in the fuel, the volatility of those species, and the conditions in the combustion chamber.

2.4.1 Sources of heavy metals

Emissions of heavy metals from biomass boilers will occur through one of two routes:

- Heavy metals from the fuel that are emitted to atmosphere (if the metals become trapped in particles that are carried up the flue).
- Heavy metals from the fuel that are emitted to land (if the metals become trapped in the ash which is then spread onto or disposed of on land).

Trees and plants take up metals from soil and water. The concentrations of heavy metals in soil and water are not uniform, dependent in part on the mineral forms present in soils. Take-up is not necessarily uniform across all metals, and some species absorb certain metals preferentially. Therefore, the concentrations of heavy metals will vary in the biomass produced from those trees and plants. There will also be variability in composition within the parts of individual trees and plants (for example between bark, knots and heartwood).

The fates of the components of fuel when it is burned depend on their behaviours in the combustion environment and in the flue gas passes. Biomass fuels for combustion generally comprise mainly carbon, oxygen and hydrogen and these together with some other components such as sulphur are converted to gases/vapours which leave the combustion system. Other components may either remain in the bottom ash from the combustor or be carried in some form in the flue gas. The material carried in the flue gas may be deposited on surfaces in the system (accidentally or deliberately through use of flue gas cleaning equipment such as filters) or be emitted to atmosphere.

The metals in biomass are largely associated with its mineral content, and mostly remain in the ash after combustion. Some metals may be preferentially driven to atmosphere during combustion, depending on their chemical state, their volatility, and the combustion conditions. Heavy metals can be classified [6] based on their tendency to partition from the bottom ash to the fly ash during combustion. Manganese, cobalt and chromium are reported to have no tendency to partition to fly ash. Arsenic, cadmium, lead and antimony are enriched in the fly ash relative to the bottom ash. The only metal which is classified as being emitted as a vapour is mercury.

Previous work [6] has established the ash formation mechanisms for trace elements in coal, however the fate of heavy metals in biomass combustion is not well understood. This is because coal combustion in utility boilers typically takes place at much higher temperatures than the temperature of biomass combustion. Therefore, the metals which vaporise and partition to fly ash in a biomass system are likely to be only a subset of those that vaporise in a coal system.

2.4.2 Units for expressing pollutant emissions

Pollutant emissions from boilers are measured using a variety of techniques and often the emission measurements are presented in a set of units that best reflect how the measurement was taken. In contrast, the various pieces of legislation that set emission limits (such as the RHI [7, 8] or the Clean Air Act [9, 10]) may do so in a different set of units. A range of units used for expressing pollutant emissions are given in Table 3. Various conversions have to be applied to convert between them. Depending on the assumptions in the conversions, the uncertainty of the converted measurement may be increased.

Table 3: Units for expressing pollutant emissions

Unit	Description	Used in
g/GJ gross input	Grams of pollutant emitted when fuel with gross energy content of one Gigajoule is burned. Of the three g/GJ units, yields the smallest number.	—
g/GJ net input	Grams of pollutant emitted when fuel with net energy content of one Gigajoule is burned. Larger than g/GJ gross input, but smaller than g/GJ output.	RHI emission limits [7, 8]
g/GJ output	Grams of pollutant emitted when one Gigajoule of useful heat is generated. Of the three g/GJ units, yields the largest number, and is impacted by boiler efficiency.	—
g/h	Grams of pollutant emitted per one hour of burning.	Clean Air Act emission limits [9, 10]
mg/Nm^3	Milligrams of pollutant present in one normal cubic metre of flue gases. Normal cubic metres means corrected to 273K and 101.3kPa, however measurements expressed in this unit require an additional set of conditions to be stated. For biomass, this is usually: dry flue gas, corrected to 10% oxygen.	Clean Air Act application pack for determining if smoke is likely to be visible [9]

2.5 How boiler operation impacts performance

The aspects of boiler operation which have the greatest impact on boiler performance in terms of efficiency and atmospheric emissions are:

- **Cycling / run-times**
- **Operating pattern / heating regime:**
  - Continuous
  - Uni-modal
  - Bi-modal
- **Load / utilisation factor**
- **Control strategies, control capabilities, including:**
  - Turndown or on / off operation
  - Ignition systems
  - Burnout of fuel on the fire bed

2.5.1 Operating patterns

Operating patterns affect biomass boiler operation through limiting the number of hours that the boiler is enabled. Operating patterns have been investigated in biomass boilers which are used in domestic and commercial applications where the energy is being used to heat buildings for human occupation. Process applications have not been investigated as the pattern of heat use is highly dependent on the requirements of the process using the heat. The use of operating patterns is not specific to the operation of biomass and is used in most space heating applications. A timer is used to set the periods when the heating system can supply heat, usually set to coincide with when the building will be occupied.

There are three main operating patterns identified from quantitative analysis of domestic and commercial boilers in the field trial, these operating patterns are:

- **Continuous** (Figure 4): Boiler is enabled continuously over a 24 hour period. This does not mean the boiler runs continuously, it is controlled by heat demand, but is able to operate at all times.
- **Uni-modal** (Figure 5): Heating pattern where the heating appliance is enabled once a day. There are standard times specified in SAP [5] for heating appliances which follow this heating pattern. This is typically between 07:00 to 23:00. This does not mean the boiler runs continuously between these times.
- **Bi-modal** (Figure 6): Heating pattern where the heating appliance is enabled twice a day. Again from SAP this is between 07:00 to 09:00 and 16:00 to 23:00. This does not mean the boiler runs continuously between these times.

All the boilers in the field trial fell broadly into these patterns of operation. Example tapestries for three sites showing the operating patterns described above are shown in Figure 4, Figure 5 and Figure 6. A further example of **tri-modal** operation (three times per day) has also been included in Figure 7.

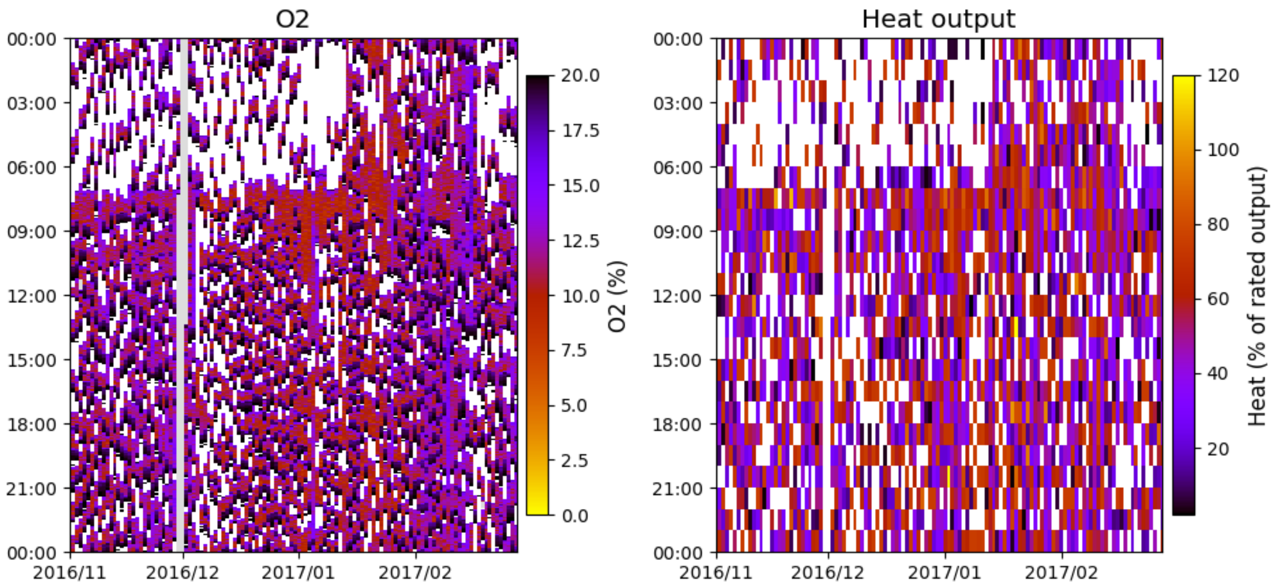


Figure 4: Tapestry showing continuous operation (B069)

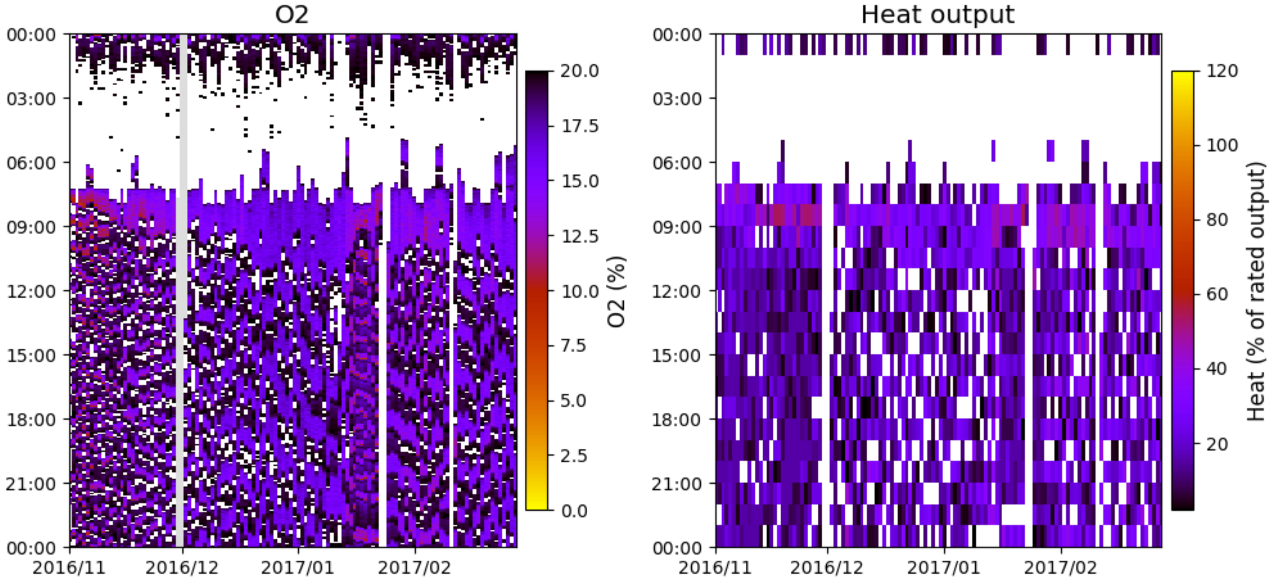


Figure 5: Tapestry showing O_2 concentration and heat output during uni-modal operation (B920)

Tapestries are a technique for presenting complex time series data sets in a way that enables patterns in the data to be identified rapidly. The tapestries show how the boilers operate for each day. The range starts at midnight at the top of the tapestry and moves down the tapestry through a 24-hour clock until it reaches the bottom at midnight again (shown in Figure 7). The areas of white on the graph correspond to data which indicates the boiler is off. For the oxygen plot, white shows an atmospheric level of oxygen, and for the heat output tapestry, it shows that no heat is being produced. By plotting the data in tapestries, it becomes easy to visualise the pattern of operation by looking at the times when the boiler is enabled. Flue gas temperature can also be visualised in the same way, behaving in roughly the opposite way to flue gas oxygen (i.e. when the boiler operates, flue gas oxygen decreases and flue gas temperature increases).

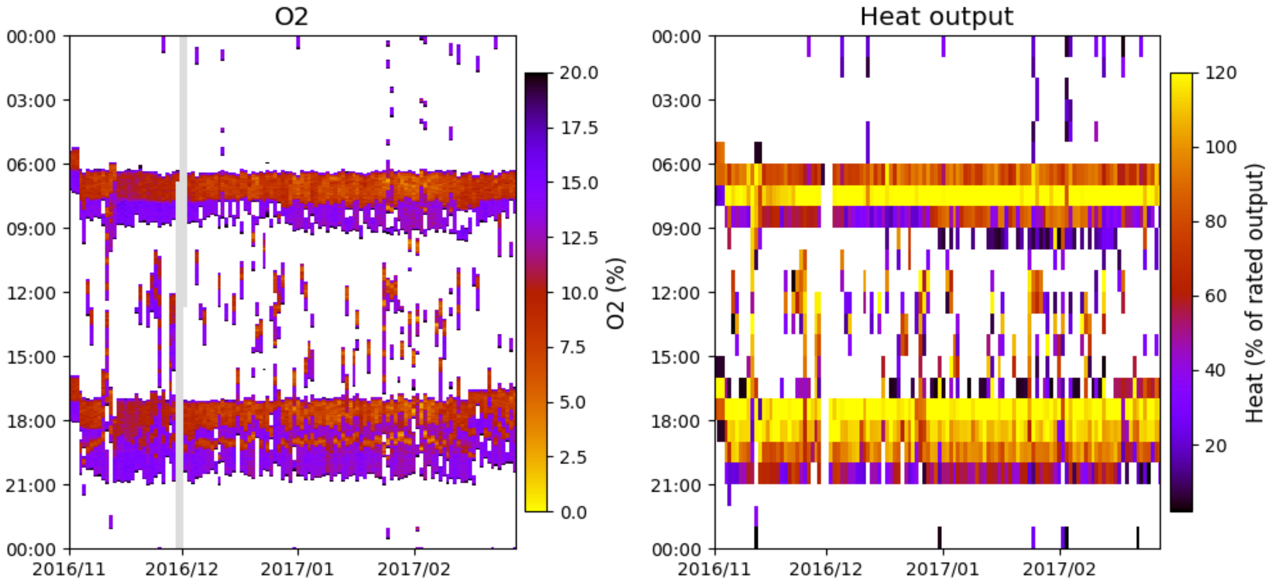


Figure 6: Tapestry showing O_2 concentration and heat output during bi-modal operation (B922)

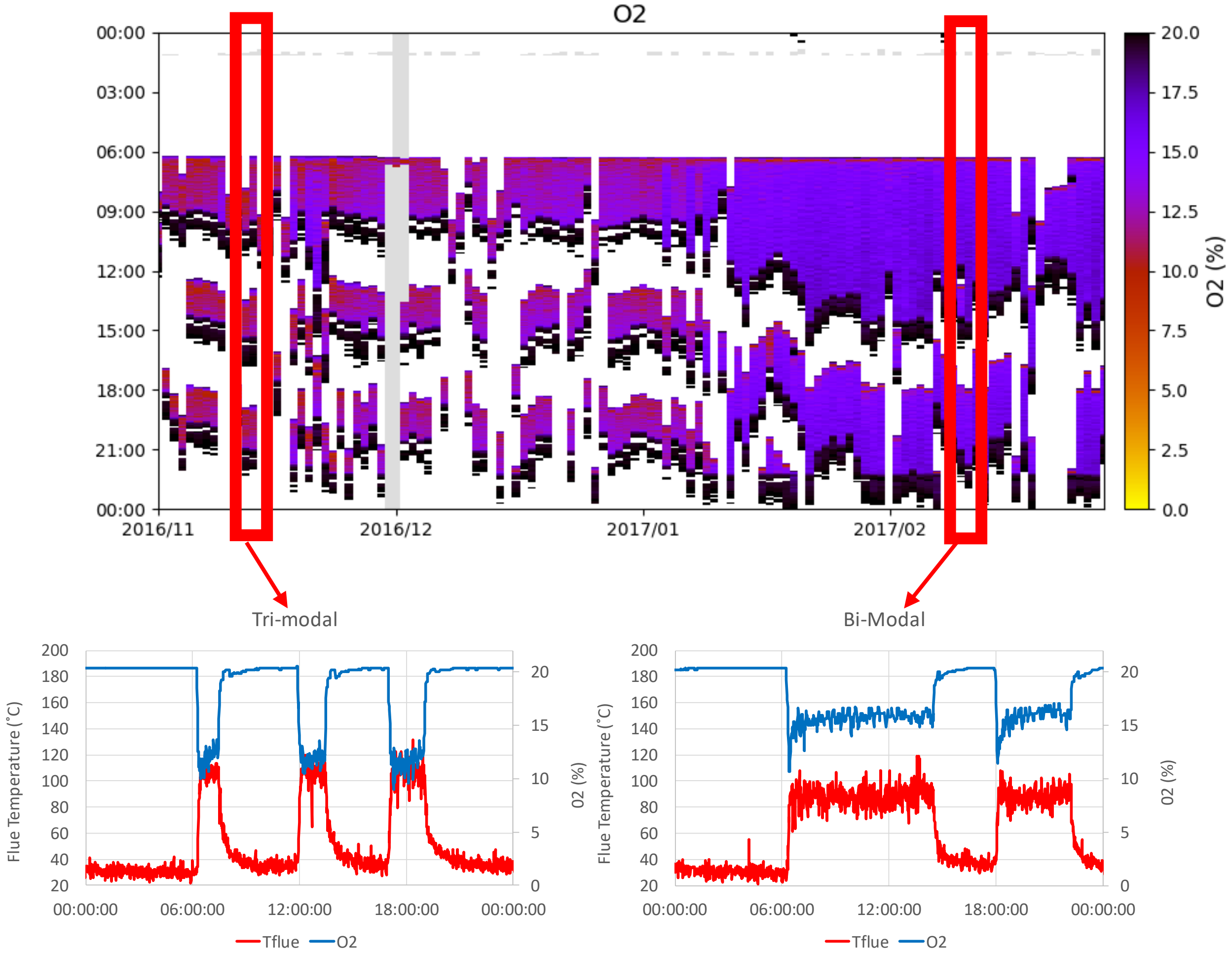


Figure 7: Tapestry showing tri-modal operation with daily graphs of oxygen, blue and flue temperature, red (B445)

The tri-modal operating pattern shown in Figure 7 shows a boiler operating from November to March. There were two distinct operating patterns occurring during this time: a tri-modal pattern and a bi-modal pattern. In this case the patterns were not controlled by a time clock but by the load on the boiler, however they are good examples of how operating patterns work. The highlighted flue gas temperatures show the operation of the boiler on a typical day following that pattern. The tri-modal pattern occurred in November 2016 when the boiler was enabled three times a day. The bi-modal pattern began half way through January 2017 and can be seen by the boiler running in two periods once in the morning and once in the evening.

2.6 Fuel type and characteristics

When burning solid fuels, the combustion design must be linked to the fuel characteristics. The boiler can be designed to burn any particular fuel, but it is very difficult to design for a very wide range of fuels to be burned on the same appliance.

The main components of biomass fuels which affect performance are:

- Organic content and heating value
- Moisture
- Mineral matter – also referred to as inorganic matter or ash
- Other constituents of the fuel such as nitrogen, and to a lesser degree sulphur

In addition, the physical presentation of the fuel must also be considered. The main types are:

- Wood pellets
- Wood chips
- Wood logs

Each of these fuel characteristics affects the behaviour of biomass fuel during combustion:

- Effects of moisture (inherent, free)
- Effects of particle size and fines
- Effects of mineral matter:
  - inherent (inorganics within cell structure)
  - adventitious (minerals trapped in structure during growth mainly in bark, especially in logs)
  - free (soil picked up during harvesting)
- Fuel type / supplier
- Impact of degrading mechanical properties of fuels due to exposure and incorrect handling

A 2015 study by Kiwa and Ecofys for Ofgem [11] examined issues around blending biomass fuels. In general, the findings relevant to this current study were that there was significant scope for inappropriate fuels to be fed to a boiler and that there was limited empirical information about the impacts of variations in fuel characteristics caused by using these inappropriate fuels.

The study focussed on the addition of recycled wood fuel to boiler fuel supplies, in cases where the testing and emissions approval for the boiler had been performed on virgin wood. It also looked at cases where the emissions certificate of the boiler stated that recycled wood was an acceptable fuel choice but emissions testing had only been performed on virgin wood. In these situations, it was questionable that there was enough evidence to support satisfactory performance when using recycled wood fuel without further testing.

2.7 Ash deposits and clinker formation

Deposits of ash in a boiler are formed on the burner surface as well as the chamber sides and roof (Figures 32-34, p.67). Where the ash is deposited depends on how the ash is formed and its characteristics. Fine ash particles are ‘blown off’ (elutriated from) the fuel bed by the primary combustion air flows which are carried to the walls and roof of the combustion chamber as well as out of the chamber with the flue gas.

The combustion chamber is refractory lined which limits heat loss from this section of the boiler so that the heat passes into the heat transfer sections. The inner surfaces of refractory linings of combustion chambers can be at temperatures close to the combustion chamber temperature.

For the combustion chamber sides and roof, the steps which lead to deposition are:

1. Particles close to the flame temperature arrive at the deposition surface
2. Particles adhere to the surface – generally more effective on rough surfaces at high temperatures and with low ash fusion temperatures
3. Further particles arrive – the rough surface produced by initial deposition increases particle capture
4. Particles fuse to form agglomerates – appear as larger particles

As deposits develop they insulate the initial deposition surface and the outer surfaces increase in temperature. As temperature increases the degree of particle fusion increases. Typically, a material with a foam-like appearance results and if temperature is sufficient full melting can occur and running slag is formed.

For burner surfaces, the steps which lead to deposition are:

1. If the temperature in the combustion bed is greater than the fusion temperatures of the mineral, sintering can occur
2. Sintered ash adheres to burner surfaces and deposits develop with the degree of fusion increasing
3. Deposits do not generally develop in air or fuel inlets. However, their growth can be particularly marked around these inlets

The degree and rate of ash deposit development depends on various factors. The ash content of the fuel and the composition of the ash will have a large effect on the rate of deposit formation. Low ash fusion temperatures are often blamed on ash build-up in biomass boilers, however poor design also has an effect. This is because fuel feed rate and air feed rates affect the temperatures and excess air levels in the fuel bed.

2.8 System design

Boiler design, system design and operation are closely interlinked. Design aspects include:

- Boiler sizing
- Thermal store sizing and use (note definitions of buffer, accumulator, thermal store)
- Thermal store design and connection to the system
- System operating philosophy.

Guidance on system design and specification is available from various sources:

- Manufacturer guidance / instructions
- MCS installer standards [12]
- The Carbon Trust provides a spreadsheet based “Biomass System Sizing Tool” supported by a user manual [13]. This provides a method which integrates the size of accumulator vessel into the boiler sizing calculation. The tool and manual uses the following differentiation:
  - buffer vessel (for system overheat protection)
  - thermal storage vessel (to reduce boiler size and improve system efficiency across all load conditions)
- CIBSE has published in 2014 a guide for biomass heating [14]. This includes guidance on the biomass boiler selection and sizing and design of buffer vessels and thermal stores.
- HETAS Technical handbook [15]
- Building Regulations (Approved Documents, Compliance Guides). Part J does not deal with this aspect of boiler installation
- European Standards and codes of practice are available for design of heating systems (for example EN 15316-4-1 [16] which is concerned specifically with biomass); these generally deal with domestic heating rather than commercial or industrial scale systems.

3 Previous work

A literature review was undertaken before the field trial started and is included in Annex A (provided as a separate document). The review contained analysis of previous work that has been completed looking at the real efficiency of biomass boilers. There were thought to be significant differences between expected performance of biomass boilers and that achieved in use. Therefore, work that contained Information collected during operation under simulated or actual in-use conditions was of interest. The review included any source that was applicable however it was particularly focussed on:

- Detailed laboratory studies examining the effect of operating boilers under simulated in-use conditions (not simple standard tests)
- Field trials – these studies could provide information about the performance of boiler systems when responding to the actual demands placed on them by heating systems or processes.
- Case studies of individual installations – could provide information about average efficiency provided that they include robust records of fuel use and heat generated.

3.1 Summary of detailed laboratory studies

There was a lack of information on laboratory test work analysing biomass boilers under simulated in-use conditions. There were several pieces of work which included laboratory tests [17, 18] however their focus was not on investigating performance issues arising from real life operation. The main focus was usually on system design and configuration or to validate field trial methodologies.

3.2 Summary of field trials

Although several one-off boiler measurements and efficiency test reports were identified, only four field trials and more general in-use simulations of biomass boilers were found [4, 19, 20, 21]. All four field trials set out to measure the performance of biomass boilers in the field however even when undertaken they did not necessarily result in collection of the data required to understand boiler performance. Where reports were available these were reviewed. The data from these other field trials showed that:

- There were difficulties in obtaining accurate fuel feed rate information which meant that the indirect method of measuring boiler efficiency was more reliable than the direct method
- There was an increase in smoke emissions especially during start-up, shutdown, and low load operation
- A significant proportion of boilers were oversized
- There were several issues around accumulator sizing / operation
- Fuel quality had a major impact on performance, particularly variations in fuel quality
- The best performing units were operated by an enthusiastic boiler operator

3.3 Summary of case studies

Many case studies of biomass installations have been published. However, these were generally focussed on showing cost saving and/or CO_2 emissions reduction achieved relative to an alternative, fossil-fuelled system.

A number of case studies were created during the desk-based study with which DECC commenced their examination of the performance of biomass boilers in the UK [22].These were based on collecting metered heat output and user records of fuel procurement over a whole year. These studies produced annual efficiencies based on a crude form of the direct method. The results provided further evidence that this method produced relatively unreliable results. This was evidenced by some unfeasibly high efficiencies. This showed the difficulty of producing efficiencies using the direct method for biomass installations. It highlighted that estimating the fuel input for biomass causes large discrepancies in the calculated efficiencies.

This was also investigated in 2015 when a methodology was produced to measure in-situ performance of biomass boilers [4]. This was driven by the need for a method for calculating efficiencies that was not dependent on the direct method which had been shown to be unreliable for large field trials. The losses method was recommended for use as it has been shown to be more accurate and reliable than the direct method.

3.4 Gap analysis

From the review of available literature on the performance of biomass boilers, a number of areas were identified where further work would extend understanding of the issues. In several areas, the factors affecting instantaneous and overall efficiency and pollutant emissions are not well understood. These gaps in knowledge include:

- Matching boiler size to load, the impacts of seasonal variations in demand on performance, optimum plant sizing strategies. Potential mis-sizing because of influence of other environmental or economic factors.
- Boiler control strategies and capabilities – degree of output modulation, boiler off/on triggers, interaction with thermal store.
- The effects of boiler cycling, and particularly the effects of frequent boiler start-up and shutdown.
- Mis-sizing of thermal stores. Correctly sized thermal stores (accumulators) should enable biomass boilers to be operated in ideal continuous mode. The impacts of under- or over-sizing.
- The impacts of different fuel types. Are boilers designed to fire logs, woodchip, or pellets more efficient or less polluting?
- Different arrangements of the system and in particular how any thermal store is connected and consequently how it is operated.
- Fuel quality (in particular moisture content) and the effects of variations in quality.

3.5 Filling the knowledge gap

The methodology for this work was developed to enable investigation of all the areas identified in the gap analysis. To explore these areas, the main requirement became to collect data on the operation of real biomass installations across the UK. The field trial methodology was therefore designed to provide performance and efficiency data from a representative sample of solid biomass boilers installed across England, Wales and Scotland. By collecting this data, it would be possible to begin investigating the effects of:

- Mode of operation
- Matching of the boiler size to the load size
- Output modulation
- Impact of thermal stores
- Rapid cycling
- Use of lower quality fuel (either mechanically degraded or from recycled wood)
- Boiler control strategies and capabilities

In combination with the collection of performance and efficiency data from sites across the UK, laboratory testing was also required to give a full picture of the issues affecting biomass. The field trial equipment was not able to evaluate pollutant emissions as it was not feasible to collect pollutant data in a cost effective and robust manner. This was due to the sophisticated monitoring equipment and the skilled labour requirements for the analysis of flue gas pollutant flows over extended periods of time. Therefore, in addition to the field trial data collection, a laboratory research programme was required to measure pollutant emissions from biomass boilers. This data could then be used to give a fuller picture of the pollutant emissions generated by sites included in the field trial. Pollutant measurements focussed on emissions of particulate matter and NO_x, however CO and hydrocarbons were also measured. Sulphur dioxide emissions could be inferred from fuel analysis, as any sulphur present was expected to be converted to SO_2.

A secondary role of the laboratory research programme was to provide more accurate measurements for the same areas identified for the field trial, in more detail. This was done by simulating behaviours observed in biomass boilers involved in the field trial. Running the boilers in different types of operation that influence performance in the laboratory tests allowed for more detailed analysis into the areas already identified. The laboratory research produced a detailed analysis of the biomass boilers under test, however care had to be taken when using this data for evaluating other boilers in the trial.

The final role of the laboratory testing was to validate the accuracy of the field trial equipment. Direct measurements of efficiency were made with laboratory equipment and compared with simultaneous indirect measurements of efficiency using the same setup of equipment that was installed in the field trial.

There were some areas that were not covered directly by the research. These included:

- different arrangements of systems and the way that thermal stores are connected
- the impact of different fuel types

4 Methodology

The project was completed in three phases, shown in Figure 8. Phase 1 was focussed on preparatory work – selecting suitable sites, installing equipment, preparing systems for data storage and developing laboratory methodologies. Phase 2 was focussed on data collection – from the field, from laboratory work and from social research, and then the analysis of that data. In Phase 3, interventions were made at selected sites and their impact was assessed by continued monitoring and analysis of data. Guidance documents on improving performance were produced and further laboratory trials on heavy metals were conducted.

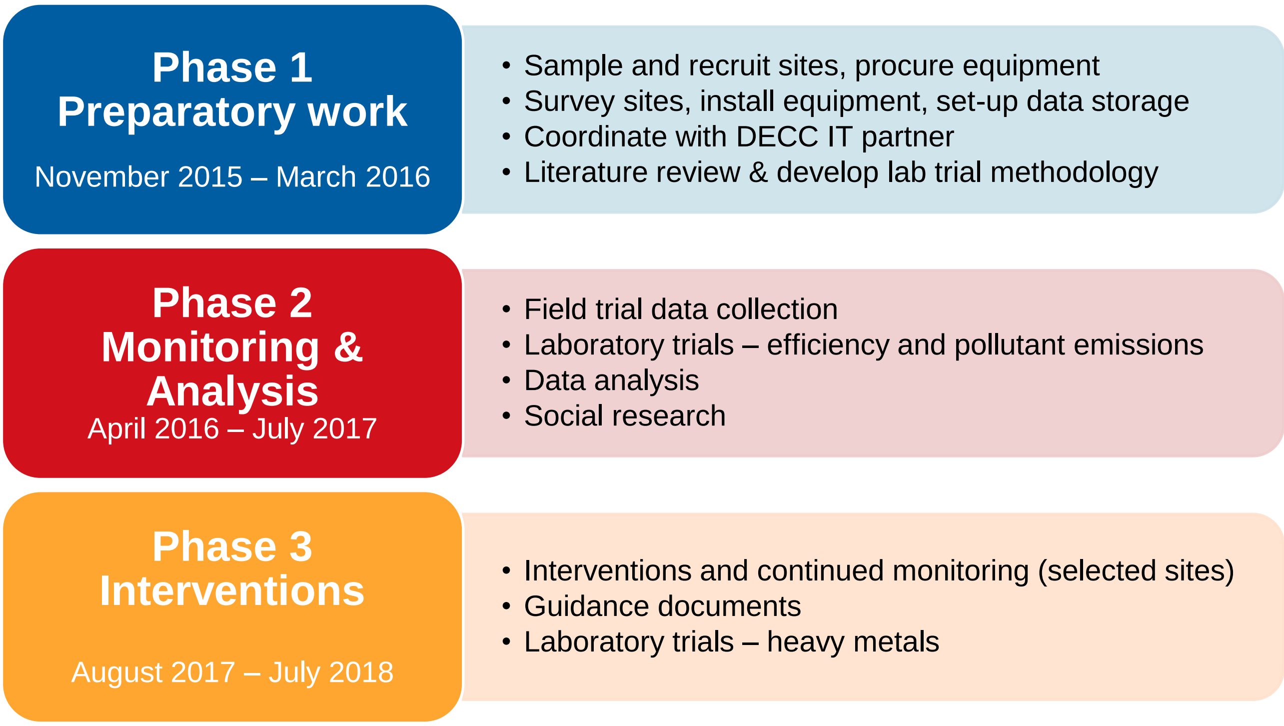


Figure 8: Project approach - Phases 1, 2 and 3

4.1 How the research questions were addressed

The purpose of this study was to enable the performance of the population of biomass boilers under the RHI scheme to be modelled. To achieve this, the study needed to collect performance data for use in the modelling.

Several key research questions were set (see Table 1), which were divided into three areas of interest:

- Energy efficiency
- Fuel
- Air quality & emissions

To answering these questions effectively, a mix of field trial measurements, laboratory trials and social research was required (see Figure 9):

- **The field trial and social research** collected data on as large as possible of the range of equipment, technologies, fuels and operating environments and practices. The focus was on energy efficiency and patterns of operation.
- **The laboratory trials**[7] investigated parameters that could be measured more robustly and cost-effectively in a laboratory setting than in the field [4]. The focus was energy efficiency and pollutant emissions during the patterns of operation that had been observed in the field trial and social research.

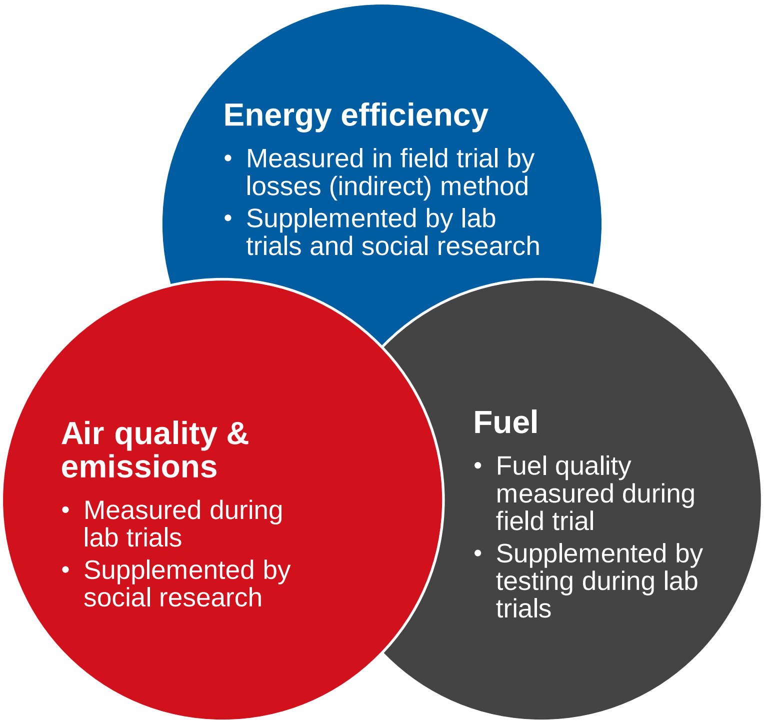


Figure 9: How the key research questions were answered by a mix of field trial, laboratory trials and social research

4.2 Field trial

The field trial studied in detail the operation of 67 solid biomass boilers, installed across 61 sites around England, Wales and Scotland. The boilers were fired by either wood pellet, wood chip or wood log and had rated outputs between 10kW and 800kW. All the boiler installations qualified[8] for either the non-domestic or domestic RHI.

Data from these boilers was collected from April 2016 until July 2017. Factors affecting the performance of the boilers were analysed and the efficiency of the boilers was calculated using the losses/indirect method (on both a net and gross basis). It was well-known that the performance of the system as a whole is dependent on many factors, including the design of and interaction between the boiler, heat distribution system and heat emitters. This created a great deal of variation and vastly increased the difficulty of the data analysis. Therefore, the focus of this project was on the performance of the biomass boiler itself, and the factors affecting this. Measuring heat output and the losses from the boiler gave a more robust measure of efficiency than a direct

[7] It is emphasised that during the laboratory trials, measurements were made under real-world conditions that were representative of those observed during the field trial (for example non-steady state operation). They yielded different results to the usual British Standard and European Standard appliance testing procedures.
[8] All the boilers were eligible for the RHI, but a small number had chosen not to claim it.

calculation based on estimated of fuel use (see Section 2.2). A number of case studies were also produced to illustrate specific effects on a boiler-by-boiler basis.

4.2.1 Defining the sampling strata

As of the start of the research, the overall population of RHI-accredited solid biomass boilers was approx. 17,600 installations in total. This comprised approx. 6,400 domestic installations and approx. 11,200 non-domestic installations [4].

Based on the finding of previous work [4], a number of strata were identified within the RHI population, shown in Tables 4- 5. These were based on the scheme (domestic or non-domestic) the boiler was part of, its fuel type (wood pellet, chip or log)[9] and its rated output. The distribution of biomass boilers within those strata is shown in Table 6, by both total number and contribution to total installed capacity[10].

In terms of both number and capacity, the population was dominated by non-domestic 150-200kW wood pellet and wood chip boilers. Therefore, it was necessary to ensure that this segment was appropriately represented in the sample, without dominating the data set to the point that the other segments were not sufficiently represented. Conversely, wood log boilers make up only 13% of the population, with the majority of these being below 100kW.

Table 4: Categories of boiler identified in the Domestic RHI

RHI Scheme	Capacity ranges (kW)	Fuel type	Feed
Domestic	10 – 20 20 – 30 30 – 45	Pellet	Continuous
		Log	Batch

Table 5: Categories of boiler identified in the Non-domestic RHI

RHI Scheme	Capacity ranges (kW)	Fuel type	Feed
Non-domestic	45 – 100 100 – 150 150 – 200 200 – 250 250 – 500 500 – 750 750 – 1,000	Pellet or Chip	Continuous
		Log	Batch

[9] The scope of the research project included installations firing all types of solid biomass. Other potential fuels include straw bales, miscanthus and cereal crops. However, no such boilers were identified during the selection process.
[10] Unit capacity is an approximate proxy for contributions from boilers as operating patterns and actual hours may have a significant effect (e.g. some log fuelled boilers are fired once a day for a few hours to charge an accumulator tank whereas for the same energy demand a smaller pellet fired unit could be used firing continuously – these could have significantly different efficiency and emissions characteristics).

Table 6: The distribution of boilers across the domestic and non-domestic RHI

Scheme	Output (kW)	Fuel	Percent of population	Percent of capacity
Domestic	<45	Pellet	34%	8%
		Log	3%	1%
Non-Domestic	<100	Chip	5%	3%
		Pellet	13%	8%
		Log	7%	4%
	100-150	Chip	3%	4%
		Pellet	5%	5%
		Log	1%	1%
	150-200	Chip	12%	19%
		Pellet	10%	16%
		Log	2%	4%
	200-1000	Chip	3%	15%
		Pellet	2%	10%
		Log	<1%	1%
Total			**100%**	**100%**

The approach to defining the sample shape was largely statistical, based on distribution of the population (in terms of both number and capacity) between the segments. However, to gain representative information for each stratum, a minimum of three boilers was monitored for each.

Consideration was also given to a number of other factors that contribute to the range of performance achieved within a stratum. Where a stratum is particularly heterogeneous in terms of one or more factors below, the sample size was increased to capture this variation. The factors identified were:

- **Distribution of installed capacity in the population.** Capacity was an approximate proxy for fuel use / heat generation and associated emissions. Boilers above 200kW, although numerically a relatively small part of the total population made a large overall contribution to generation of heat and emissions. To achieve an acceptably narrow confidence interval when scaling these segments up to the population, their representation in the sample needed to be larger.
- **The variation in boiler technology in a category.** This included: grate type, fuel feed system, combustion chamber design, air supply and control systems. Some of these technologies were known to be susceptible to performance issues. Based on our experience, we anticipated that larger-scale boilers would show a greater variation in these parameters, whereas smaller-scale boilers tended to be of a common design for the specified fuel (pellets, chips, wood logs or, in some cases, a combination of fuels). This again suggested it would be useful to have a wider range of larger-scale boilers in the sample.

- **The variation in fuel composition in a category.** Wood pellet was generally considered to show less variation in composition than either wood chip or wood log.
- **Boiler manufacturer and installer.** As the methodology report [4] identified a range of manufacturers in both schemes, consideration was given to ensure an adequate spread of boiler manufacturers during site selection.
- **Location of installations.** The geographical location of installations was an approximate proxy for the effects of prevailing weather, elevation and to some degree on fuel properties (where it is locally sourced) and conditions (particularly moisture content).
- **Heat use and demand profile.** This included: use of the heat, boiler utilisation factor, fuel feed mechanism, the number of boilers that made up the installation and the system design. Limited information about these was available at the start of the project, however eight sites with multiple boilers were chosen:
  - Four sites had a pair of identical boilers connected to the same system
  - One site had four identical boilers connected to separate heat uses
  - Three sites had two dissimilar boilers connected to separate heat uses

Taking the statistical and technical considerations into account, sample quotas for segments where greater variation was expected were increased, whereas no wood log boilers were included above 100kW.

4.2.2 Site selection

For the field trial, DECC provided a long-list of a total of 133 domestic installations and 521 non-domestic installations[11]. This list was sub-sampled and a total of 67 boilers were chosen by the following method, which is a form of disproportionate stratified quota sampling (randomised by the initial random sampling):

1. The sites were organised into the strata (groups) shown in Table 7.
2. Quotas were set on each stratum, based on the considerations described above.
3. Sites were contacted at random from each stratum (group) and their suitability for inclusion in the field trial assessed by short telephone interview. Sites willing to participate and suitable for inclusion were added to a short-list of sites. Sites unwilling to participate or where the installation prohibited detailed monitoring (e.g. use of other technologies in combination with biomass) were excluded from further selection[12,13].
4. Sites on the short-list were visited and a detailed survey conducted to confirm suitability for monitoring and determine potential locations for monitoring equipment. Sites that were suitable for inclusion were added to the final sample (or if that stratum was full, they were added to a reserve list). Sites where the installation prohibited detailed monitoring (e.g. plant room layout) were excluded from further selection[12].

[11] It is understood that these installations were selected by random sampling from the respective populations (by DECC) of the main categories of boiler identified in the methodology report [4]. The samples were only taken from sites who had previously indicated they would be interested in participating in research. No further details of the sampling method were available, so there was no indication whether steps had been taken, e.g. to ensure a geographic spread of installations.
[12] By excluding sites unwilling to take part or unsuitable for monitoring there will be a selection effect. However, it is believed that there was sufficient variation in the sites selected that this will not have a significant impact in the validity of the conclusions reached.
[13] No sites using heat for drying of wood fuel were available within the sample.

5. Sites in the final sample were visited a second time with the appropriate equipment ready-configured for installation.

The main challenge faced when trying to achieve the quotas of the strata was that in some cases the long-list did not contain sufficient installations in a stratum that were willing to participate and suitable for installation. In these cases, the following resolution was agreed:

a) Additional sites were added to the long-list, or failing this
b) The quotas for other strata were increased to capture more information about these strata using extra sites from the reserve list.

The target sample shape and final achieved sample shape are shown in Table 7 and their geographical spread is shown in Figure 10. For the reasons described above, no wood log boilers above 100kW rated output were included.

It was understood that in a population (at the time) of 17,600 installations, this sample of 67 boilers would not be statistically significant. However, in taking such a snapshot and comparing the themes observed with the behaviours examined in the laboratory trials, key insights could be made in a way never previously possible.

Table 7: The distribution of boilers in the sample (both target and actual) compared to the distribution in the population

Scheme	Output (kW)	Fuel	Target size of sample	Actual size of sample	Percent of sample	Percent of population
Domestic	<45	Pellet	8	11	16%	34%
		Log	4	4	6%	3%
Non-Domestic	<100	Chip	4	8	12%	5%
		Pellet	5	4	6%	13%
		Log	4	4	6%	7%
	100-150	Chip	4	3	4%	3%
		Pellet	4	3	4%	5%
		Log				1%
	150-200	Chip	8	8	12%	12%
		Pellet	7	9	13%	10%
		Log				2%
	200-1000	Chip	7	8	12%	3%
		Pellet	5	5	7%	2%
		Log				<1%
Total			**60**	**67**	**100%**	**100%**

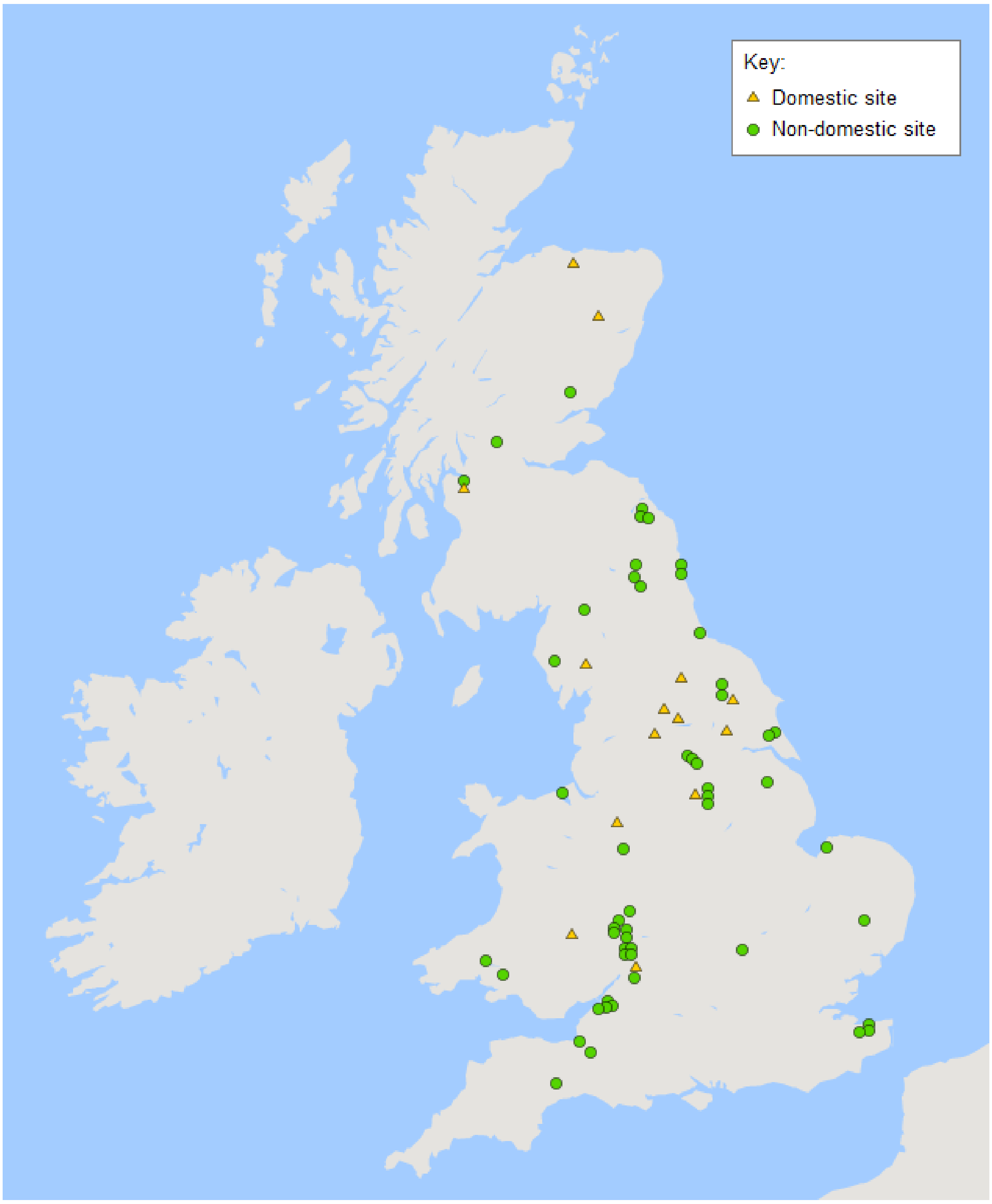


Figure 10: Geographic distribution of the participating sites
Map data: Google, GeoBasis-DE/BKG

4.2.3 Measurements taken at sites

The measurements taken at field trial sites were as per the “intermediate metering regime” defined in the methodology report [4, p. 99]. The parameters measured are given in Tables 8-10, below.

To collect data, a combination of sensors and transmitters (both battery and mains powered) were installed at each site. These took measurements from around the boiler and transmitted the data collected wirelessly to a central data logger at each site. Data was pushed from this data logger to a UK-based server on an approximately hourly basis, via a secure internet connection (over either a cellular data connection or an ethernet broadband connection).

Most slowly changing data was recorded at a fixed time interval of 5 minutes. Faster changing data was recorded on a delta basis. This was where a data point was recorded when the monitored variable changed by more than approximately 1-2ºC for temperatures and 0.1% for oxygen concentrations. This allowed detailed behaviour to be captured when things were changing rapidly, without unnecessarily collecting large volumes of non-changing data. Battery voltage data was collected daily from battery powered sensors, to identify any issues with battery life.

Table 8 shows the core variables that were measured at every site in the field trial.

Table 8: Core variables measured in the field trial

Parameter	Measurement device	Logging interval
Flue gas temperature	Thermocouple	5 minute average *or* more frequently if value is varying quickly
Flue gas O_2	Zirconia probe	5 minute average *or* more frequently if value is varying quickly
Boiler heat output	Measuring Instrument Directive (MID) Class 2 heat meter	5 minutes (cumulative reading)
Water flow & return temperatures	Matched-pair heat meter platinum resistance thermometer (direct or pocket) *or* thermistor (surface mounted on pipe)[14]	5 minutes
Electricity consumption	Current transformer (CT) coils either single *or* three phase depending on boiler supply	5 minutes (cumulative reading)
Boiler room air temperature	Thermistor in boiler room	5 minutes

Where possible, further variables were measured at sites – this depended on several factors, e.g.

a) site layout – if heat was used to heat a building, whether that building was close enough to monitor wirelessly
b) heat meter connectivity – whether the heat meter provided water flow rate data
c) flue configuration – experimental obscuration equipment was attached to six flues; this required significant flue modification and also had to be removed safely at the end of the field trial

These additional variables are shown in Table 9.

[14] The water flow and return temperatures were used for diagnostic purposes only. Heat output was always measured with a MID Class 2 heat meter.

Table 9: Additional variables measured at some field trial sites

Parameter	Measurement device	Logging interval
Outside air temperature	Thermistor outside (shaded area)	5 minutes
Boiler room air humidity	Humidity sensor in boiler room	5 minutes
Heated space air temperature	Thermistor in heated space	5 minutes
Water flow rate	MID Class 2 heat meter	5 minutes (cumulative reading)
Particulate matter (dust)	Obscuration meter	5 minutes *or* more frequently if value is varying quickly

In addition, samples of fuel were taken at least once per site and analysed. The quantities measured are shown in Table 10.

Table 10: Fuel parameters measured in the field trial

Parameter	Measurement basis	Measurement interval
Net calorific value (NCV)	as received and dry	At least once per site during the field trial
Gross calorific value (GCV)	as received and dry	
Moisture content	% by weight, as received	
Ash content	% by weight, as received and dry	
Carbon content	% by weight, as received and dry	
Hydrogen content	% by weight, as received and dry	
Nitrogen content	% by weight, as received and dry	
Sulphur content	% by weight, as received and dry	
Oxygen content	(by difference)	

At a selection of sites, additional analysis was performed to check for heavy metals in both the fuel and the ash (specifically the bottom ash). Table 11 shows the metals that the samples were tested for. The focus of the analysis was metals that are considered toxic in biological systems, such as lead, mercury, chromium, and copper.

Table 11: Heavy metals measured in the field trial (selected sites)

Parameter	Measurement basis	Measurement interval
Arsenic	mg metal / kg fuel, dry and mg metal / kg ash, dry (according to ISO 16968 [23])	One fuel sample and one ash sample, per selected site
Cadmium		
Chromium		
Copper		
Lead		
Mercury		
Nickel		
Zinc		
Antimony	mg metal / kg fuel, dry (according to ISO 16968 [23])	One fuel sample, per selected site
Cobalt		
Manganese		
Tin		
Thallium		
Vanadium		

Figure 11 shows a typical monitoring schematic at one of the biomass sites. In addition, and where practicable, spot measurements of CO_2, CO and NO_x were taken at sites using a calibrated handheld gas analyser.

Special cases

Boiler heat output was measured from the boiler's heat meter. The non-domestic sites already had heat meters installed, however at domestic sites a suitable heat meter was installed[15]. The heat meters were located:

a) In 87% of cases – before the accumulator tank
b) In 13% of cases – after the accumulator tank

In both cases the boiler efficiency, rather than the whole system efficiency was measured. However, in (b) the losses from the accumulator tank would have reduced the measured efficiency. The processing described in Section 4.2.4 was adapted, however the efficiency result was not adjusted to account for this.

At three of the four sites with a pair of identical boilers supplying the same heating system, there was a common heat meter which measured the output from both boilers. The processing described in Section 4.2.4 was adapted and the data was used to estimate the proportion of heat delivered by each boiler[16].

[15] In the domestic RHI scheme, there was no general requirement to install a heat meter. Instead the incentive payments were based on a deemed quantity of heat, calculated from a heat loss assessment of the property.
[16] The share of heat delivered by each boiler was estimated using the reduction in flue gas oxygen from 20.9% (the oxygen in air), as described in Annex E.

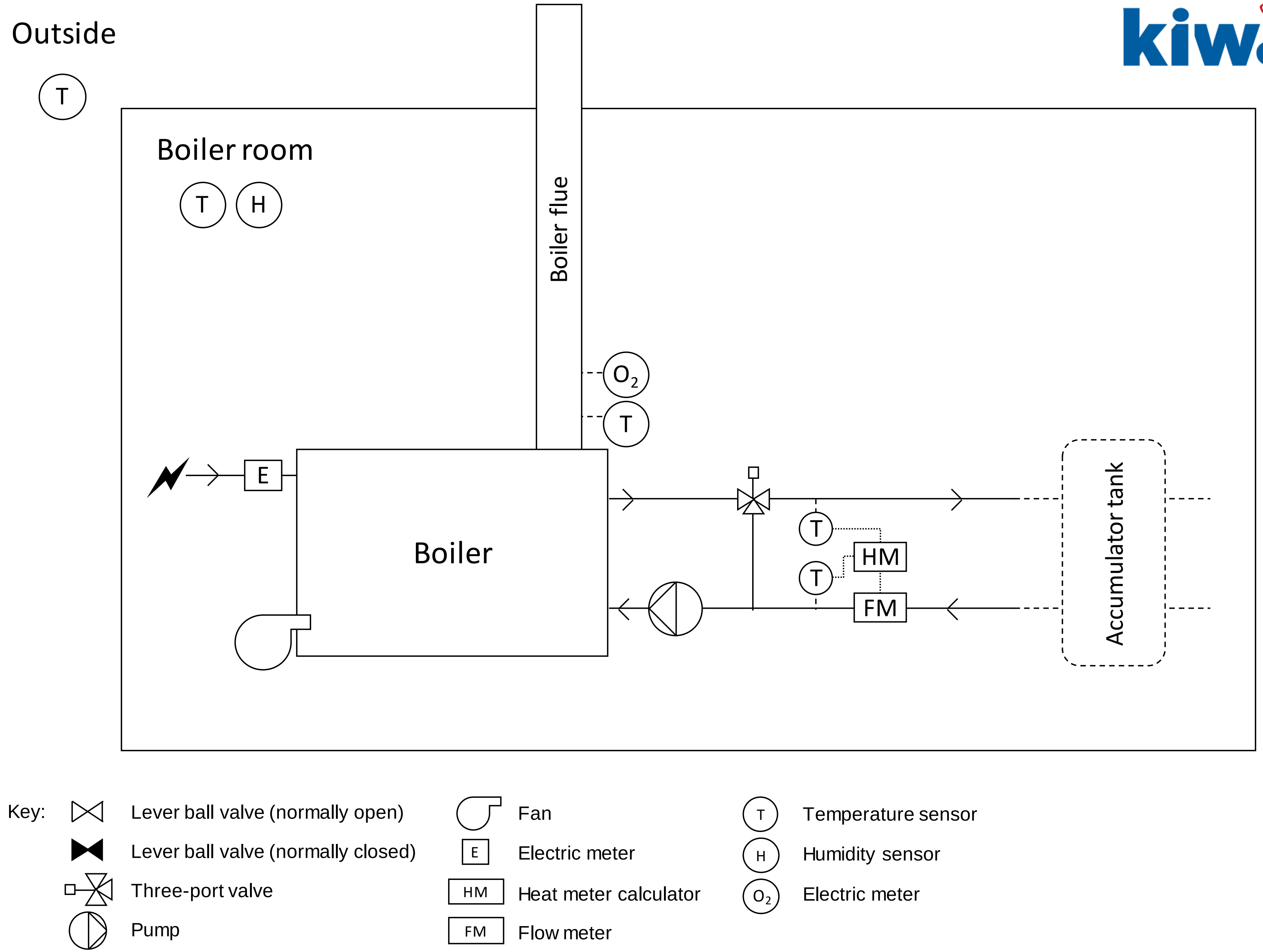


Figure 11: Field trial – typical site schematic showing installed monitoring equipment (other system components, e.g. district heating systems and further accumulator vessels, are omitted)

4.2.4 Calculation of efficiency

The field trial measured the efficiency of the biomass boiler by the losses (indirect) method. The calculation used was based on BS 845-1 [24] when the boiler was in steady operation, which is similar to the calculation in a number of other standards [25, 26]. Flue gas temperature and flue gas oxygen concentration were the primary indicators of boiler efficiency during steady operation.

None of the available standards defined calculations that could be used in non-steady state conditions, so a bespoke algorithm was designed by Kiwa. This followed the standard approach during periods of steady state operation, with adaptations to cover start-up, shutdown and off periods. The efficiency calculation algorithm is outlined in Figure 12 and documented along with assumptions in Annex E (provided as a separate document).

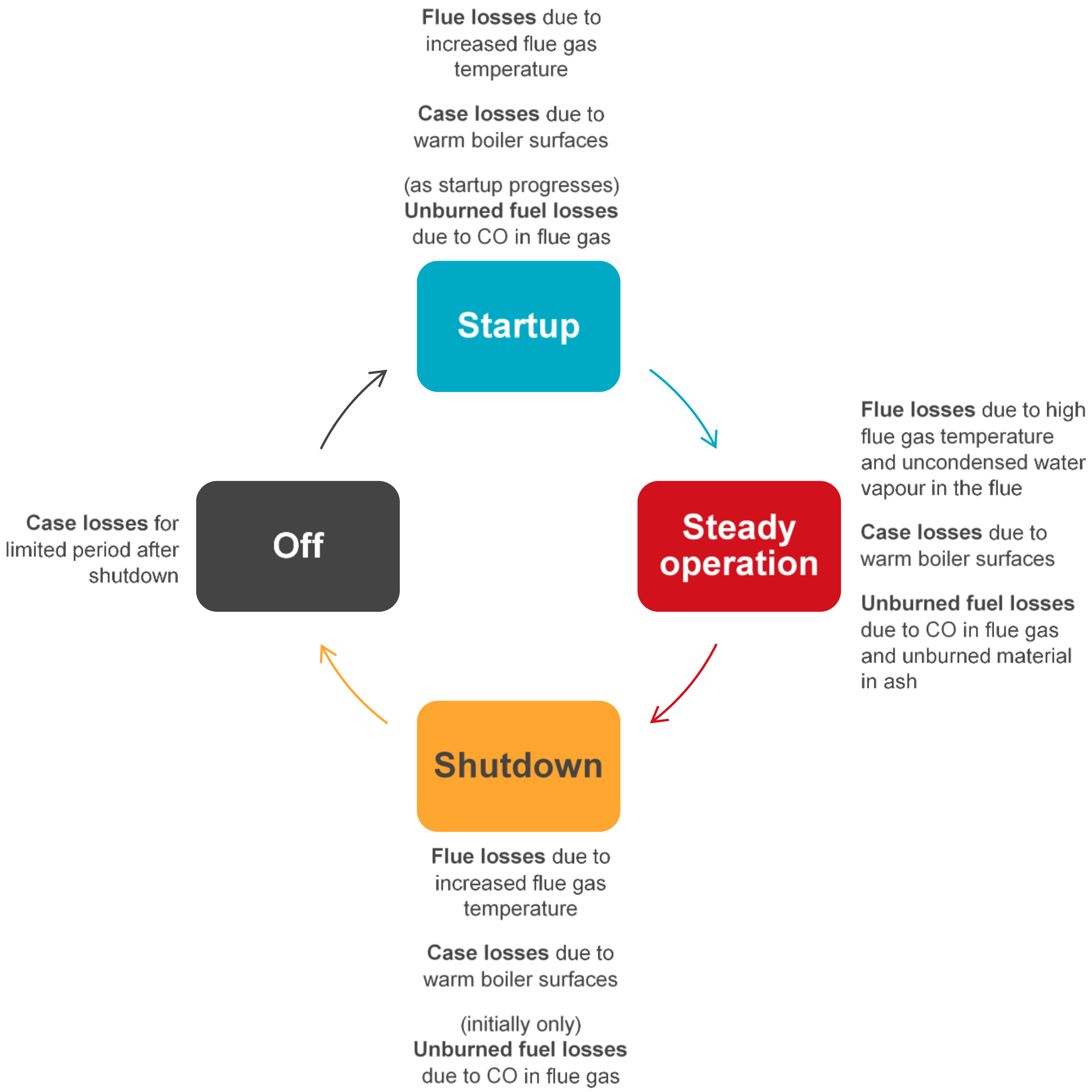


Figure 12: Outline of calculation to determine efficiency of boiler by indirect (losses) method

4.3 Laboratory trials – small boiler

The field trial was designed to investigate boiler efficiency and fuel quality. To investigate air quality and pollutant emissions in a robust way, a laboratory test programme was devised (see Section 4.1).

A 25kW wood pellet biomass boiler was tested in the laboratory using Kiwa's dynamic heat load test rig (DHLTR). The DHLTR has been designed to enable the performance of wet heating appliances to be measured under repeatable dynamic demand conditions. This allows the performance of appliances to be evaluated under conditions typical of the way in which they are operated in normal use, as required by this laboratory testing.

The DHLTR was designed to run continuously, so full 24 hour operating cycles could be simulated. In a standard setup, the DHLTR can simulate a domestic house with its associated heat loss characteristics. However, for the biomass boiler laboratory testing, the rig was configured to provide a repeatable heat demand profile consistent with those observed in the field trial data.

4.3.1 Selection of the boiler

A 25kW wood pellet biomass boiler was selected for the test work. The boiler was a non-condensing model[17] that was eligible for the RHI. The boiler was modified by the manufacturer so that it had an external fuel hopper[18], however it was the same as the original design in all other aspects. Further details are given in Table 12.

Table 12: Details of the small boiler tested in the laboratory trials

Rated output	25 kW
Fuel type	Virgin wood pellet (EN Plus A)
Fuel feed system	Automatic, conveyed from fuel store via auger (minor modifications[18])
Grate type	Overfeed grate
Air supply	Induced draught fan
Condensing mode	Non-condensing[17]
Flue gas clean-up	None

The manufacturer commissioned the boiler in the normal way, other than adjusting the parameter defining the feed rate from the (now external) auger. The control logic of the boiler was not altered and the combustion areas of the boiler were also not altered. It is therefore believed the boiler would perform the same as the commercially available version in terms of efficiency and pollutant emissions.

Based on an analysis of initial field trial data, several regimes were investigated in the laboratory trials of the small boiler, shown in Table 13.

[17] A non-condensing model was chosen to prevent additional complication when analysing the data. Some smaller domestic wood pellet boilers can operate in a higher-efficiency condensing mode with low flue gas temperatures and low return temperatures, however this is unusual with larger boilers.

[18] A boiler with an external fuel hopper was chosen so that the fuel hopper could be placed on scales during testing, allowing for accurate real-time indication of fuel consumption. In modifying the boiler, the manufacturer removed the internal fuel hopper and auger and replaced them with a metal tube to convey fuel from an external hopper and auger into the combustion chamber. The tube exited the top of the boiler through an additional hole in the case and was attached to the exit from the auger by a short section of flexible plastic tube. This flexible tube allowed the fuel/auger to be weighed separately from the boiler, whilst maintaining a seal to prevent incursion of additional combustion air.

Table 13: Laboratory trials testing regimes identified from field trial data

Mode of operation	• Continuous • Uni-modal • Bi-modal
Daily load factor	• 100% (constant operation) • 30% • 10% • 5% • 0% (standing loss)
Boiler sizing	• Boiler correctly sized to load • Boiler oversized (would be inferred from load factor results)
Modulation	• No modulation (cycling only) • Modulation
Thermal store	• No accumulator • 250-litre accumulator
Fuel quality	• EN Plus A1 virgin pellets • Mechanically degraded EN Plus A1 virgin pellets • EN Plus B recycled pellets
Cycling	Although not directly controllable, various patterns of cycles/day and average cycle length were presented during the testing. Patterns consistent with those observed in the field trial data were selected for analysis.

4.3.2 Dynamic heat load test rig

Performance testing of boilers (for British or European Standards) is conventionally based on measurement under defined steady state operating conditions. In these standard tests, boiler flow and return temperatures are fixed and tests are of short duration. Any boiler controls other than those required for safe operation at fixed output are disabled. This usual approach to laboratory testing of biomass boilers at constant load does not provide an accurate measure of performance under in-use demands, operating cycles and conditions.

In contrast, the dynamic heat load test rig was designed to enable the performance of wet heating appliances to be measured under repeatable dynamic demand conditions. This enables the performance of appliances to be evaluated under conditions typical of the way in which they are operated in normal use. Kiwa's DHLTR is shown in Figure 13 and a schematic of the set-up is shown in Figure 14.

Figure 13: The Dynamic heat load test rig
(the red hoses on the left-hand side connect to the flow and return of the appliance)

The DHLTR has a 300 litre water tank and associated computer-controlled plate heat exchangers. This system can be used to simulate a load on the heating system. It holds a volume of water equivalent to that contained in the wet heating system being simulated, however additional water volume can be simulated by adding a larger water tank.

By using the DHLTR it was possible to produce repeatable conditions for the purposes of comparison of efficiency calculations and pollutant emission measurements. The DHLTR has previously been used to successfully characterise conventional boilers, heat pumps and micro CHP appliances along with a range of control devices. The rig used a mixture of simulation model and “hardware in the loop” to provide a flexible but repeatable testing regime.

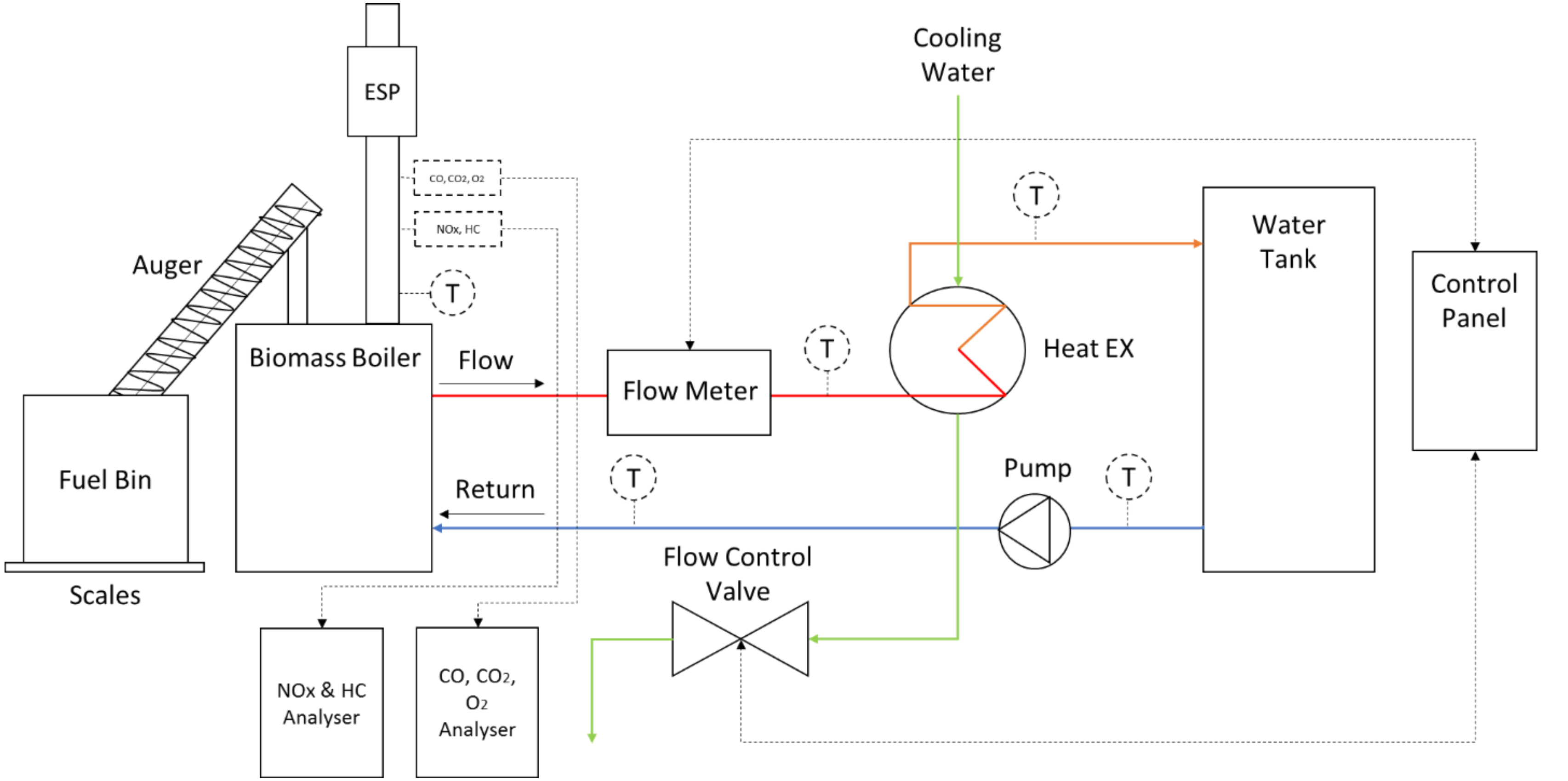


Figure 14: Small boiler laboratory trials – system schematic
(electrical power consumption and ambient temperature also measured;
control and instrumentation features that were not used for this research programme have been omitted)

4.3.3 Configuration of tests

The boiler was set with a target water flow temperature of 70°C for all tests[19]. All boiler parameters remained unchanged for all tests, unless specified otherwise. The bi-modal and uni-modal tests conducted on the boiler began with a return temperature to the boiler of 45 ± 5˚C [19].

The first stage of testing used a system water volume of 10 litres/kW. For a 25kW output boiler this was 250 litres[20]. This defined the characteristic thermal rate of response of the system.

The boiler was initially configured to run with no modulation (on/off only) and was fuelled with EN Plus A1 (virgin) pellets.

The following tests were conducted:

- Ten tests were carried out with daily load factors of 5, 10, 30 and 100% loads, each with continuous and uni-modal modes of operation
- Six tests were carried out to identify the effect of modulation on boiler performance:
  - Three tests with modulation enabled down to 50% output, at 5, 10, 30% loads
  - Three tests with modulation enabled down to 20% output, at 5, 10, 30% loads
- Three tests were used to investigate the effect of different fuels on boiler performance:
  - One test using EN Plus A1 (virgin) wood pellets were mechanically degraded with an increased fines content of 4%
  - Two tests using EN Plus B (recycled) wood pellets
- Three tests were conducted on a larger volume of water to simulate 30 litres/kW. This simulated a thermal store of approximately 750 litre volume.
- Two short 0% load (standing loss) tests were conducted for the boiler and the DHLTR. These used external electric heating to assess the heat lost maintaining the boiler at operating temperature

A total of 28 tests were carried out (including repeat tests in order to validate tests and to provide average results to reduce overall uncertainty). The full testing programme is summarised in Annex C.

4.3.4 Measurements made during testing

The efficiency was calculated via both direct and indirect (losses) method. The methodology for calculating the heat losses was similar to the field trial (according to a simplified and adapted version of the flue loss calculation from BS 845-1 [24] and EN 13240 [25]). The efficiency was calculated on both a net and gross basis, by choosing the appropriate equations from BS 845 and EN 13240, and the appropriate net or gross calorific values.

Direct efficiency was calculated by measurement of the heat output and energy in the fuel supplied over the test period:

$$\text{Efficiency}_{\text{direct}} = \frac{\text{Heat output}}{\text{Weight of fuel supplied} \times \text{Calorific value of fuel}}$$

[19] Based on observations from the field trial. A return temperature of 45˚C and flow temperature of 70 ˚C was chosen after an analysis of the 15 domestic sites, by averaging the lowest return and highest flow temperature between burn periods for each site and taking an overall average for all the sites.
[20] This value is typical for a conventional radiator system of around 4 litres/kW [40] plus a buffer tank of around 150 litres.

Indirect efficiency was calculated by measurement of heat output and flue gas and case losses (derived from measurements of flue gas carbon dioxide and temperature, according to a simplified and adapted version of the flue loss calculation from BS 845-1 [24] and EN 13240 [25]):

$$\text{Efficiency}_{\text{indirect}} = \frac{\text{Heat output}}{\text{Heat output} + \text{Flue gas loss} + \text{Case loss} + \text{Unburned fuel loss}}$$

The parameters measured and methods of measurement are shown in Table 14.

Flue gas measurements shown in Table 15 were made throughout the test periods, using laboratory-grade gas analysers. The gas analysers were calibrated daily. The fuel used during testing was characterised, as shown in Table 16. The ash produced during each test was also weighed and samples sent for analysis of total carbon content. Each fuel type tested was from the same batch from the same manufacturer. Fuel was stored together in the laboratory, sealed in bags until it was used to ensure the moisture content remained constant.

For validation of the field trial equipment, measurements were made using the same equipment as that installed in the field, with the same configuration and logging interval, shown in Table 17.

Table 14: Small boiler laboratory trials – performance and efficiency measurements

Parameter	Measurement device	Logging interval
Flue gas temperature	Thermocouple (type J)	10s
Flow & return temperatures	Platinum resistance thermometers	10s
Total water flow	Ultrasonic flow meter	10s
Boiler heat output	Calculated from flow/return temperature and total water flow	10s (calculated)
Fuel feed rate	Weighing scales	10s
Electricity consumption	Current transformer (CT coil)	10s
Ambient temperature	Thermocouple (type K)	10s
Ambient humidity	Humidity sensor	10s
Air inlet temperature	Thermocouple (type K)	10s
Surface temperature	Infrared thermometer	Boiler temperature survey

Table 15: Small boiler laboratory trials – gaseous and pollutant measurements

Parameter	Measurement device	Logging interval
CO_2	Gas analyser	10s
O_2	Gas analyser	10s
CO	Gas analyser	10s
Particulate matter (dust)	Electrostatic precipitator	Total over test period
NO_x (as NO_2)	Gas analyser	10s
Total hydrocarbons (as CH_4)	Gas analyser	10s
SO_2	Inferred from fuel analysis (assuming all sulphur released)	Total over test period

Table 16: Small boiler laboratory trials – fuel analysis

Parameter	Measurement basis	Measurement interval
Net calorific value (NCV)	as received and dry	One sample of fuel taken
Gross calorific value (GCV)	as received and dry	
Total moisture content	% by weight, as received	
Ash content	% by weight, as received and dry	
Carbon content	% by weight, as received and dry	
Hydrogen content	% by weight, as received and dry	
Nitrogen content	% by weight, as received and dry	
Sulphur content	% by weight, as received and dry	
Oxygen content	(by difference)	

Table 17: Small boiler laboratory trials – field trial equipment measurements

Parameter	Measurement device	Logging interval
Flue gas temperature	Thermocouple	As per field trial
O_2	Zirconia probe	
Boiler heat output	MID Class 2 heat meter	
Particulate matter (dust)	Obscuration meter	
Flow & return temperatures	Matched pair surface thermistors on pipe[14]	
Electricity consumption	Current transformer (CT coil)	
Ambient temperature	Thermistor	
Ambient humidity	Humidity sensor	

4.3.5 Calculations performed

Standing loss tests

To test the boiler in a laboratory setting, an accurate standing loss value for the boiler and the dynamic rig was needed to ensure that the load placed on the boiler by the DHTLR was accurate and for the efficiency calculations and energy balance validations (EBV). The standing losses were calculated by measuring the electricity required by a heater to keep the boiler at a constant temperature. Water was circulated through the boiler via an immersion heater which was attached to a temperature controller which adjusted the power supplied to the immersion heater keeping the water at a set temperature. Accurately measuring the electricity consumption of the heater allowed for measurements of the standing losses of the boiler and the DHLTR to be taken.

The power requirements at three temperatures 50, 60 and 70 ˚C were measured to calculate the heat loss of the boiler, and the overall heat loss coefficient (UA value) of the boiler in W/K. Using the UA value and the difference between the boiler flow temperature and ambient temperature, a standing loss was calculated. The UA values calculated from the electricity input were 14.6 W/K for the boiler and 11.2 W/K for the DHTLR.

The boiler standing losses were used to calculate the case losses from the boiler during testing. The case losses were a component in the overall losses and thus used in the calculation of both the indirect efficiency and energy balance validations (EBVs).

The standing loss for the DHTLR was considered when calculating the required load to be placed for the boiler. To ensure that the correct amount of heat was removed from the boiler during testing, losses from the DHLTR were considered in conjunction to the load provided by the heat exchangers on the rig. For example, if a load of 2.5 kW was required and the standing loss from the rig was 0.5 kW, then the load provided by the heat exchangers would be set at 2.0 kW.

4.4 Laboratory trials – large boiler

In order to ensure that the laboratory tests could be representative of the entire population of boilers in the field trial the laboratory tests on the small boiler was supplemented by the in-situ emissions measurements at a large boiler site. Ideally the large boiler would have also been tested in the lab as testing in the laboratory would allow for complete control over the operation of the boiler which would allow for test work to be carried out with increased accuracy. However testing a large biomass boiler in the lab was not the option that was chosen because of the difficulties in installing the boiler and the equipment capable of removing the heat produced during the test work.

Testing a boiler outside a laboratory does reduce the accuracy of results and limits control over its operation, however because of the practical issues around the temporary installation of a large boiler, in-situ testing was chosen.

An 800 kW boiler was chosen from one of the field trial participants for in-situ testing and used to investigate the effect of start-ups and shutdowns on boiler performance. The operator controlled the boiler onsite and measurements taken were comparable to the laboratory measurements.

4.4.1 Selection of the boiler

A biomass boiler was required that was representative of the larger biomass boilers monitored in the field trial. It was agreed that a wood chip boiler with a rated output between 500 and 1,000kW would be sought. Additional constraints around the selection of the site included:

- the small number of sites with boilers in the range that were participating in the trial,
- ensuring the site was physically suitable for the safe use of the measurement equipment, and
- ensuring the site was willing to participate in additional testing

An 800 kW wood chip biomass boiler participating in the field trial was chosen. Further details are given in Table 18 and a system schematic is shown in Figure 15.

Table 18: Details of the large boiler tested in the laboratory trials

Rated output	800 kW
Fuel type	Virgin wood chip (self-supplied)
Fuel feed system	Automatic, conveyed from fuel store via augers
Grate type	Underfeed stoker
Air supply	Primary and secondary forced draught fans Induced draught fan Flue gas recirculation
Flue gas clean-up	Cyclone
Thermal store	2 x 7,500 litre accumulator tanks in plant room
Heat use	Space heating Domestic hot water
Heat supply system	District heating via underground pipe runs
Backup heating system	2 x oil boilers (disabled) supply heat directly to the district heating system, bypassing the accumulator tanks

The buildings supplied by the boiler had various heat and domestic hot water demands depending on their occupancy. The boiler supplied hot water all year round, which meant it continued to operate in the summer although with a reduced load.

4.4.2 Configuration of tests

The laboratory trials measured the performance of the boiler in terms of efficiency and pollutant emissions over a number of complete cycles. During these cycles, a heat demand was placed on the accumulator tank and the boiler was enabled (and then after a time, disabled) to cause it to cycle. The boiler heated up the accumulator tank during its cycles and this maintained the accumulator water temperature to between 60-70°C.

The boiler was operated in the following manner:

- The boiler was enabled, causing it to enter ‘start-up’ mode
- After 15-30 minutes (depending on initial boiler temperature) the boiler entered ‘run’ mode
- The boiler was then immediately disabled, causing it to enter ‘shutdown’ mode
- After approx. 30 minutes, the boiler switched off

During the testing, four full cycles (start-ups and shutdowns) were observed, plus one additional start-up. Two of the start-ups were from ‘cold’ (the boiler had cooled overnight) and three start-ups were from ‘warm’ (started shortly after the previous cycle had finished).

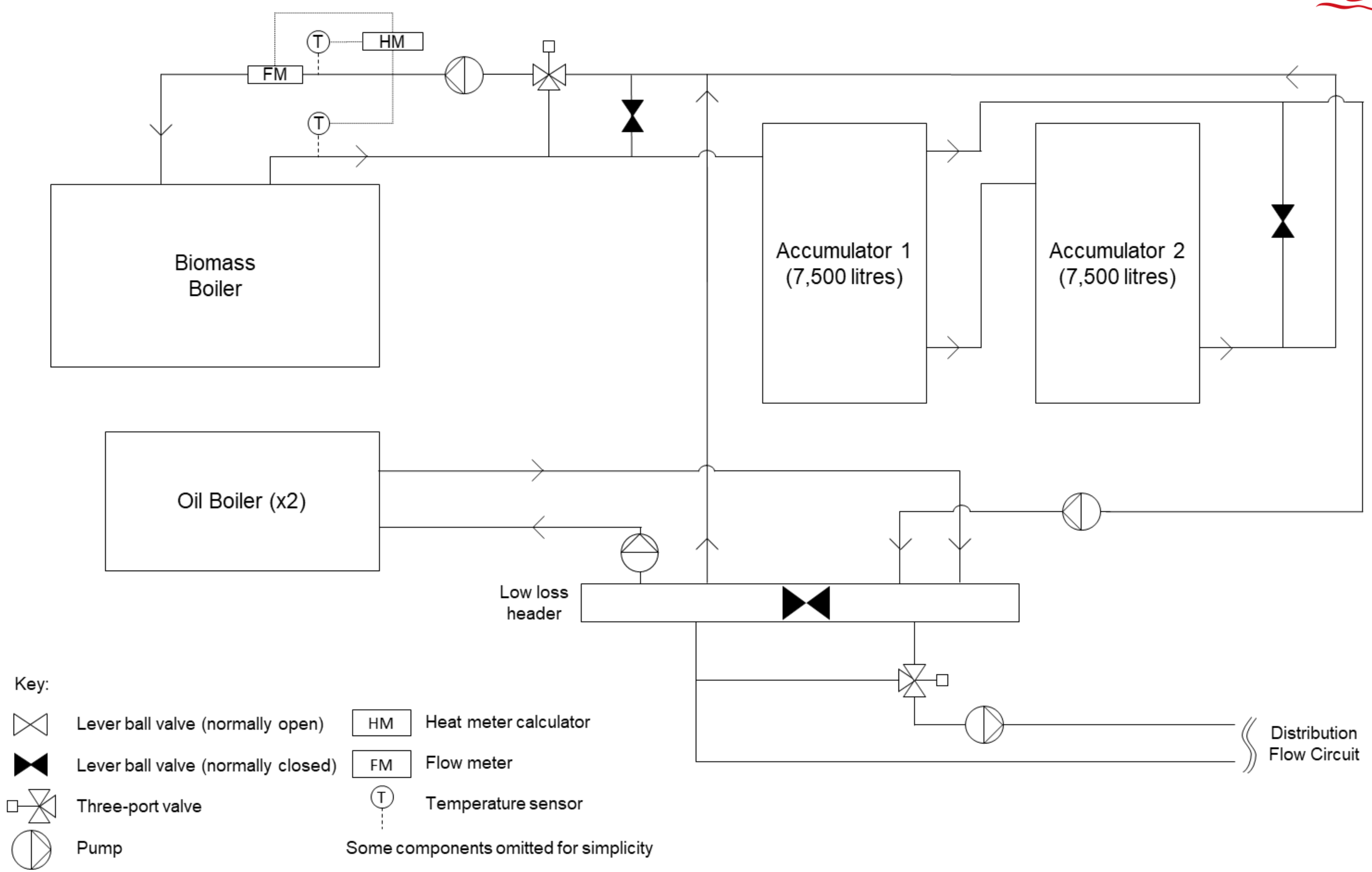


Figure 15: Large boiler laboratory trials – system schematic

4.4.3 Measurements made during testing

The efficiency was calculated via the indirect (losses) method based on measurement of heat losses (according to BS 845-1 [24]). The efficiency was calculated on both a net and gross basis, by choosing the appropriate equations from BS 845 and the appropriate net or gross calorific values. The methodology was similar to the field trial, however CO_2 was measured directly and laboratory-grade equipment was used to measure every parameter. Case losses and unburned fuel losses were also measured rather than assumed. The parameters measured and methods of measurement are shown in Table 19.

Flue gas measurements were made throughout the test periods, using standard calibrated gas analysers, shown in Table 20. The gas analysers were calibrated periodically, at times chosen to minimise any loss of useful data. The fuel used during testing was characterised, as shown in Table 21.

For validation of the field trial equipment, measurements were made using the same equipment as that installed in the field, with the same configuration and logging interval, shown in Table 22.

Table 19: Large boiler laboratory trials – performance and efficiency measurements

Parameter	Measurement device	Logging interval
Flue gas temperature	Thermocouple (type K)	5 minutes
Flow temperature	Surface probe / heat meter probes	5 minutes
Return temperature	Surface probe / heat meter probes	5 minutes
Boiler heat output	MID Class 2 heat meter	5 minutes and total
Surface temperature	IR temperature sensor	5 minutes
Ambient temperature	Thermocouple (type K)	5 minutes
Ambient humidity	Humidity sensor	5 minutes
Air inlet temperature	Thermocouple (type K)	5 minutes

Table 20: Large boiler laboratory trials – gaseous and pollutant measurements

Parameter	Measurement device	Logging interval
CO_2	Gas analyser	1 minute
O_2	Gas analyser	1 minute
CO	Gas analyser	1 minute
NO_x	Gas analyser (EN 14792)	1 minute
Particulate matter (dust)	Extractive (EN 13284-1)	Total over phase of interest (e.g. start-up, steady state), maximum 30 minutes
Total hydrocarbons	Gas analyser	1 minute
SO_2	Gas analyser	1 minute

Table 21: Large boiler laboratory trials – fuel analysis

Parameter	Measurement basis	Measurement interval
Net calorific value (NCV)	as received and dry	One sample of fuel taken
Gross calorific value (GCV)	as received and dry	
Total moisture content	% w/w, as received	
Ash content	% w/w, as received and dry	
Carbon content	% w/w, as received and dry	
Hydrogen content	% w/w, as received and dry	
Nitrogen content	% w/w, as received and dry	
Sulphur content	% w/w, as received and dry	
Oxygen content	(by difference)	

Table 22: Large boiler laboratory trials – field trial equipment measurements

Parameter	Measurement device	Logging interval
Flue gas temperature	Thermocouple	As per field trial
O_2	Lambda probe	
Boiler heat output	MID Class 2 heat meter	
Flow temperature	Surface thermistor on pipe	
Return temperature	Surface thermistor on pipe	
Electricity consumption	Current transformer (CT coil)	
Ambient temperature	Thermistor	
Ambient humidity	Humidity sensor	

4.4.4 Contextual data

Detailed contextual data was collected during the onsite testing regarding:

- heat use and patterns of heat demand
- boiler sizing
- boiler control systems, including modes of operation
- sizes and nature of thermal stores
- data regarding modulation
- fuel quality history
- maintenance and fault/breakdown history

This data was used to make qualitative comments on the efficiency of the boiler and pollutant emission results obtained at the site.

4.5 Laboratory trials – heavy metal testing

Emissions of heavy metals from biomass are caused by metals that originate in the biomass fuel, however there are two routes for emission to environment. Either the metals become trapped in particles that are carried up the flue and are emitted to atmosphere, or metals become trapped in the ash which is then spread onto or disposed of onto land.

A series of laboratory trials were designed to gain a better understanding of the fate of heavy metals in the fuel after combustion, and the extent to which they may be emitted to atmosphere and/or retained in the ash. The objectives of this laboratory work were:

- To investigate potential experimental methods for measuring the partitioning of the heavy metals.
- To gather indicative measurements to show which elements are more likely to be emitted in combustion gases and which retained in the fuel ash.
- To consider the accuracy, repeatability and cost-effectiveness of the techniques used and suggest how they might be developed in future research.

Two methods were investigated to determine the fate of heavy metals:

1. A **mass balance approach** based on testing of fuel and ash samples from boilers in the field.
2. A **simulated combustion approach** in the laboratory by testing fuels samples alone, heating them in an oven to simulate combustion temperatures.

4.5.1 Mass balance approach

The standard approach to understand the fate of particular components of a fuel, is to carry out a complete and detailed mass balance across the process, operating under controlled conditions. Setting up such an experiment in a laboratory is time-consuming and complex. It would require the boiler to be operated for a long time, to ensure an equilibrium between inputs and outputs had been reached. Even under these conditions, the experiment is still particularly challenging because the metals are only present at trace concentrations. The uncertainty in the measurements may be too great to provide understanding of what factors affect the fate of those metals.

Therefore, a simplified mass balance approach was trialled initially, where a single sample of fuel and a single sample of bottom ash were taken from boilers in the field during Phase 3. These samples were analysed for heavy metals according to ISO 16968 [23], which involved digesting them in hydrofluoric acid before testing for metals with ICP-MS[21]. It was assumed that these ash samples were representative of the ash produced from the fuel that was also sampled.

The emission of metals out of the flue was not monitored, but was inferred from the metal content of the fuel, the metal content of the ash, and the mineral content of both the fuel and ash, as follows:

$$\%\text{ Loss of metal out of flue} = 100 - 100\left(\frac{\text{Metal in ash (mg/kg)}}{\text{Metal in fuel (mg/kg)}}\right)\left(\frac{\text{Fuel ash content (kg/kg)}}{1 - \text{Carbon in ash (kg/kg)}}\right)$$

The advantages of this approach are:

- The analysis is conducted on samples of ash collected from actual boilers in the field, therefore the combustion conditions in which that ash was produced can be considered realistic.

[21] Inductively coupled plasma mass spectrometry

- A complex and long-running laboratory experiment is not required.
- It is not necessary to measure the emissions in the flue gases directly.

However, the disadvantages are:

- The ash content of biomass is a small number with a relative uncertainty around 15%, and the metal concentrations (particularly in the fuel) are small with relative uncertainties around 20%. These leads to a large uncertainty in the proportion of metal lost out of the flue. In addition, levels of arsenic and mercury are commonly below the limits of detection.
- There is not necessarily a link between the fuel sampled and the ash sampled (although it was confirmed with sites that they had not made any changes to their fuel supply).
- There was unburnt material in the ash samples (e.g. charred pellets and prices of wood chip), which made the sampling process more difficult.
- The heavy metal content of the fly ash was not considered (it was assumed this material was lost out of the flue).

4.5.2 Simulated combustion approach

In the simulated combustion approach, samples of fuel alone were taken from boilers in the field during Phase 3. These samples were analysed for heavy metals according to ISO 16968 [23], which involved digesting them in hydrofluoric acid before testing for metals with ICP-MS, however there were two deviations from the standard method:

1. The sample preparation followed standard methods [27], other than that the entire fuel sample (~1 kg) was used for the initial drying and milling to <1 mm. It was then rolled in a bag and several aliquots taken to compose each of the six sub-samples that were then analysed. This was to ensure that each of the six sub-samples were as similar as practicably possible.
2. Three of the sub-samples were heated in a muffle furnace to >550°C before the analysis stage. This was to initiate combustion of the fuel and therefore simulate the conditions within a boiler in a controlled way. Analysis of the ash-like material produced then continued according to standard methods [23], i.e. digestion in hydrofluoric acid before testing for metals with ICP-MS.

The emission of metals out of the flue was inferred as follows:

$$\%\ \text{Loss of metal out of flue} = 100 - 100\left(\frac{\text{Average metal in heated fuel samples (mg/kg)}}{\text{Average metal in unheated fuel samples (mg/kg)}}\right)$$

The advantages of this approach are:

- The method is a relatively simple and is conducted under controlled laboratory conditions, therefore is more likely to be repeatable.
- Only a fuel sample is required, and the method of sampling produces sub-samples that are as similar as practicably possible.
- It is not necessary to measure the emissions in the flue gases or in ash directly.
- A complex and long-running laboratory experiment is not required.

However, the disadvantages are:

- Although the testing involves the combustion of the fuel, it does not fully recreate the conditions inside a boiler combustion chamber.

- The sub-samples are taken from a non-homogenous fuel, so despite the efforts to make them as similar as practicably possible, there are likely to still be differences between each of the sub-samples.
- The concentrations of heavy metal in the fuel samples are still small with relative uncertainties around 20%.

As the concentrations of heavy metals in many fuels are small, two additional waste wood samples were tested. These were provided as ‘Grade A-C’ mixed waste wood according to PAS 111 [28] and were thought to have higher levels of heavy metals present, thus reducing some of the uncertainty in the metal loss calculation above.

4.6 Social research

The social research included an analysis and evaluation of behaviours, motivations and satisfaction of trial participants. It had three objectives:

1. To document how sites participating in the trial use their biomass boilers
2. To discover and understand the range of motivations and reasons for sites acting that way
3. To identify any additional contextual (e.g. site specific) factors that affect how boilers are used and function

A two-stage data collection method was employed (see Figure 16). Stage one consisted of 16 qualitative telephone interviews. Stage two consisted of a quantitative online survey which 23 out of 61 participating sites completed. After the telephone interviews were complete, a thematic analysis of responses by question was conducted. This was used to inform questions and answer categories for the stage two online survey.

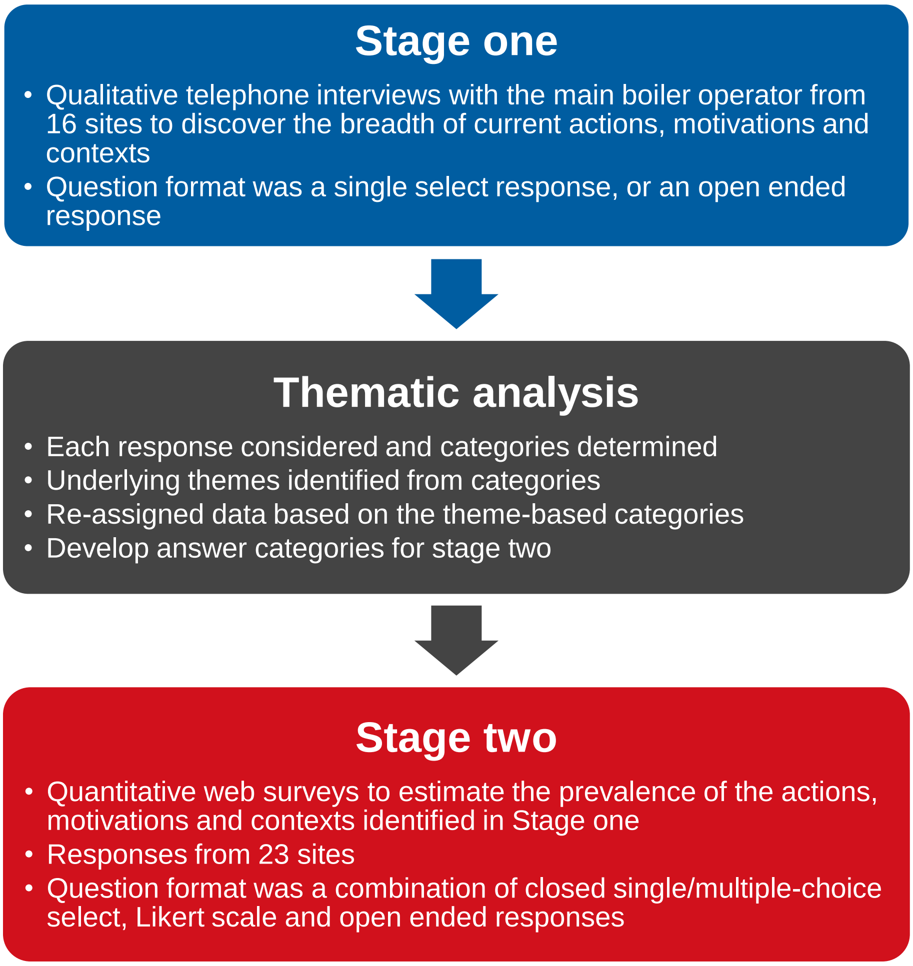


Figure 16: Social research – two stage data collection method[22]

It was originally planned that the sites sampled in the social research would be randomly selected. However, due to a low response rate the survey was opened up to all sites meaning that the sample is predominantly self-selected.

[22] Likert scale is where respondents specify their level of agreement or disagreement on a symmetric agree-disagree scale for a series of statement

4.7 Interventions

After the Phase 2 field trial ended, a smaller number of sites displaying performance issues were selected for intervention visits (as part of Phase 3). The purpose of these visits was to identify the cause of their poor performance and attempt to address the issues found. The field trial monitoring equipment was serviced (sensors checked, batteries replaced, etc.) to allow data to be collected from these sites for a further year (July 2017 – June 2018) to quantify the impact of these interventions. The findings from the interventions were then used to complete two guidance documents (domestic and commercial) for best-practice ways for biomass boiler operators to diagnose and address performance issues.

The aims of the intervention visits were:

- To produce a guide on best-practice for biomass boilers to take full advantage of the benefits of using biomass in the UK by optimising the existing biomass boiler population. Optimising the performance of boilers also improves the effectiveness of the RHI scheme by reducing greenhouse gas emissions.
- To compare boiler performance from one year to the next and provide a measure of success for any changes made, by using Phase 2 data as a baseline.
- To identify themes in installation and commissioning errors.

4.7.1 Selection of sites with performance issues

Out of the 67 biomass boilers in the Phase 2 field trial, 16 boilers with performance issues chosen for intervention visits in Phase 3 along with a further 6 boilers as a control group. These 22 boilers were spread across 21 sites.

They were a mix of:

- “Good performers” with minor issues (as a benchmark), and
- “Poorer performers” where the most advice will be given and the effects of the guidance and interventions will be quantified.

The sites were chosen, as far as possible, to include a range of boiler heat outputs, fuel types, heat uses and performance issues, to be representative of field trial sample.

4.7.2 Development of guidance documentation

Building upon the data, knowledge and expertise gained during the Phase 2 field trial, draft best-practice guidance documents were produced – one for domestic sites or commercial sites with limited knowledge of boiler operation, and one for commercial sites with a more experienced boiler operator (or a boiler maintenance contractor).

The two guidance documents (Table 23) were designed to complement existing advice from CIBSE [14] and MCS [12] on system design and draw on Kiwa’s experience as an Assessment Body and knowledge of the Boiler Operation Accreditation Scheme (BOAS) [29].

Table 23: Two types of best-practice guidance document produced

Domestic / small commercial guidance	Commercial guidance
Specific to domestic and small commercial user of biomass. To educate biomass boiler owners and operators on the common problems associated with biomass operation and make them aware of the symptoms of these problems. Giving guidance on how best to avoid these problems and when to contact a maintenance company.	Similar in many aspects to the domestic guidance, however specifically targeted at boiler operators and maintenance companies rather than boiler owners. Further guidance on strategies to improve poorly performing systems. The change in emphasis reflects the increased expertise of the intended recipient of the report; this guidance is more technical than the domestic document.

4.7.3 Intervention visits

The intervention visits were designed to be “soft”, i.e. that any changes made would be to behaviour, changes to operating pattern, boiler or system control adjustments, etc. The interventions were designed to utilise the existing installation better. Significant physical installations or adaptations to the system were avoided, for example any installations that would require the system to be drained such as mixing valves or thermal stores. However, some physical or “hard” changes were suggested, and advice provided to the site if they were interested in making the changes. It was the responsibility of the site to arrange and pay for any changes. Suggested changes included:

- A change to electrical wiring (e.g. connecting of unused immersion heaters)
- A change in pipe configuration (e.g. pipes in and out of thermal store)
- Installation of a larger DHW tank

The typical site intervention process is shown in Figure 17. During the intervention visit, the field trial monitoring equipment was also serviced (sensors were serviced to ensure continued operation, batteries replaced, etc.) to allow data to be collected from these sites for a further year.

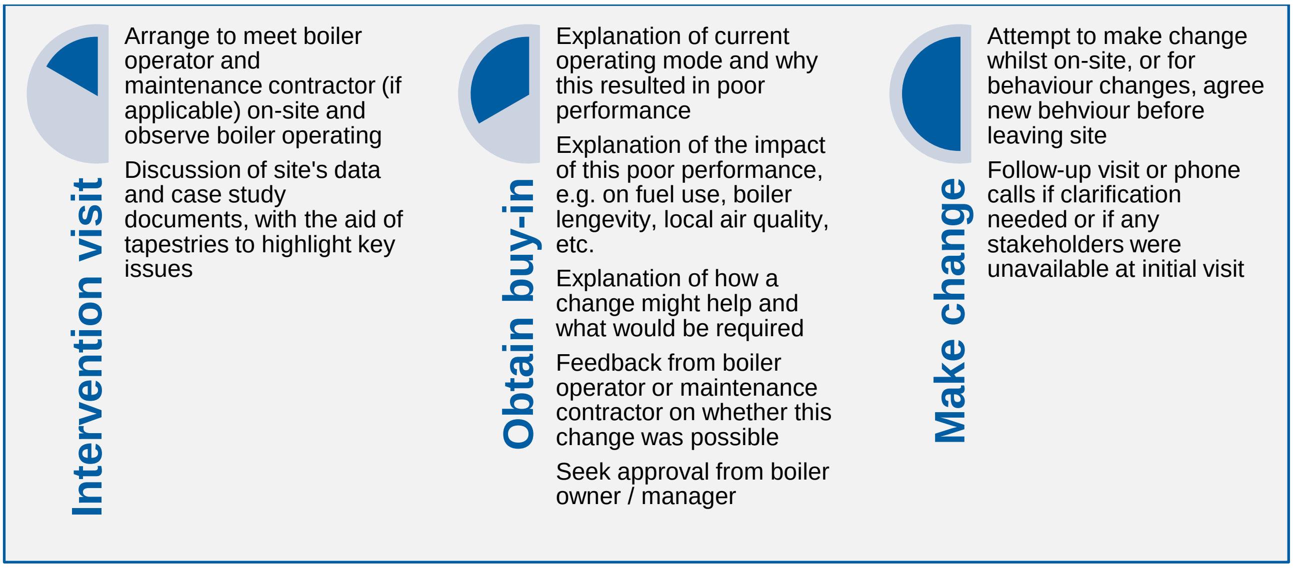


Figure 17: The site intervention process in Phase 3

4.7.4 Collection of data and weather effects

The data monitoring was continued for a further year (July 2017 – June 2018) and an additional fuel sample was taken from each of the sites in Phase 3. The same calculations were used to determine the efficiency of each of the boilers.

Weather (i.e. outside temperature) can affect the efficiency of a biomass boiler, as in many cases the boiler is providing heat to a space, and this heat requirement will depend on outside temperature. The varying conditions from year to year will change the load requirement placed on the boiler and therefore could cause an artificial increase or decrease in the efficiency of the boiler (independent of any intervention). Therefore, two techniques were used in the data analysis to account for this and allow robust conclusions to be drawn on the success or otherwise of an intervention:

1. In the initial analysis comparing the difference between Phase 2 and Phase 3, the change in average outside temperatures and the degree day heating (DDH) requirement at each site were calculated and compared with the change in efficiency. The change in efficiency at the control sites was used to establish a threshold, above which changes could be considered to be due to an actual change at the site rather than weather alone.
2. In the detailed analysis, quantities under investigation (such as efficiency, number of cycles, cycle length, etc.) were compared graphically against the DDH requirement (or load factor, for sites where the heat load was not dependent on outside temperature e.g. poultry farms where it is dependent on chick age). This technique can very quickly show whether a change is due to different weather or a change at the site (see Figure 18).

In using these two techniques, the data collected does not need to be adjusted or altered. Doing so is particularly problematic for measurements of biomass boiler efficiency, because the operating pattern (number of cycles, cycle length, control system behaviour, etc.) is highly dependent on the load factor and thus in many cases the weather. It is this operating pattern that determines the efficiency of the boiler.

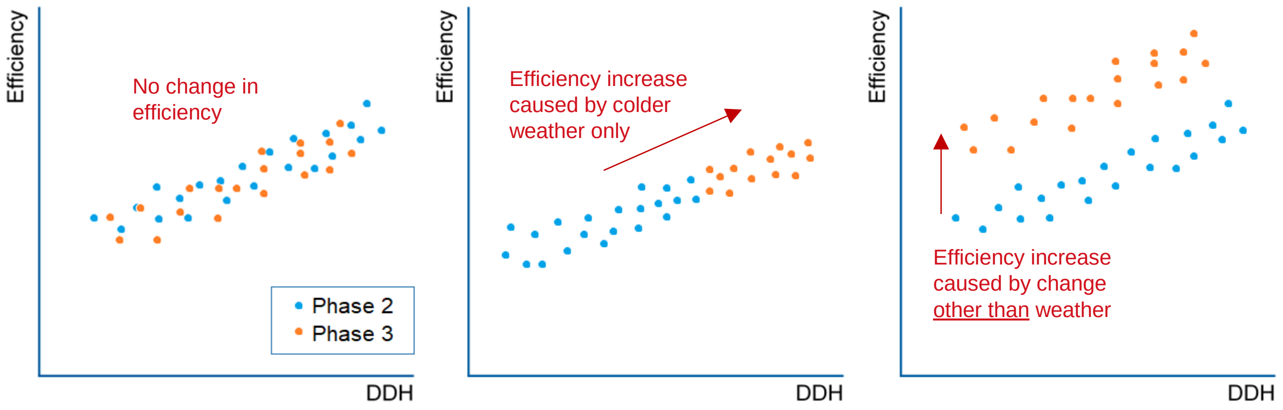


Figure 18: Technique for determining if a change in a parameter is due to weather or another factor

4.7.5 Review findings and revise guidance

The additional year of data collection and records of communications with the sites were used to determine the success of the interventions. Common themes in the reasons for success or failure of an intervention were compiled. The findings from the interventions were also used to revise the guidance to highlight the most effective strategies for improving performance.

5 Results & discussion

The following section presents a summary of the main results from the field trial and laboratory trials. The key themes observed are then explored in more detail.

Full results from the field trial, laboratory trials and social research are included in Annexes B-D (provided as separate documents).

5.1 Efficiency

The average (median) efficiency of the all boilers in the field trial was **77% net** and **70% gross**. The efficiencies of the biomass boilers were calculated over the one year period from July 2016 to June 2017 (inclusive). The distribution of efficiencies is shown in Figure 19.

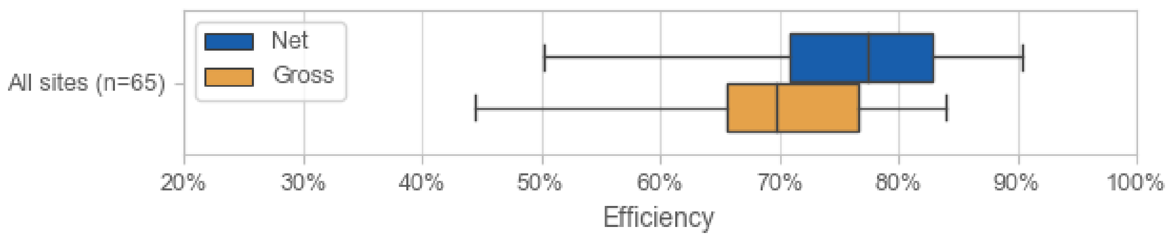


Figure 19: Efficiencies measured at all sites in the field trial, from July 2016 – July 2017

The efficiency was for the boiler[23] and did not include the effects of the heat delivery system. There was much variation in design of heat delivery systems and the losses from these varied widely and could often be significant.

The data presented is for 65 boilers. Two of the boilers were not included: one boiler had an extended breakdown lasting over 12 months, and the other was operated with out-of-specification fuel which produced very high CO, particulates and tar emissions which damaged the measurement equipment.

Efficiency was calculated using all data available for the year, to reflect the actual usage patterns of the boilers. Many of the boilers were shutdown for part of the year, for reasons including: summer shutdowns, boiler system breakdown, building closure (e.g. accommodation blocks) and intermittent heat use (e.g. poultry farms). Adjustments to the collected data were not made to accommodate boiler shutdown or breakdown[24].

5.1.1 Performance gap

The best performing boiler in the field trial had an efficiency of 90% net and 84% gross. This was within the range of values expected in standard laboratory tests at steady state [30], which are 85–95% net or 77–86% gross. However, over three quarters of boilers fell below the bottom of this

[23] Boiler heat output was measured by heat meters installed on the boilers. The non-domestic sites already had heat meters installed, however there were none at the domestic sites. Therefore, a suitable heat meter was installed by the project team. The heat meters were located: (a) after the biomass boiler backend-protection loop but before the accumulator tank in 87% of cases, and (b) after the accumulator tank in 13% of cases. See Section 4.2.3 for more information.

[24] There were also some periods of time when the measurement and monitoring equipment was switched off (along with the boiler) or was not functioning. As the overall data completeness was greater than 90% (see Section 5.11.1), and due to the complexity of the reasons for boiler shutdown, adjustments to the collected data were not made to accommodate measurement and monitoring equipment malfunction.

range. This indicates there is a performance gap of on average 15 percentage points, between standard laboratory efficiency and real-world efficiency.

This performance gap was mirrored in the laboratory trials of the larger boiler. Part of the test work was carried out at steady state, and under these conditions the boiler had an efficiency of 83% net and 78% gross. In contrast, the real-world efficiency observed from the same boiler in the field trial was 74% net and 66% gross. This is a performance gap of around 10 percentage points.

5.1.2 Seasonal variation

Individual boilers displayed seasonal variation in efficiency, although the precise behaviour differed from one boiler to another. This is explored further in the discussion sections. The seasonal variation is shown in Figures 20–22[25].

There was a slightly lower average[26] net efficiency in the summer (75% net) compared with the winter (78% net), however the gross efficiency and spread of the efficiencies was generally similar. This meant that the winter efficiency was most similar to the efficiency over the whole year, as boilers usually produce most of their heat during the winter months.

There was not a large difference in summer and winter efficiencies, which may be explained by the dry, mild winter – between December 2016 and February, the UK monthly mean temperature was 1.6-2.0°C above the long-term average for those months [31].

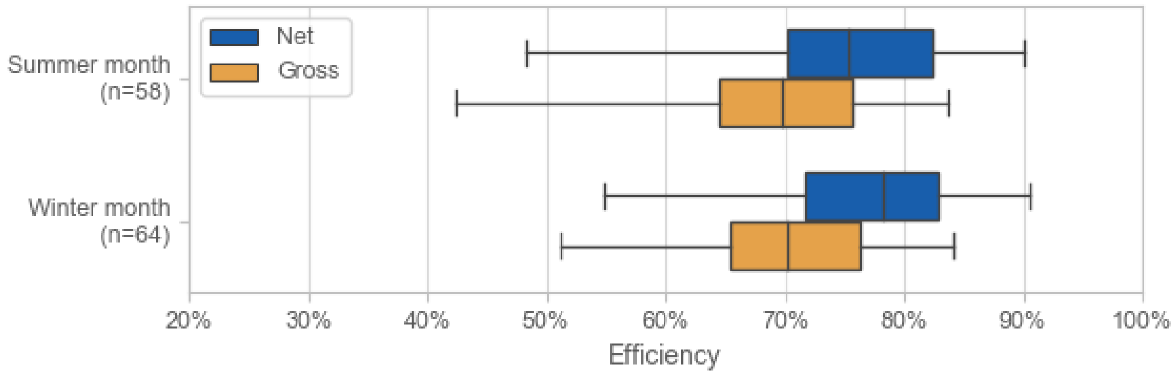


Figure 20: Seasonal variation in efficiencies measured at all sites in the field trial

[25] For comparison purposes, the months of February 2017 (for winter) and September 2016 (for summer) were chosen. However, if a site was not operating during this month, data from an adjacent month was used.
[26] The efficiencies over different periods of time were calculated using the total heat delivered and the total heat losses during that period (i.e. they are average efficiencies, weighted by energy input).

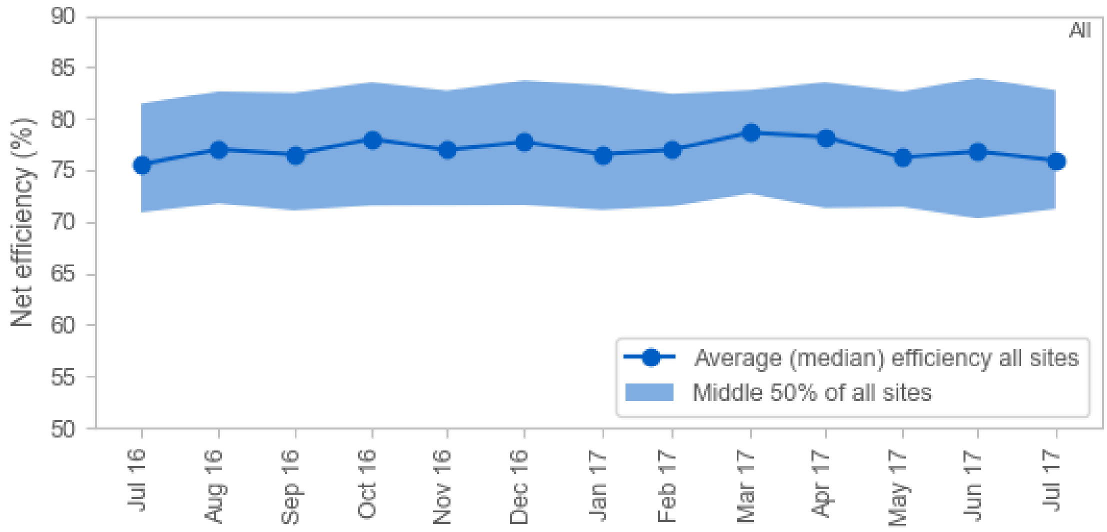


Figure 21: Monthly variation in net efficiencies measured at all sites in the field trial

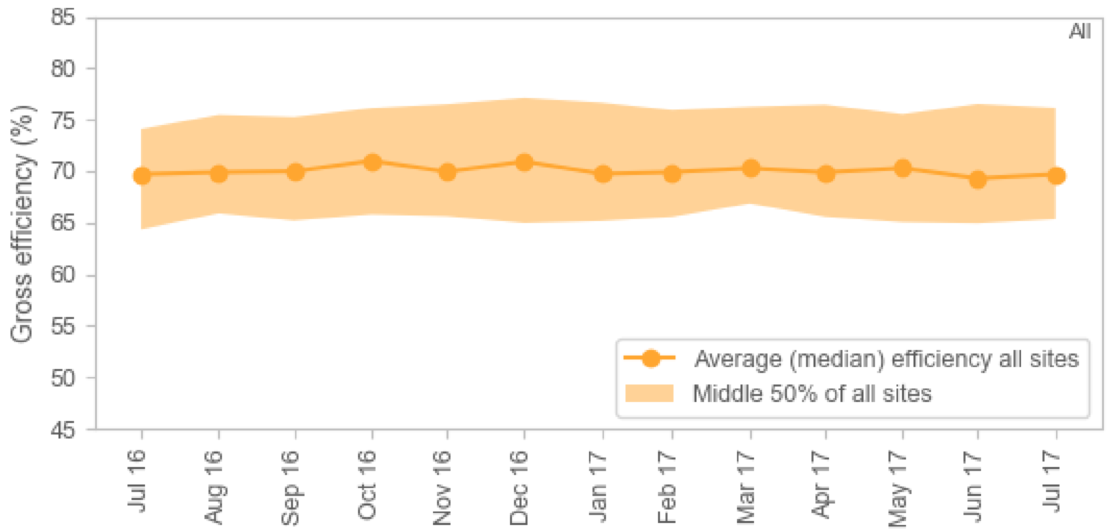


Figure 22: Monthly variation in gross efficiencies measured at all sites in the field trial

5.1.3 Variation by fuel type

The average boiler efficiency of the wood pellet boilers in the field trial (78% net, 72% gross) was higher than the average boiler efficiency of the wood chip boilers (75% net, 67% gross). The wood log boilers had the highest boiler efficiency (81% net, 74% gross). There was greater variation in the efficiencies of the wood chip boilers, and in the gross efficiencies over the net efficiencies. This is shown in Figure 23.

Rather than a fundamental difference in the efficiency of the wood fuels, the variation is thought to be because:

1. There were fewer wood chip boilers at the smaller rated outputs. Smaller boilers in the trial (<100kW) were shown to be more efficient (see Figure 24) which makes the wood chip

boilers appear to be less efficient when the results are not split per rated output (see Section 5.1.4) or extrapolated to fit the overall population (see Section 5.10)

2. The average moisture contents of the fuels were different. Wood chip was on average the wettest (28%) and wood pellet was the driest (7%). High moisture contents in the fuel will decrease gross boiler efficiency (see Section 5.4.4)
3. Manually-fed wood log boilers are operated in a different pattern to all other boilers. This means rapid cycling behaviour is not possible (see Section 5.8.3)

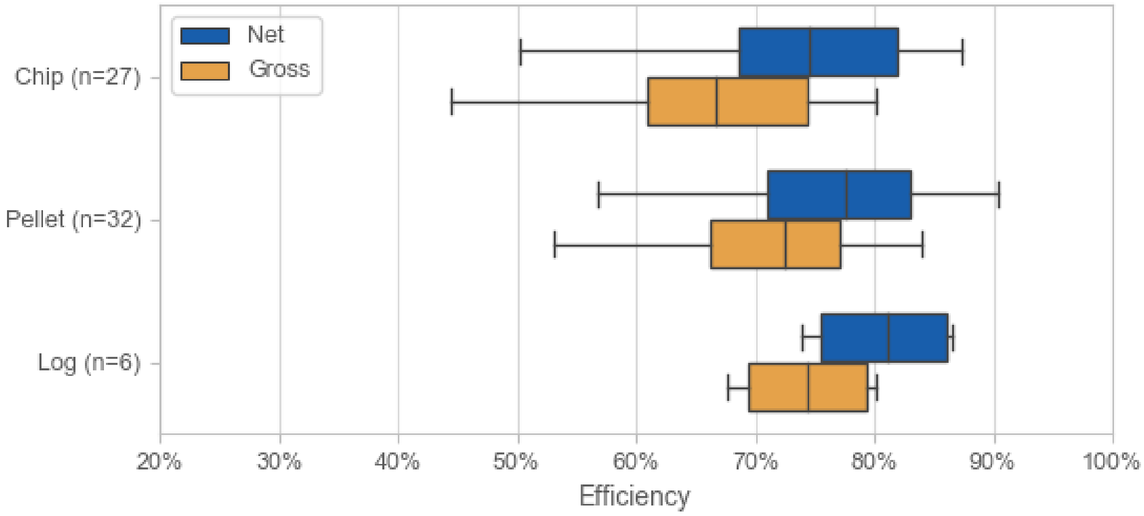


Figure 23: Efficiencies measured at all sites in the field trial over one year, split by fuel type

It was not possible to calculate an efficiency for one wood log boiler, because the operator had used out-of-specification fuel which led to very high levels of CO in the boiler and flue. There were also high levels of particulate and tar emissions which damaged the measurement equipment (see Section 5.4.7).

The ratio between net and gross efficiencies of the fuels are shown in Table 24. These are very similar to those in SAP 2012 [5].

Table 24: Efficiency conversion factors of the measured efficiencies compared to SAP 2012

Fuel	Net-to-gross conversion factor from field trial data	Net-to-gross conversion factor from SAP 2012 [5]
Wood pellet	0.93	0.91
Wood chip	0.89	0.91
Wood log	0.92	0.91

5.1.4 Variation by rated output

The variation in the boiler efficiencies across the strata is shown in Figures 24 and 25. The average efficiencies of boilers below 100kW (around 81% net, 75% gross) were higher than the average efficiencies of the boilers between 100kW and 1MW (around 71% net, 65% gross).

The distribution of the efficiencies of wood pellet and wood chip boilers is shown in further detail in Figures 26 and 27. In addition to operating more efficiently, most boilers with rated outputs below 100kW showed a narrower range of efficiencies[27]. Boilers with larger rated outputs had efficiencies

[27] Specifically, the inter-quartile range was larger.

that were spread over a larger range[27]. Some large wood chip and wood pellet boilers showed high efficiencies, but equally some showed the lowest efficiencies measured.

During stakeholder engagement events, many industry representatives believed this was primarily due to boiler oversizing (evidenced by low load factors, discussed in Section 5.6), possibly due to financial pressures. For example, the efficiencies of non-domestic wood pellet boilers with rated outputs between 100kW and 200kW were noticeably lower than the other output ranges. Stakeholders believed that a number of boilers in this range were oversized to maximise the benefits of RHI incentives, and that in these cases this was the primary reason for poor performance, rather than poor design, poor boiler installation or lack of operator knowledge. On the contrary, larger boilers were thought to have the most experienced operators.

The variation in efficiency by rated output within the entire biomass population is explored in Section 5.10.

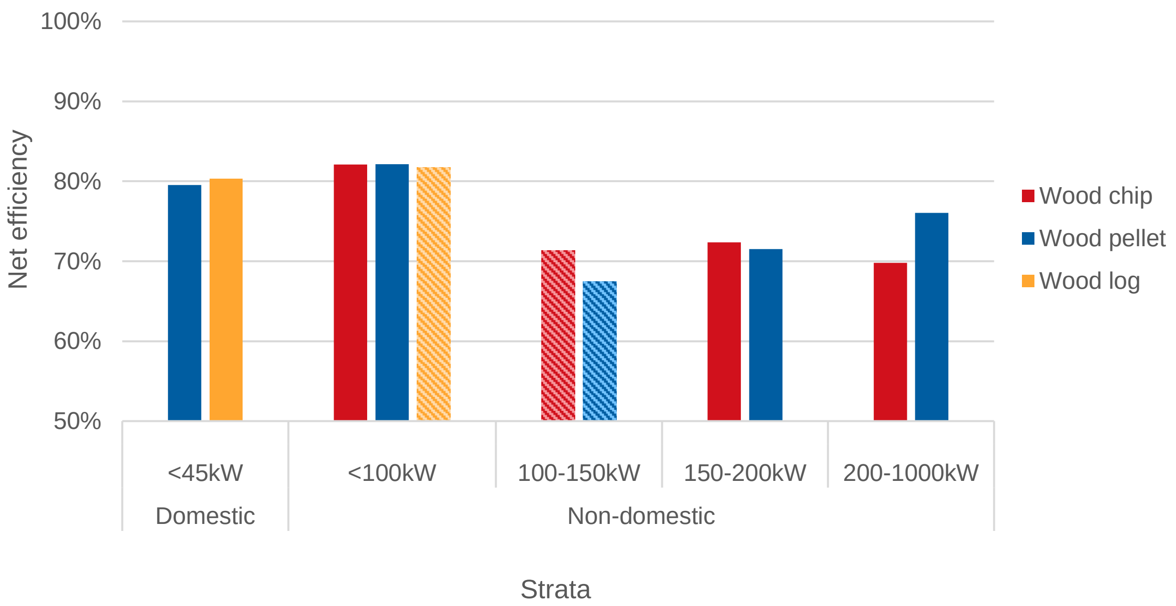


Figure 24: Net efficiencies measured over one year, split by rated output and fuel type (striped bars = small sample size)

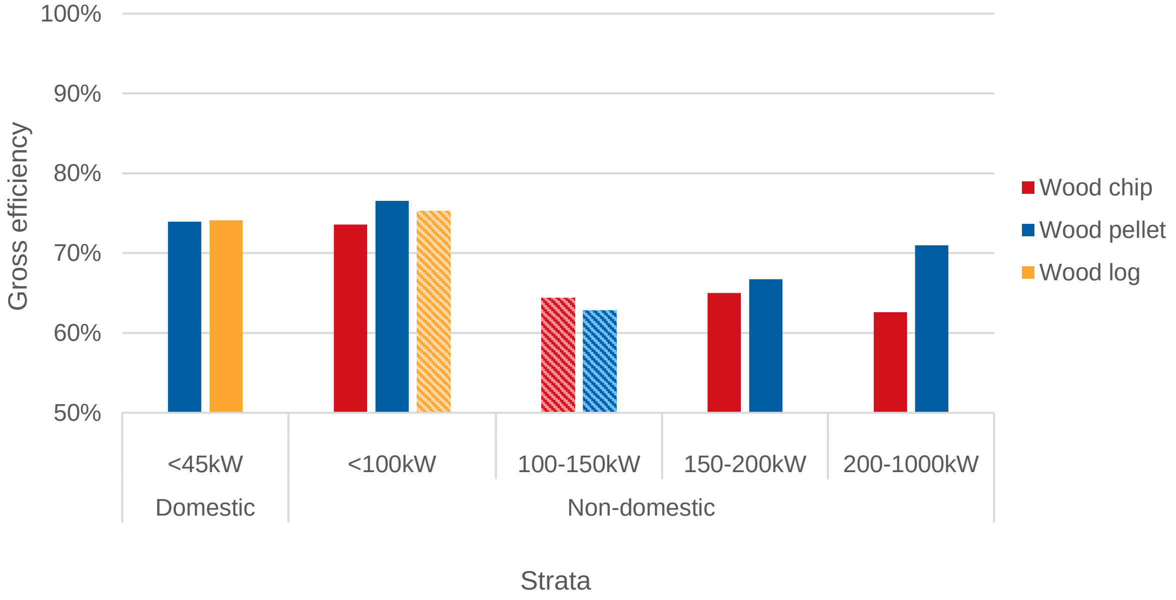


Figure 25: Gross efficiencies measured over one year, split by rated output and fuel type (striped bars = small sample size)

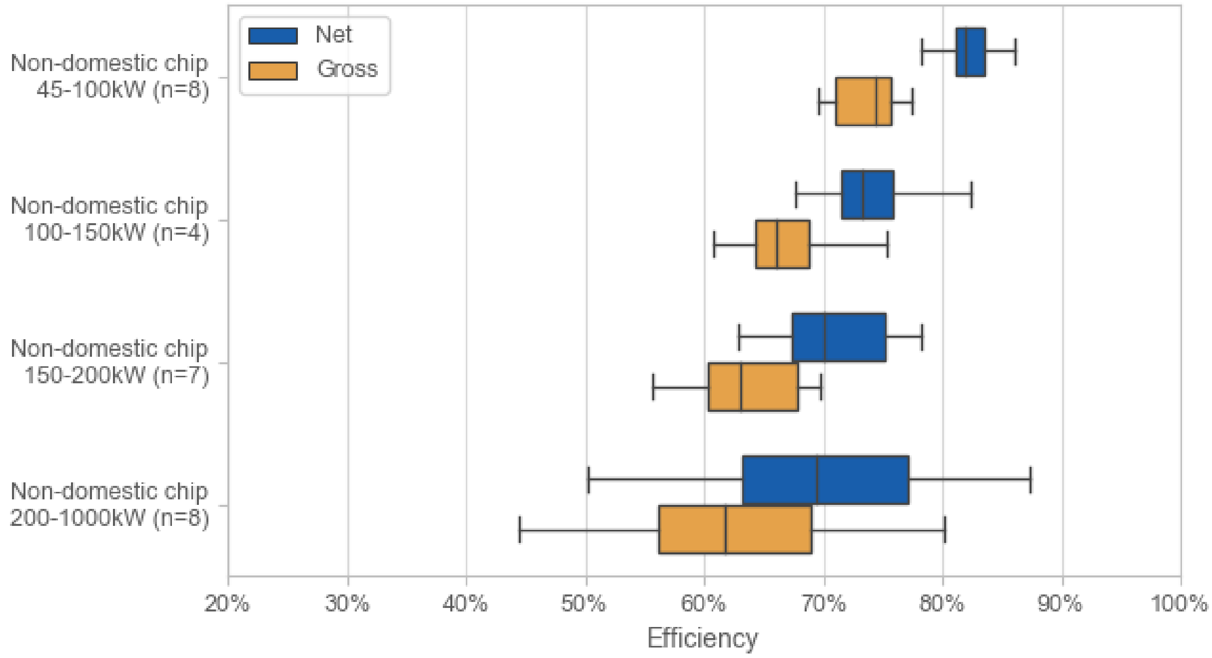


Figure 26: Efficiencies measured at wood chip sites in the field trial over one year, split by rated output

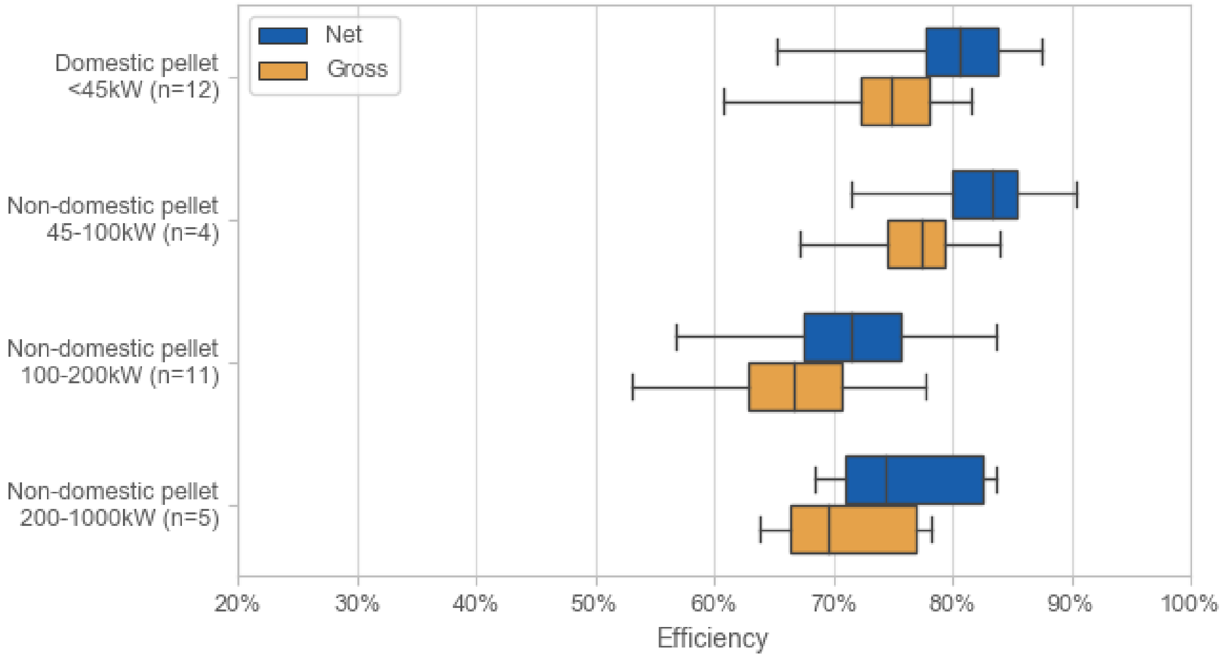


Figure 27: Efficiencies measured at wood pellet sites in the field trial over one year, split by rated output (the 100-150kW and 150-200kW wood pellet strata have been merged, as there were only two boilers operating in the 100-150kW wood pellet group)

5.1.5 Variation by system design

Some sites had a pair of biomass boilers installed to provide heat to the same system (a 'double boiler' system). They were generally connected in a shared duty configuration, so that the boilers ran alternately, unless the demand was increased, in which case both boilers operated simultaneously. The efficiencies of these systems were compared with single boiler systems as shown in Figure 28.

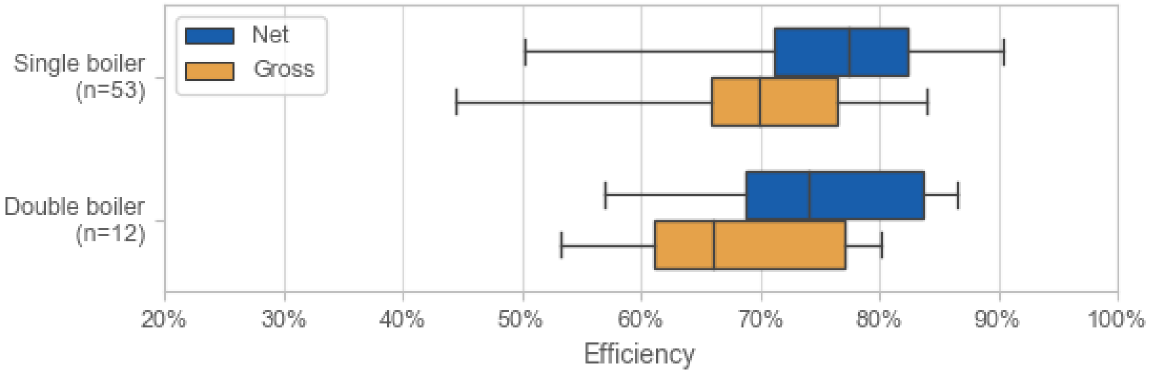


Figure 28: Efficiencies measured at all sites in the field trial over one year, split by number of linked boilers in the same system

The double boiler systems could work as well as single boiler systems, however the average efficiency of these systems was 3-4 percentage points lower (although the sample size is small). This could be because some duty cycle systems resulted in increased cycling of the boiler and more cold starts as each boiler had additional cooling time between samples (see Section 5.5).

5.2 Greenhouse gas emissions

SAP 2012, Table 12 [5, p. 199] provides emissions factor for various fuels in $kgCO_2$ emitted per kWh (gross energy content) of fuel burned. The efficiencies measured during the field trial (see Section 5.1.4) were used to calculate emission factors on an output basis, i.e. $kgCO_2$ emitted per kWh useful heat generated. These are shown in Table 25.

Table 25: Emission factors for wood biomass (using GHG Protocol Scope 3 [32, 33])

Fuel	Rated output	Emission factor – input basis ($kgCO_2e$[28]/kWh gross input) *from SAP 2012* [5]	Emission factor – output basis ($kgCO_2e$/kWh output) *from efficiency measurements*
Wood pellet	<100kW	0.039	0.052
	>100kW		0.058
Wood chip	<100kW	0.016	0.022
	>100kW		0.025
Wood log	<100kW	0.019	0.025

5.3 Pollutant emissions

All the boilers in the field trial were in receipt of (or eligible for) RHI payments. Therefore, all boilers in the field trial will have demonstrated compliance with RHI air quality requirements[29], which are:

- 30 g/GJ net heat input for particulate emissions (0.000108 kg/kWh)
- 150 g/GJ net heat input for NO_x emissions (0.000542 kg/kWh)

The RHI regulations require that boilers are operated at least 85% of their rated output when demonstrating compliance with these limits. [7, 8]. This is in effect the same as steady state testing that would be conducted in a laboratory (or under laboratory conditions) to determine efficiency.

The laboratory trials investigated both a small wood pellet boiler and a large wood chip boiler that were eligible for the RHI. Both boilers were tested in a range of cycling regimes (to mimic real-world operation) and also under steady state conditions (to the mimic standard laboratory testing used to issue their emissions certificates). Unless specified otherwise, virgin wood fuel compliant with the boiler emissions certificate was used.

The real-world cycling regimes were designed to test the boilers in conditions that they would typically see when running during normal use. The real-world testing was similar to the standard steady state testing but with three differences:

- Low daily load factors of 5-30% were used to replicate the load factors that were identified from analysis of the field trial data, unlike load factors of 85-100% used in standard testing.
- The flow and return temperatures were not fixed.
- Start-ups and shutdowns were included in the test period. The effects of boiler cycling were therefore also included in the test results.

[28] These are CO_2 equivalent figures which include the global warming impact of CH_4 and N_2O as well as CO_2.
[29] Applications receiving preliminary accreditation for the non-domestic RHI from Ofgem before September 2013 did not need to demonstrate compliance with the RHI air quality requirements with measurements from an ISO 17025 accredited laboratory [42, 2].

5.3.1 NO_x emissions

The NO_x emissions were measured using chemiluminescence as outlined in standard reference method EN 14792 [34]. The boilers had NO_x emission levels of 70–130 g/GJ net input, independent of the test performed (Table 26, Figure 29). The RHI emissions limit of 150 g/GJ net input was not exceeded in any of the tests. The variation observed from one test to another was primarily due to uncertainties inherent in the measurement techniques for measuring these species.

This demonstrated that NO_x formation was not strongly dependent on boiler operation for biomass boilers. However, NO_x format was dependent on fuel quality, as explored further in Section 5.4.

Table 26: NO_x emission rates measured during laboratory trials

	NO_x emission (g/GJ net input)	
	Standard laboratory testing regime	Real-world cycling regime
Small wood pellet boiler (25kW)	81 – 96	74 – 126
Large wood chip boiler (800kW)	73	70 – 90

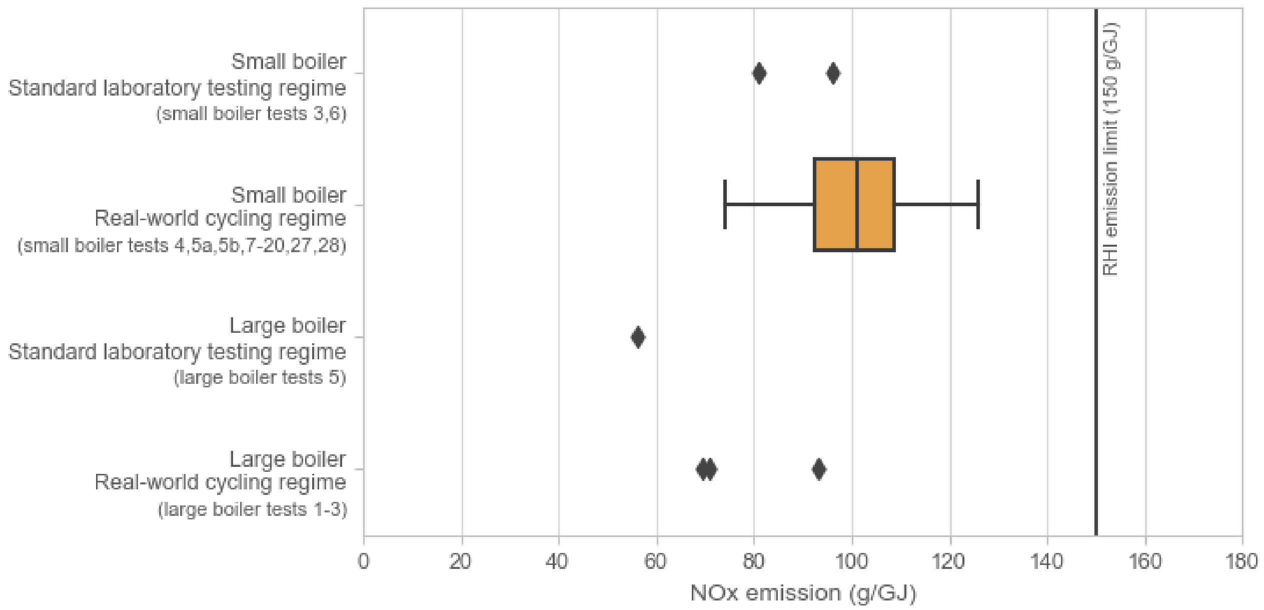


Figure 29: Distribution of NO_x emission rates measured during laboratory trials

5.3.2 Particulate emissions

Particulate emissions were measured using standard gravimetric measurement techniques as outlined in standard reference methods EN 13284-1 [35] / ISO 9096 [36] (isokinetic extractive sampling) or PD 6434:1969 [37] (electrostatic precipitator). During the tests that mimicked standard laboratory testing, the particulate emission levels of around 10–20 g/GJ net input were observed (Table 27, Figure 30). These were within the RHI emissions limit of 30 g/GJ net input.

However, during the tests that mimicked real-world operation, emission levels of around 40-170 g/GJ net input were measured, depending on the type of operation of the boiler. These were around 2–8 times higher than the steady state emission rates, and exceeded the RHI emissions limit by a factor of around 2–5. The variation observed from one test to another was due to both the cycling rate of the boiler and to the uncertainties inherent in the measurement techniques for measuring these species.

Table 27: Particulate emission rates measured during laboratory trials

	Particulate emission (g/GJ net input)	
	Standard laboratory testing regime	Real-world cycling regime
Small wood pellet boiler (25kW)	10 – 14	45 – 88
Large wood chip boiler (800kW)	21	53 – 166

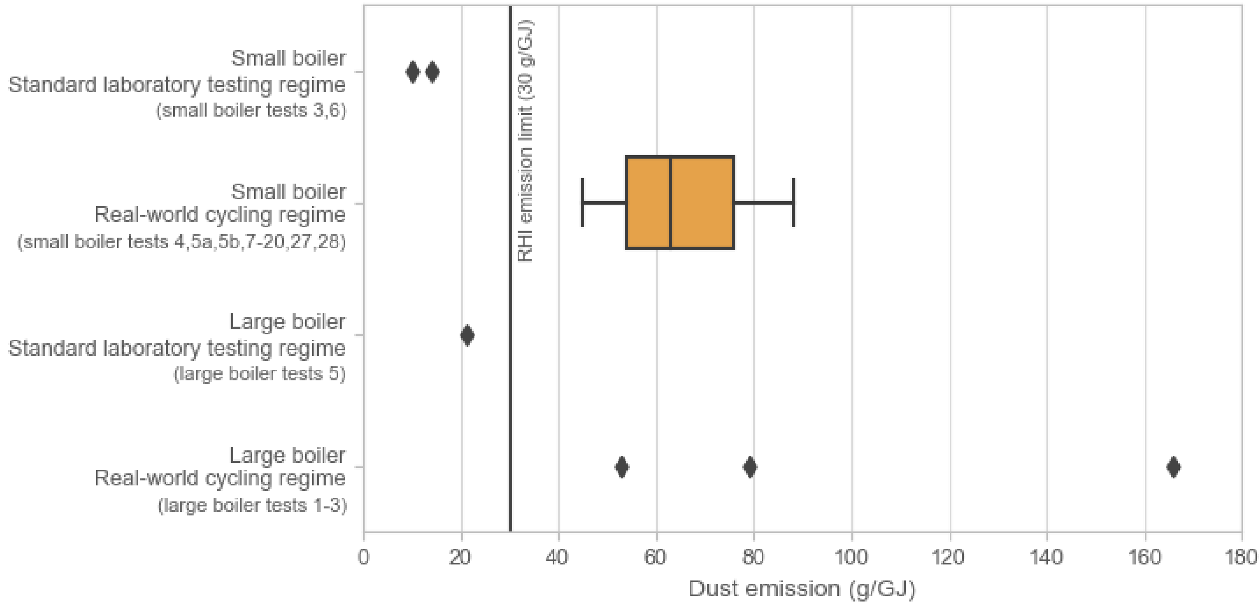


Figure 30: Distribution of particulate emission rates measured during laboratory trials

This demonstrated that particulate formation was strongly dependent on boiler operation for biomass boilers. Particulate emissions were also dependent on fuel quality, explored in Section 5.4.

The poor operational performance was observed at many boilers in the field trial, which suggests that there are likely to be a large number of biomass boilers which do not meet expected particulate emission levels during their normal operation. However, there were examples of well-operated boilers in the trial which ran for long periods at steady state and were likely to be meeting the RHI limits.

5.3.3 Other emissions

Sulphur is only present in wood at very low concentrations. In the field trial there were no sites where the levels of sulphur in the fuel exceeded 0.03% by weight, and in many cases the level of sulphur was below the detectable limit of 0.01%. Therefore, an upper limit on the sulphur dioxide emissions was determined by assuming at least 0.01% of sulphur was present, and that all sulphur present in the fuel was emitted as sulphur dioxide (Table 28).

Table 28: Upper limit of sulphur and sulphur dioxide emission from field trial sites

Fuel	Upper limit for sulphur emission (S g/GJ net input)		Upper limit for sulphur dioxide emission (SO_2 g/GJ net input)	
	mean	*range*	*mean*	*range*
Wood pellet	7	6 – 17	13	11 – 35
Wood chip	10	7 – 24	21	13 – 49
Wood log	6	*not enough data*	13	*not enough data*

5.4 Impact of fuel

In addition to the variation in average efficiency based on fuel type (see Section 5.1.3), fuel quality also had a significant impact on efficiency and pollutant emissions. However, the effects were complex and pollutant emissions were impacted before efficiency.

During the laboratory trials, some small changes in fuel quality were found to have immediate changes in pollutant emissions. This was particularly apparent for particulate emissions but also the case for NO_x emissions. In reality, an operator is most likely to use visible indications (such as smoke or clinker formation) and efficiency (based on fuel purchased) as a way of telling if the boiler is running well. However, in the laboratory and trial, visible effects and changes in the efficiency only became apparent when very low quality fuel was used.

Visible smoke is not a good guide of whether a boiler meets the RHI particulate emission limit. This is because smoke is typically visible at particulate concentrations greater than 150mg/m^3 (dry gas at STP and stack O_2) [9]. This equates to particulate emissions of roughly 70 g/GJ net input [38], more than twice the RHI limit. Therefore, it is possible for pollutant emissions to be significantly poorer than expected with little or no sign to the operator. By the time smoke becomes visible, the RHI limits have already been exceeded by some margin.

The social research revealed that around 40% of operators saw soot or smoke coming from their boiler. It appeared that some operators believed that the production of smoke was a standard feature of biomass boilers, reporting that their boiler produced “just regular wood smoke”. They may not have been aware that smoke should only be visible briefly during start-up and shutdown and should not be prolonged.

5.4.1 Lower-grade wood pellet

To investigate the effects of changing fuel quality alone, in the laboratory trials the small wood pellet boiler was tested at steady state with a standard ENplus A1 fuel [39, 40] and with a lower grade ENplus B fuel. The ENplus A1 fuel was manufactured using virgin wood and supplied in 15kg bags. The ENplus B fuel was manufactured using recycled wood – the supplier was only able to supply ENplus B pellets in bulk 1 tonne pallets, however they did offer to supply ‘equivalent’ grade pellets in 15kg bags, without the ENplus B certification.

Table 29 shows the chemical composition and metals content of the fuels. The analyses for both fuel were similar, however the ENplus B fuel did show increased levels of some metals. Most notably these were increased levels of zinc and copper which occur in popular wood treatments and preservatives.

There was no significant difference in boiler efficiency when operating on the two different fuels, however the pollutant emission rates were higher on the ENplus B fuel (see Figure 31). When the boiler was operated with ENplus A1 fuel, it met both the particulate and NO_x emission limits for the

RHI. However, when operated with ENplus B fuel, the boiler did not meet the particulate emission limit.

Table 29: Chemical and metal analyses of fuels used during laboratory trials of a small wood pellet boiler

		ENplus A1 wood pellet	ENplus B wood pellet
Moisture	(% by weight, wet basis)	9.0	8.1
Gross CV	(MJ/kg, wet basis)	18.428	18.438
Net CV		16.839	17.025
Ash	(% by weight, dry basis)	0.6	0.7
Sulphur		0.01	0.01
Carbon		51.2	51.9
Hydrogen		6.07	6.00
Nitrogen		0.18	0.22
Oxygen		41.9	41.2
Cadmium	(mg/kg, dry basis)	0.02	0.04
Zinc		3.45	8.10
Lead		0.57	0.50
Copper		0.44	1.01
Chromium		1.13	1.25
Nickel		0.32	0.53
Arsenic		0.24	<0.10
Mercury		<0.01	<0.01

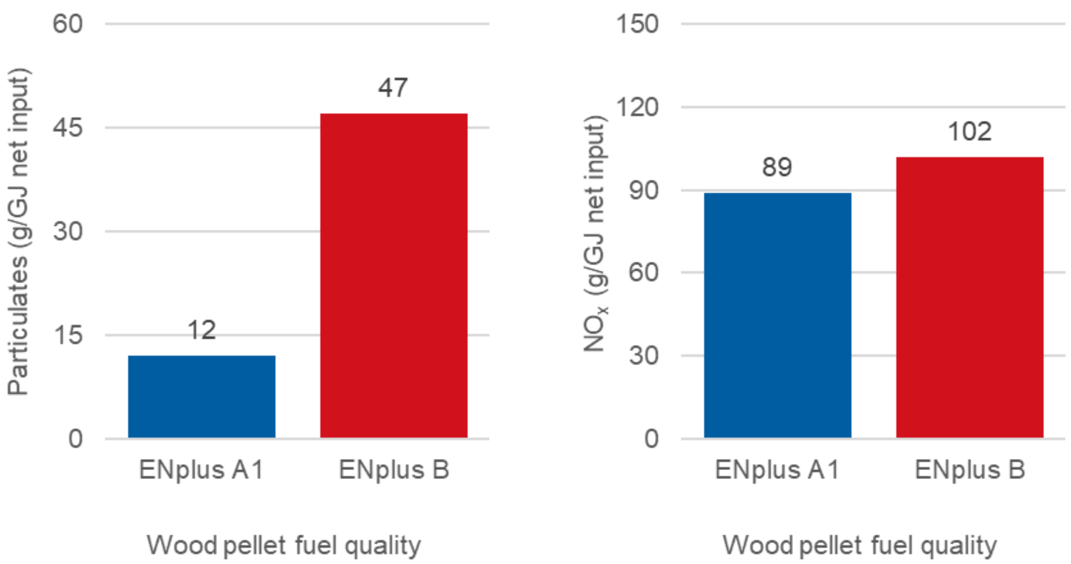


Figure 31: Pollutant emissions of particulates (left) and NO_x (right) using ENplus A1 and B pellet

Particulate emission rate was nearly four times as high with ENplus B pellet, compared with ENplus A1. NO_x emission rate was around 15% higher, as a result of increased nitrogen content in the fuel (which was around 20% higher). In combustion, NO_x is produced by one of three main mechanisms (see Section 2.4). The main mechanism for NO_x formation in biomass combustion at this scale is fuel NO_x[30], where all the emission comes from nitrogen in the fuel. This increased nitrogen content in the fuel can be caused by presence of from glues, resins and plastics.

There were no significant differences in VOC or SO_x emission rates when using either fuel.

5.4.2 Lower-grade self-supplied wood chip

The laboratory trials also investigated a large wood chip boiler that was affected by lower-grade wood chip. The wood chip was self-supplied from a virgin wood source, however the operator was able to vary the ratio of trunks and branches to forest residue in the mixed wood chip. The forest residue contained significant adventitious material (dirt, stones, leaves etc.)

When a fuel with a higher proportion of forest residue was used, there was excessive build-up of ash deposits in the combustion chamber (Figure 32). These ash deposits fused together to produce an extremely hard, glassy clinker material. This eventually led to the boiler requiring shutdown and manual removal of the deposits. The removal of the deposits also caused damage to the refractory lining of the boiler.

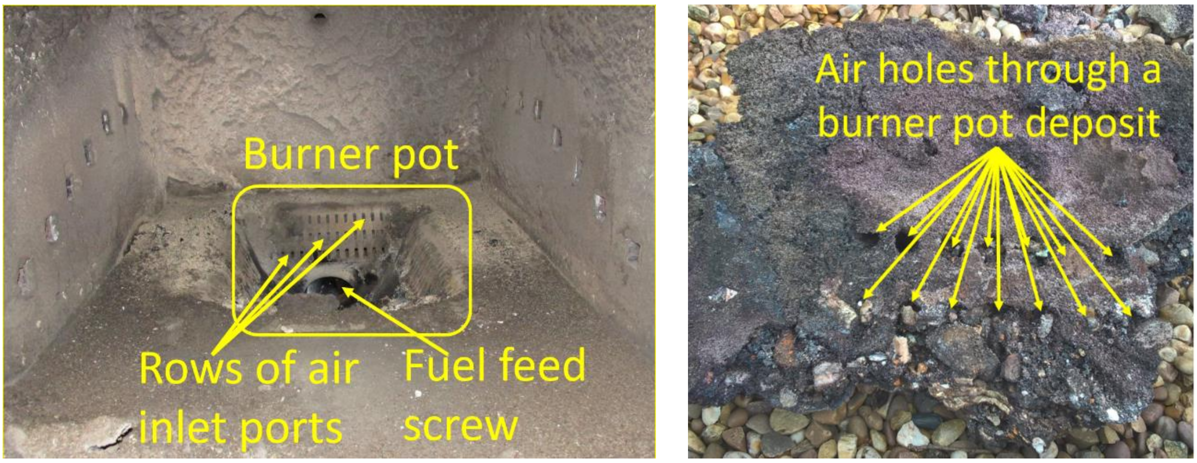


Figure 32: The burner pot and an example of ash deposits removed from burner pot

The boiler incorporated an underfeed stoker type burner as shown in Figure 3. Primary combustion air was fed under the fuel bed by three rows of slot shaped air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and the residual ash was thus pushed across the floor of the combustion chamber to the ash removal channel/screw.

Holes through the deposit were created by the primary combustion air flows. However, the flow regime will have been affected and not as designed. This affected the combustion within the boiler and changed the air distribution such that thick smoke was observed by the operator, until the boiler shutdown and was unable to operate until it was cleaned and the deposits removed.

During this time, it was likely that the boiler exceeded the RHI limits for particulate emission by many times. This is because smoke is typically visible at particulate concentrations greater than 150mg/m^3 (dry gas at STP and stack O_2) [9]. This equates to particulate emissions of roughly 70 g/GJ net input [38], more than twice the RHI limit.

[30] There is a little prompt NO_x, however this requires large excess air ratios which are seen in diesel cars rather than biomass boilers. Thermal NO_x is only formed at temperatures above 1,300°C, and under normal operation a biomass boiler does not reach these temperatures. If this temperature is exceeded then other issues are also likely, such as clinker formation. This is because the ash fusion temperature of the ash deposits from biomass is also around 1,200°C.

The deposits formed in the burner chamber were examined to see how the ash was forming in the deposits. Typically, the deposits were formed of underlying layers of more sintered material which was then covered with fine particles which probably arrived during the shutdown phase as the temperatures fall and thus had not been fused into the deposit (see Figure 33).

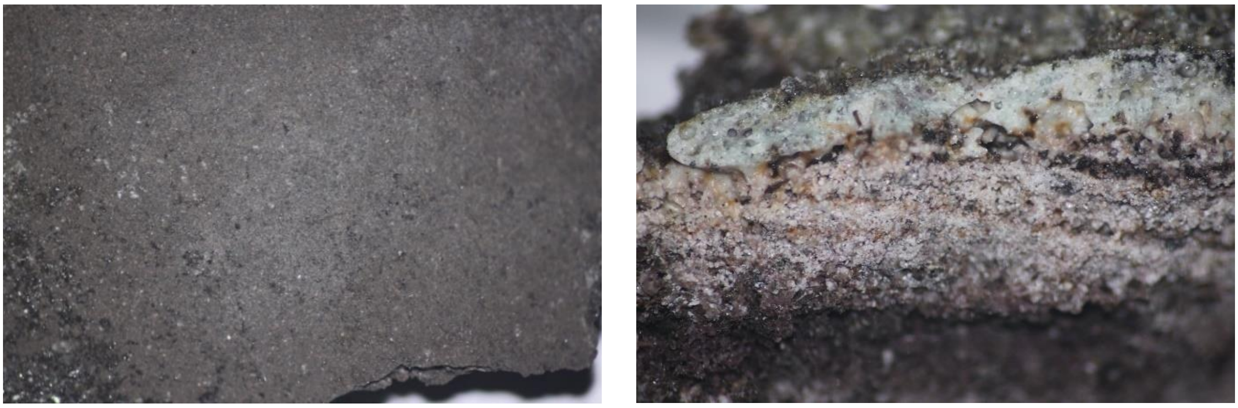


Figure 33 Example of deposit form combustion chamber floor

The outer surface was covered in fine particles which were not fused and inside the deposit is layered with fused and partly fused material. Colouration can give indication of changes in the composition which can be indicative of changes in the material fed to the combustor. An example of extensively fused deposit is shown in Figure 34. The colouration implied the presence of some material distinct from the bulk of the deposits. It appeared to have formed a distinct layer and to have lower fusion temperatures than the surrounding material.

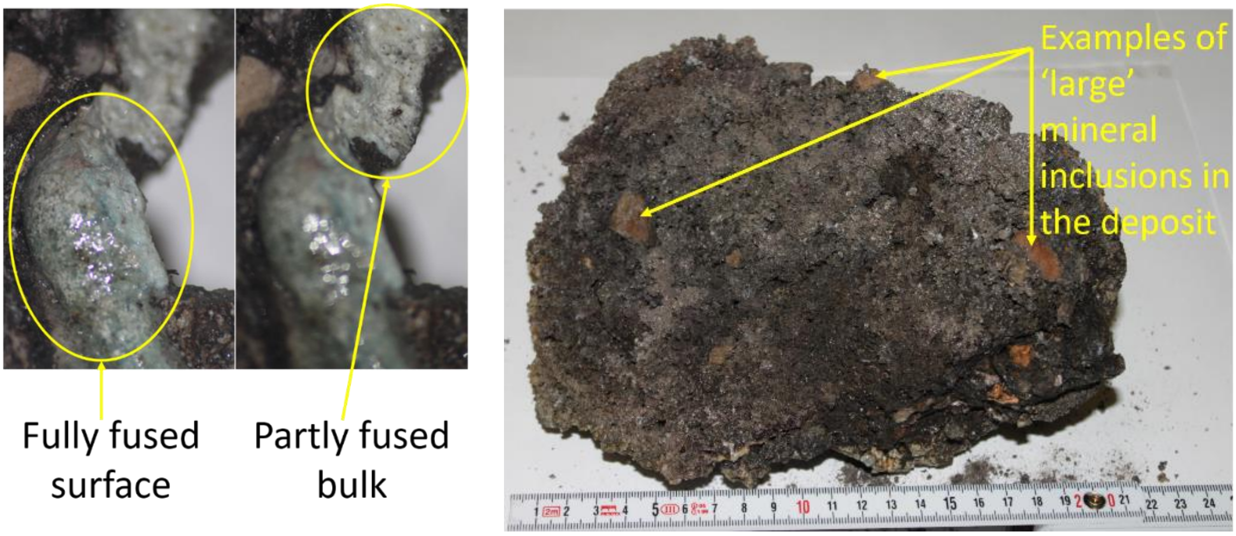


Figure 34 Close-up of fused ash deposit and evidence of contaminated fuel

Within the piece of deposit, several pieces of material are visible. These appeared to be stones. This is not material that would be present in clean wood chip fuel and have entered the combustion chamber whilst it was being fed with recovered forest residue material.

5.4.3 Mechanically degraded wood pellet

The laboratory trials on the wood pellet boiler also investigated steady state operation using 6mm ENplus A1 wood pellets that had been mechanically degraded to produce a fuel with an increased fines content of 4%. This is typically the maximum permitted in blown deliveries of biomass pellets.

The as-supplied ENplus A1 wood pellets had a fines content of 0.5% <3.15mm (0.2% <1mm). This is within the permitted levels in the ENplus standard. This was compared with wood pellets that had been mechanically degraded to 4% <3.15mm (with the same proportion of particles <1mm). However, not all the fines in the degraded fuel were conveyed into the boiler (some remained in the fuel store). The fuel supplied into the boiler combustion chamber had a fines content of between 2.4% and 3.2% <3.15mm.

There was no significant difference in boiler efficiency, particulate emissions or NO_x emissions when operating on the two different fuels (see Figure 35).

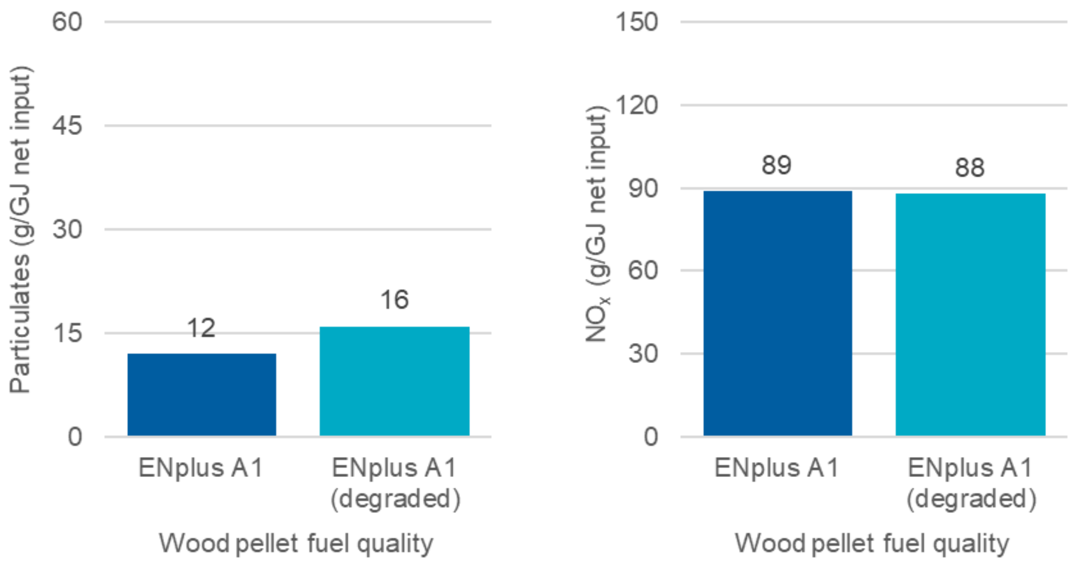


Figure 35: Pollutant emissions of particulates (left) and NO_x (right) using degraded ENplus A1 pellet

5.4.4 Variation in wood fuel in the field trial

Fuel samples were collected from the field trial sites. When the fuel supply was variable (e.g. wood chip) more than one sample was taken, if possible. When the fuel supply was consistent (e.g. wood pellet) only one sample was taken. The average fuel analyses are shown in Table 30.

Table 30: Average (median) chemical analyses of fuels collected during the field trial

		Field trial average wood chip	Field trial average wood pellet	Field trial average wood log
Moisture	(% by weight, as received)	27.8	7.0	15.0
Gross CV	(MJ/kg, as received)	14.26	18.83	17.25
Net CV		12.62	17.41	15.76
Ash	(% by weight, dry basis)	0.6	0.3	0.9
Sulphur		0.01	0.01	0.02
Carbon		51.3	53.5	51.7
Hydrogen		6.0	6.1	6.0
Nitrogen		0.19	0.13	0.28
Oxygen		41.7	39.9	41.4

Due to its method of manufacture, wood pellet was the most consistent fuel. The samples of wood pellet had moisture contents in the range 4 – 9% and ash contents in the range 0.1 – 0.8% (dry). Fuel samples taken during the field trial showed that all except one wood pellet boiler used fuel the was consistent with the chemical analysis requirements in ENplus A1[31], shown in Table 31.

One boiler was using fuel with a nitrogen content around 10 times as high as the average and an ash content around twice as high as the average. This fuel also had a higher moisture content and thus a lower wet-basis net CV. This fuel did not meet the ENplus A1 requirements and is likely to contain recycled content with glues, resins or plastics. The NO_x emissions from the boiler are also likely to be around 3-4 times the limit set in the RHI.

Table 31: Chemical analyses of wood pellet fuels collected during the field trial, compared with ENplusA1 requirement (Key: figures in red indicate values outside the requirement)

		Field trial average wood pellet	Field trial worst case wood pellet[32]	Field trial outlier wood pellet	ENplus A1 requirement
Moisture	(% by weight, as received)	7.0	8.4	9.3	≤ 10
Gross CV	(MJ/kg, as received)	18.82	18.54	18.03	-
Net CV		17.40	17.13	**16.48**	≥ 16.5
Ash	(% by weight, dry basis)	0.3	0.5	**0.8**	≤ 0.7
Sulphur		0.01	0.03	0.01	≤ 0.04
Carbon		53.5	55.9	52.5	-
Hydrogen		6.1	6.9	6.7	-
Nitrogen		0.13	0.19	**1.11**	≤ 0.3
Oxygen		39.9	42.1	38.8	-

In contrast to wood pellet, samples of wood chip and wood log showed much larger variation in moisture content. Wood chip samples had moisture contents in the range 8 – 39% and wood log samples had moisture contents in the range 8 – 37%.

Wood chip boilers can be designed to run with various moisture contents, however often the boiler parameters need to be adjusted for each specific range of moisture contents. However, even if adjusted for a wetter wood chip, a wetter fuel will increase start-up times and decrease the overall efficiency of the boiler. This is shown in Figure 36. Wetter fuels are also likely to show higher particulate emissions rates.

The variation observed in the wood log samples was due to one site using green wood logs. As with wood chip, wetter fuel will decrease efficiency and increase particulate emission rates.

Wood chip and log samples also showed more variation in ash content. Wood chip samples had ash contents in the range 0.1 – 2.9% (dry) and wood log samples had ash contents in the range 0.1 – 1.3% (dry). The presence of ash in wood chip may be to fuel contamination with ground and forest residue.

[31] The fines and metals contents, and sustainability of the fuels were not checked.
[32] Excluding one outlier.

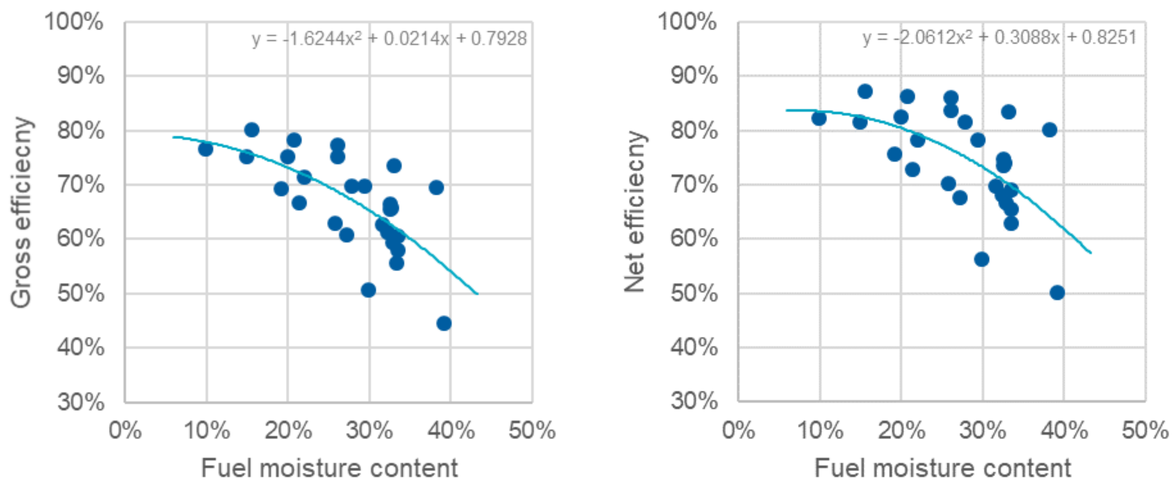


Figure 36: Variation in efficiency by fuel moisture content for wood chip boilers

5.4.5 Heavy metals in fuel and ash

During the second year of monitoring (July 2017 – June 2018), 20 sites were selected for additional heavy metals analysis in both the fuel and the ash (specifically the bottom ash). The focus of the analysis was metals that are considered toxic in biological systems, such as lead, mercury, chromium, and copper, and these were tested for both the fuel and the ash samples. However, a standard laboratory suite of metals was tested which included tests for additional metals, the results of which are reported in Tables 32 and 33. The limits set in ISO 17225 [39] for B-grade wood (including chemically untreated used wood) are also provided for comparison. Full results from the analyses are set out in Annex C.

Table 32: Table showing the average metal concentrations in the fuel samples
(= maximum value reported, where there was a large difference between the two samples)*

Element	Average metal in fuel (mg/kg dry fuel)					
	Wood Pellet (n=6)		**Wood Chip** (n=6)		**Wood Log** (n=2)	
	Sample average	**ISO 17225 B-grade**	**Sample average**	**ISO 17225 B-grade**	**Sample average**	**ISO 17225 B-grade**
Antimony	< 0.10		< 0.10		< 0.10	No limits defined (chemically untreated used wood is not permitted)
Arsenic	< 0.10	≤ 1.00	< 0.10	≤ 1.00	< 0.10	
Cadmium	0.08	≤ 0.50	0.12	≤ 2.00	0.05	
Chromium	0.5	≤ 10.0	2.1	≤ 10.0	0.8	
Cobalt	< 0.10		0.17		0.19	
Copper	2.2	≤ 10.0	4.0	≤ 10.0	3.5	
Lead	0.5	≤ 10.0	2.1	≤ 10.0	16*	
Manganese	69		97		83*	
Mercury	< 0.01	≤ 0.10	< 0.01	≤ 0.10	< 0.01	
Nickel	0.6	≤ 10.0	2.5	≤ 10.0	1.4	
Thallium	< 0.10		< 0.10		< 0.10	
Tin	< 0.10		< 0.10		< 0.10	
Vanadium	0.30		0.41		0.55	
Zinc	9.0	≤ 100.0	14.9	≤ 100.0	15.7	

Table 33: Table showing the average metal concentrations in the bottom ash samples (= maximum value reported, where there was a large difference between the two samples)*

Element	Average metal in ash (mg/kg dry ash)		
	Wood Pellet (n=11)	Wood Chip (n=7)	Wood Log (n=2)
Arsenic	3.4	4.8	148*
Cadmium	6.2	6.4	1.9
Chromium	209	332	274*
Copper	273	252	418*
Lead	13	132	120*
Mercury	0.04	0.04	0.05
Nickel	98	218	29
Zinc	363	201	531

Only two wood log boilers were selected for further fuel and ash analysis; where there was a significant difference between the concentrations of metal in the samples, the larger of the two values was reported. Additionally, at eight of the sites (primarily wood pellet) it was not possible to collect a fuel sample safely during the second visit to the site.

Figure 37 shows the concentrations of eight metals (arsenic, cadmium, chromium, copper, lead, mercury, nickel and zinc) relative to their limits in the relevant parts of ISO 17225 [39], with vertical bars showing the entire range of metal concentrations detected in all samples.

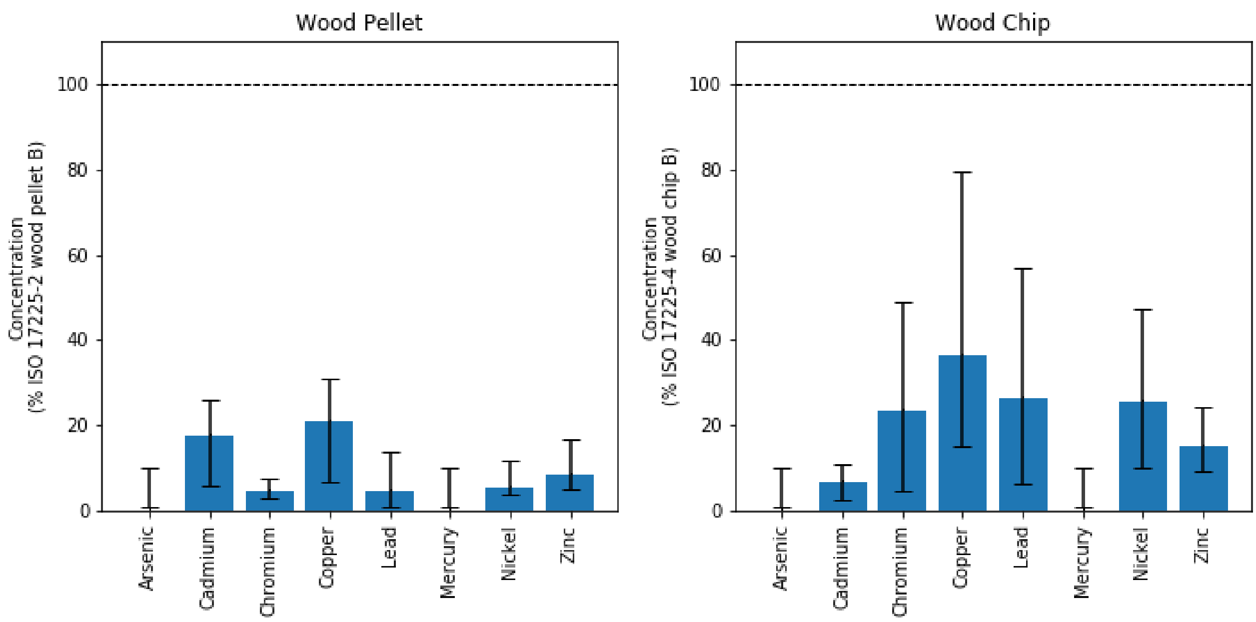


Figure 37: Average concentration of heavy metals (blue bars) and maximum range observed (vertical black lines) in wood pellet and wood chip as a percentage of the limits set out in ISO 17225 [39]. Arsenic and mercury were always at or below the limit of detection and so only a vertical black line is shown.

None of the average metal concentrations in either wood pellet or wood chip exceeded the requirements of ISO 17225 [39] for B-grade fuel[33], and there was no evidence that any of these sites were using fuel that was contaminated with non-virgin material. One of the wood log sites had fuel with levels of lead higher than would be allowed in pellet chip (at 16 mg/kg). In this specific case the fuel was self-sourced from trees in an area of historical lead mining and next to a busy road, so the contamination is suspected to be environmental.

There were much higher concentrations of the heavy metals in the ash samples than in the fuel samples. Typically, the concentrations in the ash samples were between a factor of x20 and x160 higher than the concentrations in the fuel samples (on x64 higher). However, one wood log site had high levels of arsenic, chromium and copper (see starred entries in Table 33). This may be indicative of wood treated with chromated copper arsenate (CCA) preservative.

5.4.6 Potential for heavy metal emission

There are two potential routes for heavy metal emission to the environment. Either the metals become trapped in particles that are carried up the flue and are emitted to atmosphere, or metals become trapped in the ash (as analysed above) which is then spread onto or disposed of onto land.

Bottom ash from wood is traditionally spread to land as a fertiliser, as was found in the social research. The spreading to land of ash from biomass burning which is non-domestic is regulated by law, but its benefit in agricultural situations is accepted because it contains the essential plant nutrient potassium (one of the three elemental components of artificial 'NPK' fertiliser) and is alkaline (so will raise the pH of acid soils and improve crop production). There are several regulations and permitting requirements in this area, however in summary the Environment Agency interpretation of the various regulations is that the land spreading of bottom ash from biomass boilers onto agricultural land is acceptable and should be done under a U4 exemption[34] that has been registered with the Environment Agency.

In order to better understand the fate of heavy metals in the fuel after combustion, and the extent to which they may be emitted to atmosphere and/or retained in the ash, two methods were trialled to measure the split of heavy metal emission between flue gases and ash. A summary of the success of each approach is provided below, and full results from the analyses are set out in Annex C.

Mass balance approach

The mass balance approach did not yield partitions of metal between the flue gases and ash that were realistic. These was in part because of:

- The small ash content of fuels – in many cases these were less than 1%. The calculation in the equation (see Section 4.5.1) was very sensitive to the ash content. This value was affected by both the variation in sampling the fuel and by uncertainty of measurement.
- The variation between the fuel (as sampled) and the ash (as sampled). Although the sites had not made any changes to their fuel supply, the fuel that was sampled did not necessarily have the same composition of the fuel that produced the ash that was sampled.

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[33] Most of the sites met the requirements of the RHI by way of an emissions certificate, and these emissions certificates usually specify A1 or A2-grade fuel [11]. For A-grade wood pellet, the same limits for heavy metals apply, however for A-grade wood chip, the fuel is assumed to be virgin wood and so there are no defined limits.
[34] Interpretation confirmed correct as of June 2018, see 'Burning of waste as a fuel in a small appliance' (smaller than 0.4 MW) https://www.gov.uk/guidance/waste-exemption-u4-burning-of-waste-as-a-fuel-in-a-small-appliance

- Unburnt material in the ash samples (e.g. charred pellets and prices of wood chip), which had to be removed, although for small particles this was difficult to achieve.

Some of the values calculated for percentage loss of metal in the flue gases were outside of the reasonable range (i.e. 0-100%) and the standard deviations in some cases were as wide as 90-270% (percentage points). Therefore, it was very difficult to make useful conclusions from this approach.

Simulated combustion approach

To reduce the uncertainties around the amounts of heavy metals present in fuels and related ashes a small-scale laboratory-based methodology was devised. Although it is not a full simulation of the effects of firing a fuel in a boiler, this methodology provides means to characterise the behaviour of heavy metals under defined conditions. This ensured a relationship between the samples of fuel and ash although some uncertainty remains which is related to the inherent variability of woody biomass fuels.

Two of the field trial sites were chosen for analysis; these were sites already identified as containing higher heavy metal concentrations in their fuel, however these concentrations were still close to the limits of detection for the laboratory analysis. Therefore, in addition, two samples of waste wood[35] were analysed. These showed significantly elevated concentrations of all the heavy metals except manganese and zinc, which made them more suitable for the investigation.

The percentage loss of metal in the flue gases was estimated using the average of the three fuel analyses and the three ash analyses using the equation in Section 4.5.2. The calculated losses, the conclusions drawn and the confidence in these conclusions are shown in Table 34.

There is some variation between the different fuel samples. This may in part be because the volatilisation behaviour of metals is dependent on the chemical form in which they are present. For example, metals may be less volatile as oxides but more volatile as chlorides. This may be relevant if the wood is contaminated by heavy metals absorbed from the air or ground, or whether it has been painted or treated. So, interpretation of results for heavy metal behaviour during biomass combustion is likely to require knowledge of the form in which the metals are present.

The approach was sufficient to enable a qualitative understanding of the fate of some heavy metal species as a result of combustion of biomass. It was not designed to provide statistically robust data about the amounts of heavy metals released during combustion. The level of confidence in the conclusions is therefore also only qualitative.

Further refinement of the methodology and sufficient number of measurements could provide a statistically significant result, especially for the metals lead, chromium, and copper which are known to be toxic and were detected at measurable levels during the field trial.

[35] Waste wood has the potential to be contaminated and thus contain higher concentrations of heavy metals. These may have been added to the wood during its lifetime in paints, preservatives, adhesives and other treatments.

Table 34: Summary of results from simulated combustion approach (Below LOD = the concentrations of metals in the samples were below the limit of detection and therefore a value could not be calculated)

<table>
<tr><th rowspan="2">Element</th><th colspan="4">Metal lost in flue gases (calculated %)</th><th rowspan="2">Conclusion</th><th rowspan="2">Level of confidence</th></tr>
<tr><th>Field trial (1)</th><th>Field trial (2)</th><th>Waste wood (1)</th><th>Waste wood (2)</th></tr>
<tr><td>Cadmium</td><td>89%</td><td>80%</td><td>62%</td><td>92%</td><td>Majority is lost to flue gases</td><td>Somewhat</td></tr>
<tr><td>Antimony</td><td>45%</td><td>Below LOD</td><td>13%</td><td>-12%</td><td rowspan="3">Majority is retained in ash</td><td rowspan="3">Low</td></tr>
<tr><td>Chromium</td><td>5%</td><td>35%</td><td>29%</td><td>1%</td></tr>
<tr><td>Cobalt</td><td>-21%</td><td>Below LOD</td><td>2%</td><td>1%</td></tr>
<tr><td>Copper</td><td>29%</td><td>68%</td><td>29%</td><td>-13%</td><td colspan="2" rowspan="6">No conclusion due to variation in results</td></tr>
<tr><td>Lead</td><td>-3%</td><td>44%</td><td>9%</td><td>-16%</td></tr>
<tr><td>Manganese</td><td>20%</td><td>59%</td><td>23%</td><td>12%</td></tr>
<tr><td>Nickel</td><td>31%</td><td>67%</td><td>34%</td><td>10%</td></tr>
<tr><td>Vanadium</td><td>11%</td><td>Below LOD</td><td>17%</td><td>25%</td></tr>
<tr><td>Zinc</td><td>34%</td><td>58%</td><td>8%</td><td>-6%</td></tr>
<tr><td>Arsenic</td><td>Below LOD</td><td>Below LOD</td><td>41%</td><td>11%</td><td colspan="2" rowspan="4">No conclusion due to low detected levels</td></tr>
<tr><td>Mercury</td><td>Below LOD</td><td>Below LOD</td><td>77%</td><td>Below LOD</td></tr>
<tr><td>Tin</td><td>Below LOD</td><td>Below LOD</td><td>27%</td><td>3%</td></tr>
<tr><td>Thallium</td><td>Below LOD</td><td>Below LOD</td><td>Below LOD</td><td>Below LOD</td></tr>
</table>

5.4.7 Potential for misfuelling

Broadly, the potential for misfuelling a biomass boiler is dependent on its fuel type. Misfuelling may be either deliberate or accidental, but was not widely observed in the field. This evaluation is of the potential degree of misfuelling possible, based on observations made during site visits, reviews of fuel handling and feed systems, and assessments of operator knowledge.

Wood pellet

Wood pellet boilers have the least potential for misfuelling. Often, they have fuel feed systems that are only compatible with small (i.e. 6mm) wood pellets. If fuel is supplied pneumatically then manual access to the fuel store may be very difficult. Opportunities for misfuelling therefore arise from:

- Procurement of the incorrect grade of wood pellets – this may be driven by economic factors, as lower grade and recycled pellets can be considerable cheaper. However, with the RHI fuel sustainability requirements and the unwillingness of fuel suppliers to supply ENplus B pellets in small bags (for consumers), the risk is more likely from,
- Incorrect grading of wood pellet by suppliers – this may result from the contamination of the supply chain with non-virgin or lower grade material. This is difficult to verify, and even more so if the fuel is supplied pneumatically.

Wood chip

Like wood pellet, one route for the misfuelling of wood chip boilers is the incorrect grading of wood chip by suppliers. This may be due to the contamination of the supply chain, however once wood is chipped is it difficult to assess its quality. Poor fuel quality may only be noted if the moisture content or the fines content are particularly high, or if there are large pieces of non-virgin material in the wood chip.

Another route for misfuelling is self-supplied wood that has been sourced from non-virgin or lower grade material (such as forest residue), or if this material has not been dried sufficiently.

Whether purchased or self-supplied, interactions with sites highlighted that it was difficult for operators to assess quality and quantity of fuel delivered. Wood chip is often sold or produced by volume and such measurements may be approximate. This is demonstrated by the much larger range of EBV closures calculated for wood chip boilers in the field trial (see Section 5.11.2).

Wood log

Of the three fuel types, wood log boilers are generally the easiest to misfuel. Wood logs require minimal preparation and so it is easy to introduce wood logs of an inappropriate moisture content, or load the boiler with non-virgin wood material. Depending on the design of the boiler and the size of the fuel chamber, this could range from small pieces of fence post, to demolition material such as large kitchen cupboards and worktops.

If wood logs boilers are misfuelled with non-virgin material, then the likelihood of it containing wood treatments, glues, resins, plastic and other hazardous components is high.

5.5 Impact of cycling

To understand the impact of cycling in detail, we have split the operation of a biomass boiler into four phases, shown in Figure 38.

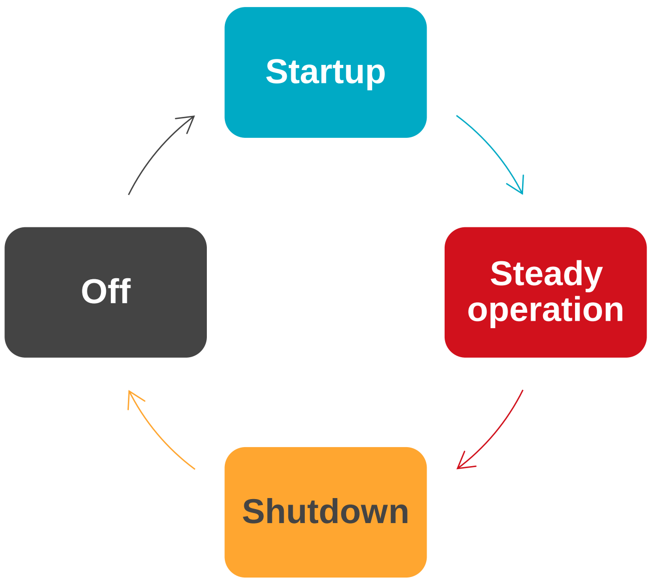


Figure 38: Four phases of boiler operation

Each model of boiler will have its own control strategy and sequences, however broadly one cycle will follow these four phases:

- The **start-up** sequence is from when the boiler begins to ignite the fuel, to when combustion is established (but the boiler has not fully warmed up). This may include:
    1. Delivery of a fixed amount of fuel to the combustion chamber
    2. Initial operation of (usually) an electric hot air gun to light the fuel
    3. Addition of more fuel at a fixed rate until the hot air gun can be switched off and operation is stable.
- The **steady operation** period includes the boiler warm-up time and then its continued operation with flue gas oxygen around 10%. During this time, boiler output may change and it may modulate (i.e. steady operation does not imply steady-state).
- The **shutdown** sequence is from when the combustion in the boiler begins to stop, and flue gas oxygen levels rise. There is no significant combustion at the end of the period, however there may still be a fire bed which will slowly cool.
- The **off** period is from the start of this cooldown period until the boiler fires again.

The start-up and shutdown sequences of biomass boilers can take relatively long periods of time. The field trial showed that start-up times were 10 to 30 minutes, broadly dependent on the size boiler. This is a design feature to ensure that the fuel ignites and that a sustainable fire bed is established before the boiler control system adjusts the fuel-air-ratio to keep flue gas oxygen (i.e. excess air) low. This is to prevent fire side explosions where flammable gases build up in the boiler and then ignite. This can be a serious problem, and the long start-up times help to prevent it.

Boiler shutdown can take 5 to 30 minutes. This is to ensure that the fuel on the firebed has time to burn out, and that the heat produced can be used. This energy is often used to heat water in a accumulator vessel which can then be used to speed up restart times. Thus, cycle times for a biomass boiler can be long, this depends on boiler size and start-up and shutdown strategy, but is often controlled by a timer to ensure ignition and complete burn out occur. This is in contrast, with a gas/oil boiler where it is possible to complete this cycle in around one minute.

The results of the laboratory trials showed that boiler efficiency was higher during prolonged periods of operation at high output. During start-up and shutdown the boiler efficiency was significantly lower. This is due to high levels of oxygen (i.e. high excess air) and high levels of CO in the boiler. There is also increased electrical consumption from boiler fans running at high speed. This was demonstrated by putting varying loads on the small wood pellet boiler, which caused it to cycle. In tests with lower loads, the boiler ran for few hours during the day and cycled. Its efficiency also dropped, as shown in Figure 39.

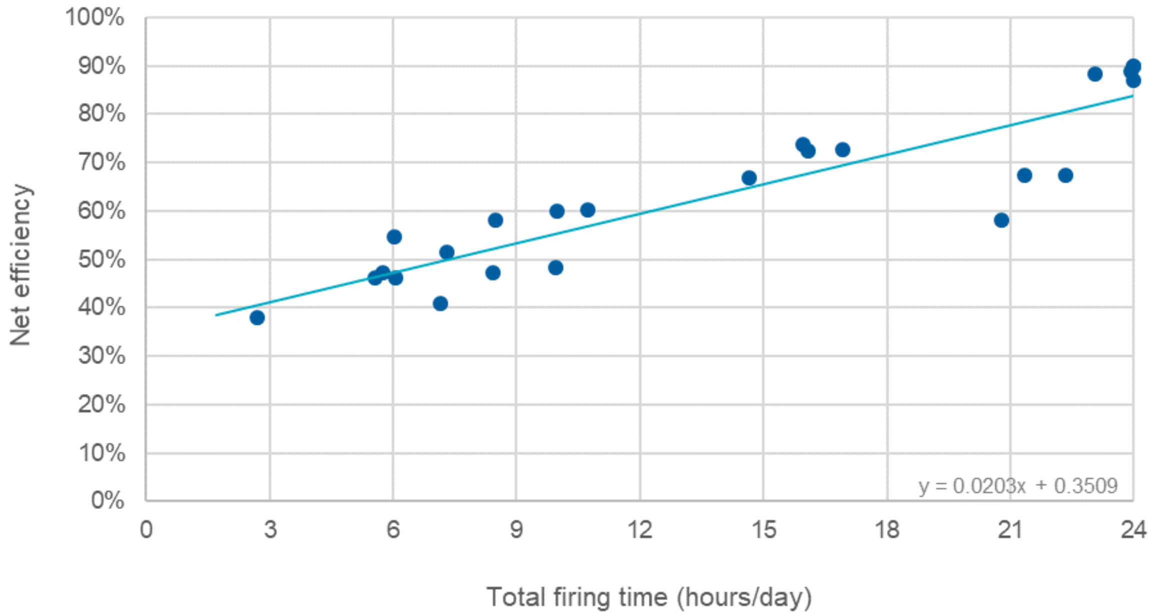


Figure 39: Variation in net efficiency versus total day firing time (i.e. total time in "Steady operation" phase) for the small wood pellet boiler during the laboratory trials. Modulation was disabled or did not occur during these tests

Similarly, emissions of particulates were significantly worse during start-up and shutdown periods compared with periods of steady operation, demonstrated by both boilers in the laboratory trials. This is likely due to colder temperatures in the combustion chamber and poor mixing of air with the fuel.

The small wood pellet boiler showed increased particulate emission rates (expressed in g/h) as the number of boiler starts per hour was increased (see Figure 40).

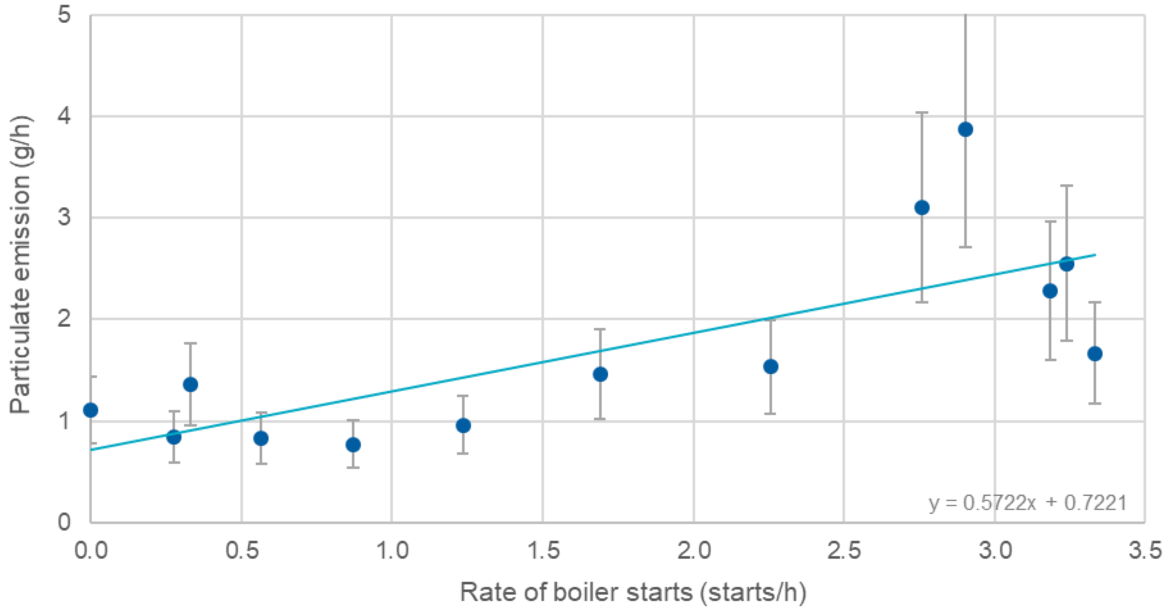


Figure 40: Particulate emission rates under various cycling regimes for the small wood pellet boiler in the laboratory trials

The particulate emission rates are high during the start-up and shutdown phases, and with more start-ups, more of the boiler's operation falls in these phases. This effect was most pronounced with the large wood chip boiler (see Figure 41). Particulate emissions (expressed in g/h) were significantly higher when start-ups were from when the boiler was cold (up to 6.7 times as high as steady operation). These were also the periods with the highest CO and VOCs.

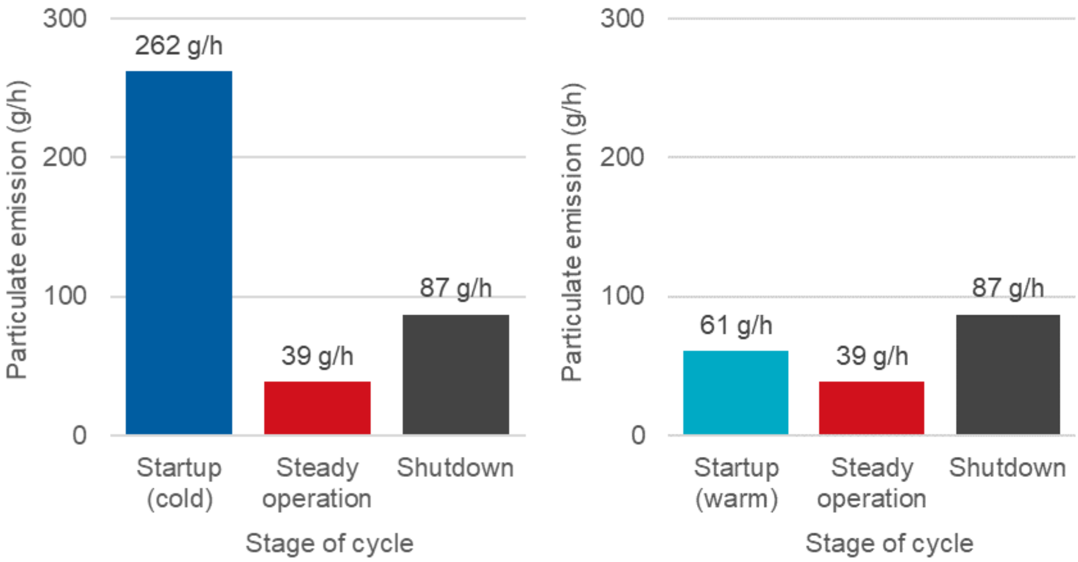


Figure 41: Particulate emission rates at various stages of cycling for the large wood chip boiler in the laboratory trials

Rapid cycling of the large wood chip boiler was simulated in the laboratory trials by running the boiler for the minimum possible time in the steady operation phase. The particulate emission rates (expressed in g/GJ net input) are shown in Figure 42. The average rates of particulate emission are significantly higher when the whole cycle is considered. They are around 2–8 times higher than the steady operation emission rates, and exceed the RHI emissions limit by a factor of around 2–5.

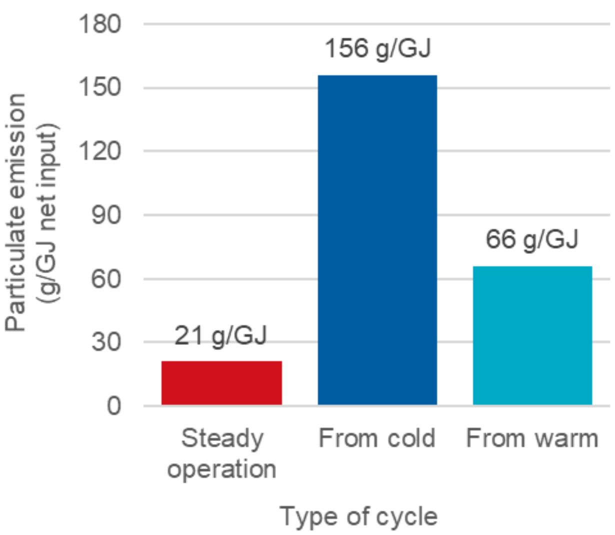


Figure 42: Particulate emission rates for different types of cycle for the large wood chip boiler in the laboratory trials. Cycles were the minimum length possible – the boiler spent 10-30 minutes in the start-up phase (depending on whether it was hot or cold) and then 15 minutes in the shutdown phase

Because of this, it is better to operate a biomass boiler for long periods of time under steady conditions to ensure that boiler efficiency is high and particulate emission rates are low. Frequent cycling of start-up, operation, and shutdown can result in low efficiency and high emission rates, i.e. poor boiler performance. If rapid cycling occurs, a boiler will go through its start-up procedure, but by the time it enters steady operation, the heat demand from the building or process will have been satisfied. The boiler will then switch into shutdown mode and goes through its shutdown procedure. The plant will then wait for a demand signal and then go through a further start-up, very short operating time, and shutdown sequence. The boiler will spend most of its operation in these poor-performance start-up and shutdown phases.

This was observed during the field trials, with some boilers cycling very frequently (see Figure 54). This resulted in poor efficiencies and increased particulate emissions compared with operating the boiler for prolonged periods at steady state with high output.

5.5.1 Causes of rapid cycling

The possible causes of rapid cycling include low load factor due to the boiler being significantly oversized for the demand. It should be noted that boilers are frequently sized for the maximum demand, i.e. to produce enough heat to satisfy the demand on a very cold day. Therefore, by definition, they will be oversized for the demand most of the year. (And grossly oversized for summer demand which may only consist of domestic hot water demand.)

This is not such a problem for gas or oil boilers as they can cycle more rapidly without such a large impact on efficiency or emissions. Biomass boilers cannot cycle rapidly, so system designs can incorporate an accumulator tank which is a large store of water from which the heat demand of the building is satisfied. The heat in the store is then topped up by running the boiler for a prolonged period. It is important that the thermostatic controls on the accumulator are set up correctly, with a large difference between the higher set point and lower set point (the 'bandwidth'), to ensure that the boiler can run for a long period of time to heat the accumulator, and that the building/process demand is uncoupled from the boiler supplying the heat.

Another way to prevent rapid cycling is to make the boiler modulate so that it is producing heat at a rate which is closer to the demand. If the boiler modulates down quickly enough, then it may prevent shutdowns and rapid on/off cycling. However, most boilers start their steady operation firing period at full output and then modulate down if the demand is lower than the output. During the laboratory trials, the boiler was observed trying to modulate down, but frequently the boiler could not reduce output quickly enough. This meant the demand was satisfied before the boiler control system could reduce output, so the boiler started cycling frequently. As expected, this happened more frequently when the demand was low, i.e. at low load factors.

5.5.2 Performance penalty per cycle

The laboratory trials demonstrated that in terms of particulate emission, biomass boilers suffer from a performance 'penalty' each time they are cycled. Each cycle adds an equivalent number of hours of operation to the boiler's emissions.

The small wood pellet boiler emitted particulates at an average rate of 0.7g/h during steady operation. Each cycle (through shutdown, start-up and back to steady operation) caused the emission of another 0.6g of particulate. This meant that in terms of particulate emission, each cycle added an equivalent of just under 1 hour of additional operation.

Similarly, the large wood chip boiler emitted particulates at an average rate of 40g/h during steady operation. Each cycle involving a cold start-up caused the emission of a further 180g of particulate, and each cycle involving a warm start-up emitted 73g. This meant that in terms of particulate emission, each cycle from cold added an equivalent of around 4.5 hours of additional operation, and each cycle from warm added just under 2 hours of additional operation.

The equivalent operating times for both boilers are shown in Figure 43. Further laboratory work (in the shaded area) is required to demonstrate if other boilers lie in a similar range.

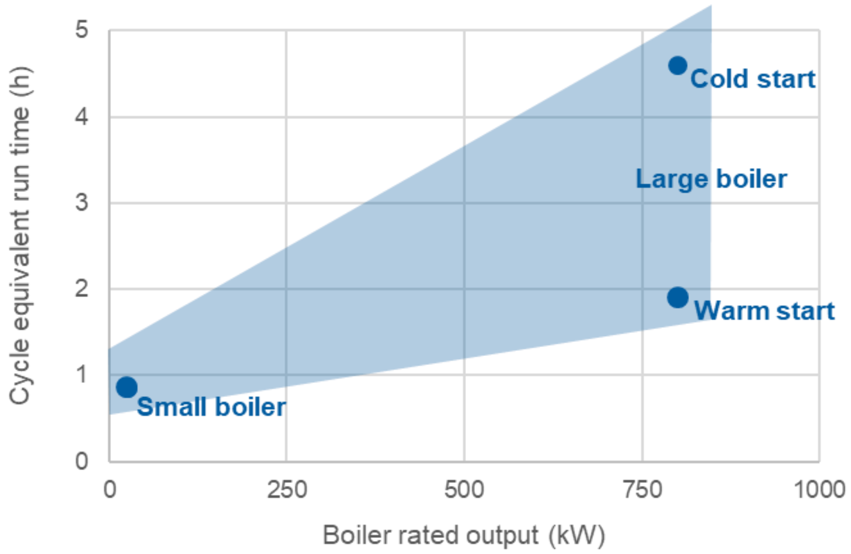


Figure 43: Equivalent operating times or performance 'penalty' for particulate emissions from boilers in the laboratory trials. The shaded area represents a zone in which more data is required to determine if this relationship exists for other boilers

5.6 Impact of load factor

Throughout the field trial, the annual load factor averaged around 14% (see Figure 44). However, there was quite a large spread with a third of the sites having an annual load factor below 10%, and a few where the annual load factor was high. There was variation in load factor across different fuel types and boiler sizes (see Figure 45).

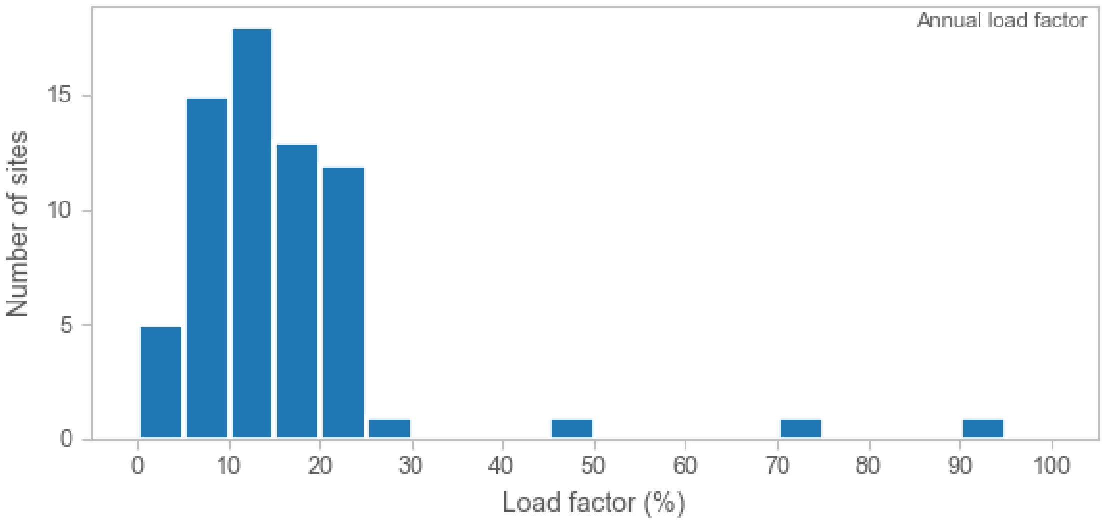


Figure 44: Histogram of annual load factor

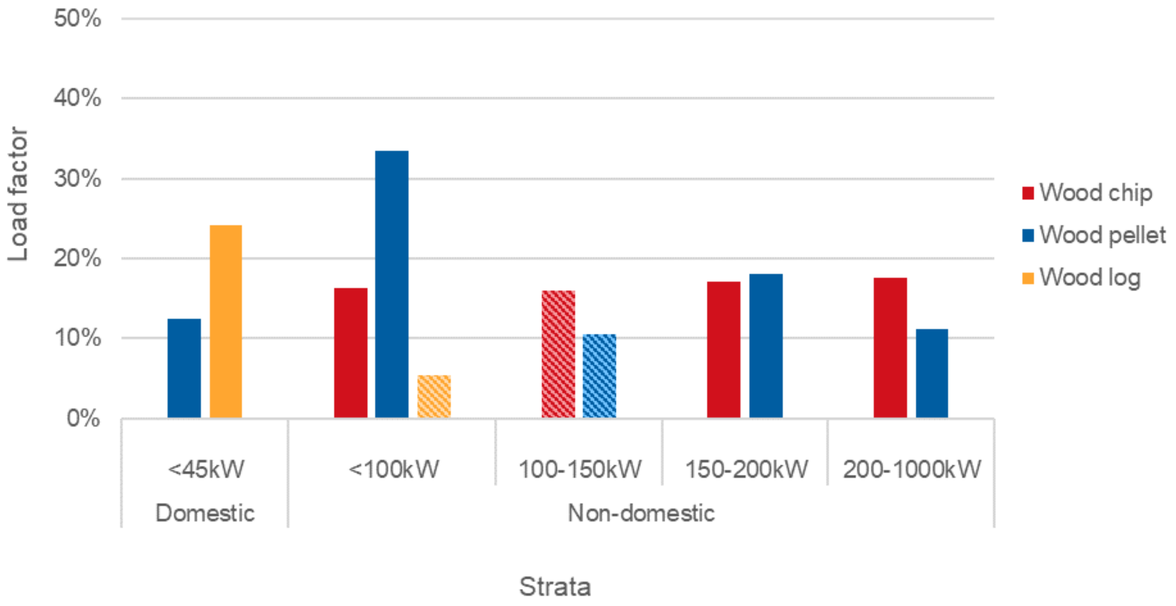


Figure 45: Average annual load factors measured in the field trial, split by rated output and fuel type (striped bars = small sample size)

The Tier 1 boundary in the Renewable Heat Incentive was set at a load factor of 15% (for non-domestic boilers less than 1 MW [41]). This is based on the expectation that every biomass system should be able to achieve a load factor of at least 15%. A load factor of less than 15% is an indication that the boiler has been oversized for the application. If the boilers have been sized correctly, annual load factors around 20% would be expected [14]. This suggests that a number of the boilers in the trial were over-sized for the heat demand that they were installed to meet.

The average winter month load factor was around 24% (see Figure 46). The winter is the time when the boiler should be working the hardest.

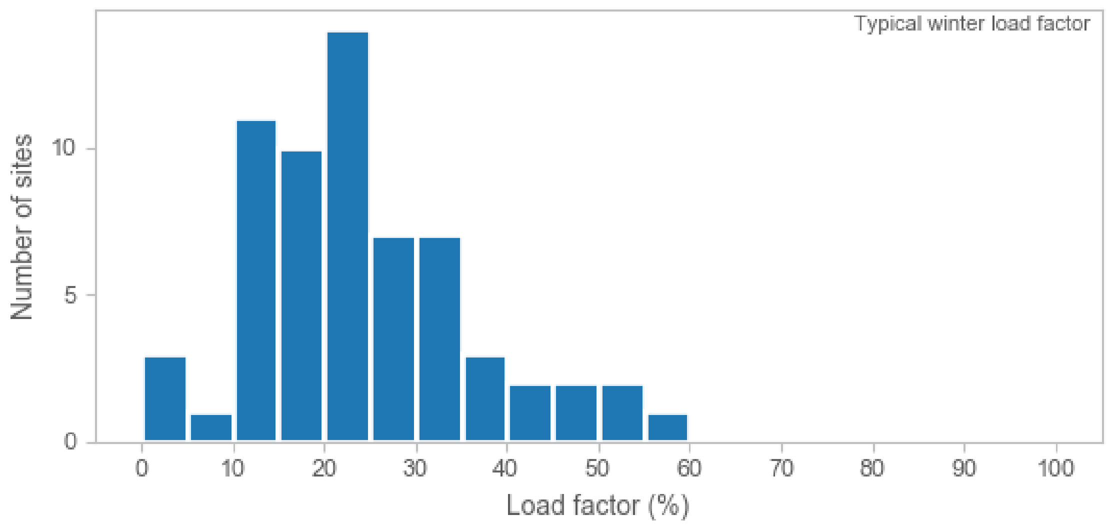


Figure 46: Histogram of winter load factor. Note: two boilers were excluded due to high load factors ~140%, indicating that they were incorrectly badged

Figure 47 shows that the average summer month load factor is around 7%. Low load factors are expected in summer, and a number of boilers are switched off. However, nearly 60% of boilers left on have load factors less than 10%.

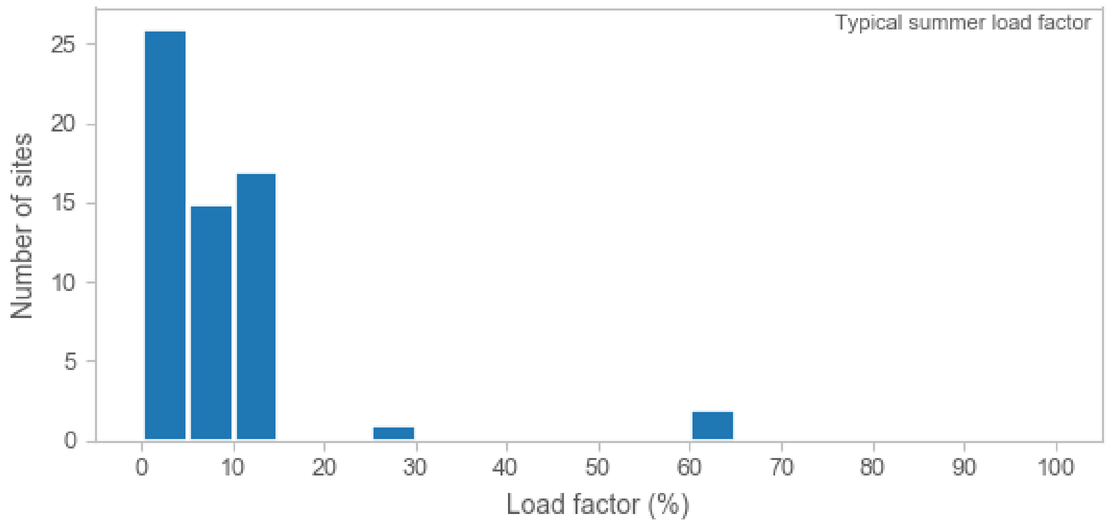


Figure 47: Histogram of summer load factor

To perform a basic test of the hypothesis that low load factors lead to lower boiler efficiencies, in previous work a simple theoretical model of net boiler efficiency was built [4] based on the calculations found in BS 845-1 [24]. This theoretical model was developed for illustrative purposes in order to gain an understanding of how load factor can affect boiler efficiency. It considered a theoretical boiler of 200kW rated output burning a typical wood chip of 20% moisture, however the trends shown in this model can also be shown for wood fuel of other moisture content.

The model simulated a boiler operating over a 24 hour period and analysed its efficiency at 5 minute intervals throughout this period. BS 845-1 gives radiative, conductive and convective losses through the boiler casing, as percentages of boiler output for a range of boiler types and outputs.

Figure 48 shows data points which are outputs from this illustrative model. This shows a relationship between low load factors (called ‘utilisation factors’ in the graph) and low efficiencies. A trend line has been fitted to this data but is not considered to be truly representative at either minimum or maximum extreme of load factor. The trend line should level out (below 100 % efficiency) as the load approaches 100 % and approach zero at zero load. In this model, the efficiency is set by the assumed boiler CO_2 concentration and the flue gas temperature.

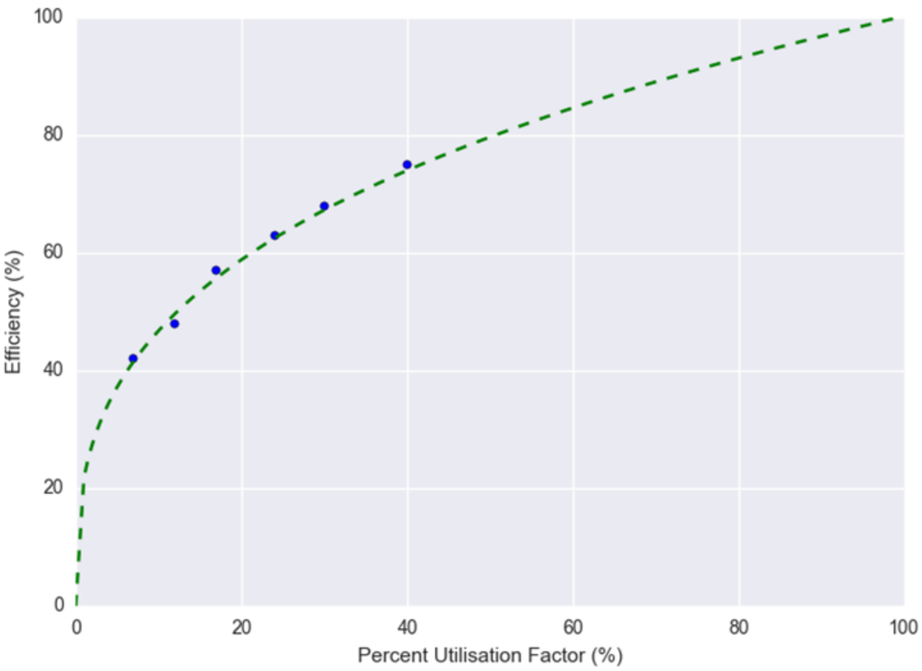


Figure 48: Theoretical model results showing the effect of load factor ('utilisation factor' in the graph) on efficiency [4]

It should also be noted that low load factors led to increased cycling as the boiler tried to satisfy low demands for heat. In many cases, this led to the boiler switching on, operating steadily for a very short period of time, then going into shutdown mode. As described in Section 5.5 above, rapid cycling also had an impact on boiler efficiency.

The results from the field trial showed that the model produced results which were broadly correct. Figure 49 shows the calculated boiler efficiency of all the boilers in the field trial plotted against load factor. The picture is complicated by site-specific effects, however the efficiencies were high at high load factors. Although some boilers were still efficient at low load factors, the spread in efficiency is much larger. In general, the lowest efficiencies were achieved when the load factor was very low and when the boilers were cycling.

The figure also demonstrates that the majority of the data points from the trial were at load factors of less than 20%.

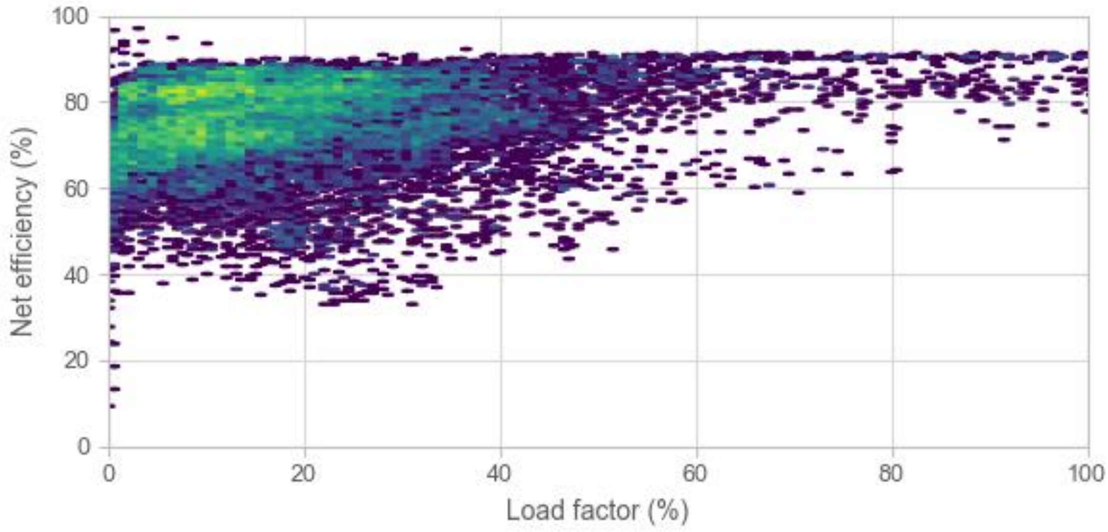


Figure 49: Field Trial results showing the effect of load factor on efficiency – daily efficiencies and load factors shown for all boilers in the field trial. The density of points is shown with a logarithmic colour shading: white (no points) – purple (low density of points) – green – yellow (highest density of points)

The laboratory test work also demonstrated the effect of load factor on efficiency. The relationship seen in the field is shown more clearly in the results from the laboratory trials. As part of the laboratory work, the small boiler was operated at a range of different load factors. When efficiency was plotted against load factor, the shape of the fitted curve was similar to that predicted by the modelling. This is shown in Figure 50.

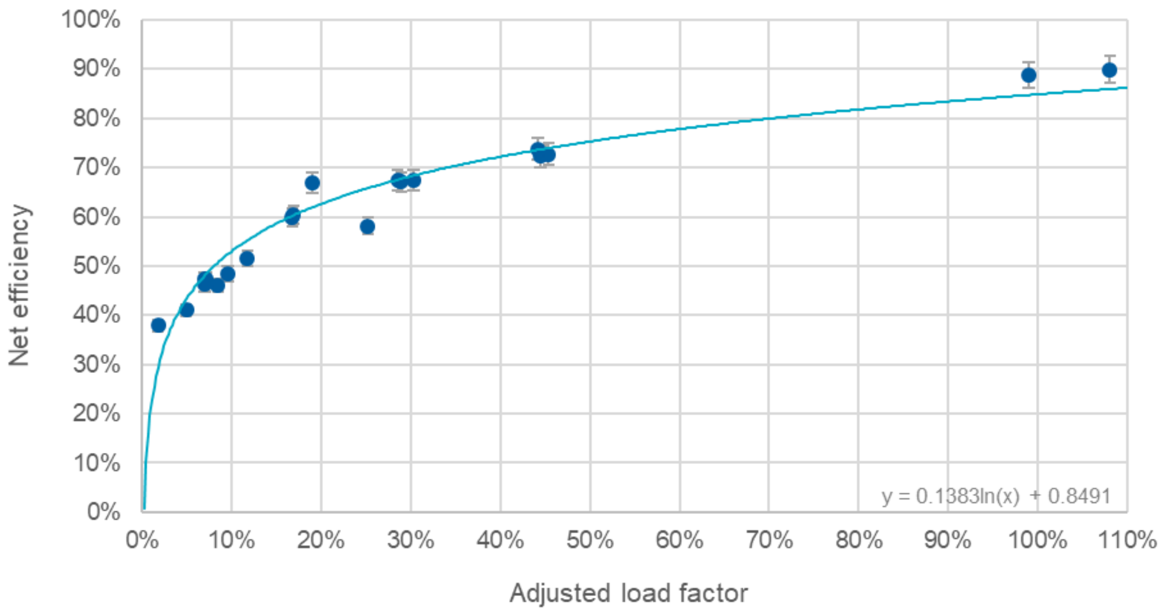


Figure 50: Results from the laboratory tests on the small boiler. Note: the load factor has been adjusted to account for uni-modal and bi-modal tests. These tests limited the hours of operation of the boiler, making it work harder during the periods it was enabled. For this graph, the load factor was increased to consider only the heat that could have been delivered during the on-periods, to give a true reflection of how load affects efficiency.

5.7 Impact of boiler modulation

In some of the laboratory tests using the small boiler, the boiler modulation was disabled so that the boiler was forced to meet the demand by switching off and on as part of the investigations into the impacts of cycling. The laboratory tests with modulation aimed to investigate the effects of modulation on the thermal and emissions performance of the boiler. Nine modulation tests were carried out in total and the results of the tests are shown in Figure 51.

It was expected that enabling modulation would result in better control of output and slow the frequency of cycling, thus increasing efficiency. Five of the nine tests had modulation enabled down to 20% of full output, and in four of the tests modulation was enabled down to 50% of full output. However, only two out of the nine modulation tests showed modulation throughout the whole test (indicated by the two points on the graph above the logarithmic trendline).

As a rule, modulation was only effective if the instantaneous load was greater than the lowest output to which the boiler could modulate. However, the behaviour of the boiler was more complicated:

- Modulation down to 20% did influence the beginning of the start-up tests – it increased the length of the initial cycle which initially made the boiler more efficient. However, after reaching temperature the boiler entered a normal cycling pattern – with no improvement in efficiency. This is because the ignition phase provided a fixed heat output and if this satisfied the load on the boiler then the control system was not able to modulate the boiler down before the boiler had to switch off (see Section 5.5).
- The 50% modulation tests did not influence boiler performance as the load was less than modulation in any of the tests, i.e. the demand was less than the minimum boiler output, so it was forced to switch off.

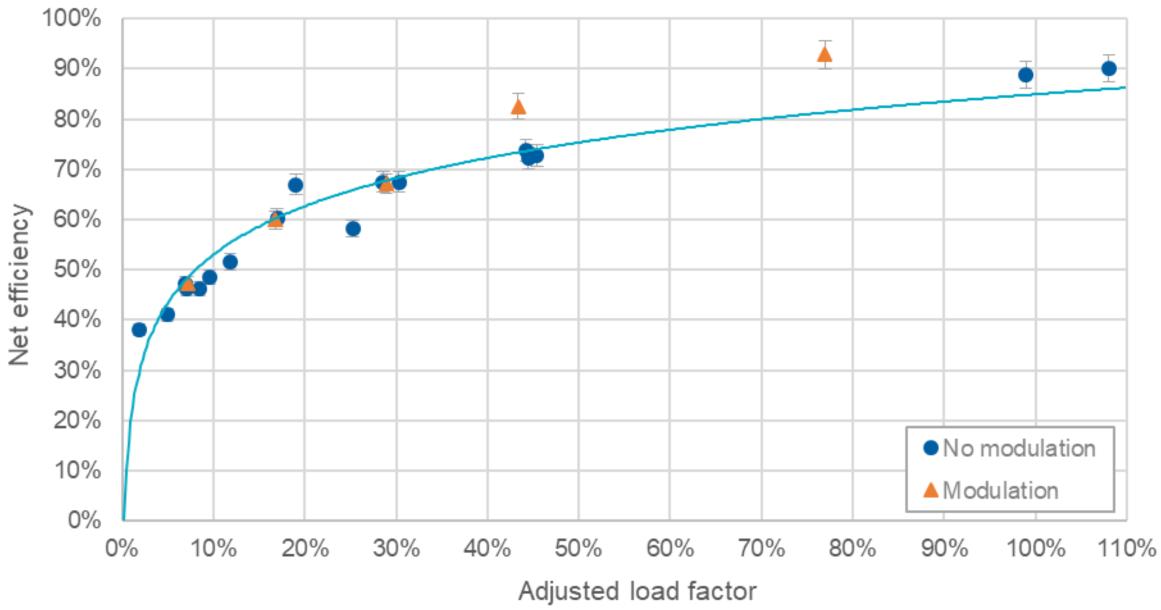


Figure 51: Results from the laboratory tests on the small boiler, including tests with modulation. Note: the load factor has been adjusted to account for uni-modal and bi-modal tests. These tests limited the hours of operation of the boiler, making it work harder during the periods it was enabled. For this graph, the load factor was increased to consider only the heat that could have been delivered during the on-periods, to give a true reflection of how load affects efficiency

5.8 Impact of controls

The control of biomass boilers is a very complex topic. Different manufacturers use different degrees of sophistication when designing the control systems for their biomass boilers which often depends on the type, size and complexity of the installation. As a general rule, the complexity of the control strategy used increases with boiler size as the control parameters and auxiliary equipment required increases.

Although this amounts to a range of controls used to operate biomass boilers, all installations typically have the same driving factor which is to maintain combustion in a safe manner which is used to provide heat. As all biomass boilers have this same basic requirement, the controls they use, although different, are comparable because they are trying to achieve the same outcome. This allows comparisons and lessons to be learnt from poor examples of control allowing future control systems to be improved. The controls considered broadly fall into one of two categories.

- **Controls that cannot be changed by the user:** These are the primary control factors required to maintain combustion in the biomass boiler. These control parameters directly affect the thermal efficiency of the boiler. Primary controls will set air ratios, fuel feed rates and control ignition, run mode and burnout periods. The owner of the biomass boiler does not usually have control over these parameters and they are usually set by the manufacturer and/or the installation company during commissioning of the boiler.
- **Controls that can be changed by the user:** These are the secondary control factors and control how the boiler operates. These control parameters do not directly affect the thermal efficiency however they can have a significant impact on boiler performance. Secondary controls will set the times when the boiler is activated as well as the set point for the hot water temperature.

The main ways that these controls were observed to impact performance were the following.

- Using a time clock to change the operating pattern could improve the performance of a boiler by limiting the hours of operation. The boiler runs for longer when it switches on and losses due to heating at unnecessary times are reduced.
- Thermostat set-points and the bandwidths could cause poor performance if not utilised correctly. Too small a bandwidth could cause increased cycling.
- Manual operation of log boilers can lead to long burn periods and cycling is effectively prevented because the boiler will not run again until it is refuelled.
- Other non-controllable parameters set by the manufacturer or installer can be detrimental to performance if they are not set correctly and cause the boiler to use a poor control strategy.

5.8.1 Time clock and operating pattern

Operating patterns affect biomass boiler operation through limiting the number of hours that the boilers are enabled. The use of operating patterns is not specific to the operation of biomass and is used in most space heating applications. A timer is used to set the periods when heat is required, e.g. usually to coincide with when the building will be occupied. Limiting the hours of operation of the biomass boiler -

- Means the boiler works harder and for longer during the periods when it is enabled, and operates closer to its rated output. This leads to increased efficiency and lower particulate emissions;
- Reduces heat losses through keeping the water system (e.g. accumulator tanks and heat distribution pipes) hot at times when heat is not needed;

Nearly all domestic and commercial biomass boilers in the field trial used time clocks to achieve this. Conventional heating appliances are controlled by time clocks and therefore most biomass operators have the knowledge of how to use them. Sites that did not use time clocks to limit the operation of biomass boilers had problems with cycling and with heat losses due to the production of heat which is not utilised.

From the case studies produced as part of the field trial, there are examples of sites which utilised operating patterns well and sites which did not. More detail is provided in the case studies.

Good performance: Limited operating hours of a 40kW wood pellet boiler installed at a detached farm house (B477)

The boiler used a range of operating patterns effectively to maximise the performance of the biomass boiler. A quick summary of the site showed that it:

- Had average net efficiency of 88% (high compared with other sites in the trial)
- Changed operating pattern throughout the year to match demand (switching between bi-modal in summer and uni-modal in the winter)
- Was not activated at night

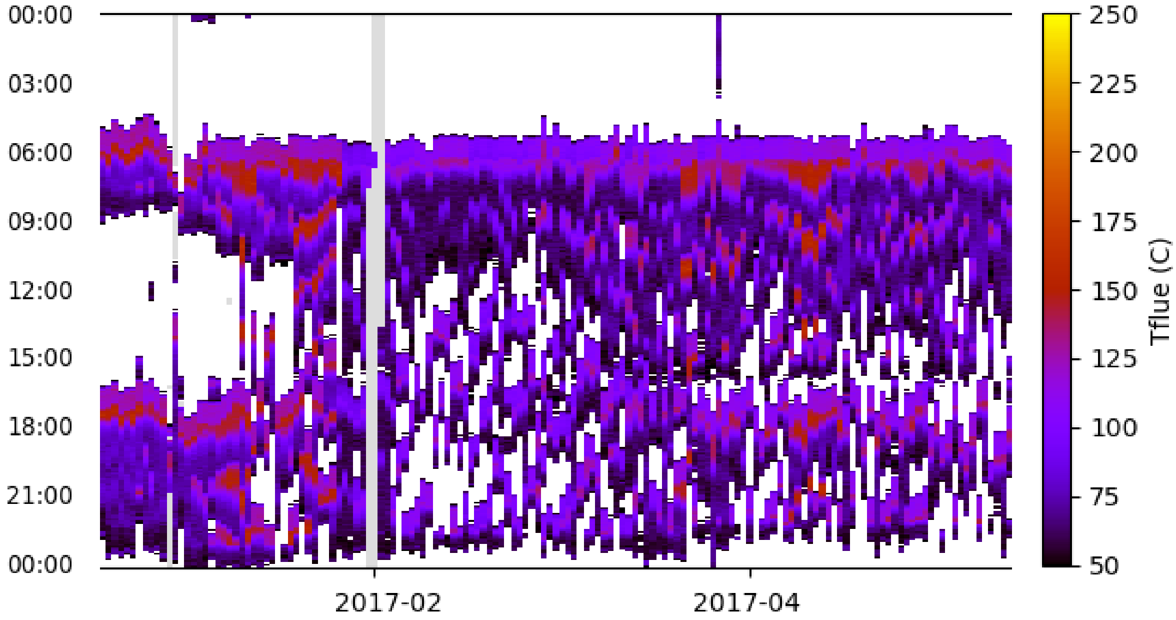


Figure 52 Flue temperature tapestry for B477 from December 2016 to June 2017

Poor performance: Continuously enabled 120kW wood pellet boiler installed at a members-only sports club (B464)

The boiler used a continuous operating pattern all year round. A quick summary of the site showed that it:

- Had an average net efficiency of 67% (poor compared with other sites in the trial)
- Did not change operating pattern at all throughout the year
- Was left enabled, and operated at night when the building was empty
- Had no load during the night, which caused rapid cycling
- Using time clock to limit operation at night would improve efficiency.

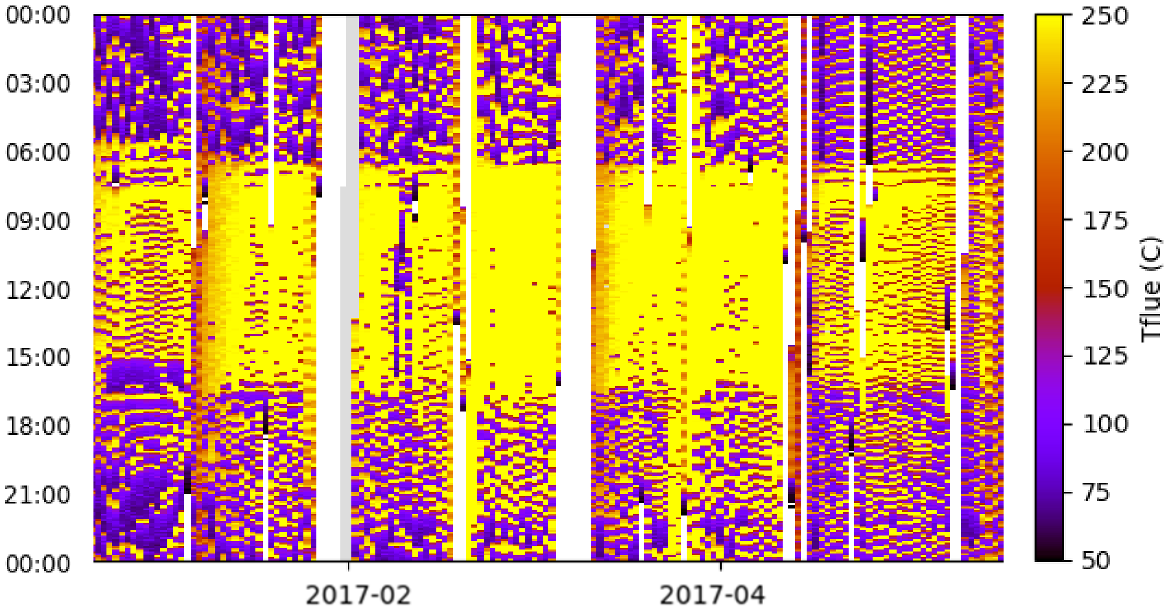


Figure 53 Flue temperature tapestry for B464 from December 2016 to June 2017

The boiler that performed well transitioned from a bi-modal to a uni-modal operating pattern in the winter (Figure 52). The operating pattern of the poorly performing boiler did not change in the winter (Figure 53).

The number of cycles per day was also much greater in the case of the poorly performing boiler. It was activated all-day and rapid cycling was much more prevalent during the night. Figure 53 shows steady operation throughout the day, however in the early evening the boiler began to cycle and continued to cycle throughout the night. This was caused by the reduced load as there was no longer any requirement to provide heat. Cycling caused the performance of the boiler to be reduced as discussed in Section 5.5. Furthermore, the heat produced was used to keep an accumulator at high temperature throughout the night which increased the heat losses from the system.

Operating pattern can also be used to improve performance by managing variations in heat requirements. This is especially important in the summer when load factors are much lower. The impact of load factor on boiler performance has been discussed in Section 5.6 and can cause many problems with biomass boiler performance. Most domestic and commercial sites change operating pattern between seasons. This may take the form of a change in pattern or an increase in the hours the boiler is activated. Table 35 shows domestic pellet sites that are less than 45 kW included in the field trial and their summer and winter operating modes. The table shows the efficiencies in winter and summer. There is a small change in the efficiencies of the boilers which changed operating pattern typically 1 or 2%. When boilers do not change operating pattern some also showed only 1 or 2% changes however boilers did show changes in efficiency of up to a 12%.

Table 35: Operating pattern of small domestic pellet boilers in the field trial

Site ID	Mode of operation		Changed operating pattern	Efficiencies		Comments
	Summer	Winter		Summer	Winter	
B922	Bi-modal	Bi-modal	Yes	84%	86%	Winter - longer burn times
B477	Bi-modal	Continuous	Yes	85%	87%	Modulates down after initial burn
B542	Bi-modal	Bi-modal	Yes	74%	75%	On all year runs longer in winter
B910	Bi-modal	Uni-modal	Yes	72%	70%	Bi-modal in summer
B920	—	Uni-modal	Yes	—	68%	Runs 7am-12 pm
B921	—	Uni-modal	Yes	—	80%	Winter - Uni-modal
B919	Bi-modal	Bi-modal	No	83%	79%	Winter operation longer burn times
B650	Bi-modal	Bi-modal	No	71%	83%	Less cycling in winter
B625	Bi-modal	Bi-modal	No	74%	81%	On all year
B499	Bi-modal	Bi-modal	No	65%	65%	Winter - longer runs
B069	Continuous	Continuous	No	73%	71%	Cycles on and off times throughout the day
B180	Continuous	Continuous	No	81%	79%	Summer - rapid cycling
B222	Continuous	Continuous	No	82%	82%	Winter - cycles frequently

5.8.2 Thermostat set points and bandwidths

All the biomass boilers in the field trial were used to heat water to provide either space heating, hot water, or both. A thermostat is used in biomass boilers to control the maximum temperature of the water supplied. It also sets the temperature at which the boiler will switch on to provide heat. The difference between these temperatures is often called the bandwidth or 'dead band'. Control over the system upper and lower temperatures is one of the main parameters used in the operation of biomass boilers. System design and the type of use are the deciding factors which decide the set point for the thermostat temperatures. Choosing the correct set points for a boiler:

- Will limit the maximum temperature the boiler can reach which limits the temperature in the system and can protect it from damage
- Reduces heat losses as the water in the system (accumulator tanks and heat distribution pipes) are not at higher temperatures than is required
- Ensures that the system keeps consistent temperature when supplying heat
- Ensures that the boiler does not run when heat is not required.

All the boilers in the field trial were controlled by thermostats. Their use varied from just limiting supply temperature to close control of when the boiler came on and off. Good use of thermostatic controls was common across the field trial. It is a technology which is mainstream and therefore well understood by most boiler operators. Using thermostats poorly did not punish sites in terms of performance if there was a constant high load factor. At low load factors, however the poor use of thermostats has a large impact on performance.

Poor performance: 230kW wood pellet boiler installed on an estate (B912)

The boiler operated in a uni-modal pattern between 6am and 6pm and used a thermostat to limit the maximum temperature. A summary of the site showed that it:

- Had a load factor of 14% in the winter and summer load factors were 2%
- Was used to heat a large accumulator
- Used a bi-modal pattern all year round
- Operated for very short burn periods all year round.

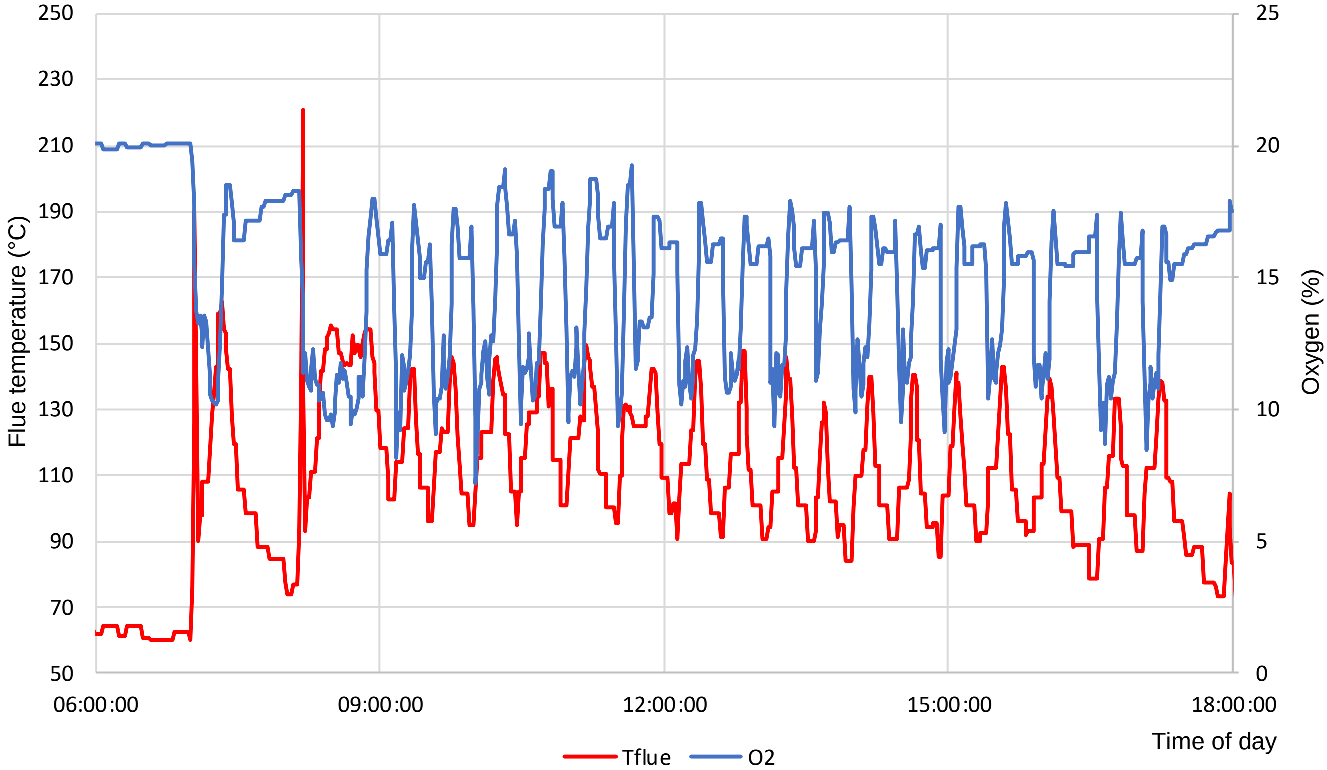


Figure 54: Oxygen and flue gas temperature on a typical December day

Figure 54 and Figure 55 show the effect that a very small bandwidth has on boiler operation. Both figures show the boiler running for very short cycles. At this site the boiler maintains an accumulation vessel at 70°C. The cycling occurs because the lower temperature set point is only 1°C lower than the tank set point, creating a very small dead band. When the accumulator vessel falls below this lower set point the boiler turns back on to provide heat which is satisfied before the boiler can reach steady operation. This behaviour is exaggerated in the summer periods when the load factor is very low.

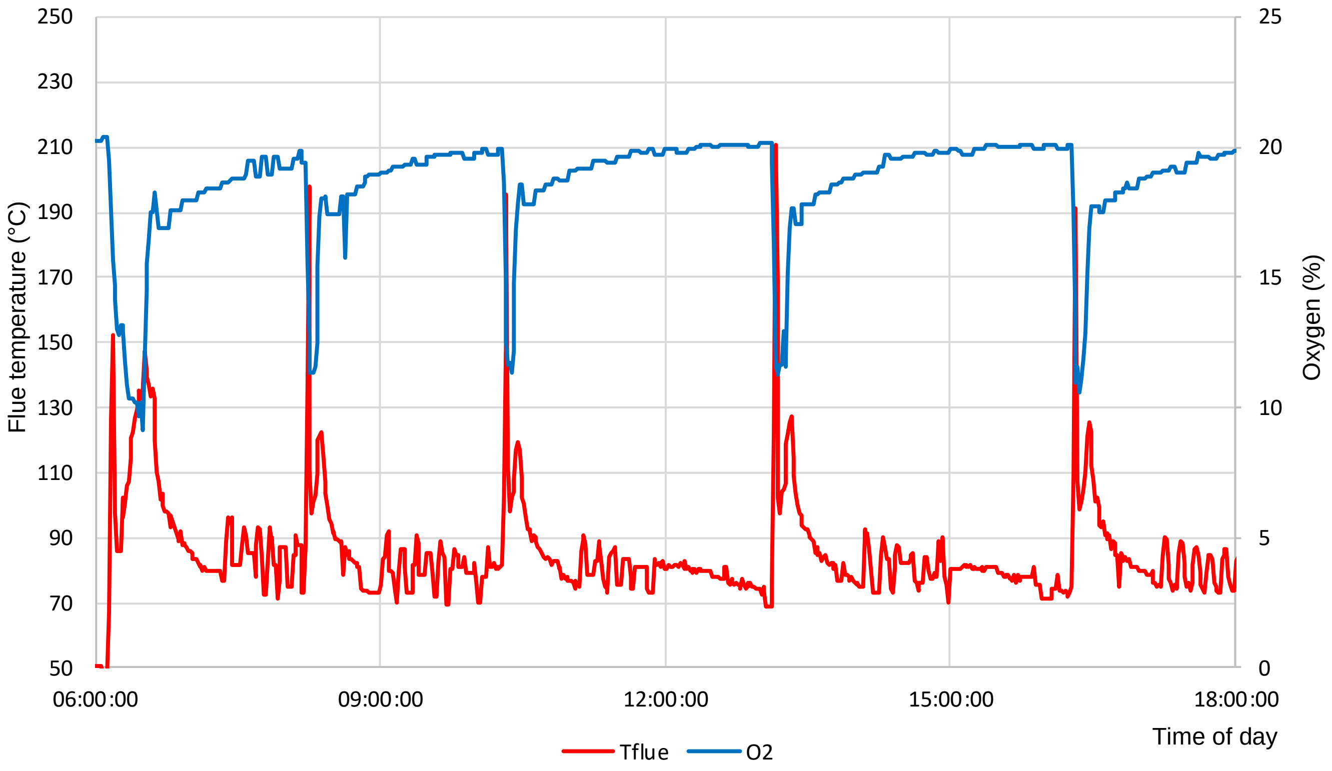


Figure 55: Oxygen and flue gas temperature on a typical June day

5.8.3 Manually operated boilers

Some wood log boilers are loaded with logs and then ignited manually. On such boilers, rapid cycling is not possible because after ignition, the boiler with continue to operate until all the fuel has been combusted. The boiler will only fire a second time after manual intervention from the operator (i.e. when it re-fuelled and ignited again).

5.9 Impact of operator behaviour and maintenance

A wide range of operator involvements in day-to-day biomass boiler operation and maintenance regimes were observed during the field trial and in the social research. It was clear that the level of operator knowledge and training also varied widely. This is most likely due to the diversity in sites and industries in which biomass boiler are installed.

There were some trends across sites:

- Most operators had received information on the correct operation of the boiler from their installer, the boiler manufacturer or their maintenance company
- However, based on operator behaviours, it was unclear whether the best practice advice given to operators was consistent
- Around half the operators questioned in the social research suggested that more information could have been provided to help ensure the smooth operation of their boiler

Generally, there was a positive perception of the biomass boiler performance and positive satisfaction amongst the operators, however there were examples of:

- Specific behaviours of operators that negatively impacted boiler and system performance, e.g.
  - Electric immersion heaters installed for summer hot water heating being disabled and instead the biomass boiler was operated all year, resulting in both boiler cycling and large system losses during the summer
  - Leaving the boiler enabled, keeping thermal stores at high temperatures when heat is not required, e.g. when the building is unoccupied
  - Some operators regarded ongoing visible smoke from the boiler as a normal occurrence and were not aware it was indicative of greatly increased emissions (see Section 5.4).
- Specific individuals that were unhappy with the performance of their boiler and system, e.g.
  - Issues with breakdowns (especially the fuel feed system) and long delivery times of replacement parts from abroad
  - Additional regular maintenance (weekly or monthly) over and above what was suggested by installer or manufacturer.

Some of these issues were because operators had failed to take basic energy saving steps. This might be due to a combination of lack of incentive to reduce usage due to the cheap nature of heat provided by the biomass boiler, and lack of education into how the system works.

At small domestic sites, the operator was the homeowner. In some cases, they had very limited knowledge of the ideal operation of the system. For larger sites, there may have been either:

- a dedicated boiler operator on site,
- a subcontractor for all maintenance operations,
- a janitor whose duties also included looking after the boiler, or
- an employee who only knew how to reset the boiler in the case of power failure.

Sites without a dedicated 'boiler champion' with both a degree of knowledge and enthusiasm about the biomass boiler tended to see greater maintenance issues.

The collation of best practice advice for operators (that could also be distributed via manufacturers, installers and distributors) would educate operators and allow them to identify poor operating practices and regimes. It would help ensure the negative practices are avoided and may also help to avoid some of the perceived negative performance issues experienced by operators.

5.10 Implications for the wider population

The original site selection methodology was a form of disproportionate stratified quota sampling, randomised by an initial random sampling (see Section 4.2.2). Therefore, the average of the efficiencies measured during the field trial is not necessary a true estimate of the average efficiency of all biomass boilers in the RHI population. To make this estimation, it was necessary to weight the efficiencies measured in each strata, according to either:

- The numerical share of the population occupied by that stratum (Table 36), i.e. the percentage of boilers in the population that are represented by that stratum, or
- The capacity share of the population occupied by that stratum (Table 37), i.e. the percentage of total installed capacity in the population that is represented by that stratum.

The overall efficiency is presented for the entire population, and separately for boilers with rated outputs under 100kW and over 100kW.

Table 36: Overall efficiencies of population, weighted by numerical share. The number after the ± is a 95% confidence interval, using a coverage factor based on a t-distribution with n-1 degrees of freedom (where n is the size of each stratum)

Population	Net efficiency	Gross efficiency
Entire population	(77 ± 3) %	(71 ± 3) %
Boilers with rated output <100kW	(81 ± 4) %	(75 ± 4) %
Boilers with rated output >100kW	(71 ± 3) %	(65 ± 3) %

Table 37: Overall efficiencies of population, weighted by capacity share. The number after the ± is a 95% confidence interval, using a coverage factor based on a t-distribution with n-1 degrees of freedom (where n is the size of each stratum)

Population	Net efficiency	Gross efficiency
Entire population	(74 ± 3) %	(68 ± 3) %
Boilers with rated output <100kW	(81 ± 5) %	(75 ± 5) %
Boilers with rated output >100kW	(72 ± 4) %	(66 ± 3) %

5.11 Robustness of results

5.11.1 Data completeness

The completeness of the data collected was calculated by considering the number of valid data points that were collected during the field trial, out of the total potential data points that could have theoretically been collected. A common set of measured parameters were considered, along with a critical set, shown in Table 38. A data point was valid if (a) it was received via telemetry from the data collection equipment, and (b) the measurement equipment was functioning correctly at the time.

Table 38: Common and critical measured parameters considered during data completeness calculation

Common parameters	Critical parameters
Flue gas temperature	Flue gas temperature
Flue gas O_2	Flue gas O_2
Water flow temperature	Boiler room air temperature
Water return temperature	Boiler heat output
Boiler room air temperature	
Outside air temperature	
Boiler heat output	
Electricity consumption	

The data completeness was calculated using the equation:

$$\text{Data completeness} = \frac{\text{Total data points collected}}{\text{Total possible data points that could have been collected while operating}}$$

The average data completeness of common parameters over the entire field trial was 93%. The average data completeness of the critical parameters was 92%. Issues that affected the data completeness were recorded in an issues log.

5.11.2 Energy balance validation for field trial and laboratory trials

An energy balance validation was conducted for:

1. **Field trial** – 13 of the boilers in the field trial responded with fuel delivery data that was sufficiently detailed to calculate an EBV. These were:
   a. Eight wood pellet boilers
   b. Four wood chip boilers
   c. One self-supplied wood and waste wood boiler

2. **Laboratory trials** – all of the tests with the small boiler (where fuel input was measured)

Table 39 shows the energy inputs and outputs considered during the EBVs. The EBV was calculated with the equation:

$$EBV = \frac{\text{Useful heat out} + \text{Flue losses} + \text{Case losses} + \text{Unburned fuel losses} + \text{Heat added to boiler}}{\text{Energy supplied by fuel} + \text{Electricity supplied}}$$

Table 39: Energy inputs and outputs considered during the EBVs

Energy flow	Description	Method of measurement or calculation	
		Field trial	Laboratory trials
Input	Energy supplied by fuel	Measurement based on fuel supply data from site and calorific value of the fuel	Measurement based on weight of fuel supplied and calorific value of the fuel
Input	Electricity supplied	Measurement of total electricity consumption of boiler (primarily to ignitor gun but also motors, fans and pumps)	
Output	Useful heat out	Measurement of temperature change of water and flow rate of water through the boiler	
Output	Unburned fuel losses (CO in flue gas and ash)	Calculations based on assumed flue gas CO and assumed ash losses	Calculations based on flue gas CO, mass of ashes collected and percentage carbon in the ashes
Output	Flue losses	Calculation based on flue gas temperature and flue gas O_2	Calculation based on flue gas temperature and flue gas CO_2
Output	Case losses	Calculation based on assumed case loss	Calculation based on measured heat loss coefficient of boiler, from standing loss tests
Storage	Heat added to boiler[36] (considered as an output)	Not measured	Calculated based on difference between initial and final boiler water flow temperatures

The EBVs obtained in the field trial and laboratory trials are summarised in Table 40 and shown in more detail in Figure 56.

[36] During the laboratory trials, the heat content of the appliance increased during the test. This extra heat in the appliance was accounted for in the EBV.

Table 40: Energy balance validations – typical ranges of EBVs

Part of study	Fuel type	Typical range in EBV (%)
Field trial	**Wood pellet**	100 – 120%
	Wood chip	80 – 120% but may be significantly different
	Wood log	difficult to determine fuel feed rate accurately
Laboratory trials	**Wood pellet (load factor > 60%)**	95 – 105%
	Wood pellet (load factor < 60%)	85 – 100%

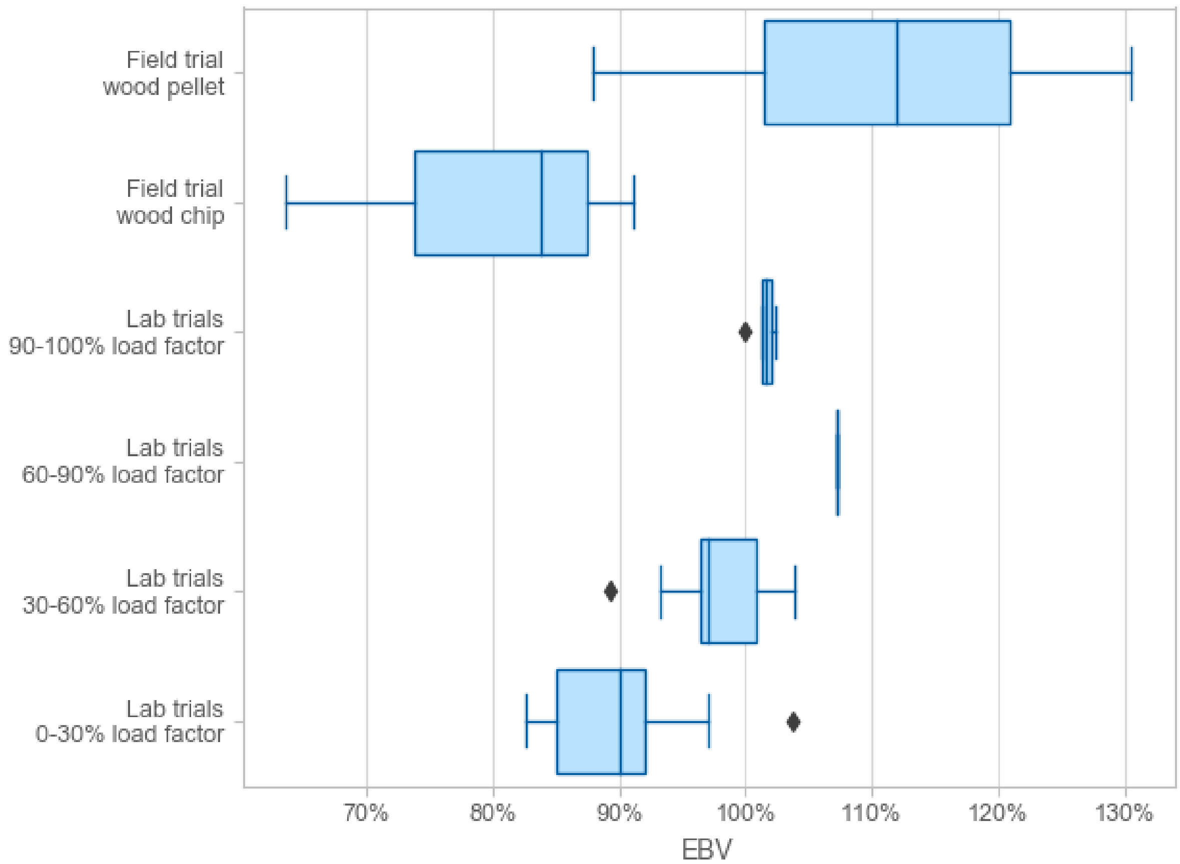


Figure 56: Energy balance validations – box plots of EBVs grouped by fuel type and load factor
Note: The EBVs of the self-supplied wood / wood waste boiler and of one wood chip boiler have been omitted from the figure, as the fuel consumption readings from the site suggested wildly unrealistic direct efficiencies of 150-200%. This demonstrates the robustness of the indirect method of efficiency measurement.

The laboratory trials typically had EBV closures within 5% for high load factors. At lower load factors the level of agreement decreased. Agreement in the field trial was typically within 20%, however for wood chip and log boilers the agreement could have been significantly poorer.

This reflected the difficulty that sites had in accounting for their fuel consumption (not deliveries) over a given period. At some sites, the physical layout of the fuel storage system and method of fuel delivery made this difficult, e.g. self-supplied chip or log of unknown moisture content, recorded by the 'tipper-load' or 'container-full'. Efficiencies calculated for these sites using only the fuel supply data (i.e. via the direct method) could have resulted in wildly unrealistic values of 150-200%. In contrast the indirect efficiencies were 70-80%. This demonstrated the robustness of the indirect method of efficiency measurement.

In an ideal situation, the EBV closure should be close to 100%. Practically, achieving such a close balance is only possible during steady state operation. Standards such as PAS 67 [42] define limits for steady state testing for gas-fired appliances (Table 41). However, for the field trial and laboratory trials carried out in this project, the appliances were not in steady state, and there are no standard acceptable ranges of EBV closures.

Table 41: EBV permitted discrepancies for PAS67

Heat load on appliance	PAS 67 permitted EBV range
90 – 100%	98 – 102%
60 – 90%	97 – 103%
30 – 60%	96 – 104%
0 – 30%	94 – 106%

Due to non-steady state operation in the field and laboratory trials, and the variability and particle size of the fuel in biomass, the EBV agreements are expected to be poorer than gas. This is due mainly to the fact that whereas in gas boilers the combustion is almost instantaneous and tiny amounts of fuel exist in the burner at any one time, in biomass boilers combustion takes some time and a variable and potentially large amount of unburned fuel can exist in the grate at any one time.

Despite this, an EBV still provides an important check and helps to identify the likely sources of uncertainty e.g. assumptions about the adjustments required to account for non-steady state operation. Given the nature of biomass boiler operation compared with a gas boiler, it is advocated that these higher EBV discrepancies observed in the field trial and the laboratory trials still allow a high degree of confidence in the test results.

5.11.3 Verification of shortened laboratory method

The laboratory trials on the small boiler required 24 hour test cycles for continuous, uni-modal and bi-modal tests. Tests on continuous operation were performed for 4 hours after the boiler had reached steady state operation. The test data for continuous tests was then extrapolated to give results for a full 24 hour test of continuous operation.

During initial testing it was noted that during the bi-modal and uni-modal tests, the boiler flow and return temperatures and flue temperature settled down after a relatively short time (1.0-1.5 hours) into a steady cycling pattern that remained approximately unchanged for the remainder of the test period.

To allow for more laboratory tests to be performed within the timeframe, rather than conducting a number of full-day uni-modal and bi-modal tests, an extrapolation method was developed. In this method, two shorter tests were carried out:

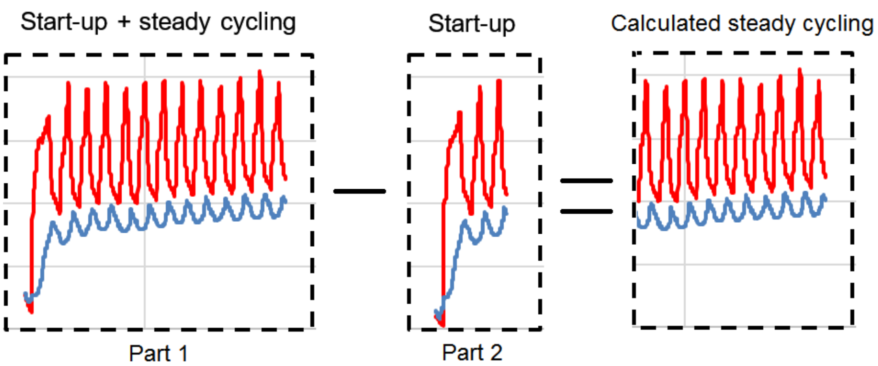
- Start-up of the boiler (approx. 1.5 hours)
- Start-up or the boiler (approx. 1.5 hours) plus a period of steady cycling (approx. 3 hours)

Based on the efficiency and emissions measurement results from these two tests, the equivalent results from a full day of uni-modal or bi-modal operation could be calculated. The extrapolation method is shown in Figure 57 and was validated on test 5, a uni-modal test at 30% daily load factor.

This test was conducted both:

- for a full 16 hours of boiler operation (corresponding to 07:00–23:00)
- in two parts, covering the start-up and start-up + steady cycling

Figure 58 shows the full test and the two parts of the extrapolated test. The full test is at the top of the graph and shows the boiler cycling as it tries to maintain a flow temperature of 70˚C. The two lower graphs are the start-up to steady cycling and the start-up tests and these are combined and extrapolated into a full 16-hour test.



1. Starting from the defined starting boiler return temperature (see Section 4.3.3), the boiler was operated for an average of 4.5 hours, so that the 1.5 hour start-up and approx. 3 hours of steady cycling regime were captured. This test was labelled ‘part 1’, i.e. for test 5 this was labelled ‘5.1’.
2. Starting from the same defined starting boiler return temperature, the boiler was operated for an average of 1.5 hours, so that the start-up was captured. The monitoring was stopped when a cycle ended and steady cycling had started (based on the observations from the 4.5 hour test). This test was labelled ‘part 2’, i.e. for test 5 this was labelled ‘5.2’.
3. Readings for the boiler start-up were directly available from the part 1 test. Readings for the steady cycling part of the test were derived from the difference between part 1 and part 2.
4. The equivalent full test results were then calculated by taking the measured start-up (part 1) and extrapolating the readings from the steady cycling (part 1 – part 2) to cover the remainder of the test period.

Figure 57: Extrapolation method used for uni-modal and bi-modal tests

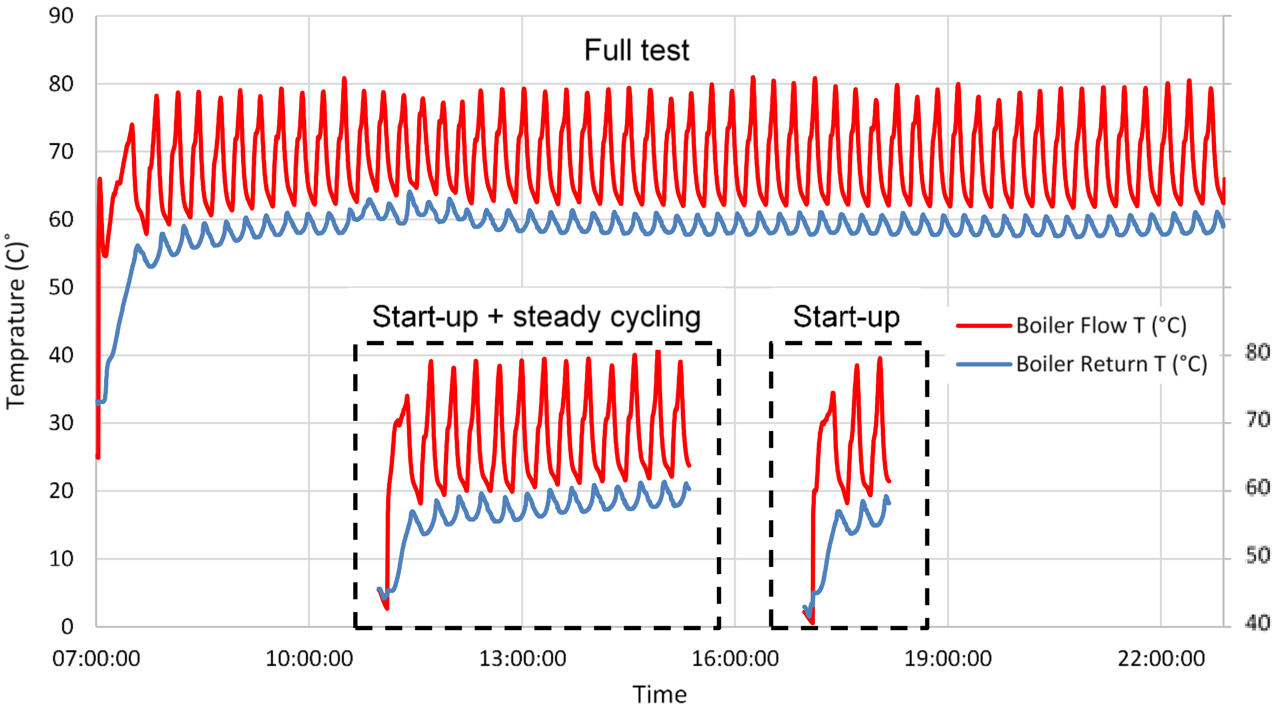


Figure 58: Validation of extrapolation method – flow and return temperatures for test 5, including the start-up and start-up + steady cycling

The percentage difference between the extrapolated test and full test for fuel consumption was 2.9% and for heat output was 0.57%. This level of agreement was considered appropriate and so the extrapolation method was used in all uni-modal and bi-modal tests.

6 Interventions

After the Phase 2 field trial ended, a smaller number of sites displaying performance issues were selected for intervention visits (as part of Phase 3). The purpose of these visits was to identify the cause of their poor performance and attempt to address the issues found. Data was collected from these sites for a further year (July 2017 – June 2018) to quantify the impact of these interventions.

The findings from the interventions were then used to complete two guidance documents for best-practice ways for biomass boiler operators to diagnose and address performance issues. One of the guidance documents is aimed at owners and users (more likely at smaller, domestic sites), the other is aimed at more advanced operators and service engineers (more likely at larger non-domestic sites). The guidance documents are provided in Annex G.

6.1 Sites chosen

Out of the 67 biomass boilers in the Phase 2 field trial, 16 boilers with performance issues were chosen for intervention visits in Phase 3 along with a further 6 boilers as a control group. These 22 boilers were spread across 21 sites. The sites were chosen, as far as possible, to include a range of boiler heat outputs, fuel types, heat uses and performance issues, to be representative of field trial sample. The sites chosen for interventions are shown in Table 42.

Two of the original sites chosen to be included later withdrew from the trial, and so replacement sites were chosen and are included in the figures above. The data from the sites that withdrew has not been included in the analysis. One of the included sites removed their monitoring equipment in February 2018, but the data up to this point has (where possible) been included in the analysis.

Table 43 shows those chosen for control monitoring. The location of the sites was also chosen to be geographically spread across England, Scotland, and Wales.

Approximate locations of all sites are shown in Figure 59.

Table 42: Intervention sites

Site ref.	No. biomass boilers monitored	Fuel type	Boiler rated output (kW)	Type of site	Issues identified
B542	1	Pellet	15	Domestic house	Boiler operating when not required
B909	1	Log	25	Domestic house	Periods of less efficient operation
B921	1	Pellet	45	Domestic house	Boiler cycling
B586	1	Log	60	Hotel	Accumulator not optimised
B445	1	Chip	75	Sports facility	Boiler operating when not required
B464	1	Pellet	120	Sports facility	High flue gas oxygen High flue gas temperature Boiler operating when not required Boiler cycling
B920	1	Pellet	130	Farm buildings	Boiler cycling
B907	1	Chip	199	Country house/estate	Boiler cycling
B908	1	Chip	199	Farm buildings	High flue gas oxygen High flue gas temperature
B900	1	Pellet	199	School	Boiler cycling
B901	1	Pellet	199	School	Boiler cycling
B001	2	Chip	220	Sheltered housing	Boiler cycling
B912	1	Pellet	230	Country house/estate	Summer use with very low load Boiler cycling
B358	1	Pellet	450	School	Boiler cycling
B046	1	Chip	800	Country house/estate	Summer use with very low load High flue gas oxygen Poor quality fuel

Table 43: Control sites

Site ref.	No. biomass boilers monitored	Fuel type	Rated output (kW)	Type of site
B919	1	Pellet	26	Domestic house
B477	1	Pellet	40	Farm buildings
B127	1	Chip	50	House & offices
B180	1	Pellet	153	Country house/estate
B250	1	Pellet	194	Poultry farm
B271	1	Chip	300	Plant nursery

Figure 59: Locations of intervention (circle) and control sites (triangle)

6.2 Summary of interventions

The different issues identified at the intervention sites are summarised in Table 44. Some sites had multiple issues, although these may have had the same cause, for example lack of proper maintenance can cause inefficient oxygen control and a build-up of soot in the smoke tubes of a boiler, which also causes poor heat transfer, leading to high flue gas temperatures.

Table 44: Issues identified at intervention sites

Issue	No. sites exhibiting issue	Fuel types exhibiting issue	Rated outputs (kW) exhibiting issue
Boiler cycling	9	Chip, Pellet	45-450
Boiler operating when not required	3	Chip, Pellet	15-120
High flue gas oxygen	3	Chip, Pellet	120-800
High flue gas temperature	2	Chip, Pellet	120-199
Summer use with very low load	2	Chip, Pellet	230-800
Accumulator not optimised	1	Log	60
Periods of less efficient operation	1	Log	25
Poor fuel	1	Chip	800

During the intervention visits, the ***most widespread issue was boiler cycling*** (60% of sites), which was symptomatic of either:

- Boiler oversizing, or
- Specific cases of poor boiler controls configuration.

Another common issue was ***operation of the boiler when either not required, or when another source of heat should be used instead*** (33% of sites). The operation of the boiler when heat was not required was generally caused by the incorrect configuration of (or complete lack of) time clocks to switch the boiler off when heat was not required. This was a particular problem at two sites:

- At one site where there was a permanently pumped system. The boiler was left enabled at night when there was no load, and the losses from the various pipe runs caused the boiler to cycle frequently which led to poor performance.
- At another site, there was a large hot water storage vessel with no insulation on either the vessel itself or any of the pipes surrounding it. The time clock was enabled up to three times a day, and there was no adjustment to the controls when the building was unoccupied. This caused the boiler to provide high temperature hot water to a tank with high losses when there was no need for the heat. The losses from the tank were so high that the plant room was also used as a drying room when the building was occupied.

The operation of the boiler when another source of heat should be used instead was caused by two factors:

- At one site, the management had directed that it was financially advantageous to provide summer hot water with biomass heating rather than electric immersion heaters. This was despite the biomass boiler operator complaining of increased maintenance effort and costs during this summer period. There were also heat losses from a long underground heat main, whereas electric heaters could have been utilised at point-of-use (they were installed although just not connected).
- At another site, the management had directed that company policy was to ensure the use of renewable technologies over fossil fuels wherever possible. However, the use of the

biomass boiler during the summer periods of low load led to cycling which caused high level of particulate emissions (higher than the LPG boilers which could have been activated during these periods).

6.3 Summary of intervention results

The strategies chosen to address the issues found, and the results of those interventions are summarised in Table 45. More detailed case studies and a more detailed table of intervention results are given in Annex F.

The most effective method of improving efficiency was to check that the flue gas oxygen set point of the boiler was set correctly, that the boiler's oxygen sensor was serviced, and checking that the smoke tubes were cleaned to extract the maximum energy from the flue gases. This may be because maintenance teams are well-trained in carrying out these changes.

The effectiveness of changing the settings on the boiler or system controls was mixed. If a biomass boiler was oversized for the heat load or a thermal store is undersized then it was very difficult to achieve any large improvement in boiler performance (either in boiler efficiency or reduced particulate emissions by reduced cycling). Changing the controls did help to a limited degree in a few cases, however the success of this depended both on the ability of the maintenance company to make the change (i.e. was the setting locked or hidden in an 'installer' part of the menu system), and on their skills and experience with adjusting control systems.

6.3.1 Maintenance contractor

For many of the interventions, a maintenance company (contractor) assisted with the change in some way. Their assistance did not guarantee that the change would be successful, however in all cases where there was a successful change, a maintenance company had been involved. Of the maintenance contractors engaged during the interventions, most would only normally visit the biomass boiler once per year for an annual service, or sooner if the boiler developed a fault. During this visit, it was common that the site would switch off the boiler beforehand so that it was cool ready for the maintenance. When the boiler was switched on after the maintenance, the system would have cooled, so boiler cycling would not start straight away. A side effect of this was that the maintenance companies never observed the boiler operating under normal conditions for an extended period. This was a common factor at most sites where the maintenance operator was unaware of operating issues which they would otherwise address.

6.3.2 Operator knowledge

The two worst performing sites had no regular operator contact, i.e. no one on-site who checked the boiler regularly. In these cases, the plant room was only entered for periodic maintenance or when the boiler broke down, and the sites were unaware their boiler was cycling and in even in one case that one of the control valves had jammed shut, causing erratic boiler behaviour. This showed the need for someone, i.e. the operator, to be the 'boiler champion'. Their job must include regularly visiting the boiler to check it is operating well. They must have the knowledge of the symptoms of poor performance, but do not necessarily need the ability to address the issues themselves (as this can be done by the maintenance company).Remote monitoring of at least flue temperature (to identify cycling) by the boiler maintenance company, and periodic checks of flue gas oxygen during normal running would also be beneficial, however these are not a substitute for the physical presence of an operator / 'boiler champion' to check the operation of the boiler is as intended.

6.3.3 Barriers to intervention implementation

During the visits to the intervention sites the boiler operators were given one or more intervention actions to improve the performance of the boiler. Seven of these intervention actions were unsuccessful as they either had no impact on the boiler performance or they were not completed by the site. The reasons why the interventions were not successful varied depending on the type of site and the presence of a boiler champion.

It was found that some approaches were also much more successful than others. Interventions to correct boiler cycling were most numerous and of the 8 intervention actions only one boiler was unable to adjust the boilers operation. Explanations on how cycling affects boiler performance in terms of emissions, efficiency and maintenance was enough to get the sites involved in the interventions. The site that did not make changes was unable to do so due to limited boiler control.

In contrast two sites were asked to make changes to behaviour around how they operated the biomass boiler. Both interventions were unsuccessful as neither site was willing to make the change in the long term. Although the sites started the intervention or made attempts to, the requirement to alter behaviour around the operation of biomass was not sustainable. Minimal contact with the boilers was expected from most sites as people expected them to operate without impacting on their lives. This is not a surprising finding however it should be considered in any further work on improving biomass performance in the UK.

Of the other intervention actions that were not completed cost was the biggest barrier to the intervention being completed. Three of the interventions that were not completed out of the total of seven were due to the cost of implementing the suggestion. Out of these three, two were to implement simple controls where time clocks were needed to prevent boiler operation overnight. The cost of implementing these controls was not excessive however, the sites still chose not to invest in improved control.

Table 45: Strategies to address issues and their results

Issue	Strategy / results	Success
Boiler cycling	**Increase thermal store bandwidth**	
	At one site: reduced cycling and increased efficiency	Yes
	At two sites: small change in operation (e.g. slightly increased runtime of boiler) but no great change in efficiency at one site	Slight
	At one site: unable to adjust controls	No
	Recommission circulation pump control system	
	At one site: reduced cycling and increased efficiency	Yes
	At one site: limited effect on performance	No
	Use two boilers in a duty cycle rather both enabled	
	Boiler cycling reduced	Yes
	Increase load on boiler by installing additional DHW storage	
	Change masked by improved efficiency due to servicing	Unclear
Boiler operating when not required	**Limit boiler operation with time clock**	
	At two sites: unable to make change	No
High flue gas oxygen	**Service boiler – adjust O_2**	
	Boiler efficiency improved	Yes
High flue gas temperature	**Service boiler – clean smoke tubes**	
	Boiler efficiency improved	Yes
Summer use with very low load	**Turn boiler off in summer**	
	At one site: unwilling to turn boiler off and use auxiliary heating	No
	At one site: Agreed to turn of biomass in the summer	Yes
Accumulator not optimised	**Reconfigure thermal store piping**	
	Work not carried out due to expenditure required	No
Periods of less efficient operation	**Change householder behaviour to facilitate more efficient operation modes**	
	Householder unwilling to alter behaviour	No
Poor fuel	**Monitor fuel source (self-supplied fuel)**	
	Fewer breakdowns and less maintenance required	Yes

6.4 Data analysis including weather effects

Weather effects needed to be accounted for when comparing boiler performance between the first year and the second year of monitoring (after interventions were made). More detail on how weather affects boiler performance is presented in Section 4.7.4, along with how these effects have been accounted for Figure 18.

Weather correction is often used when comparing heating technologies across different years. It allows direct comparison of data by adjusting values with relevant factors which remove the effects of different weather between years. This can only be done on quantities where there is a well-defined and well understood relationship with weather conditions. Heat output is a good example of a quantity that can be weather corrected, because there is often a well understood and strong correlation between heat demand and weather. For biomass boilers however, values such as efficiency cannot be weather corrected in the same way. This is because a change in weather will alter the operating pattern of the biomass boiler, which will impact efficiency in a complex way (far more than for other technologies such as gas or oil). It is therefore not appropriate to use weather corrections for biomass when comparing between years.

To compare between years, degree days are used as they also allow direct comparison. Degree days are an assessment of heating requirement based on the difference between the ambient temperature and a base temperature (usually assumed to be 15.5°C in the UK). The higher the number of degree days, the colder the outside temperature was on average. Using degree days allows for similar heating days to be compared and allows data from different periods of operation. It allows for years with different weather conditions to be compared directly without having to weather correct the data first. The impact of any changes made by the interventions can now be to be considered.

The average outside temperatures and average degree day heating (DDH) requirement of the sites in the first and second year are contrasted from the same sites in Figure 60 and Figure 61. From the graphs it can be seen that both years were similar. In the first year, the total DDH requirement from June 2016 – July 2017 was on average 1,855 degree days (with a standard deviation of 243 degree days) and the average outside temperature was 11.5°C (sd = 1.1°C). The second year was slightly colder, between June 2017 – July 2018, the total DDH requirement was on average 2,047 degree days (sd = 259 degree days) and the average outside temperature was 10.7°C (sd = 1.6°C).

This difference is consistent with the Met Office summary of weather for the two years – the 2016/17 winter was mild and the mean winter temperature was 1.6-2.0°C above the long-term average [31], whereas during the 2017/18 winter, the temperatures fluctuated either side of average and the mean temperature was 0.2°C below the long-term average [43]. Due to the relationship established between efficiency and load factor found during the first year, it was anticipated that the efficiency of most biomass boilers would have been slightly higher in the following year, which was indeed the case. The average efficiency of the control sites increased from 84.7% to 85.6% (net) and from 77.4% to 78.8% (gross). This increase of around 1-2% is considered as the order-of-magnitude change that can be attributed to weather.

Four sites showed efficiency increases due to interventions (B046, B464, B901 and B921) had an increase in efficiency of between 4 and 14%. These were investigated in further detail using the graphical analysis shown in Figure 18. The analysis (Figures 62-63) shows an increase in efficiency at all of these sites that is independent of weather, compared with one of the control sites (Figure 63, bottom) that shows no change in efficiency.

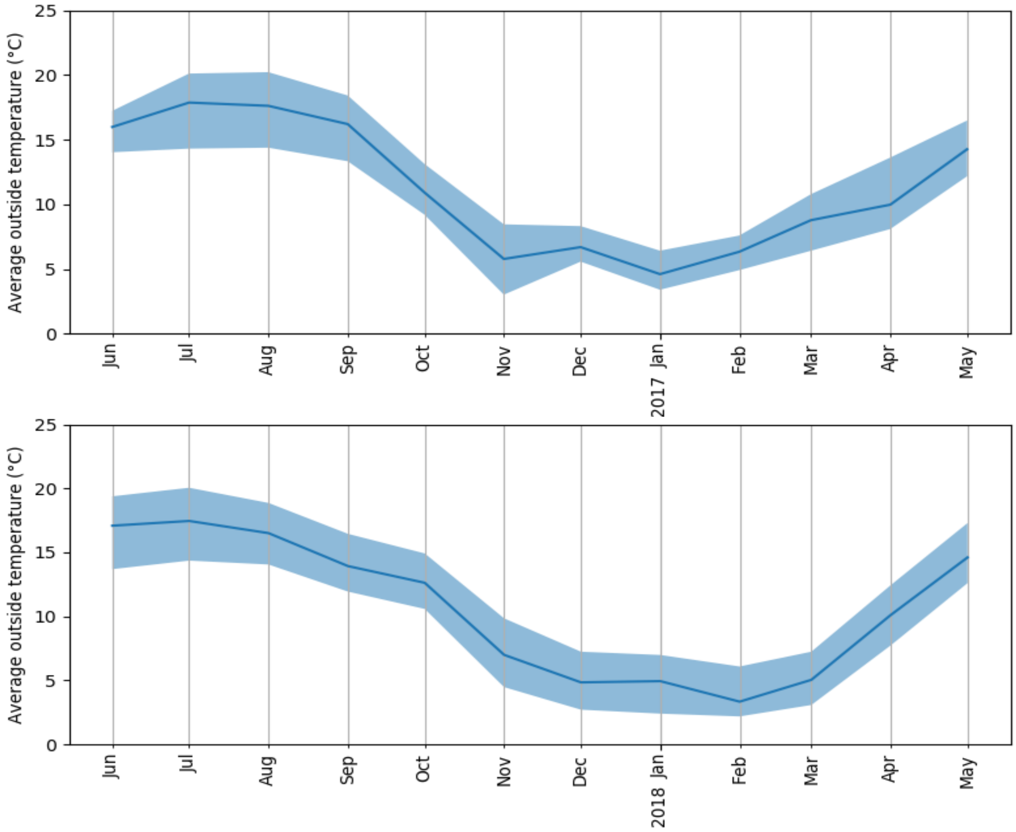


Figure 60: Monthly average outside temperatures in Phase 2 and Phase 3

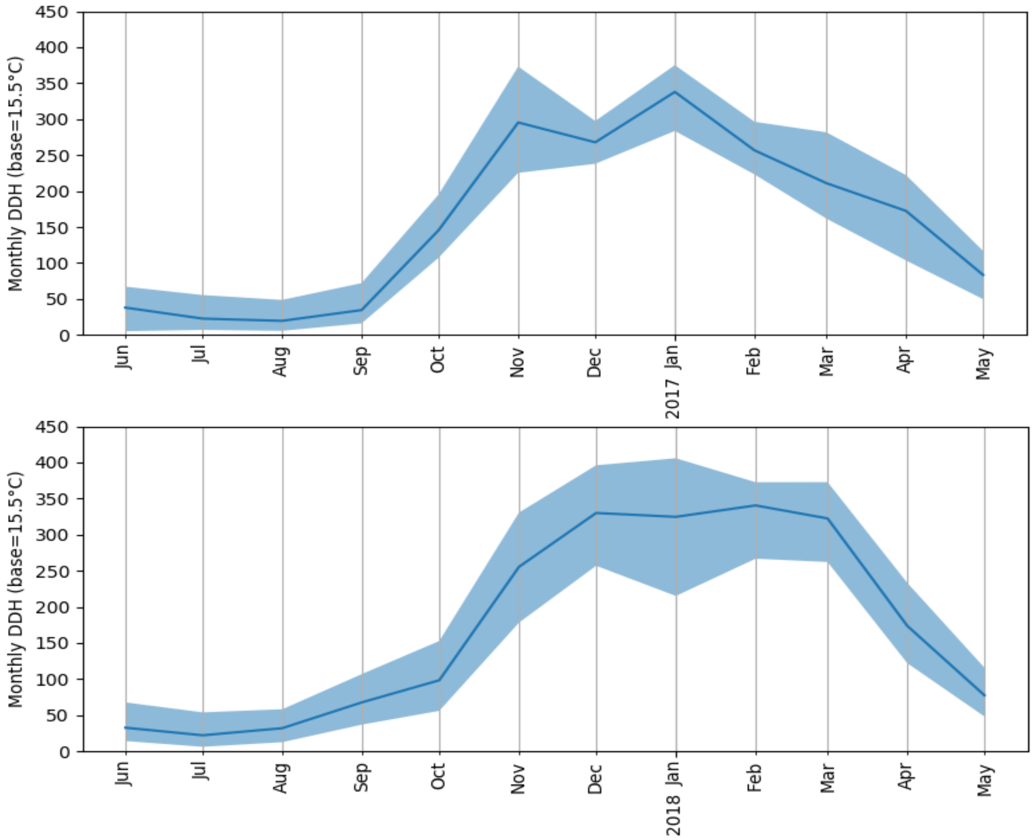


Figure 61: Monthly average DDH in Phase 2 and Phase 3– the line is the average and shaded regions is the range.

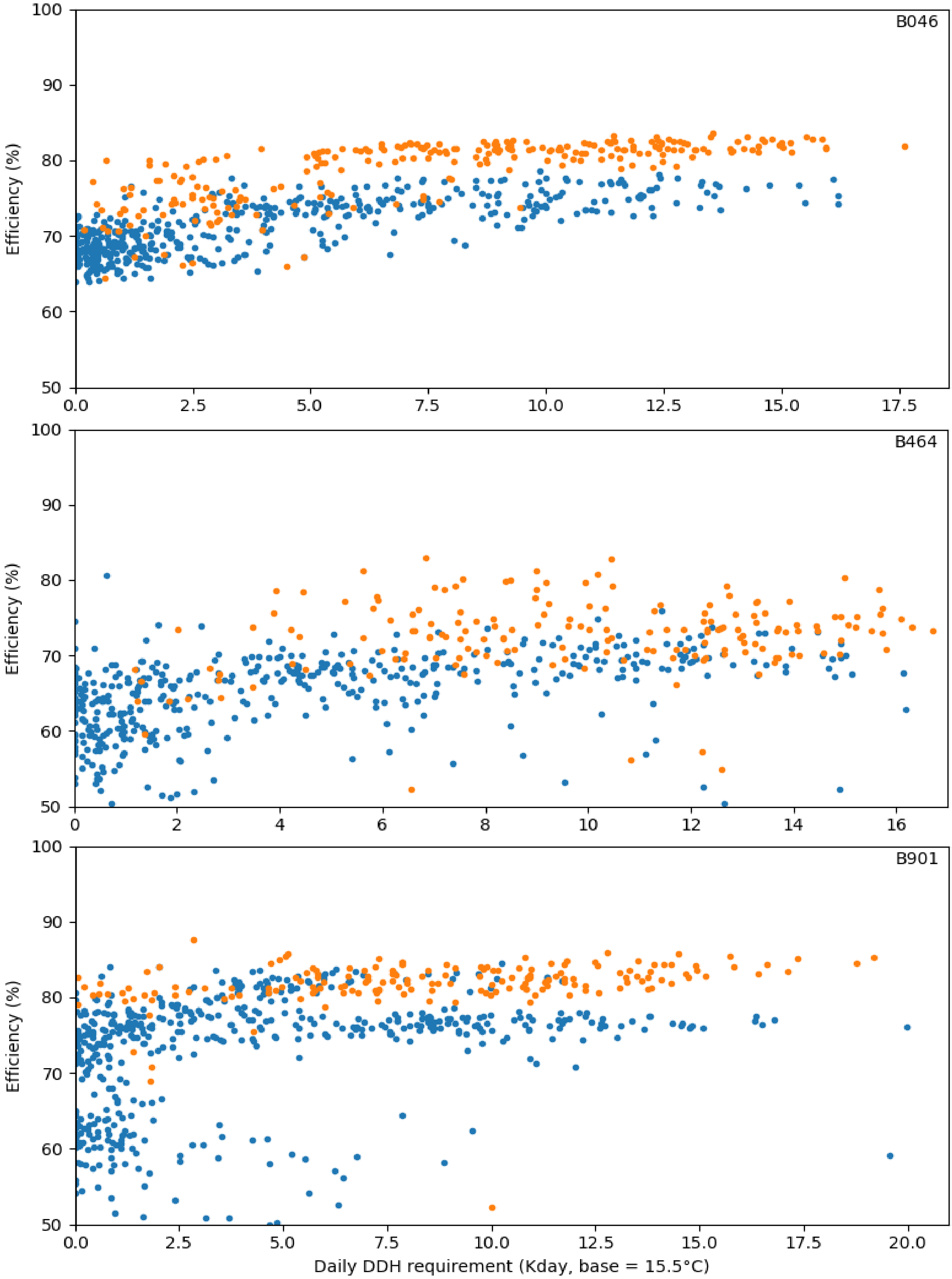


Figure 62: Comparison of efficiency at various DDH requirements in Phases 2 and 3 (three sites with increased efficiency) – Key: blue points = before intervention, orange points = after intervention

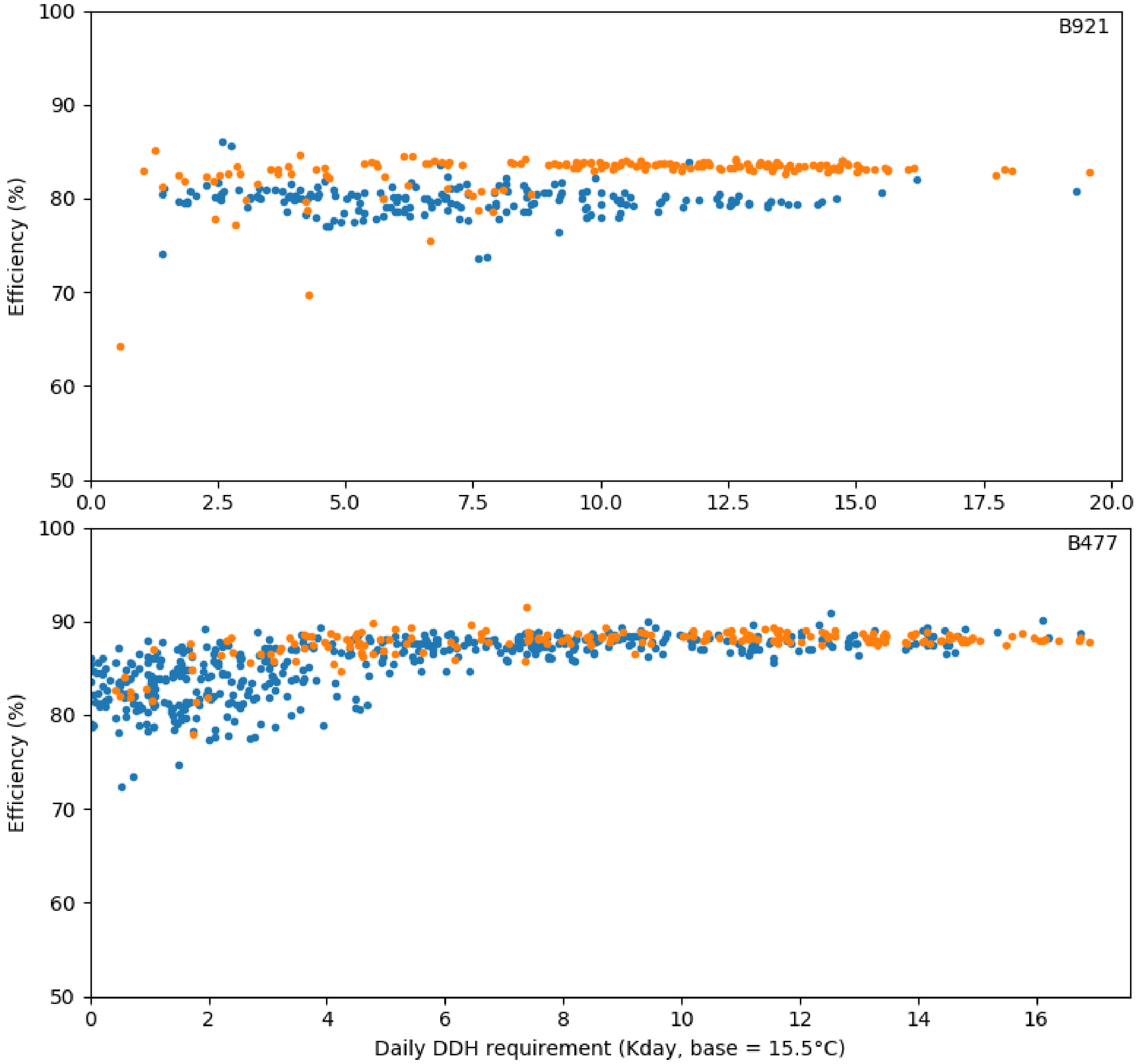


Figure 63: Comparison of efficiency at various DDH requirements in Phases 2 and 3 (top: sites with increased efficiency, bottom: control site) – Key: blue points = before intervention, orange points = after intervention

7 Conclusions

A field trial, laboratory investigation and social research programme was carried out. In total, 67 boilers were monitored across 61 sites over a period of a year from July 2016 to July 2017. The programme measured the real-life performance of the boilers in terms of efficiency and pollutant emissions. The efficiency was calculated under real-world conditions throughout the test programme, using an algorithm based on the indirect or losses method. Pollutant emissions from two boilers were measured using a dynamic test rig which simulated a range of real-world conditions. Energy balance validations were used to give confidence in the robustness of the data reported.

This work found a performance gap, both in terms of energy efficiency and emissions of particulates, when biomass boilers are operated under real-world conditions. The cause of this performance gap was a complex combination of issues specific to each biomass boiler in the trial, however the three common themes were rapid cycling, poor fuel or lack of operator knowledge (and therefore maintenance of the boiler). Many of the biomass boilers observed were oversized for the heat demand they were supplying, and this was one of the causes of frequent cycling.

7.1 Key findings

The average efficiency of biomass boilers under real-world conditions was **77% net** or **70% gross**. Boilers with rated outputs below 100kW had on average higher efficiencies (81% net or 75% gross) than boilers with rated outputs between 100kW and 1MW (71% net or 65% gross). The findings indicate there is a performance gap of on average 15 percentage points, between standard laboratory efficiency and real-world efficiency.

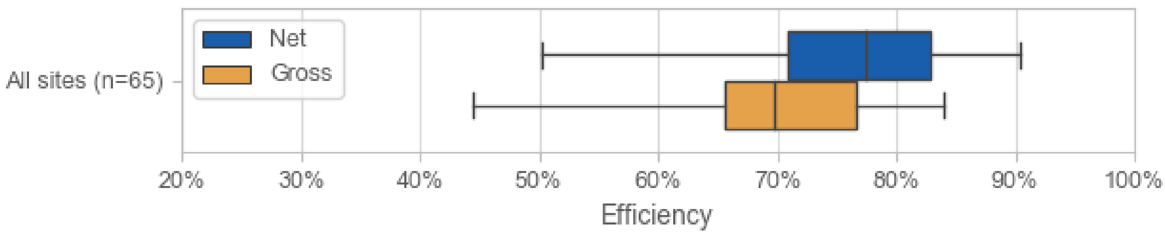


Figure 64: Efficiencies measured at all sites in the field trial

The particulate emissions from two biomass boilers studied in detail were **50-160 g/GJ net input** under real-world conditions. These were 2-8 times higher than the standard laboratory emission rates, and exceeded the RHI emissions limit of 30 g/GJ net input for particulate emissions by 2-5 times, although they may not have been either visually noticeable or (even if they were noticeable) of alarm to the operator.

The NO_x emissions from the two boilers studied in detail were **70-130 g/GJ net input** under real-world conditions with standard virgin wood fuel. These were comparable with the standard laboratory emission rates, and did not exceed the RHI emissions limit of 150 g/GJ net input. Non-virgin fuel with higher nitrogen content led to correspondingly higher NO_x emissions.

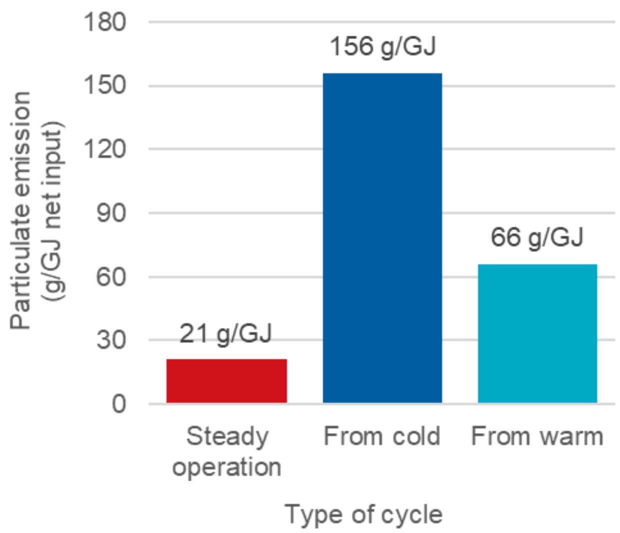


Figure 65: Particulate emission rates for different types of cycle for the 800kW wood chip boiler in the laboratory trials

7.2 Factors impacting performance

The predominant factors causing poor performance were rapid cycling, poor fuel or lack of operator knowledge (and therefore maintenance of the boiler). However, the root cause of these factors was a complex combination of issues specific to each biomass boiler in the trial. The common themes observed are summarised below and in Figure 66.

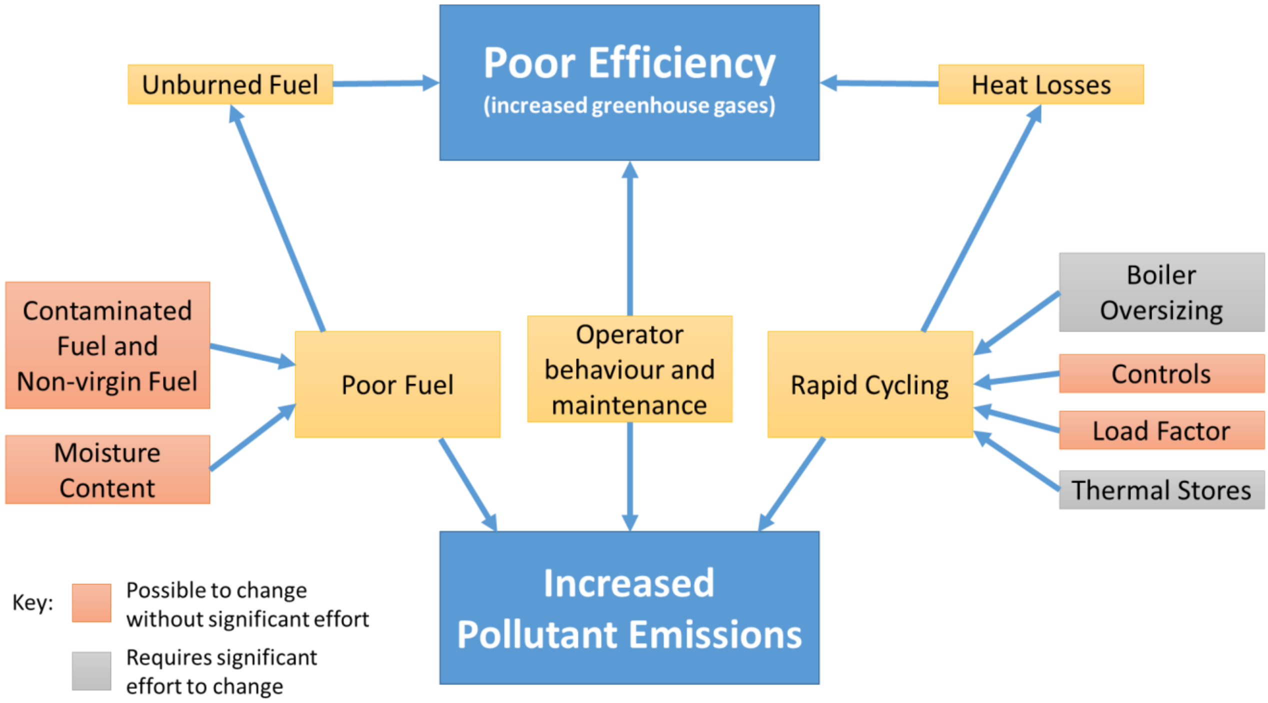


Figure 66: Root causes of the predominant factors impacting biomass boiler performance

7.2.1 Rapid cycling

Boiler efficiency was higher during prolonged periods of operation at high output. During start-up and shutdown the boiler efficiency was significantly lower. When the demand for heat was low, boilers tended to cycle on and off frequently and in some cases unburned fuel was left in the grate. This led to large drops in efficiency.

Similarly, emissions of particulates were significantly worse during start-up and shutdown periods compared with periods of steady operation. Each cycle of the boiler was equal to an equivalent extra number of hours of operation (between 1 and 5 hours extra operation per cycle for the boilers tested).

The root cause of many of the rapid cycling issues was:

- Low load factor (14% over the year rather than an ideal design value of 20%) due to the boiler being significantly oversized for the demand. Modulation is often used to address low load factors, however if boilers are not able to modulate down quickly enough, either during or shortly after the start-up sequence, then they will continue to cycle rapidly.
- Controls (either of the boiler or the system) that cause frequent boiler operation, such as:
  - Dead bands set too narrow
  - Set points unnecessarily high
  - Accumulators kept hot unnecessarily when there is no load
- The lack of a large enough accumulator tank, however this is difficult to change and often constrained by the physical space available.

7.2.2 Poor fuel

Poor fuel impacted both efficiency and pollutant emissions. Misfuelling was not widely observed in the field, however the potential for misfuelling was greatest with wood log boilers. Wood chip boilers were also susceptible to misfuelling as it is it difficult to assess the quality of wood once it has been chipped.

The most common causes of poor efficiency or increased pollutant emissions were:

- High moisture leading to low efficiency
- Non-virgin wood or contaminated material in the fuel – this led to increased particulate emissions, and if there was an increased nitrogen content in the fuel (due to contamination) it also led to increased NO_x emissions

7.2.3 Lack of operator knowledge and boiler maintenance

The level of operator knowledge and training, and therefore the boiler maintenance undertaken, varied widely. Most operators had received information on the correct operation of the boiler from their installer, the boiler manufacturer or their maintenance company. However, it was unclear whether the best practice advice was consistent, as several (even experienced) operators did not identify symptoms of poor operation, such as visible smoke or rapid cycling. Around half of operators suggested that more information could have been provided to help ensure the smooth operation of their boiler.

In some cases, operators had failed to take basic energy saving steps. This might be due to a combination of lack of incentive to reduce usage due to the cheap nature of heat provided by the biomass boiler, and lack of education into how the system works.

Sites without a dedicated ‘boiler champion’ with both a degree of knowledge and enthusiasm about the biomass boiler tended to see greater maintenance issues.

7.3 Recommendations and further work

The specific issue of boiler oversizing can be best addressed at the design stage of new installations, and so it is recommended that the proper sizing of biomass boilers for the existing heat demand is prioritised for new installations.

For existing installations, there are several strategies that could be adopted to improve their performance. The objective of all of these is to encourage best practice behaviour from whoever operates the biomass boiler. This best practice should optimise the good operation of the biomass boiler, in terms of energy efficiency, reduction in carbon emissions and reduction of pollutant emissions, rather than solely maximising the heat output.

Key recommendations are:

1. The two guidance documents developed as a part of this work focus on improving the knowledge and education of owners and operators of biomass boilers, to encourage best practice and to enable the indications of poor performance to be recognised. The social research indicated some sites in the field trial had observed these indications but were unaware they were symptomatic of poor performance. It is therefore recommended that the guidance is widely disseminated, along with other education initiatives, to improve the understanding of owners and operators and highlight the differences between biomass and other technologies. Avoiding the use of biomass during periods of low demand (often these are the summer months) may be beneficial, as in the field trial these were the times when biomass boilers were most polluting.
2. A comprehensive annual boiler service to check the proper operation of the boiler should be encouraged. This should include checks of the levels of oxygen and carbon dioxide in the flue (as these directly impact efficiency), and adjustments if necessary. Many sites already have annual maintenance, however a distinction should be drawn between regular cleaning and maintenance checks. Annual service invoices could be used as a way of providing evidence these checks are carried out on a regular basis.
3. To get the best out of a service the engineer must be aware of the normal pattern of operation of the boiler, as often the annual service will take place when the boiler is switched off (for example, over the summer). This could be achieved through inspection of the number and duration of boiler cycles each day. Some systems collect this information[37], and in other cases the facility could be added.

There are some areas identified in this work where further work could better inform future policy direction.

Key areas of further work are:

1. This work demonstrated that there are increased particulate emissions during biomass boiler start-up, and it quantified those for two boilers. “Equivalent hours of operation per boiler start-up” were shown to be a way of estimating the contribution to pollutant emissions from each start-up. It is recommended that the level of knowledge in this area is increased by further measurements of the particulate emissions during start-up from a range of other boilers.
2. There is limited knowledge of the fate of heavy metals in wood fuel emitted in flue gases or are retained in ash (bottom or fly ash) collected from the boiler. This work has demonstrated a simulated combustion approach to study the fate of these metals from

[37] Some companies offer remote monitoring of biomass boilers which alerts them if the boiler is not functioning as expected or if there is a need for adjustments.

biomass fuels. With an increased number of replicate measurements, this approach has the potential to provide a better understanding of the fate of these metals, especially for lead, chromium, and copper which are known to be toxic and were detected at measurable levels during the field trial.

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