A Methodology for Evaluating the In-Situ Performance of Solid Fuel Biomass Boilers

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Executive Summary

Renewable heat from the combustion of biomass is an important renewable technology to help the UK meet its renewable energy targets. A priority for DECC is to encourage the uptake of renewable technologies for heat generation to help reduce the amount of CO_2 emitted in the UK. The Renewable Heat Incentive (RHI) is DECC's primary mechanism for supporting renewable heat and consequently they are interested in evaluating the technologies incentivised by the RHI. A desk based study has been performed to review the performance and installation practices of biomass boilers (Steve Luker Associates Ltd., 2014). This report concluded that a number of biomass boilers were not performing as expected based on the data available to the authors. Varying levels of underperformance were indicated in the analysis, however the data was not sufficiently robust to draw clear conclusions. A recommended that further investigative work should be carried out in this area to clarify the level of performance in biomass boilers under the RHI. This work specifically looks to develop a methodology to facilitate collection of robust data to understand performance levels in solid biomass boilers.

That level of underperformance has economic implications for the owners of systems, increases emissions and reduces the amount of carbon savings from the RHI. Poorly performing systems may also have lower reliability, increased maintenance requirements and shorter lifetimes. As a result DECC wish to evaluate the in-situ performance of biomass boilers installed under the RHI. To do this a suitable methodology is required to be devised for possible roll out in a large field trial. This work evaluates all available data from the RHI and designs and develops a methodology for evaluating the in-situ performance of biomass boilers.

The first stage of this current work analysed data provided by DECC to understand the population of biomass boilers installed under the RHI. Data from DECC and Ofgem was supplemented with data made available through stakeholder contact. This data was analysed and used to categorise the type of biomass installations by purpose, fuel type, fuel feed system and capacity. A methodology was then developed to evaluate the performance of these categories.

Before a methodology was developed the possible reasons for good and poor performance of biomass boilers were evaluated. Due to the plethora of reasons for poor boiler performance, this is not an exhaustive list. The parameters required to evaluate the performance of biomass boilers and the associated reasons for good or poor performance have been identified along with possible measurement techniques. These parameters and measurement techniques were then used to develop a methodology applying an indirect (losses) method to measure boiler efficiency and applying the principle of obscuration to measure particulate emissions.

A domestic scale wood pellet fired biomass boiler was used to pilot this methodology. The methodology was piloted in a laboratory for validation and further investigation into the possible reasons for poor performance, in particular the effect of low load on boiler efficiency. The particular appliance tested showed a significant decrease in efficiency with an associated decrease in load.

Following from validation of the methodology in the laboratory, a non-domestic site was chosen to pilot the methodology in the field. The methodology was trialled at this site using remote data logging equipment and the data was transmitted to the Kiwa office for analysis. Successful analysis of the data allowed for the efficiency of the boiler and particulate emissions to be calculated.

Finally this report offers recommendations and pricing regimes for different levels of monitoring for the roll-out of an extensive field trial.

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1 Introduction

A previous desk-based study commissioned by DECC reviewing the performance and installation practices of biomass boilers indicated a possible underperformance in efficiency of these boilers of between 10% and 20% when compared to manufacturers reports, based on theoretical load factors calculated from RHI data and some isolated case studies (Steve Luker Associates Ltd., 2014).

A priority for DECC is to encourage the uptake of renewable technologies for heat generation to help reduce the amount of CO_2 emitted in the UK. If biomass boilers are underperforming they will require greater fuel input to satisfy the required heat load of the process being supported. Another consequence of the underperformance and associated increased fuel consumption of these boilers will be increased pollutants emitted to the atmosphere; this is particularly important in areas which are already close to air quality limits for pollutants like oxides of nitrogen (NOx).

As well as emissions issues, there are also economic implications for the owners of these systems, who could be facing an increase in expenditure on fuel, and probably increased maintenance costs.

It is therefore important to understand the reasons for the underperformance of biomass boilers, in situ, in order to develop strategies to increase their performance.

DECC are considering the commissioning of a follow on project which will be an extensive field trial of biomass boilers and the aim of this current project is to develop a field trial methodology which will be able to characterise boilers in terms of performance (efficiency) and air pollutant emissions.

The tasks associated with this project are shown in Table 1.

Table 1: Project tasks

Task 1	Develop categories of biomass boilers by heat type and load
Task 2	Develop evaluation methodology(s) for each category of boiler determined in Task 1
Task 3	Develop air quality emissions methodology(s)
Task 4	Testing and pilot of methodology

This final report presents the results and outputs from each of these tasks.

2 Development of categories of biomass boilers by heat type and load

In recent years there have been reports of underperformance of biomass boilers installed in the UK undermining the environmental and energy saving case for their installation. Previous studies commissioned by DECC have suggested that biomass boilers currently installed under the RHI could be underperforming in terms of boiler efficiency by up to 10-20% based on the theoretical load factors indicated by the data (much of which is self-reported) (Steve Luker Associates Ltd., 2014). The aim of the project is to understand the reasons for such underperformance.

The reasons for the underperformance of these installations may be different depending on the type of biomass boiler technology. Similarly the methods to examine the underperformance issues may need to be tailored for different boiler categories.

The development of the suitable categorisation of biomass boilers installed in the UK is therefore the first step required to fulfil the overall objectives of the study, specifically:

- Develop a suitable efficiency evaluation methodology for existing biomass boiler installations;
- Develop a methodology for measuring air quality and emissions from biomass installations;
- Testing and piloting the methodologies developed in the field to establish whether current installations are underperforming in terms of boiler efficiency.

While the size of biomass boilers installations is not strictly limited under the non-domestic RHI, the study focuses on the domestic biomass boiler sizes and smaller biomass boilers in the non-domestic installations (up to capacity of 250kW). This is because this study uses biomass boiler data collated under the RHI and according to the data received from DECC provided by Ofgem, 87% of non-domestic RHI installations are ≤250kW (DECC (a), 2015). It is noted that many more biomass boiler systems may have likely been installed without claiming RHI assistance and being recorded by the scheme. Unfortunately there is no readily available dataset on these installations that could be used for this study. Biomass CHP installations are excluded from the scope of this study. It should be noted that a single installation may include more than one biomass boiler on site.

2.1 Categorisation methodology

Development of categorisation of the most commonly installed biomass boilers was undertaken in the following steps:

1. Cleaning of the relevant biomass RHI data supplied by DECC (DECC (b), 2015)– information in the database, such as manufacturers and models, fuel types etc. are recorded inconsistently in the database. Before proceeding with the analysis, the database was filtered to remove duplicate entries, and the entries have been standardised as far as possible to allow categorisation of the installations. Specifically data was standardised for the following parameters:

    - Manufacturer / boiler brand

- Boiler model
- Fuel type

2. Initial analysis of biomass RHI data to determine the types of information provided (refer to Table 2 for data summary) and identifying gaps in the data.

3. Gap-filling with information recorded in other data sources – data from other datasets (i.e. MCS database and RHI eligibility list) were matched where available using common boiler model identification numbers or unique identifying record numbers (such as the RHI record number). This data was integrated into a single spreadsheet.

4. Analysis of consolidated data – the number of installations reported in the following categories was calculated:

Table 2: Parameters used for the analysis of the RHI installations data

Domestic Installations	Non-domestic installations
Manufacturer	Manufacturer
Installed capacity	Installed capacity
Fuel used (primary and secondary)	Whether the installation is a CHP plant
Feeding system (automatic versus manual)	Purpose of the installation (provision of space, water, process and district heating)
Modulation	Onsite versus offsite use of heat
Integration with hot water cylinder	PM and NOx emissions reported

5. Additional research to identify trends in most popular biomass boilers – information on the biomass boilers most commonly installed in the UK was sourced from manufacturers' websites and through direct contact with suppliers and other stakeholders (see below for further details).

6. Kiwa performed analysis of the Non-domestic biomass RHI payment data supplied by DECC. This data was analysed to understand the variation in utilisation factors of these sites. A simple model was constructed to analyse the variation in boiler efficiency with utilisation factor.

7. Consolidation of all information gathered to draw conclusions on the potential biomass boiler categorisation.

2.2 Review of the data sources

2.2.1 Biomass RHI data supplied by DECC

DECC have provided data on all biomass boilers installed under the RHI, which served as the primary source of information for the review of most common types of biomass boilers. Table 3 presents an overview of the information contained in the database. Information on the domestic and non-domestic installations have been analysed separately, given the differences in the information provided in the database for the two installation types. For example, different numbers of installations were recorded for each type, with over 6,400 domestic installations and over 11,200 non-domestic installations recorded.

Table 3: Information in the biomass RHI data supplied by DECC

Information type	Description	Domestic	Non-domestic
Previous system	Information on what system has been replaced with the biomass boiler and what fuel was previously used; in addition non-domestic installations contain data on the system replaced and its capacity	✓	✓
Product data	Product name, manufacturer, product number, description	✓	✓
Annual generation	Estimated annual generation by the installation	✓	-
Installed capacity	Total installed capacity (kW)	✓	✓
Property information	Is the property metered for payment, days the property is occupied, floor area and property type (recorded together for England and Wales and separately for Scotland), space and water heating requirements (EPC response).	✓	-
Purpose	Domestic installations: space heating, hot water. Non-domestic installations: space heating, water heating, process heating, district heating.	✓	✓
Heat use	Information on whether the heat is used on site or off site; estimated heat output.	-	✓
District heating data	District heating network temperature, potential for district heating expansion, separate metering for district heating properties.	-	✓
Back-up system	If used, the type of back-up boiler and size of back-up	-	✓
Emissions	NO_x and PM emissions data	-	✓

Metering	Domestic installations: information on whether installation is on the Meter Monitoring Service Pack. Non-domestic installations: information on hot water and steam metering.	✓	✓

Depending on the type of installation, the database contained very limited information on the technology deployed, fuels used or design specification. Large data gaps were identified specifically for non-domestic installations. For example around 29% of non-domestic installations had no record of the manufacturer of the boiler installed. These gaps have prevented development of the classification of boilers solely using the biomass RHI data supplied by DECC. The missing information is not currently collated by the RHI scheme and therefore it could be useful for the scheme to collect it in the future. The data had to therefore be supplemented with information from additional sources as described below.

2.2.2 Additional information sources

The baseline data has been supplemented from the following additional sources of information:

- Microgeneration Certification Scheme (MCS) certified biomass boilers list (provided by DECC);
- HETAS Database (provided by DECC, supplemented with the Official Guide to HETAS Approved Products and Services (HETAS, 2014));
- RHI Eligibility List (published online by Ofgem (Ofgem, 2015));
- Non-domestic biomass fuel type analysis (provided by DECC);
- Manufacturer websites; and
- Evidence collected through direct contact with biomass suppliers.

The aim of this data gathering has been to compile as far as possible a more complete set of information for boiler types identified in the DECC database[1]. The following sections describe the information available in the sources listed above.

Microgeneration Certification Scheme (MCS) certified biomass boilers list

The list covers boilers with capacity up to 45kW (upper limit of the biomass boilers which are eligible for the RHI support subject to MCS certification). The data provides information on the following parameters:

- Product type: whether it is a boiler, room heater stove with cooker and integrated boiler, room heater with integrated boiler, standalone room heater / stove.
- High level description: this information generally includes fuel used and the type of feeding system (automatic versus manual feed).

[1] The research focused on the biomass boilers installed under the RHI scheme. Boilers not benefiting from the RHI support were not investigated.

- Information on the model, manufacturer, certification number, country of origin and in some instances contact information of manufacturers; as well as testing standard used for the purpose of certification.
- Technical parameters of the boiler: whether it is integrated with hot water cylinder, modulating, the minimum output value and primary & secondary fuels used.

HETAS Database and accompanying guide

The HETAS database provided by DECC contains the following data:

- MCS Certification number
- Product name, model and manufacturer
- Installation capacity
- Measured PM and NOx emissions (in g/GJ net heat input) (HETAS, 2013).

The Official Guide to HETAS Approved Products & Services contains information on the boiler models accredited by HETAS. While the information reported per type of boiler and manufacturer may not always be consistent, the guide contains information on fuel type, rated output, gross and net efficiencies and refuelling period of the accredited products. Given the format of the document and the large quantity of information on products and manufacturers, the information has not been embedded within the main spreadsheet file used for the purpose of the analysis. This information source covers primarily domestic size products.

RHI Eligibility List

The RHI eligibility list assesses the eligibility of the renewable heating product against the domestic RHI criteria on the basis of the information available from the MCS. The list is divided into installations commissioned before and after 9 April 2014, when the domestic RHI scheme was launched. The database contains information on:

- Whether the boiler is eligible for the RHI and eligible for an optional monitoring package.
- Product and certification information (type, name, manufacturer, model, certification number, certification body, date the product was certified).
- Types of biomass product that have to be used as a fuel and the maximum moisture content of this fuel.

This data contains information on the domestic size boilers. It should be noted that manufacturer data is not anonymised however individual installation level information is not presented in this report.

Non-domestic biomass fuel type analysis

Given the sources described above provide additional information on the boilers eligible for support under the domestic RHI scheme (i.e. of capacity lower than <45kW and requiring an MCS certificate), there were outstanding data gaps in the information on biomass boiler installations of capacity >45kW, expected to be installed in non-domestic sector. In response to this, DECC provided additional information sourced from Ofgem on the fuels used in the non-domestic installations. The data provides information on the fuel used depending on the RHI tariff band and boiler capacity (the installed capacity of boilers reported in this data vary from <20 kW to 1,000kW).

Manufacturer websites

Websites of manufacturers of the most commonly installed boilers in non-domestic installations[2], as identified from the biomass RHI data, were reviewed as a source for further research. This focused primarily on identification of the efficiency data, (as efficiency data for each boiler model was missing from the RHI data). Collecting this information comprehensively for all boilers for all manufacturers was not feasible within the timescales of this project and given that quoted efficiencies can differ to in-situ performance (which is the main focus of this study) the information is not presented as part of this report.

Evidence provided through direct contact with stakeholders

A number of stakeholders (including suppliers and related organisations) were identified from our existing knowledge of the industry and a review of the manufacturers found in the biomass RHI data (the five manufacturers of the most common models were identified to be contacted). These organisations were contacted to gain better understanding of the most common boilers installed and the factors influencing biomass boiler efficiency. The following organisations provided evidence in the study:

- European Biomass Association
- Renewable Energy Association

At the time of writing this report there is one outstanding response expected from the European Biomass Industry Association. Each stakeholder contacted was asked a standardised set of questions exploring the links between biomass boiler design, their use and their efficiency. Any further comments provided were also recorded.

2.3 Results of the analysis

2.3.1 Data for domestic installations

Over 6,400 domestic installations were recorded in the biomass RHI data. Figure 1 presents an analysis of the number of new domestic biomass installations that are claiming domestic RHI (no data was available on whether they were claiming Renewable Heat Premium Payments) and that were installed annually between 2009 and 2014. As demonstrated, the number of new biomass appliances installed in homes and claiming domestic RHI increased significantly in 2014 when the domestic RHI scheme was launched. The installations dated pre-2014 are the so-called “legacy” sites which were installed after 15th July 2009 when the Government’s Renewable Energy Strategy was published, and before the domestic RHI was first introduced in April 2014; however this is not stated in the database.

[2] Given additional information on boilers with capacity less than 45kW was available from other sources identified, the manufacturers of most commonly installed domestic boilers were not prioritised for this research. Nevertheless it is recognized that there is an overlap in the boilers models and manufacturers between the domestic and non-domestic installations.

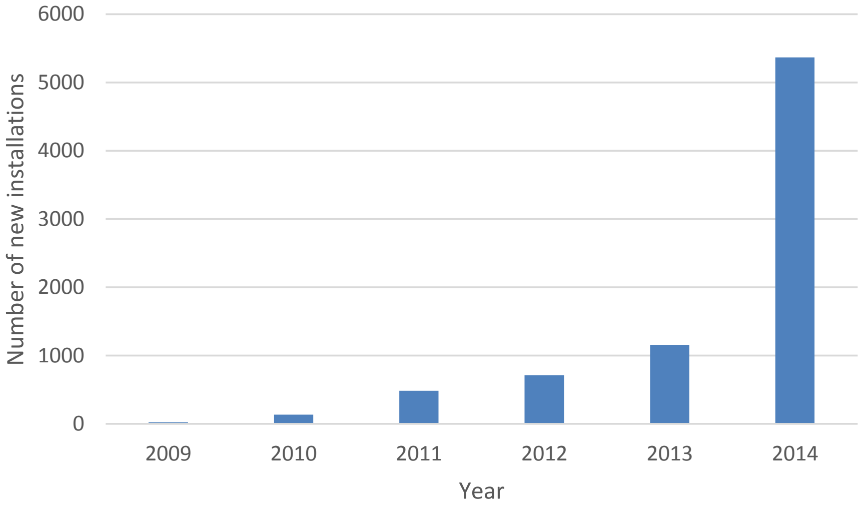


Figure 1: Number of new domestic installations per year under the RHI scheme

Around 63% of the domestic boilers that are claiming RHI are in the capacity range of 20-45kW as can be seen in Figure 2 below. Boilers with capacity lower than 20kW were installed in less than 20% of the total number of installations. For around 16% of the installations no information regarding the installed capacity was available.

All installations were providing hot water and space heating which is expected in most domestic settings. The database does not include information to specify whether or not the biomass boilers have been integrated with hot water cylinders or solar thermal systems.

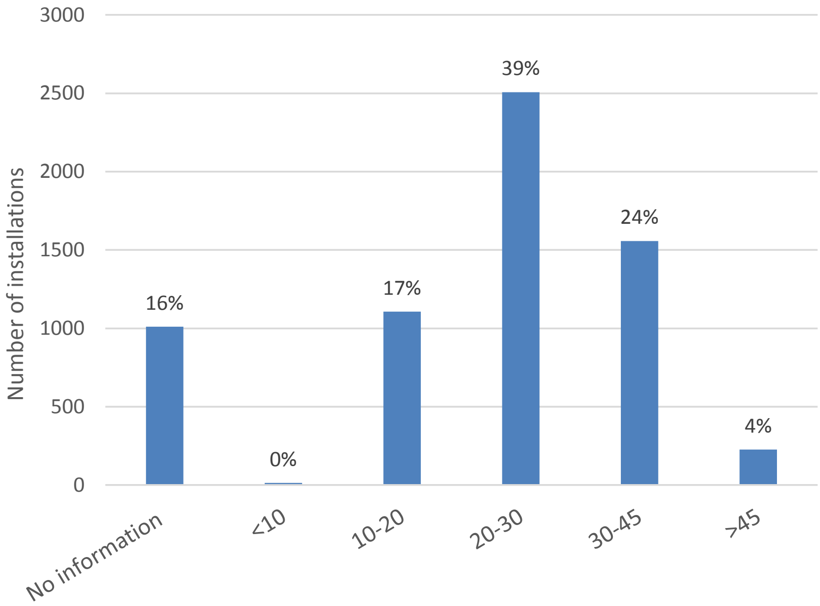


Figure 2: Capacity of biomass installations in the domestic installations under the RHI scheme

2.3.2 Fuel types

As shown in Figure 3 below, the boilers installed in over 88% of installations are primarily using wood pellets and the majority of the remainder are using wood logs. Use of secondary fuels with biomass boilers receiving the domestic RHI requires metering – the use of such secondary fuels was rarely reported in the domestic data (only 109 installations or less than 2% of the total).

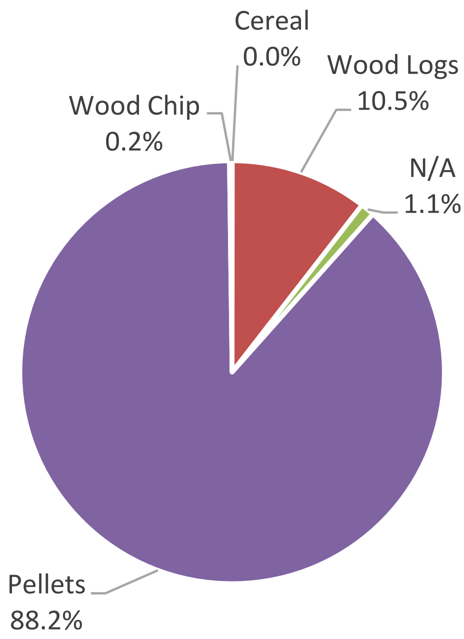


Figure 3: Primary biomass fuels used in the domestic installations under the RHI

2.3.3 Fuel handling and feed system

It can be difficult to define an automatic feed system for some products. One definition is "a system that requires no manual intervention to initiate fuel feed to the boiler". However manufacturers may disagree about the definition to use. There is a clear link between the use of automatic feeding systems (most common, reported for at least 60% of installations) and the use of wood pellets for fuel. All hand fired installations were wood log fuelled (in around 6% of installations) as there are no automatic feed systems for logs. For a large number of installations feeding system data was unavailable.

Figure 4 below shows the fuel feed systems used per fuel type under the RHI. N/A denotes that no data was provided on the fuel feeding system.

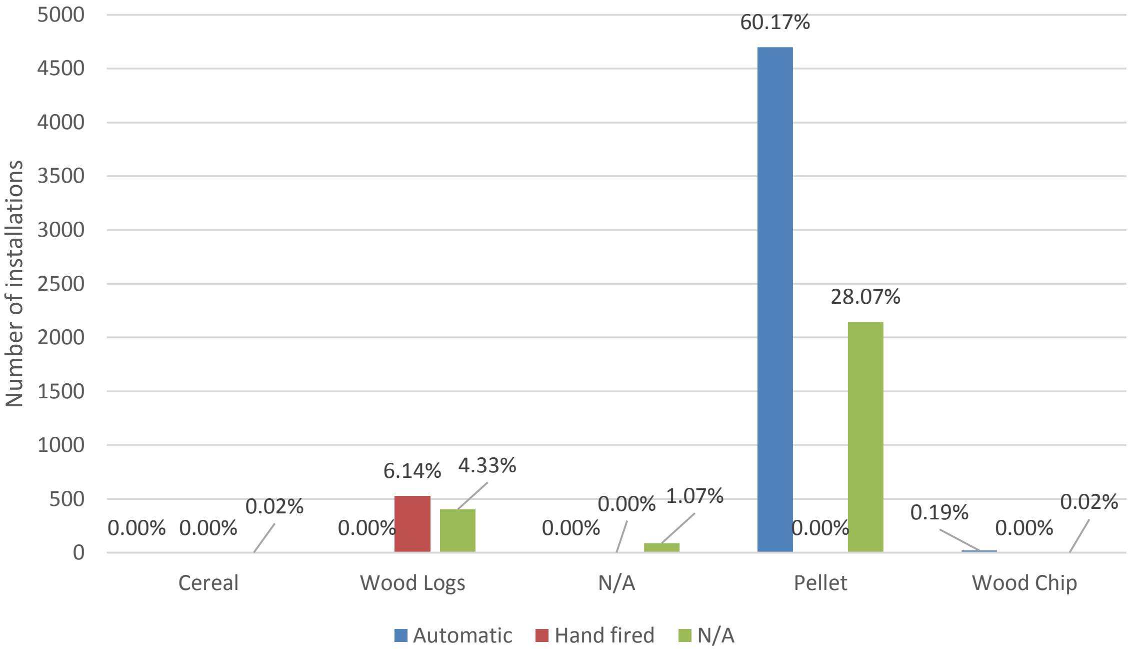


Figure 4: Fuel feed systems used per fuel type under the RHI.

2.3.4 Output modulation

Modulation of the boiler heat output was reported in 78% of installations. The majority of these modulating boilers were wood pellet fed. Modulation was absent in 7% of installations. For the remaining 15% of installations no data was available.

2.3.5 Boiler manufacturers

From our analysis, 64 manufacturers of biomass boilers were identified in the data. However just 14 of these manufacturers accounted for over 80% of biomass boiler installations in the domestic market by installed generated capacity. These were defined as 'most commonly' installed domestic boilers by manufacturer if they accounted for greater than 2% of the total installed generation capacity of all RHI biomass boilers installed.

2.3.6 Characteristics of the most common biomass boiler models

An analysis of the most commonly installed biomass boiler models in the domestic installations showed the following main trends:

- The most popular domestic installations are pellet fuelled. Most boilers reported use of a single fuel only.
- Modulation is common with over 70% of all installations reported as having a modulating boiler installed.

- 50% of the domestic installations use one of 23 most common boiler models. Almost all of these boilers operate on wood pellets and are modulating.

- All boilers for which information was available (80%) utilise automatic feeding system. All of these boilers were modulating and operated on wood pellets.

In Figure 5, the yes columns corresponds to the boiler being declared as modulating, no, the boiler was not declared as modulating and N/A; no data was provided as to whether the boiler was modulating or not.

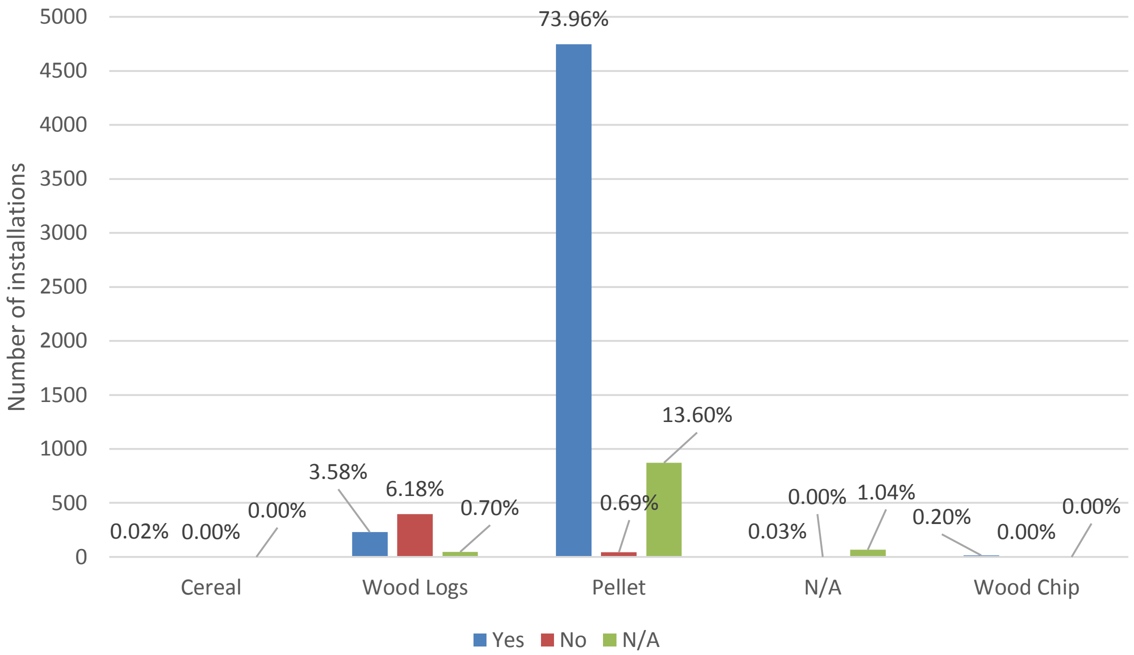


Figure 5: Modulating boilers per fuel type under the RHI.

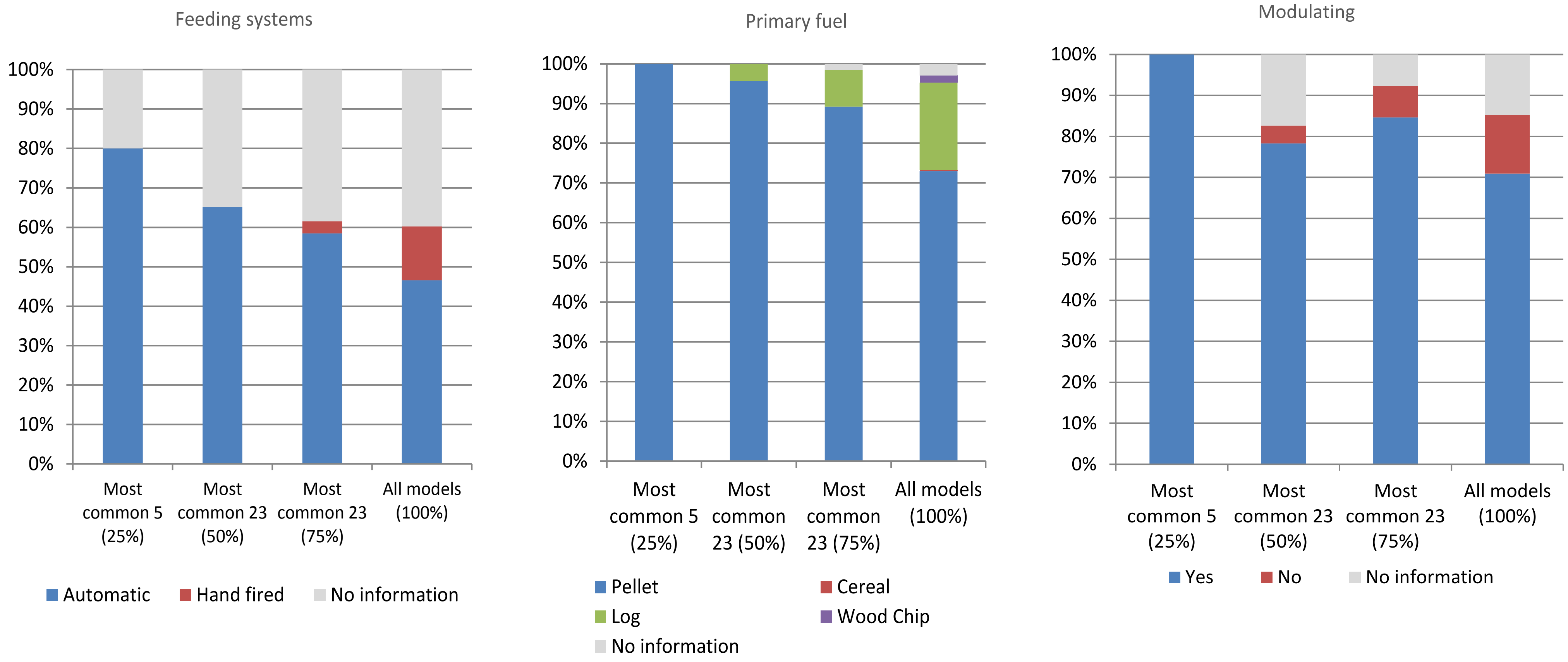


Figure 6: Summary of the key trends in the domestic installations – based on the 5, 23 and 65 most common boiler models installed

2.4 Non-domestic installations

2.4.1 Installed capacity

Over 11,200 non-domestic (duplicate entries removed) installations were recorded in the biomass RHI data. Of these only 11 were reported as being used as part of a CHP installation. As shown in Figure 7 the majority of non-domestic installations were in the capacity ranges of 45-100kW and 150-200kW. Around 11% of installations were found to be within a domestic capacity range of 10-45kW. These trends can be in part explained by the banding and tiers in the RHI and by the requirement to have micro generation certification scheme accreditation for installations <45kW. Therefore, it can reasonably be assumed that trends in future are likely to be influenced by policy as long as biomass boilers require subsidies to make them economic to install.

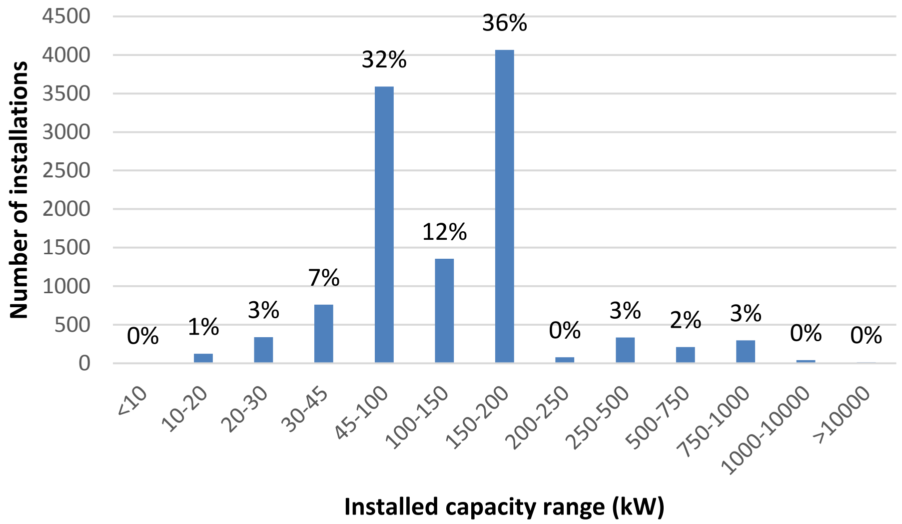


Figure 7: Capacity of boilers in non-domestic installations (kW)

2.4.2 Lifetime generation of non-domestic installations

If the installed capacity data from section 4.3.1 above is compared with the estimated lifetime generation of each installed capacity range it shows that although there are relatively few large capacity biomass boilers installed they account for the vast majority of lifetime MWh's generation out of all installations. It also shows that although there are a large number of mid-range boilers installed with capacities between 30-200 kW there lifetime generation is extremely small by comparison to larger installations between 1000 and >10,000kW. This is very important to note when considering the targeting of policies to improve efficiency of different installed capacity ranges of biomass boilers.

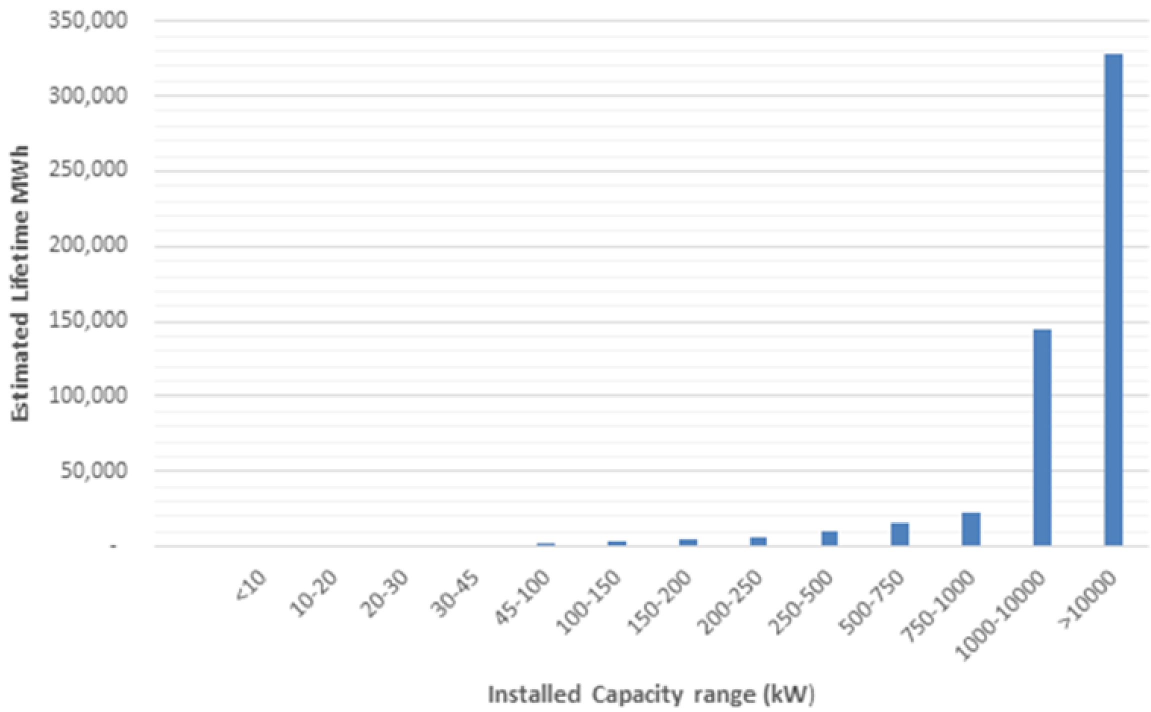


Figure 8: Estimated Lifetime MWh generation of boilers by capacity range in non-domestic installations

Note: The following assumptions have been made when estimating lifetime boiler MWh generation totals.

A. Installed capacity is assumed to be the median of each capacity range (e.g. 10-20kW is 15kW).

B. Boiler Lifetime is 15 years.

C. Boiler Utilisation factor is 20% (based on utilisation factors findings in section 4.6).

D. Installed capacities are outputs.

E. Higher end of >10,000 kW capacity range is 15,000 kW (as biomass boilers above this range are more likely to fall under the EU Emissions Trading Scheme and cannot receive RHI subsidies).

2.4.3 Installation purpose

The majority of non-domestic installations were used to provide space heating and water heating; only 9% of the total number of installations were providing process heating. Figure 9 below illustrates the data reported. Where the cells in the database have been left blank these are indicated as “No information”. It is likely that lack of data entry indicated lack of use for a given purpose but this is not stated explicitly in the data.

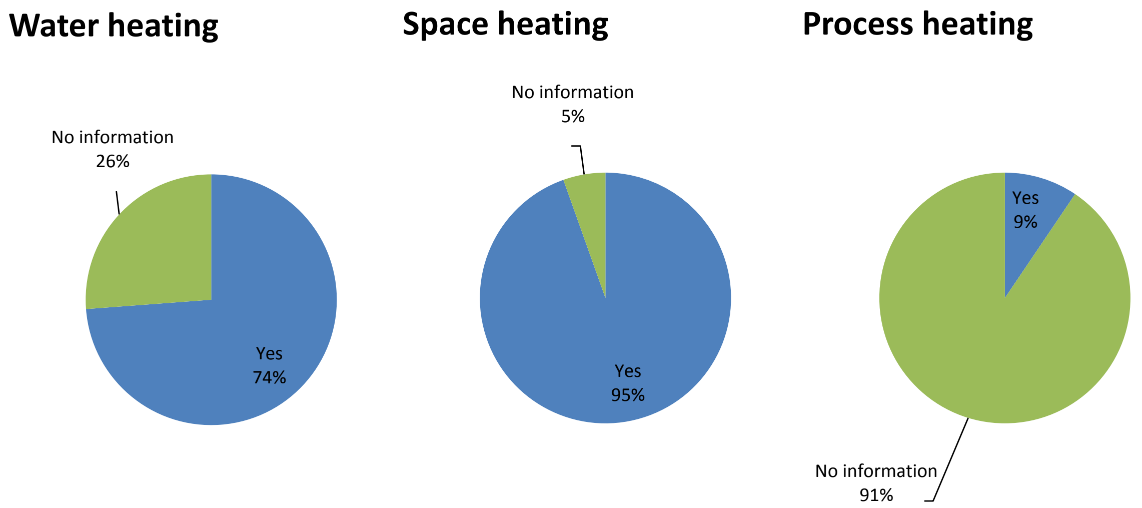


Figure 9: Purpose of the biomass boiler installation in the non-domestic RHI

2.4.4 Emissions

NO_x and particulate matter (PM) emissions were reported for around 75% of non-domestic installations. Of those installations 62% recorded between 50-100g/GJ (net input) of NO_x while emissions of PM were more evenly spread between those reporting <10g/GJ to those reporting >10g/GJ. In all cases the reported emissions were below the limits specified in the RHI eligibility criteria (less than 30 g/GJ PM and less than 150 g/GJ NOx). The remaining 25% of installations with no information were installed across the range of years that the installation data covers (2009-2015), therefore there is no correlation with the period before air quality regulations came into force. This data is presumed to come from manufacturers declarations rather than measured specifically for each installation; hence it does not necessarily reflect the real emission performance on-site.

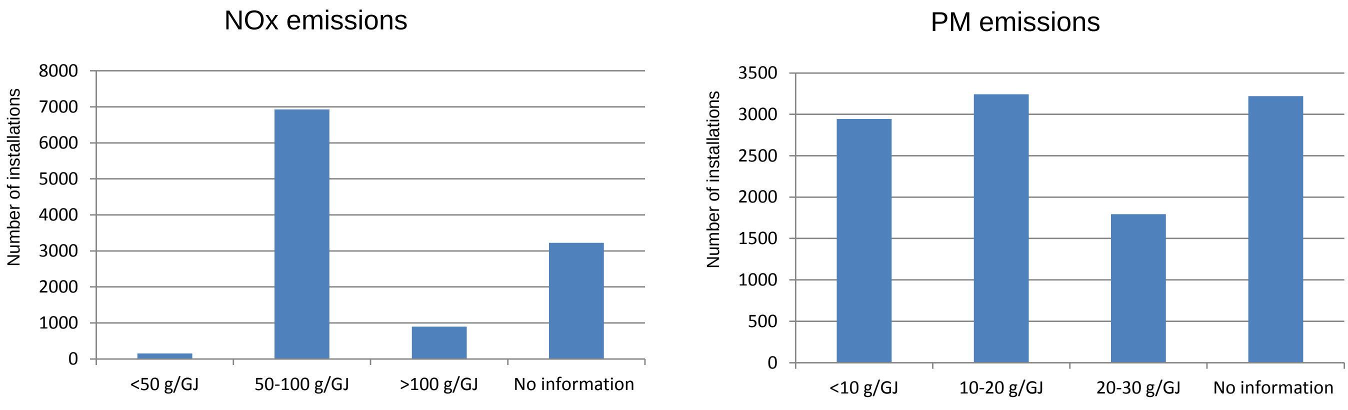


Figure 10: Range of emissions level of boilers installed in the non-domestic market

2.4.5 Boiler manufacturers

There were 160 separate manufacturers of non-domestic boilers identified from the data, of those 160, 17 manufacturers of boilers cover around 50% of all non-domestic installations. This is likely to be because non-domestic installations are more readily installed for specialised / bespoke uses (compared to domestic installations). Therefore there is a broader scope in the non-domestic market for the types of systems that can be installed allowing for a more varied market offering. The larger sizes of biomass boilers and their higher sale prices (by comparison to domestic boilers), are also likely to make the non-domestic biomass boiler market more appealing to manufacturers.

2.4.6 Fuel used in non-domestic installations

Additional questionnaire based information provided by DECC on the types of fuels used in non-domestic installations indicates that 44% of installations overall operate wood pellet boilers, 35% are wood chip boilers and 16% are wood log boilers. The remaining 5% of installations use either: waste and recycled wood, agricultural residues, energy crops or other fuels.

Figure 11 illustrates the main types of fuel used in the non-domestic installations with boiler capacities below 200kW (as discussed above over 90% of the non-domestic installations have installed capacity below 200kW). For illustrative purposes waste and recycled wood, agricultural residues, energy crops or other fuels have been grouped into single category “Other”. Similar to domestic installations, wood pellets are the most commonly used fuel, especially at lower installed capacity ranges, this could be due to a number of factors such as availability, cost or convenience of fuel, or self-suppliers.

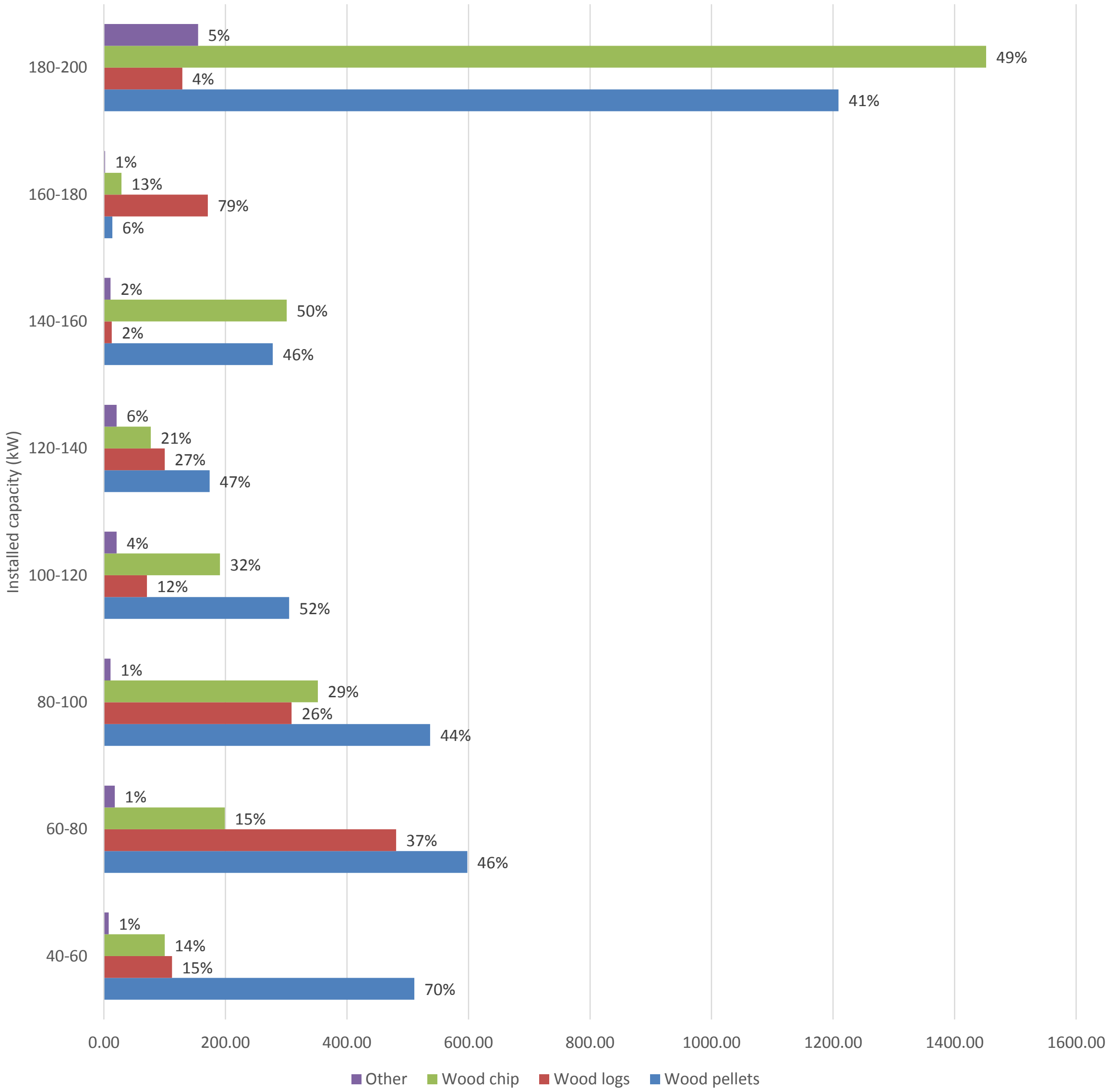


Figure 11: Fuel types used in the non-domestic installations with boiler capacities below 200kW

2.4.7 Less common fuels used in non-domestic installations.

Table 4 shows the separate percentage totals for the use of waste/recycled wood, energy crops, agricultural residues and other fuels compared against a combined total percentage for more commonly used biomass boiler fuels. As can be seen the total use of less common fuels in non-domestic boilers is very small. The greatest use of less commonly used fuels can be found in the capacity ranges above 120kW. This is likely to be due to a greater use of larger capacity boilers in agricultural installations (especially at poultry farms) as a combined way of disposing of agricultural waste and producing heat for farming processes. It is important to note that although waste derived fuels are not common they can lead to higher emissions of NOx and lower efficiencies. For example build-up of deposits inside boilers, higher nitrogen content of the fuels and variation in the fuel composition can increase NOx and PM formation and lower efficiency.

Table 4: Information on less common biomass fuels in RHI data

Capacity Range (kW)	Total for Wood pellets, chip and logs	Waste / recycled wood	Energy crops	Agricultural residues	Other
0-20	0%	0%	0%	0%	0%
20-40	0%	0%	0%	0%	0%
40-60	99%	1%	0%	0%	0%
60-80	99%	1%	0%	0%	0%
80-100	99%	0%	0%	0%	0%
100-120	96%	1%	0%	0%	2%
120-140	94%	1%	3%	1%	1%
140-160	98%	1%	0%	0%	0%
160-180	99%	0%	0%	0%	0%
180-200	95%	1%	1%	1%	3%

2.4.8 Installations of purpose of District Heating

In the non-domestic sector 77 installations (less than 1%) are reported as district heating schemes. Where the boilers provide heat for district heating, they most commonly heat one or two properties (58% of the 77 installations providing heat for district heating). Only six installations provide heat to more than 40 properties. The number of boilers per installation vary with 64% sites having installed a single boiler, and 7% between two to six boilers (no information was available for 29% of installations).

2.5 Stakeholder contact

A small focused consultation was carried out contacting four biomass boiler manufacturers and seven suppliers in the UK along with a UK trade association and two similar associations that operate at EU level. The selected companies were identified as key UK suppliers and manufacturers and their responses are thought to be indicative of wider UK trends. Of the 11 companies contacted, seven have responded (including three non-domestic suppliers, two domestic suppliers and two which supply to both non-domestic and domestic clients). We have been unable to establish contact with the remaining four.

It must be made clear that the information acquired from the suppliers and manufacturers is taken from a small sample and may show bias or be product specific. We are aware that historically many retailers of biomass products, in particular importers, have been misinformed about certain aspects of boiler efficiency and performance factors and that there are many misconceptions in the field. Therefore any claimed relations in this section should be tested if they cannot be supported by evidence.

2.5.1 Fuel types

The majority of stakeholders claim that wood pellets are the preferred fuel (six of the seven respondents), although three of the respondents specialise in pellet boilers which could explain this preference. Two of the respondents also refer to the use of wood chips and logs as being quite popular. Wood pellets and wood chips are also the preferred fuels for biomass boilers at EU level; the former is most commonly used for boilers with an output below 50kW whilst wood chips are typically used for larger scale boilers. According to some of the stakeholders, there is a correlation between the choice of fuel and boiler efficiency, particularly with high quality wood pellets having the most efficient results. The type of fuel used has become more specific in the past seven years according to one stakeholder who has observed that people are more careful with what they burn now. This has positive implications for efficiency due to issues with burning waste or cheap fuel that can release harmful chemicals to the boiler, such as potentially corrosive chlorides from the burning of grass. The responses given in relation to preferred fuel types are in keeping with information reported by the Renewable Energy Association (REA). According to the REA, the most recent statistics for non-domestic biomass boilers show that 91% of fuels used are wood based (meaning wood pellets, wood chips and logs). The remaining 9% of fuel used is straw, agricultural waste, recycled wood and waste and bioenergy crops (short rotation coppice and miscanthus) – all of which have varying moisture content and energy densities. Although our respondent at REA did not have the figures to support the statement, it is probable that the most common fuel for domestic biomass boilers is wood pellets as they require less storage space, the have high energy density and the highest output.

2.5.2 Feeding systems

All stakeholders responded that feed systems are now fully automated and the differences in the available technologies are not thought to be a major factor affecting boiler efficiency. According to one respondent this shift towards automated feeding systems has taken place over the past 10 years more or less with up to 75% of biomass boilers installed as manually fed in the past.

2.5.3 Efficiency rates

The efficiency rates reported by manufacturers are from standardised laboratory spot testing conducted at steady state. These claimed efficiency rates for the biomass boilers supplied by the consultation stakeholders range from between 89% and 94%; although it was not specified whether these are quoted on the net or gross basis (in the EU it is common to only report net efficiencies, but gross values are sometimes quoted). The REA noted that some of their members report net efficiencies up to 95%. Although many view the difference between efficiency rates as marginal, a number of factors were identified by stakeholders as affecting efficiency, particularly in relation to smart technologies (referred to by four respondents). Examples of smart technologies include:

- multiple separate air supplies into the combustion chamber that can be adjusted intelligently
- thermal stores / energy stores
- variable speed pumps
- weather compensation

Assuming correct installation, the efficiency of a biomass boiler is dependent on how the user treats the system. Through their work with biomass boiler users (including a series of workshops), the REA have found that users in the domestic sector will often comply with the rules for usage set out by the manufacturers as the equipment is expensive and they would like to achieve optimum efficiency to save money whilst ensuring that their investment is well maintained. Equally in the non-domestic sector (although to a slightly lesser extent than in the domestic sector), it is suggested that users will follow guidance in a bid to achieve optimum efficiency, and thereby reduce operating costs. Thus, as maintenance and regular servicing is recognised by manufacturers and suppliers as an important factor affecting efficiency, it can be assumed that users are keen to maintain their biomass boilers. One stakeholder commented that 1mm of dust on the whole of the heat exchanger can lead to a 10% reduction in efficiency. This is true of heat exchangers as a component regardless of the boiler type. Appliance efficiency is reported as rising 5% after a service. The quality of installation, and equally the quality of boiler design were also recognised as factors affecting efficiency (the latter was raised by all respondents whereas just two referred to the quality of installation).

The REA commented that, in their view, the quality of installation is typically to a very high standard; however, a number of new companies have entered the industry in recent years in response to government incentives which do not specialise in biomass boilers, installing solar panels along with double glazing, and that the quality of installations has suffered as a result.

Through the communications with stakeholders it became apparent that there was confusion between boiler and system efficiencies, emphasising the point at the beginning of this section that the information provided by these stakeholders could be misleading. In the opinion of Kiwa this confusion becomes particularly acute in underperforming mini district heating schemes where there is clearly a lack of understanding of the contributions made by:

- Poor boiler efficiency (possibly due to excessive cycling);
- Loss of heat from buffer tanks;
- Loss of heat from distribution pipework.

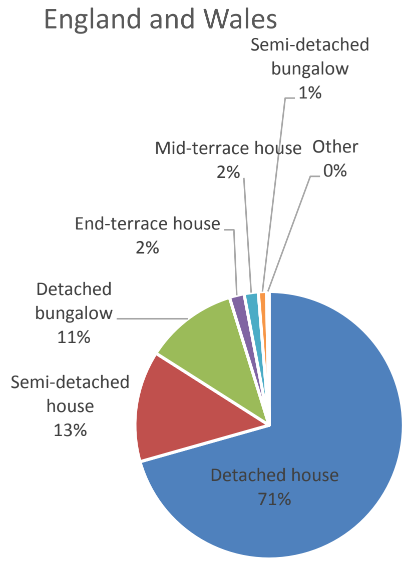
2.6 Trends in biomass boiler deployment

This section describes trends in installation types in the domestic sector based on the evidence gathered in this study. Similar data for non-domestic installations was not recorded in the RHI data provided by DECC.

75% of installations included in the RHI database were in England and Wales, with the remaining in Scotland. Most boilers were installed in detached houses and bungalows. In England, 76% of installations were in properties with 100-300m^2 of floor area, and 19% in properties larger than 300 m^2, with the remaining 5% in properties with a floor area smaller than 100m^2.

Scotland follows a similar trend with 77% of boilers installed in properties with a floor area between 100-300m^2 and 13% in properties with a floor area larger than 300m^2. 98% of properties which installed biomass boilers were occupied for more than 6 months in a year.

The majority of installations (73%) were reported as located in areas with no connection to a local gas distribution network.



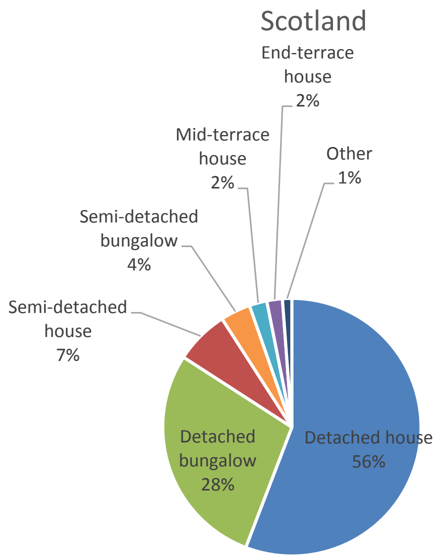


Figure 12: Types of properties which installed biomass boilers

2.7 Categorisation recommendations

Based on this analysis of biomass boilers installed under the RHI, there are two categories of boiler which represent the majority of the installations. These are:

- At domestic scale, 30kW pellet boilers producing central heating and domestic hot water for a single, relatively large dwelling.
- At a larger scale, 180-200kW pellet boilers producing central heating and hot water for one or more business premises (e.g. farm buildings or offices) plus domestic dwellings.
- If possible, installation type data should be collected for non-domestic boilers under the RHI scheme for better characterisation of installations.

Finally, a methodology will be developed that can assess the performance of biomass installations in terms of efficiency and emissions over the entire range of installation size found in this report. This methodology will be presented in the subsequent sections of this report.

2.8 Categorisation conclusions

The trends in installations that have been identified in the report can be attributed to different factors depending upon whether the installation is domestic or non-domestic. From our analysis of the data, the choice of boiler for domestic installations is more likely to be influenced by the following;

- there is a less varied market offering (the number of manufacturers of domestic boilers in the data is much smaller than the number of non-domestic boiler manufacturers);
- domestic consumers prefer automatic pellet feeding installations for greater convenience; and
- RHI banding policy influencing the spread of boiler sizes for installations in the non-domestic scheme.

Boiler choice for non-domestic installations is more likely to be influenced by the following;

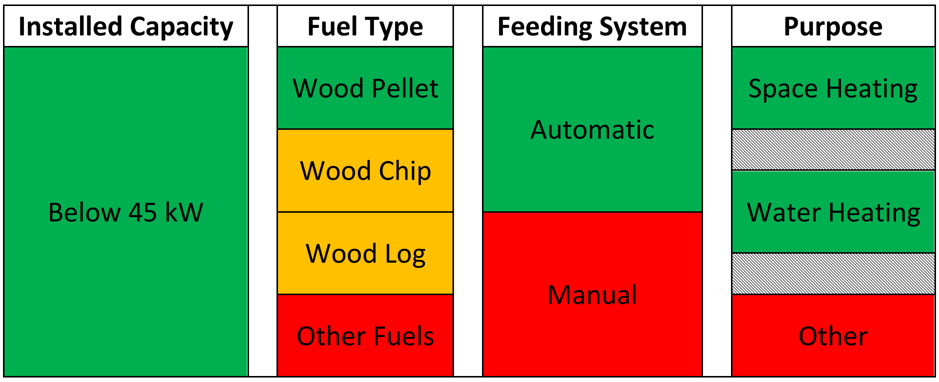
- there is a more varied market offering (there are many more non-domestic boiler manufacturers compared to the domestic data);
- the wider range of uses of non-domestic boilers; and
- the wider range of fuel types used in non-domestic boilers.

Based on the evidence gathered in this study, the following categorisation of biomass boiler installations is proposed to inform the development of the testing methodology in the latter parts of the study. In order to illustrate the most common types of boilers, a traffic light system has been applied in the table below, with:

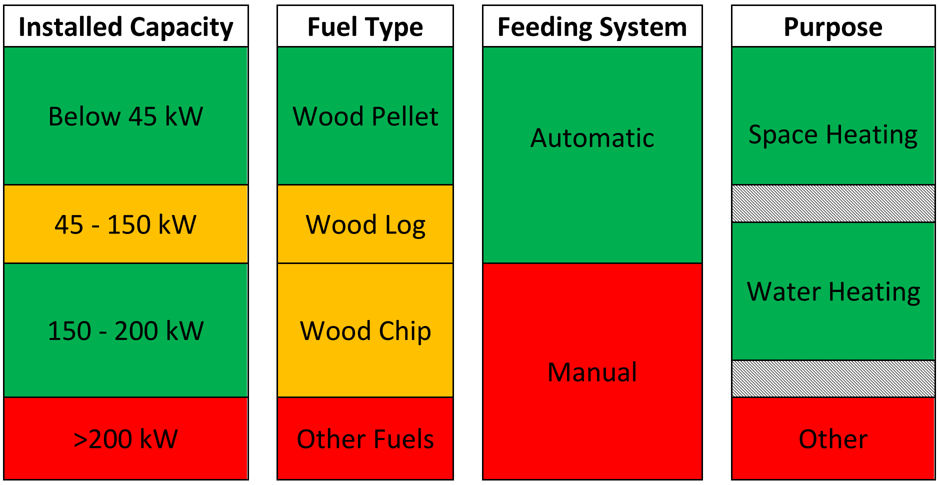
- green demonstrating most common types of biomass boiler installations;
- orange illustrating categories of boilers that are installed less frequently; and
- red highlighting categories of boilers that are rarely installed.

It should be noted that each column indicates the most common characteristic under each heading but the tables do not indicate the most common combinations of characteristics.

Domestic



Non-domestic



Based on our findings the categorisation of biomass boilers will be slightly different for domestic and non-domestic installation types. Non-domestic boilers will need to be categorised by their installed capacity given the wider range of installed capacities for this installation type. Domestic boilers are defined as being below a capacity threshold of 45kW and so are better categorised using other categorises such as feed system and fuel type. Further categorisation of biomass boilers by other additional characteristics such as type of boiler (e.g. boiler or stove), burner type, ignition type, buffer tank or installer would require more detailed characteristic data than available in the RHI data.

3 Factors influencing boiler performance and emissions

3.1 Performance

This section of the report identifies the key factors that can influence the performance of biomass boilers, both in terms of efficiency and emissions. Some of these are well documented elsewhere in publications such as CIBSE AM15, therefore we have not detailed all possible factors influencing performance.

3.1.1 Utilisation factor

Utilisation factor is the extent to which the installed plant is utilised and is defined as the hours per year full load equivalent operation divided by the number of hours per year (8760 hours).

Traditionally most heating systems have been designed to maintain the building at a defined internal temperature (typically 21°C) at a conventionally defined external temperature (typically -3°C) giving a design temperature difference of 24°C. Therefore boiler systems are by definition oversized for most days of the year.

Due to internal thermal gains from lighting, biological gains, IT systems etc. it is conventional to judge the internal temperature required of the heating as 15.5°C, this then gives the following theoretical heat demand for 2014 and the average of the previous 20 years for a building (data taken from (Vesma Degree Days, 2015)). This reference temperature of 15.5°C may not be valid for modern, well insulated houses. However most biomass systems are installed in relatively old properties, so we have used the traditional reference temperature.

Table 5: Utilisation factor degree days, (Vesma Degree Days, 2015)

	Degree days			Utilisation Factor	
	Actual	20-year		Monthly	20 year
Month		Average	Max	2014	Average
Jan-14	324	346	744	44%	47%
Feb-14	286	302	624	46%	48%
Mar-14	246	276	744	33%	37%
Apr-14	164	205	720	23%	28%
May-14	122	133	744	16%	18%
Jun-14	55	66	720	8%	9%
Jul-14	28	34	744	4%	5%

Aug-14	53	31	744	7%	4%
Sep-14	40	64	720	6%	9%
Oct-14	113	145	744	15%	19%
Nov-14	226	247	720	31%	34%
Dec-14	334	347	744	45%	47%
Total	1991	2196	8712	23%	25%

Thus it can be seen that typical design winter utilisation factors are just below 50% and summer below 10%.

Recently, dynamic models have enabled the more accurate prediction of heat utilisation and the matching of installed boiler capacity. However, in Kiwa's experience, in practice clients prefer larger boilers as they offer greater flexibility. Consequentially there is some reluctance on behalf of suppliers to specify a biomass boiler which is designed to heat the building when the outside temperature is -3°C, this leads to a greater degree of oversizing of boilers. All of these factors can result in average utilisation factors nearer 15%.

Of course within the RHI and the wider biomass boiler population there are plants that are not supporting typical heating and / or hot water loads, for example they may be providing heat to a process that is performed constantly for 8 to 10 hours per day, or they may be supporting an environment that has a constant demand for heat 24 hours per day. These sites will have much higher utilisation factors than those providing typical heating and hot water demand.

There are other ways of designing heating systems whilst maintaining high annual utilisation factors. This is particularly prominent when modern oil and gas boilers are relatively inexpensive and where clients demand back-up boilers. The degree of such back-up is client dependent but is often at least two boilers, each of 66% capacity. There is an argument for the installation of a biomass boiler and a fossil fuel boiler each sized to around 66% of peak load. The biomass boiler can then be used to satisfy the demand for most days of the year, with the fossil fuel boiler only operating on the few cold days a year when demand is very high. This ensures that the biomass boiler has a high utilisation factor which leads to better performance in terms of higher efficiency and reduced pollutant emissions.

Evidence of low utilisation factor from RHI data

Kiwa have performed an analysis of non-domestic biomass RHI payment data, provided by DECC (DECC (a), 2015), to understand the average monthly utilisation factors at which these biomass boilers are operating. The key parameters required from this data to calculate utilisation factor are; heat measured, via heat meter, and the installed capacity, as reported by the user. As both values are user reported there are inaccuracies in the data.

The capacity of the boiler is as stated on the boiler nameplate which is submitted to Ofgem with the RHI application. The boiler may operate at a greater output than stated on the nameplate, however this should not be significantly different as the 97% of biomass boilers in the RHI data are ≤500kW output and will have been tested to BS EN 303-5, BS EN 12809, or BS EN 14785 standards which report the nominal output and rebadge it if found to be >±8%. Larger boilers, typically 1MW and above, will have more complex control systems. The output of these boilers will be set upon commissioning and may be different to the badged nominal output. If the output of a boiler is greater than the reported nominal output, this will be difficult to see from the reported data. However larger boiler nominal outputs (for the same reported heat generated), will result in lower utilisation factors.

The eligible heat generated by the biomass boiler is reported regularly to Ofgem by the user. This introduces the potential for misreporting of data, however we cannot account for this in our calculations and Ofgem have procedures in place to prevent such fraud.

With the preceding possible uncertainties in the data, Kiwa still believe that the information reported in the Non-Domestic RHI Biomass Payment Data provides a good basis to perform an analysis to understand the utilisation factors in the non-domestic RHI. This is because the majority of RHI installations, particularly non-domestic sites (that have been subject to independent metering reports) will be badged and metered correctly and honestly. These boilers incorporated automatic ignition systems which allowed them to switch off when demand was very low. Systems without automatic ignition go to “slumber mode” during periods of low load but this can involve quite high fuel use just to keep the boiler warm.

Utilisation factors were calculated as follows:

- The number of days between the start date and end date of the monthly payment period was found;
- Average kWh / day was calculated from the heat measured (kWh) and number of days;
- The installed capacity (kW) for each site was extracted from another data set provided by DECC (Biomass RHI Data) using the unique RHI application number;
- Utilisation factor was then calculated as (kWh/day) / installed kW.

Figure 13 reveals that few boilers operate near the expected value in winter (the 90th percentile) but very many boilers operate far below all these values. For six months of the year they are operating below a 15% utilisation factor i.e. only an average of 9 minutes in the hour. This may be satisfactory for a gas boiler where it might operate in a burst of 3 minutes every 20 minutes, but for a biomass boiler which will take at least 20 minutes to reach optimal operating conditions plus a shutdown period it can be seen these sort of utilisation factors must detract from operation.

Effect on efficiency

We hypothesise that low monthly utilisation factors could be a large influence potentially leading to low in-situ efficiencies of biomass boilers installed under the RHI. We have drawn this hypothesise because it is known that a low utilisation will cause multiple start-up and shutdowns of the boiler. Suitably sized buffer tanks and thermal stores can ameliorate the situation but a high level of over-sizing will even cause these to underperform. To compound the situation, anecdotal evidence suggests that there are many biomass boilers installed without thermal stores, usually due to space and / or capital cost constraints. The situation was less serious when large volume heating systems without sophisticated zone control were common, as these effectively acted as a buffer. Modern small volume systems are even known to hinder the performance of gas boilers.

Effect on emissions

The control strategy for many biomass boilers is designed to minimise smoke production during start-up and shutdown. Thus, primary air will be introduced at a relatively high rate during the start-up period leading to high excess air levels. This high excess air minimises smoke production, but causes significant amounts of heat to be lost in flue gases which lowers the boiler efficiency. The same is true for shutdown periods, during this time no further fuel is added to the firebed, the remaining fuel continues to burn cleanly. As the firebed burns out and the remaining fuel is consumed, this results in increased amounts of excess air and heat losses up the flue. Hence multiple start-up and shut-downs will decrease the boiler efficiency.

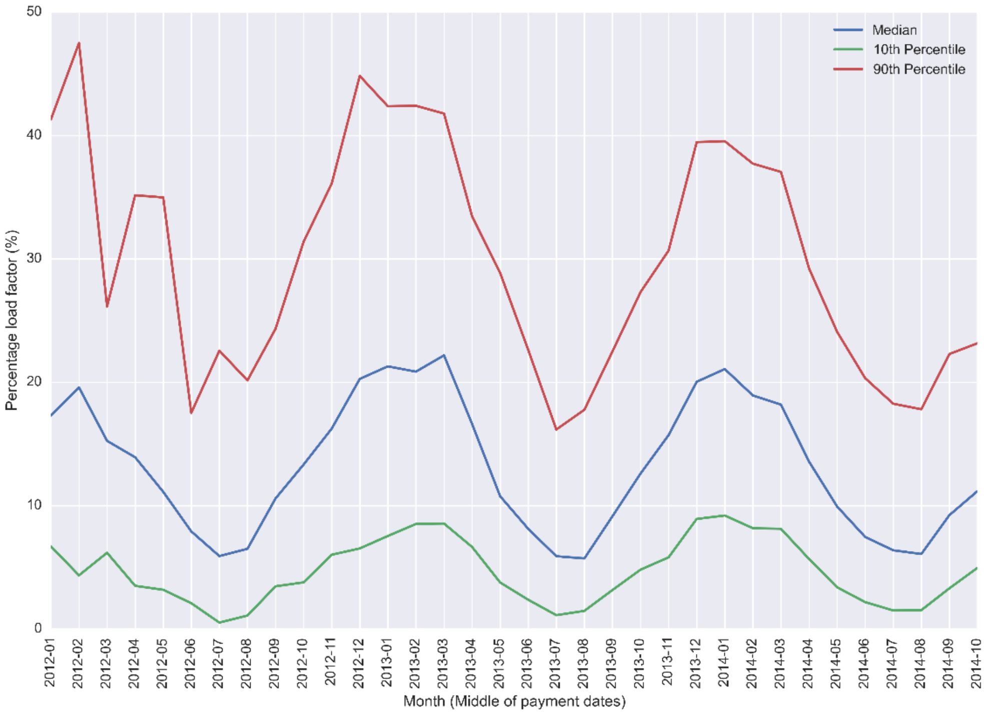


Figure 13: Percentage load utilisation factor of non-domestic biomass RHI installations versus time

How utilisation factor influences performance

To perform a basic test of the hypothesis that low utilisation factors lead to lower boiler efficiencies we have constructed a simple theoretical model of net boiler efficiency based upon the calculations found in BS845-1:1987 (Assessing thermal performance of boilers for steam, hot water and high temperature heat transfer fluids). This theoretical model is strictly for illustrative purposes in order to gain an understanding of how utilisation factor can affect boiler efficiency. It considers a theoretical boiler of 200 kW rated output burning a typical woodchip of 20% moisture, however the trends shown in this model can also be shown for wood pellet and wood chip of other moisture content.

The model simulates a boiler operating over a 24 hour period and analyses its efficiency at 5 minute intervals throughout this period. BS845-1 gives radiative, conductive and convective losses through the boiler casing, as percentages of boiler output for a range of boiler types and outputs. These percentage losses range from 0.3% to 4%, with the smaller percentage losses attributed to larger output boilers. Using the information from this standard, a case loss of 2.5% of output has been assumed for the 200 kW boiler considered in this simple model. It should be remembered that this case loss can often be effectively continuous (in kW) and independent of boiler output. Thus a 200kW boiler suffering a 5kW case loss (i.e. 2.5%) may still suffer a 5kW loss (or only slightly less perhaps 4kW) at 20kW whereupon the effective case loss has gone up to a very material 20% of the fuel feed.

Flue losses are calculated from assumed flue temperature, CO_2 concentrations and fuel input, these losses are subtracted from 100% to calculate instantaneous efficiency. Assumed flue temperatures ranged from 70 °C – 150 °C, these are typical of the range of flue temperatures found in non-condensing biomass boilers of this type. CO_2 concentrations ranged between 1% and 10%, again typical for a biomass boiler of this kind.

Average daily utilisation factor is calculated as energy generated in this 24 hour period as a fraction of rated output. Overall efficiency is calculated as energy delivered as a fraction of energy input.

Figure 14 shows data points which are outputs from this illustrative model. This shows a relationship between low utilisation factors 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 utilisation factor. We know from experience that the line of this graph is justified. The trend line should level out (below 100 % efficiency) as the load approaches 100 % and approach zero at zero load. In this model this efficiency is set by the assumed boiler CO_2 concentration and the flue gas temperature.

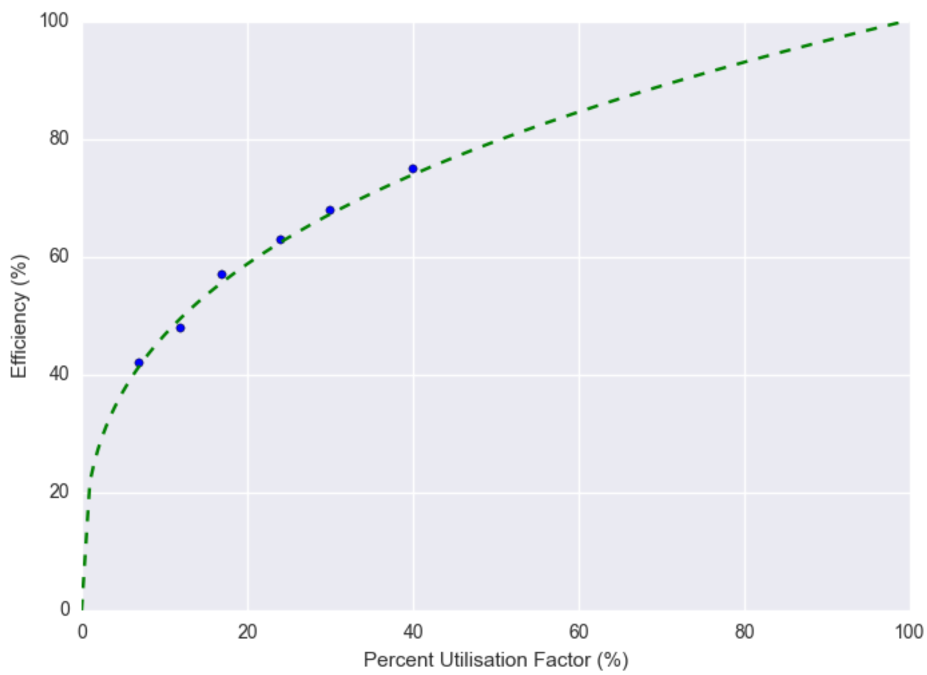


Figure 14: Variation of boiler efficiency with percentage utilisation factor for a 200kW boiler cycling three times per day during normal demand driven operation.

Why low utilisation factors affect efficiency

Large plants, greater than 3 MW, often contain considerable quantities of refractory materials which can hold large amounts of energy. Therefore the response time of large boilers to changes in heat demand can be very slow as the refractory material slowly gains or loses energy. Smaller biomass boilers do not contain such a large mass of refractory and can therefore respond to changes in demand much more rapidly, however due to the nature of solid fuel biomass this will still be much slower than oil or gas fired boilers.

As a result of this, it may take approximately an hour for a large boiler to change load from say 100% to 60% output. This factor is something which may have been unknown to some site operators prior to installation (particularly if they have previously operated oil fired boilers which can be turned up and down relatively quickly). To deal with this problem, a well-designed system may operate two or more boilers with the larger biomass boiler as near to steady state as possible running the base load, and a second smaller biomass and / or fossil fuel boilers and / or accumulator to manage the swings in demand.

In addition to the impact of refractory materials, the problem of slow response time is inherent to all biomass (and solid fuel) boilers due to the nature of the fuel. Typically oil or gas boilers will have less than one second worth of fuel within the combustion chamber. This compares with a solid fuel firebed that may have 20 minutes of fuel bed in the combustion chamber during operation.

Low utilisation performance is conventionally tested by cycling on for 3 minutes and then off for 7 minutes, however the concept of switching a biomass boiler like this on for 3 minutes is impossible – it may take 5 minutes alone for the ignition system to light the bed without reaching optimum combustion conditions. Kiwa have found from experience of visiting sites with plant between (100 kW to 500 kW) that some boilers are oversized, in some cases this is potentially in order to maximise the RHI payment, however this cannot be substantiated. The work on categorisation has shown that the majority of sites use the heat generated for space and water heating; heating will typically cease during summer months, leaving only a very small domestic hot water load. The result would be an average yearly demand of only a few hours per day.

Kiwa have found from our experience that pellet boilers of this medium size typically take approximately 20 minutes to reach full output and wood chip approximately 60 minutes. Therefore running this kind of boiler for short periods of time will not allow them to reach full output and achieve good combustion over the firebed. The level of modulation of these boilers can show substantial variation. When combined with a building energy management system which may not allow for the unresponsiveness of biomass boilers, further problems can arise. Low heat demand from the building will result in short boiler run times, therefore many starts / stops, and total start-up / shutdown time becomes an appreciable part of the total run time.

Smaller domestic scale boilers (<100 kW) can start-up and shutdown more rapidly, and larger boilers (larger than 3MW) tend to be operated at base load with fewer start-ups. The worst problems of low demand leading to efficiency loss caused by rapid on / off cycling are probably seen on the medium sized boilers (100 kW to 500kW, even up to 3MW) where site operators / building managers are unlikely to be aware of the daily start-ups and shut downs of the boiler. Therefore it is important that operators are educated in these matters, and ensure correctly sized and controlled buffer vessels or thermal stores are used to minimise this.

Connection of the biomass boiler to advanced building management systems designed for gas boilers, and thus expecting rapid response and sophisticated load following, would exacerbate this problem.

3.1.2 Fuel Quality

Fuel quality is an important factor in the performance of biomass boilers. Fuel must be of the correct type for the boiler, particularly the feed system. If fuel quality does not match the boiler manufacturer's specification, jamming of automatic feed systems is possible. For example use of waste woodchip in a boiler designed only for wood pellets may lead to jamming of the feed system due to the larger fuel size.

The RHI does not have explicit fuel quality requirements, although the air quality requirements mean that boilers must use the particular type of fuel set out in their emissions certificate. Some boilers have emissions certificates which allow them to burn a range of different fuels. In general, moisture content, particle size and calorific value are the fuel properties which have the biggest influence on the efficiency and emissions from a biomass plant. This why boilers have different rated outputs for each fuel type it can accept

Wood chip

Wood chip is an inherently diverse fuel which can have large variations from day to day and load to load. Kiwa have experience of performing onsite testing of many biomass boilers and have noted that the variance in quality of wood chip can be large and the quality expected by the customer is not always delivered by the supplier.

Recycled wood chip possesses issues that virgin woodchip does not. Depending on the grade of recycled wood chip, the materials contained in this fuel can vary widely, often containing constituents of plastic and treated wood.

If recycled wood chip contains halogenated organic compounds, heavy metals, or is from construction and demolition waste, this fuel will fall under the Waste Incineration Directive of EN 14961-1:2010 and biomass plant burning this fuel will require an Environmental Permit, thus the emissions from these plants should be more closely monitored.

There are regulatory issues related to the contamination of biomass fuel with some of these constituents, however matters concerning these are not considered in this study.

Wood pellet

Wood pellet is a more consistent fuel when compared to wood chip. This is due to the fact that pellet fuel is a more homogenous fuel than wood chip, is of higher calorific value, lower moisture and lower ash contents, but even so there is anecdotal evidence that a percentage of pellets used in the commercial and domestic market are not the ENPlus A1. This is the category most pellet boiler manufacturers recommend. They may well be diverted from pellets originally destined for the power station market and as a result the emissions and efficiency of boilers using these pellets may be significantly reduced. For RHI eligibility biomass boilers must burn the fuel as stated on the emissions certificate.

Fuels burned in the RHI programme

Analysis performed on the categorisation of biomass boilers in this project showed that for domestic installations 99% of fuel type is pellet, log or chip and for non-domestic installations 95% of fuel was pellet, log or chip. In the non-domestic RHI less than 2% of installations use waste / recycled wood, less than 1% energy crops such as miscanthus.

3.2 Factors affecting boiler emissions

The main emissions from biomass boilers are carbon dioxide (CO_2), carbon monoxide (CO), water vapour (H_2O), oxides of nitrogen (NO_x), oxides of sulphur (SO_x), polyaromatic hydrocarbons (PAHs) and particulate matter (PM). The emissions that we are interested in monitoring in this study are:

- CO_2, a greenhouse gas, this allows us to calculate boiler efficiency via the indirect losses method;
- Particulate matter (also known as smoke) this is of particular interest to air quality;
- NO_x, affects air quality, N_2O is a greenhouse gas; and
- SO_x which also impacts on air quality.

The features of the combustion process can be summarised as:

1. Drying – as material is heated for ignition, free moisture evaporates.
2. Pyrolysis – at the surface of the fuel the chemical structure starts to break down in the presence of a limited oxygen availability. Initially smaller chemical groups cleave from the structure. As the temperature rises larger groups are freed including longer chain and ring hydrocarbons and related species.
3. Volatile Combustion – as the gas and vapour species reach more oxygen rich environments they burn to a degree which depends on how much oxygen is available and temperature.
4. Char Combustion – the structure left once volatile matter has been released is a combination of a carbonaceous skeleton char and mineral ash. Once the temperature is high enough and oxygen is available, the char burns to CO_2, or if the oxygen level is deficient, to CO.

3.2.1 Particulate Matter

Potential sources of particulate emissions include:

- Partially burned pyrolysis product – fine char particles;
- Ash particles;
- Incompletely burned char particles;
- Pyrolysis products condensed on the surfaces of other solid particles.

The amount of particulate matter emitted depends on several factors, but primarily:

- The air flow through an appliance is crucial but the effects are complex. Reducing the air supply increases carbon dioxide levels which in turn nearly always increases carbon monoxide (CO) and soot / tar formation. Conversely the same action can reduce velocities through combustion chambers and this tends to reduce particle ‘carry over’ rates from the fuel bed into the flue gas clean up equipment and ultimately up the chimney. In both instances the ratio of air provided above and below the grate is critical. Plots of CO and particulate vs excess air levels often have a so-called bath-tub shape with an optimum level in the middle (ideally about 12-14% CO2) and increasing emissions with either too little or too much air.

- The fuel moisture content can have a significant influence on PM emissions. As fuel moisture increases, the drying and pyrolysis zones become larger, and the combustion temperature may be reduced. This can result in more condensable hydrocarbon particles (smoke) being emitted.

- The fuel particle size and how easily the fuel breaks up (friability) can also have an impact on the PM emission rate. The smaller and more friable the fuel, the more likely it is that PM will be carried out of the combustion chamber with the flue gases.

3.2.2 Oxides of Nitrogen, NO_x

NOx formation in combustion systems is complex. A range of contributing mechanisms have been identified:

1. Fuel NO_x - nitrogen in the fuel is converted to NO_x during the combustion process. This is particularly prominent in fuel crops like miscanthus that are grown with nitrogen fertiliser
2. Thermal NO_x - direct combination of oxygen and nitrogen in the combustion air and becomes significant above about 1300°C, which is not such an issue in biomass boilers where combustion temperature is typically much less than this as boilers are designed to maintain combustion temperatures ≤1200°C.
3. Prompt NO_x – indirect losses route where air nitrogen first combines with fuel and then behaves as fuel nitrogen

Temperature and nitrogen and oxygen availability are the main controlling factors.

Some of the factors that affect smoke formation also influence NO_x formation. However, the complexity of the overall NO_x formation process makes it difficult to predict without detailed knowledge of the conditions in the combustion chamber.

3.2.3 Oxides of Sulphur, SO_x

Biomass fuel contains very low levels of sulphur, typically <0.5% on a dry basis. As a result the emissions of SO_x from biomass fuels is very low. Therefore we suggest it is not worthwhile considering measuring SO_x for this trial.

3.3 Other technological considerations affecting boiler performance and emissions

3.3.1 Combustion control strategy

The combustion control strategy for most biomass boilers gives precedence to smoke reduction by operating at high excess air, particularly during start-up and shutdown. This is in order to minimise particulate emissions to meet air quality requirements. However, it is well known that operation at high excess air leads to poor efficiencies. These issues were first noted many decades ago in relation to coal fired boilers and cost effective solutions have proved very challenging. The use of wood fuel adds further complication as the fuel particles have lower density compared with mineral fuels. These lower density particles from wood fuel are more likely to lift off from the fire bed and be emitted from the chimney as smoke / particulate matter.

In general, a number of issues must be taken into account by the designer:

- Upper firebed combustion rate ($kg/m^2/h$) is limited by particulate lift off and slag formation (slag will typically only be formed with biomass fuels such as straw).
- Minimum firebed combustion rate is limited by bed stability and modulation is limited due to decreasing firebed temperature and deficiencies of fire evenness due to uneven air distribution without large grate pressure drop.
- Firebed cross lighting rate is finite which creates start up smoke.
- Firebed shut down rate is finite which creates shut down smoke.

The use of technologies such as compartmentalised under grate plenums can be used to control the supply of primary air to different areas of the firebed, but this is challenging with a naturally variable and unrefined solid fuel, such a wood chip.

Many biomass boilers have oxygen trim control, a system that measures the free oxygen in the boiler flue gas (in order to calculate excess air) and adjusts the excess air accordingly. This should be beneficial on a well-run plant with a consistent fuel analysis and uniform fuel feed rate, however, if the firebed suffers local instability, most likely because the fuel quantity is variable, an oxygen trim controller may negatively impact the efficiency of the boiler.

3.3.2 Boiler Architecture

Boiler design can vary greatly dependent upon boiler size, fuel type and manufacturer. Stoker, heat exchanger, flame and ignition characteristics of boilers will have an impact upon boiler performance in terms of both efficiency and emissions.

Different types of combustion system, e.g. underfeed, top feed and cross feed stokers have different characteristics. Characterising the effect of these parameters on system performance is very difficult, as separating the influence on efficiency of stoker type from tube type or ignition type is complicated.

3.3.3 Effect of flues and flue draft on biomass boiler performance

Generally the efficiency and emissions from modern biomass boilers with Forced Draft (FD) and Induced Draft (ID) fans are much less dependent upon flue conditions than those of years ago, and the fundamental effect on operational efficiency is likely to be modest. However, the following should be considered:

- Most solid fuel fired appliances operate with an FD fan to supply air to the combustion zone. Traditionally, solid fuel boilers operated under natural draft flues. These inevitably required high flue temperatures (~250^{0}C) to guarantee chimney operation and a low pressure heat exchanger, which conveniently also produces high flue temperatures. This inevitably resulted in low boiler efficiencies.

- Nearly all appliances over 45kW (the domestic threshold) are now fitted with ID fans, to enable operation with low flue temperatures and hence operate with reasonable efficiencies except at the lowest turn-down rates. These ID fans also reduce the risk of explosion from delayed ignition, as they may be used to clear fume build-up over the fire bed. Large boilers without ID fans tend to be of modest efficiency unless below tall chimneys.

- Boilers with very tall chimneys may be fitted with flue gas draft dampers which allow cool air into the flue to limit the draft on the combustion chamber and hence the risk of fuel burning back into the fuel feed, but the position and setting of such a damper needs careful consideration to avoid the risk of it becoming a source of CO in the boiler house.

- Unless the boiler is a condensing boiler, condensation in the flue is to be avoided. History indicates the condensate from biomass boilers should generally be regarded as hazardous unless proven otherwise. Several pellet boilers are now undoubtedly sufficiently clean to operate in condensing mode and put condensate to foul drain.

- The flue should discharge at sufficient height and sufficient velocity so as not to produce offensive / hazardous fume at ground level or allow re-entry into a building during either ignition or shutting down.

- Long and complex flues should be avoided due to the possibility of blockages occurring.

3.3.4 Control strategy / architecture measurement strategy

Measuring the performance in terms of efficiency and emissions will not be affected by control system or boiler architecture. The proposed methodology will record the boiler control strategy and boiler technical characteristics so that conclusions can be drawn about the different categories of system or control strategy. Records will be kept of boiler type, design fuel, feed system, grate system, gas clean-up equipment, and control upon installation of the monitoring equipment.

3.3.5 Boiler electricity use

Boiler electricity use can be quite variable from boiler to boiler, and although probably less than 1% of the energy input to the plant at full output can become more significant at low loads. However, biomass boiler electricity use is significantly higher than for an oil or gas boiler due to the requirement for mechanical handling equipment and extra fans etc.

Electricity use can certainly be used to determine whether the boiler is firing or not and may be possible to determine power output level. This depends upon the control strategy.

4 Solutions to poor performance

4.1 Solution to low utilisation factor

There are a number of technological solutions to the low efficiencies caused by low utilisation factors. A simple way to deal with low loads is to install a thermal store. At this point it may be helpful to clarify the difference between a thermal store and a buffer tank in relation to boiler systems:

- A thermal store is a large vessel used to store hot water in order to manage swings in demand, allowing a boiler to operate at full output irrespective of demand.
- A buffer tank is a smaller water tank that improves system efficiency by accepting the residual heat left by the fuel remaining on the firebed after the boiler is shut down and then releasing this heat upon boiler start up.

Installation of a thermal store allows swings in demand to be managed. With an appropriately sized thermal store, a biomass boiler can operate at maximum output for the entire time it is running, storing the generated heat in the thermal store and delivering it as required. Consequently the boiler is always operated at a high load which helps optimise efficiency.

It should be noted however that these thermal stores do operate over substantial temperature ranges and have significant volume. The following table indicates the mass of water required to enable a 200kW boiler to fulfil a utilisation factor of about 9% i.e. operate about 144 minutes per day. This is about 7 tonnes or 7m^3 of water cycling between 60 and 85°C. As an aside, there is a further complication because many sites would not permit the dispatch of water at 85°C due to concerns over excessive radiator temperature. The installation would thus require secondary low temperature circulation loops.

Table 6: Illustrative properties of a thermal store

Boiler	**kW**	200
Run time	**minutes**	60
Tank Low	**°C**	60
Tank High	**°C**	85
Mass water	**kg**	6890
Load	**%**	10
Run time	**minutes /day**	144

Secondary boilers can also be used to allow for lower utilisation factors on a biomass boiler system. When installing a biomass boiler it could be argued that the best system may possibly be a smaller biomass boiler with a small gas or oil fired boiler to provide fast response when there are short term demands or when there is a peak in demand that the biomass system cannot satisfy. Kiwa appreciate the fact that this may not be received as an acceptable option to some, who are installing a biomass system to lower CO_2 emissions and move to a renewable technology. However, there is a possibility that a biomass boiler operating very inefficiently due to on / off cycling could have higher carbon emissions than a smaller biomass boiler operating for long periods of time coupled with a fossil fuel boiler for peak shaving.

4.2 Solutions to high emissions- abatement technologies

Compared to conventional fuels (such as fossil fuels), biomass combustion emits higher levels of oxides of nitrogen (NO_x) and particulate matter (PM) with negative consequences for localised air quality, this is still significantly lower than emissions from diesel vehicles. A number of abatement technologies have been developed to prevent the formation of both NO_x and PM, known as primary abatement technologies, along with secondary abatement options which target the emissions once formed. The following review is based on a report which considered technically feasible abatement options for biomass and/ or combined heat and power plant (Amec, 2013).

4.3 Oxides of nitrogen

A combination of factors from biomass combustion contribute to the formation of NO_x, including:

- The fuel-bound nitrogen (FBN) content in biomass fuels;
- The peak flame temperature;
- Oxygen content at peak flame temperature;
- Residence time at high temperature.

Addressing the formation of NO_x in the first instance can reduce NO_x emissions from biomass combustion.

4.3.1 Primary NO_x abatement

The FBN content varies with the type of biomass fuel. The combustion of biomass with low FBN content can reduce NO_x emissions – wood chips, wood pellets and wood logs from native softwood varieties typically emit the lowest level of NO_x emissions while herbaceous energy crops such as miscanthus will typically have higher emissions (emission concentrations are set out below in Table 7).

Table 7: Typical NOx emissions according to biomass fuel types (measured at 11% O_2)

Fuel type	Typical NO_x emission concentration
Native softwood - evergreen, coniferous species	100-200
Native hardwood - deciduous, broadleaved tree species	150-250
Established herbaceous energy crops - switch grass, miscanthus, straw	300-800
Urban waste wood and demolition wood	400-600

Previous research in this study shows that small biomass boilers which are installed in the UK are typically designed for wood chip and wood pellet combustion. As well as their low FBN content, native softwood and hardwood chips and pellets are also recognised as highly efficient biomass fuels which are easy to store and cost-effective with few apparent barriers to uptake. Urban waste wood and demolition wood can have significantly higher emissions due to contaminating compounds present.

Technologies to monitor the combustion temperature and the level of oxygen content, thus limiting the formation of NO_x, have become increasingly commonplace and are incorporated within the design of modern biomass boilers. The relevant primary abatement technologies incorporated in modern biomass boiler design are outlined below:[3]

- Staged combustion: this affects the way biomass combustion occurs, restricting oxygen levels in the first stage of combustion and maintaining a lower temperature level in the second stage of combustion. Technologies to facilitate staged combustion have advanced significantly over the past 10 years and it is now considered standard practice for biomass boilers to be equipped with this technology. Staged combustion can reduce NO_x emission by up to 50%.

- Automated process control systems: these systems monitor temperature and oxygen levels to ensure optimum conditions for reduced NO_x formation during combustion. Automated process control systems can also be used to benefit general boiler efficiency, for example to monitor CO levels, and regulate fuel feed rates along with flue gas recirculation rates. It is now considered standard practice for biomass boilers to be equipped with this technology particularly to monitor temperature and oxygen levels. Automated process control systems

[3] Additional abatement technologies exist for biomass combustion which are not included here as they are not compatible with biomass boilers with a capacity below 200 kW. These include dry low NOx burners and exhaust gas recirculation.

can limit NO_x emissions to 65-100 g/GJ in the case of biomass boilers with a capacity below 1 MW.

- Flue gas recirculation rates: this process reuses waste gases to lower the combustion temperature and reduce oxygen levels. Where installed, it can be monitored by automated process control systems to achieve optimum reductions. This abatement technology is not commonplace in biomass boilers for NO_x reduction due to the limited reduction potential it has for small solid fuel appliances such as biomass boilers with a capacity below 1 MW. However it is widely used to help with boiler operation and heat transfer, and it can result in reductions in NO_x of up to 15%.

4.3.2 Secondary abatement technologies

Secondary abatement technologies to mitigate NO_x emissions once formed are typically designed for large combustion plant rather than smaller domestic and commercial biomass boilers. Cost, space and technological compatibility are the main reasons for this. For small biomass boilers only selective catalytic reduction (SCR) is applicable (currently only available to boilers with a capacity greater than 300 kW). This process involves the injection of a chemical reagent (ammonia based) into the gas stream at the point of highest temperature in the combustion chamber. The reagent changes the composition of NO_x to molecular nitrogen and water. The process requires a precise quantity of chemical reagent and high temperatures ranging between 180 – 450˚C, otherwise the changes to the chemical composition of NO_x will be incomplete and can lead to increased NO_x emissions (referred to as 'slippage').

Due to the high temperature required for this process, it can be difficult to retrofit as most biomass boilers typically operate below 200˚C. As well as technical limitations, there are spatial limitations, for example space needed for an ammonia storage installation, and capital costs for the equipment. In the case of small biomass boilers, retrofitting SCR requires supplementary heating, resulting in greater operating costs (see Table 8). Furthermore, the catalyst needed for this process must be replaced regularly to overcome the build-up of dust and sulphurous compounds which have adverse effects on the potential reduction efficiency of this process.

Technological developments have meant that this process has become available to biomass boilers with a capacity of 300 kW for specific designs; however, this process is not commonly used in small biomass boilers due to the cost and spatial requirements outlined above.

Table 8: Range of costs for NO_x reduction methods for biomass boilers with a capacity below 300 kW

Reduction method	Capital cost (£)	Operating cost (£)	Total annualised cost (£)	Reduction efficiency (%)
SCR	690 – 3,001	2,509 – 2,538	2,595 – 2,908	40

Source: (Amec, 2013)

Note: The range of costs derive from low and high cost scenarios and assume that the reduction method is applied to a modern boiler with staged combustion and an automated combustion control system.

4.4 Particulate matter

4.4.1 Primary abatement options

Primary abatement options for particulate matter are much the same as for NO_x and are commonly incorporated within modern biomass boiler design. Assuming that the boiler is fitted with staged combustion and an automated combustion control system, PM emissions are generally less than 30 g/GJ.

The correlation between fuel selection and PM emissions is not discussed in the literature reviewed. The composition of the fuel, for example inorganic salts content, can however influence PM emissions.

4.4.2 Secondary abatement options

The following secondary abatement technologies to mitigate PM emissions once formed can be applied to small domestic and commercial biomass boilers:

- Multicyclones: This system consists of multiple cyclones which use gravity and centrifugal force to gather particles on the wall of the cyclones. It can collect between 50 and 75% of the PM_{10} formed and up to 10% of the finer $PM_{2.5}$. It is a relatively simple and unobtrusive abatement technology with modest costs that is compatible with small biomass boilers.

- Electrostatic precipitators (ESP): An electric charge is passed through the flue gas flow charging PM and causing it to move towards a collection plate which must be maintained with regular cleaning. This process is currently limited to large plants in the UK but can be applied to small biomass boilers as evidenced by its increasing popularity elsewhere in Europe. Abatement efficiency for $PM_{2.5}$ and PM_{10} is typically greater than 90%. Capital costs are greater than other secondary abatement options but operating costs are less – these costs have not been included in the scenarios.

- Filtration: Dust filters act as a barrier preventing PM from escaping the flue, consisting of either fabric or ceramic material. A fan is positioned to push the gas flow through the filter. The filters require regular maintenance to remove the PM that has accumulated, and require replacement every two years or less (particularly where the biomass fuel has a high moisture content). Filters are regarded as the most efficient secondary abatement technology for PM_{10} with removal efficiencies of 99% – whereas for the smallest particles ($<PM_{2.5}$) ESP offers better reduction. Capital costs can be up to 30% of the boiler and operating costs are higher than the other secondary abatement technologies for PM due to the cost of cleaning maintenance and additional power needed to operate the fan (costs and reduction efficiency are presented below in Table 9).

Table 9: Reduction methods for biomass boilers with a capacity below 300 kW

Reduction method	Capital cost (£)	Operating cost (£)	Total annualised cost (£)	Reduction efficiency (%)
Multicyclones	340 – 620	130	170 – 200	50
Fabric or ceramic filter	3,900 – 13,500	270	750 – 1,940	99

Notes: The range of costs derive from low and high cost scenarios and assume that the reduction method is applied to a modern boiler with staged combustion and an automated combustion control system.

5 Measurement of boiler performance

5.1 Boiler efficiency

Efficiency measurement – direct and indirect losses

There are two ways of measuring boiler efficiency:

1. The **direct** method
2. The **indirect losses** (or losses) method

Note: At this point, a distinction must again be drawn between net and gross CVs of fuel, which make different assumptions on the energy reclaimed by water vaporised during combustion. A gross CV assumes that the energy in vaporised water is reclaimed whilst a net CV does not. For historical reasons, most CVs are quoted gross in the UK and (until the introduction of the Energy related Products directive (ErP)) net in the rest of Europe.

The traditional method employed in fieldwork such as this is the direct method, which means measuring all the useful energy output and dividing by the energy input. In this case, the useful energy input is the mass of fuel in, multiplied by the calorific value (CV) of the fuel. The principle adjustment in the case of biomass is for the moisture content of the fuel. The useful energy output is recorded by a heat meter.

Therefore the direct method is based upon the measurement of the following parameters: temperature of the water out of the boiler (flow), temperature of the water into the boiler (return), the mass flow rate of the water, mass flow rate of fuel to the boiler, fuel CV and fuel moisture. The temperature difference between the flow and return temperatures along with the water mass flow rate yield the heat energy transferred to the water. The fuel mass flow rate, fuel CV and moisture yield the energy content supplied to the boiler.

We do not recommend the use of the direct method of measuring boiler performance in a field trial for the following reasons:

1. Accurate measurement of the fuel feed rate is required to use the direct method. This is difficult in a field trial for many reasons, for example:

- Fuel can be fed to the boiler using a variety of technologies such as walking floors, screw feed augers or sweeping arms, with the fuel delivery system often being bespoke to each site. The result of this is that any automatic methodology for measuring fuel feed rate must be specifically engineered for each site.
- Enlisting the site operators / mangers to measure all fuel into the boiler over an extended period may be successful with enthusiastic owners / operators or by providing incentives for doing so. However even the most enthusiastic operator will inevitably introduce uncertainties into the measurement
- Fuel stores are inherently dangerous spaces, due to sweeping arms, augers, hollows formed under the fuel surface, the possibility of high CO, other combustion products, and the possibility of ignition.
- With large non-domestic sites with large fuel consumption the manual measurement of fuel feed rate will be physically impossible over any suitable timescale. As this would require the effort of at least two dedicated people manually feeding the boiler for the entire period of the trial, clearly impractical for large sites with large feed rates and long operating hours.
- Measurement of fuel from fuel store to fuel delivery system may not reach the boiler for a significant length of time due to distance covered by feed system.

2. Due to the issues regarding measurement of fuel feed rate, it will be impossible to calculate instantaneous efficiency measurements without extremely detailed fuel feed data. This is possible using the indirect losses method.

3. At very low utilisation factors (~5%) direct efficiency measurement over short periods can easily be distorted by the thermal mass of the boiler, yet it is precisely these periods of extreme poor performance which are of interest to boiler designers and site operators. In many ways the indirect losses method is more responsive to the loss of significant heat up the flue.

4. No information on the way in which heat is lost from the boiler (consequently reducing efficiency) will be gathered. This is measured using the indirect losses method, which will give greater insight into how / why boilers perform well / poorly.

5. Only one set of data, heat delivered to the transfer medium (water / steam), will be available to give information on boiler cycling as the fuel feed rate data will be unreliable.

6. The heat delivered to the transfer medium (water / steam) is measured by a heat meter. From Kiwa's experience of visiting non-domestic RHI sites, we have found that the heat meters on some biomass sites may be incorrectly installed and or installed in a position that would provide erroneous results for the proposed field trial, for example if placed after a large thermal store. As such additional meters would need to be installed.

7. The direct method is used to assess annual performance and becomes less accurate the shorter the measuring timeframe, such as month by month or week by week.

An alternative method Kiwa use regularly when measuring the performance of large biomass boilers is the **indirect losses** or **losses** method. The indirect losses method is a robust method and is the prescribed method in the British standard BS 845-1 (Assessing thermal performance of boilers for steam, hot water and high temperature heat transfer fluids). A flow diagram of the indirect losses procedure is shown in Figure 15. This method involves calculating all the losses (sources of inefficiency), and subtracting them from 100%. In the case of a biomass boiler, the largest source of losses is usually due to the sensible heat in the flue gases. However, there are also losses due to conduction, convection and radiation from the case of the boiler (collectively called case losses), losses due to enthalpy in flue gas water vapour, losses due to unburned flue gases, losses due to combustible matter in ash, and condensate in the case of condensing boilers. (Although there are some condensing biomass boilers installed in the UK, so we do not expect them to form a major part of the field trial.)

Kiwa have considerable experience in the application of both methods of measurement, and have found that for biomass boilers (especially those using fuels which vary in quality i.e. fuels other than wood pellet), the consistency and rate of fuel supply requires careful and considered measurement if accurate results are to be obtained. This can be very difficult in practice, even with dedicated engineers present, therefore in a field trial this becomes even more complex and introduces large uncertainties. This may then have a material impact upon the direct method as this method is strongly dependent upon knowing fuel feed rate accurately, as illustrated in Figure 16.

The indirect losses method will successfully yield boiler efficiency values without knowledge of the fuel feed rate to the boiler. Therefore the indirect losses method is an attractive method for a field trial as it can yield boiler efficiency results with a higher degree of accuracy without the requirement of directly measuring fuel feed rate. Heat output (via a heat meter) is still required to correct for electrical input and case loss but the level of uncertainty from this value can be much larger than in the direct approach and yet still yield the same level of confidence in the final plant efficiency.

Parameters required for the indirect losses method

Both the indirect losses and the direct methods require measurement of a number of parameters which relate to boiler performance. As indicated previously long experience of the direct method indicates the great challenges of this method. A large electricity generating station will have a whole department (many full time staff) measuring fuel input. They do this because at this scale (>£10,000 / hour of fuel) they really need to understand the subtleties of variation in combustion of the different feedstock's. Therefore Kiwa strongly recommends the indirect losses method.

To calculate the losses, the indirect losses method requires taking measurements of flue gas temperature, ambient temperature, case temperatures and areas, flue gas CO_2 (or O_2 as a proxy) and fuel specification (elemental analysis and calorific value). A flow chart of the measured parameters and how they fit into the indirect losses efficiency measurement methodology is shown in Figure 15, and for comparison a flowchart of the direct method is shown in Figure 16. Therefore this method requires the following parameters shown in Table 10.

Table 10: Indirect losses method, losses and variables found in the related equations

Loss due to	**Variables in equation**
Sensible heat in the dry flue gases	• Carbon content of fuel • Flue gas temperature • Ambient temperature • Concentration of CO_2 in flue
Enthalpy in the water vapour in the flue gases	• Moisture content of fuel • Hydrogen content of fuel • Calorific value of fuel • Ambient temperature • Flue gas temperature
Unburned gases in the flue	• Concentration of CO_2 in flue • Concentration of CO in flue
Radiation, convection and conduction losses	• Case surface temperatures • Thermal properties of case material • Ambient temperature • Actual rate of heat input to boiler • *Alternatively these losses can be estimated from empirical data as prescribed in BS845-1*

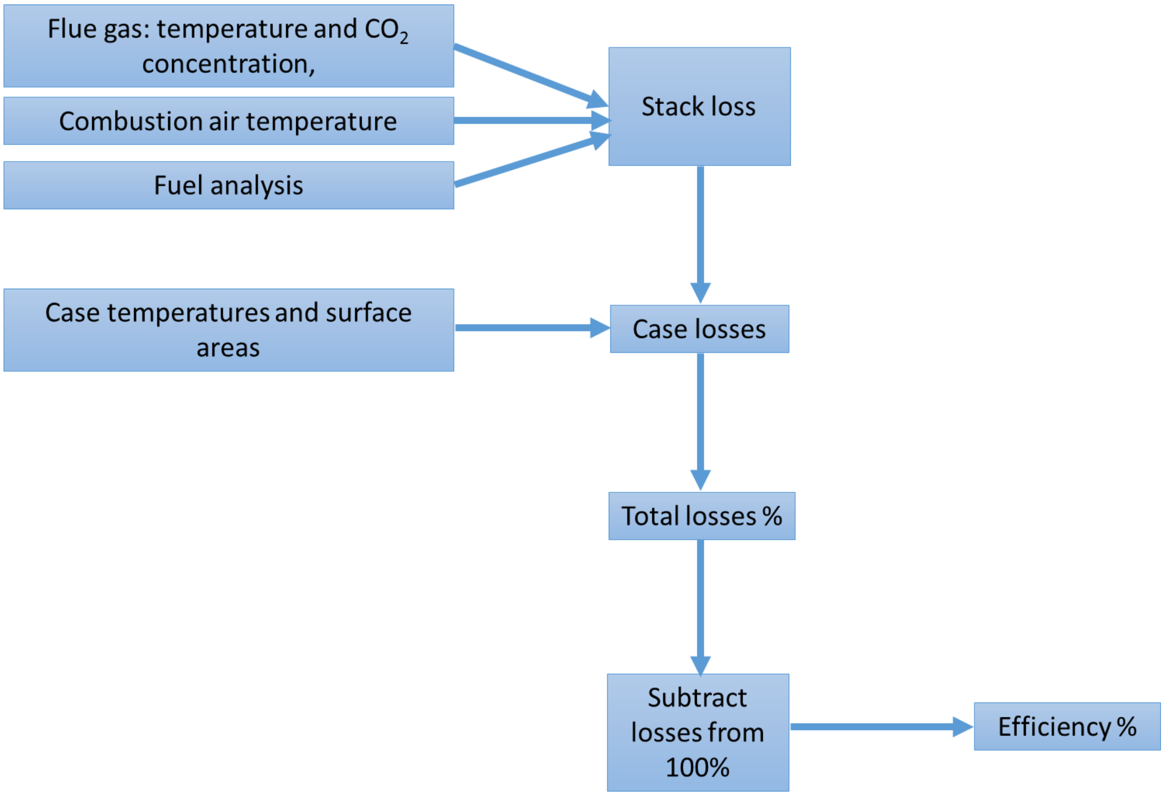


Figure 15: Indirect losses (losses) method flow chart

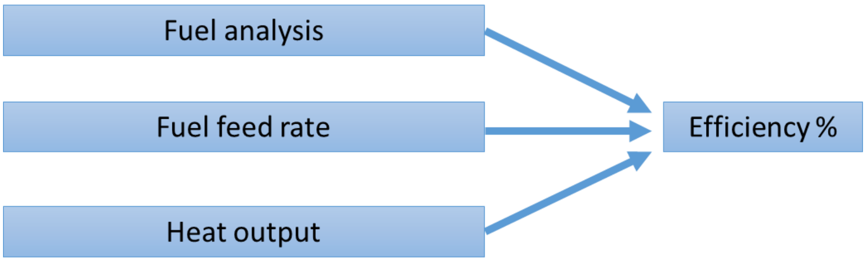


Figure 16: Direct method flowchart

5.2 Emissions

5.2.1 Flue gas NO_x

Flue gas NO_x emissions are one of the two air pollutants of particular concern for biomass boilers. Flue gas NO_x measurement over extended periods requires the installation of an extractive gas analysis system which will require regular maintenance and calibration by skilled staff. This would involve installing a sample point within the flue and taking an extractive sample. This would require purchasing a gas analyser for every site that was chosen for monitoring NO_x. In the same way that extractive CO_2 and O_2 analysis would be very complicated and costly, extractive NO_x sampling would suffer from the same drawbacks. The extractive NO_x analyser would require changing or cleaning of filters daily, weekly calibration and tri-monthly servicing. Hence we do not recommend measuring NO_x in an extensive field trial.

Typical methods of determining NO_x levels are:-

- Non-dispersive infra-red (NDIR) measurement absorption. This technique can measure NO, but not NO_2 because of interference from water vapour (a species inevitably present in biomass exhausts).
- Chemiluminescence - NO only
- Electrochemical Cell - NO only

The authors have used NOx detection methods over many years. Apparatus (including sample preparation lines) is usually of the order of £15,000 to £25,000 and does require routine calibration against reference gases. In our opinion it is very much designed for spot readings as might be the case in a garage or in a fully manned laboratory. The authors are unaware of equipment designed to take and clean up an inevitably dirty sample from a biomass flue over extended periods. It is unlikely commercial guarantees could be enforceable in such operation.

The formation of NO_x from biomass is a complex scenario that is dependent on the equipment, the fuel and, to a very great extent boiler control strategy. Therefore, without direct measurement of NO_x, calculation of NO_x emissions from theoretical relationships is extremely complex and would not be possible for a field trial where each boiler may be of a different design.

5.2.2 Flue gas particulate

The other important air pollutant is particulate matter (smoke). Measurement of particulates is a challenging operation although known to be important as some current biomass boiler installations are regarded as polluting by neighbours. The measurement of particulate rates from on-line cycling / modulating boilers is particularly challenging. The most accurate method of measuring particulate emissions at steady state (usually 100% load) is to use a European Standard method (BS EN 13284-1) where flue gas is extracted isokinetically from the chimney or ductwork and the particulate material is separated using a pre-weighed filter. This method gives a spot measurement and tests must be carried out during all phases of the boiler operation if the emissions are to be properly characterised. It is worth noting however that even when tests are carried out at a range of steady state outputs this is not the same as the instantaneous emissions from a modulating boiler where it is likely the fuel bed / air ratio may be sub-optimal. The highest levels of smoke are always observed during ignition or shut down.

With some fuels there is a strong relationship between particulates and chloride (sodium and potassium) levels and particulates. An alternative method is to use an obscuration meter where light is passed across a flue duct or chimney and the amount of light reaching a detector on the opposite side is measured. This is known to be quantitatively less accurate than the extractive measurement, but it can be arranged to give a continuous measurement of obscuration which allows the emission to be calculated over long periods of time. Obscuration devices have a long history of being used for both ambient and stack emissions monitoring and have the advantage of being a reliable technology requiring little maintenance.

Operating Principles of Obscuration

There are a number of relationships that exist between:

- Obscuration
- Specific optical density
- Concentration (number of particles per unit volume of flue gas at flue conditions)
- Particle specific gravity
- Rate of mass discharge of particle from a flue

The fundamental principles of these relationships were described by Rayleigh, Mie and Beer in the late 19th and early 20th Centuries and are well understood.

The instrumentation in an obscuration meter measures the attenuation of a light beam across the flue diameter as a function of the Beer Lambert law. The light intensity at the photoreceptor is related to the initial intensity of the un-attenuated beam which gives the transmittance, from this the specific optical density is found. This can then be correlated to a mass concentration of particulates using empirical data relating obscuration to mass concentration of particulates from wood smoke. This empirical relationship has been shown to be approximately linear in the work illustrated below, but also in many other investigations with smoke produced from a variety of sources (Dept. of Scientific and Industrial Research, (1960); Beutner (1974); US Dept. of Agriculture (1966);Thielke & Pilat (1978))

Historical Data

Figure 17 shows data from Foster (1959), Tran (1990) and the Kiwa laboratory. Each of these investigations measured the optical density of wood smoke flue gases. This data illustrates a strong correlation between the optical density of flue gases measured and the mass concentration of particulates in the flue gas. The relationship between optical density and mass concentration is dependent upon the particle densities. However it is known that most of the particles produced from wood combustion are oil or tars with density in the range of 900 – 1200 kg/m^3 and the particle size range of particulates from wood smoke are likely to be the same for all industrial wood smoke, therefore the relationships shown in the presented data will hold for all wood fuels.

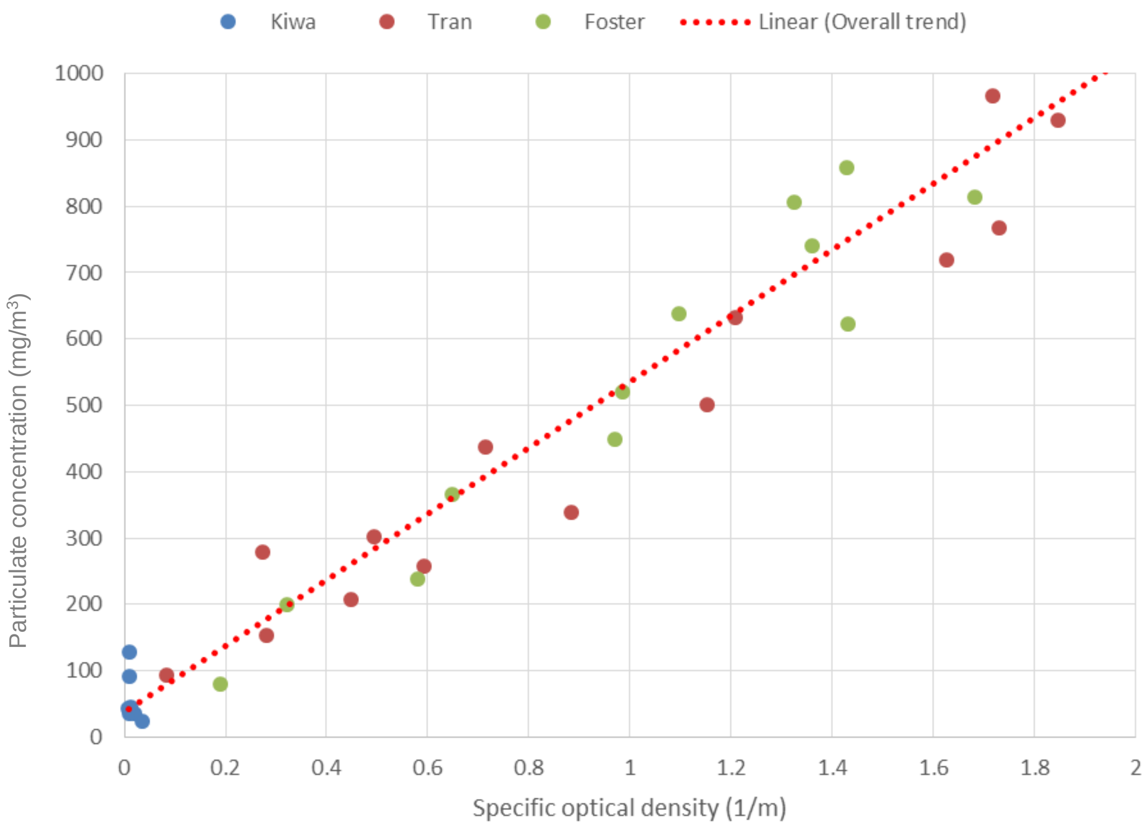


Figure 17: Data extracted from (Foster, 1959)**,** (Tran, 1990) **and the Kiwa laboratory showing mass concentration against specific optical density**

The Kiwa laboratory data was collected from wood pellet fired biomass boilers, at high and low outputs, using a photoreceptor and tungsten lamp to measure the optical density and an electrostatic precipitator (ESP) to collect the particulates in the flue gas and calculate the gravimetric particulate concentration. The ESP is weighed before and after the test to find the mass of particulates collected. The mass concentrations shown here have been corrected for actual flue temperature and percentage oxygen.

We suggest for this field trial that particulate emission measurements should be performed using obscuration meters as this is a measurement technique that can be used to perform long term measurements and is extremely low cost when compared to isokinetic measurement. It must be noted however that particulate measurement via obscuration may only give an indicative particulate matter measurement within a range and that (at the time of writing this report) work to clarify the relationship between particulate concentration and optical density is currently being performed by Kiwa (independently of this project).

6 Parameters required to be measured for indirect losses methodology

As stated above, the parameters required to be measured for the indirect losses method efficiency calculation are as shown in Table 11. In this section of the report we describe these parameters and the associated methods of measuring each.

Table 11: Indirect losses method, losses and variables found in the related equations

Loss due to	Variables in equation	Source of data
Sensible heat in the dry flue gases	• Carbon content of fuel • Flue gas temperature • Ambient temperature • Concentration of CO_2 in flue	• Fuel sampling and analysis • Flue gas temperature probe • Ambient temperature • Gas analyser
Enthalpy in the water vapour in the flue gases	• Moisture content of fuel • Hydrogen content of fuel • Calorific value of fuel • Ambient temperature • Flue gas temperature	• Fuel sampling and analysis • Fuel sampling and analysis • Fuel sampling and analysis • Temperature probe • Flue gas temperature probe
Unburned gases in the flue	• Concentration of CO_2 in flue • Concentration of CO in flue	• Gas analyser • Gas analyser
Radiation, convection and conduction losses	• Case surface temperatures • Thermal properties of case material • Ambient temperature • Actual rate of heat input *Alternatively these losses can be estimated from empirical data as prescribed in BS845-1*	• Heat produced from heat meter • Temperature probe • Fuel sampling and analysis • Fuel sampling and analysis • Empirical data

6.1 Required Parameters

6.1.1 Fuel sampling and analysis

In order to perform calculations of the losses due to: the sensible heat in the dry flue gases, enthalpy in the water vapour, radiation and convection, an elemental analysis of the fuel is required. Therefore the fuel must be suitably sampled and analysed to acquire this information.

There are a number of options available for performing fuel sampling and analysis of wood chip or wood pellets such as:

- Asking sites to report their monthly fuel usage and send a sample for laboratory analysis with every new delivery. The fuel data must be corrected for stock (i.e. the operators will need to adjust delivery information based on existing stockpile levels).

- A more frequent and regular sampling strategy that is designed to be most frequent at the beginning of the trial, if results are found to be approximately constant, a reduction in sample frequency will be performed whilst still being frequent enough to gather information on seasonal variation. These samples will then be sent for ultimate analysis in a laboratory.

- Use of moisture probes can give an indicative measurement of fuel moisture content, as well as limited chemical composition. However these meters only give spot measurements and can lead to results which are not representative of the fuel supply.

We suggest that the only way that fuel quality can be accurately determined is to take fuel samples for laboratory analysis, the frequency of the sampling strategy will be strongly budget dependent.

An advantage of fuel sampling for laboratory analysis is that a more precise and thorough examination is made, yielding information such as particle size, calorific value and ultimate (elemental) analysis. As a minimum we suggest that fuel samples are analysed for moisture content and selected samples will have ultimate analysis, calorific value, and particle size analysis performed.

The strategy for sampling fuel will be strongly dependent upon the size of each site to be monitored in any proposed field trial. Sampling of fuel should be performed in a manner that will provide a representative fuel sample. A series of incremental samples should be taken and combined to form a composite sample, of which a smaller sample will be extracted by the laboratory performing the analysis. This is always challenging. The health and safety implications of taking such samples must be carefully considered. Full written method statements should be prepared for each individual site.

When devising a sampling strategy for each site the location of the sample extraction should be carefully considered with priority placed on sampling the fuel immediately before combustion as the extracted sample is to be as representative as possible of what is combusted.

It is suggested that fuel sampling should be most frequent at the beginning of a field trial, if budget constraints permit so, weekly sampling and analysis would be initially recommended. If fuel quality is found to be relatively constant over the first few months the frequency could be decreased to bi-weekly and then perhaps to monthly, depending on the laboratory analysis. It is important that when decreasing sampling frequency sampling should be made frequent enough for seasonal variance to be accounted for. Although fuel sampling could be decreased to monthly during summer months it is suggested that during the wetter winter months it be increased to weekly or bi-weekly to assess any excess moisture gains.

Fuel analysis should be performed in the following decreasing order of importance;

1. Moisture
2. Calorific value
3. Carbon

4. Hydrogen
5. Nitrogen
6. Chloride
7. Ash.

This fuel analysis will be determined by performing an ultimate analysis in a laboratory. The moisture content of the fuel samples received will be determined using a procedure based on a European Standard method (British Standard BS EN 14774-2 , 2009). The fuel sample will be weighed, then dried in an oven for 24 hours at 110ºC and weighed again to calculate the moisture content in the fuel. The bulk density and a size analysis will also be undertaken on some of the fuel samples to give an indication of the consistency of the fuel. Complete analysis of the fuel including carbon, hydrogen, nitrogen, sulphur, oxygen, and ash content along with calorific value (Net and Gross) will be carried out on selected fuel samples. It should be noted that appropriate packing of samples is required to ensure that the sample is received by the laboratory in the same condition as it was despatched. Appropriate packing is performed using a fuel sample bag, sealed with waterproof tape by twisting and folding the open end and sending to the laboratory in a box. This method is extremely simple and can be demonstrated to sites at time of installation of equipment. It is important that the fuel sample is sealed correctly to ensure no loss or gain of moisture to or from the fuel sample as this could have a material impact on results.

Recommendation

Devise a bespoke sampling strategy for each site, initially taking weekly samples and decreasing frequency if laboratory analysis is constant. All samples to be sent to laboratory for elemental analysis, selected samples to also have particle size analysis.

6.1.2 Fuel feed rate

As described above; fuel feed rate is a key parameter in the direct method efficiency calculations and not required for the indirect losses method calculations. However, to quantify emissions on a mass per energy input basis (g/GJ) or on a mass per unit volume of flue gas basis (g/m^3) the fuel feed rate to the boiler must be known. Alternatively the flue gas flow rate must be known for g/m^3, this can be calculated from knowledge of the fuel feed rate and fuel analysis.

There are a number of ways of measuring fuel input into a biomass boiler:

1. Measure fuel in over a long term using delivery notes, invoices and fuel analyses for fuel purchased from a supplier. It is best to record over as long a timescale as possible to reduce boundary effects (e.g. changes in stock levels). So long as all information on fuel delivered is available, this can be an accurate method to determine fuel feed rate for the period, but is still challenging to match delivered fuel quality against quantity, unless using automatic sampling off a belt feeder or similar device.

2. On small sites the above can be simplified by asking the site operator to record each time the fuel store is loaded. Some cooperation from the site is needed here. Fuel samples would also be required in order for a fuel analysis to be performed, however, (as indicated above) modern boiler house practice makes taking fuel samples and estimating changes in stock level challenging from a Health and Safety perspective.

3. Record or data log the movements of fuel feed system on a continuously fed boiler, e.g. number of turns of auger/screw or pushes of ram into stoker, etc. Some boilers have counters internally that record these actions; some use a fixed '1 ram push every 60 seconds' methodology. Kiwa have logged these internal counters or mechanical movements in the past, with very mixed results, this is because the amount of fuel provided per push or turn can vary due to mechanical operation, fuel density or packing factor[4]. With some effort these mechanical devices can be calibrated (e.g. kg/turn or kg/push) but the results are very dependent upon bulk density which itself is very dependent upon chip / pellet size and shape factors. These can easily change, especially for chip.

Overall, accurate fuel input measurement is often very difficult, and very site dependent. A site with an enthusiastic boiler owner / operator can yield reasonable results, but without this enthusiasm, missing data is almost inevitable with serious impacts on accuracy over a long time frame. The situation is completely different for oil and gas boilers where fuel is standardised and easily metered.

We therefore suggest that fuel feed rate is measured over a long time period and is calculated by site operators recording all fuel deliveries mass or volume. The installation of automatic fuel feed rate measurement systems could theoretically increase the accuracy of the measurement and provide more discrete data than the proposed method, but each site would require bespoke design, fabrication and installation of essentially unproven design.

The only truly proven technique is belt weighers but the capacity of these is usually several tonnes per hour and costs are high (including installation and redesign of the boiler feed system possibly over £100,000). Therefore installing automatic fuel feed rate measurement systems on a large field trial would be impractical and (it is suggested) prohibitively expensive. As a result, fuel feed rate will be used as supplementary information as the method we propose for measuring boiler efficiency, the indirect losses method, does not require this information.

Recommendation

Fuel feed rate is measured by recording all fuel deliveries mass or volume over the entirety of the trial.

6.1.3 Flue gas carbon dioxide

Knowledge of the carbon dioxide concentration in the flue gases is used to feed into the indirect losses efficiency calculation directly, enabling calculation of the losses due to sensible heat in the flue. In addition, if the flue gas CO_2 concentration, flue gas flowrate, and fuel analysis are known, the fuel feed rate can be calculated by carbon balance. As the rate of CO_2 being emitted by the boiler is known, the amount of carbon is known, this must equal the carbon input (assuming CO concentration is negligible), as the amount of carbon in the ash will be negligible. Knowing the rate of

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[4] Packing factor is the fraction of volume that is occupied by constituent particles.

carbon input to the boiler, along with the carbon content of the fuel from an ultimate analysis, the fuel feed rate can be calculated and with the fuel calorific value will yield energy input.

Flue gas CO_2 measurement over extended periods requires the installation of a gas analysis system which will require regular maintenance and calibration by skilled staff. In general, even for the most basic analysers daily calibration would be required in order to pick up and correct any zero or span drift. For very expensive Continuous Emissions Monitoring (CEMs) equipment, automatic calibration is possible. All MCERTS CEMS have a minimum requirement for maintenance interval of no greater than 8 days, most CEMS having a certified maintenance interval of 1 - 3 months. To achieve this they all have automated calibration regimes, including daily span and zero gas injections etc., necessitating the installation at site of sample handling systems, calibration gas manifolds and gases, gas conditioning systems, data recording etc. Most sites installing CEMs would make decisions for a 5-10 year investment period as costs would be £25 - £50K minimum for even a simple analyser system and quite possibly more when including service contract arrangements etc. Thus, the costs of this would be prohibitive except on a few large sites.

Recommendation

We suggest not measuring CO_2 but measuring O_2 as a proxy.

6.1.4 Flue gas oxygen

If the flue gas O_2 concentration and the fuel analysis are known, the flue gas CO_2 concentration can be inferred. CO_2 content can be calculated knowing the stoichiometric volume of CO_2 and the measured oxygen using:

Equation 1

$$CO_2 = \left[1 - \frac{O_2}{20.9}\right] CO_{2\ max}$$

Where 20.9 is the percent of oxygen in air, and CO_2 max is the stoichiometric volume of CO_2. Once the CO_2 has been determined, carbon balance can be performed along with fuel analysis to calculate fuel feed rate.

There are numerous ways to measure flue gas oxygen concentrations including:

- Zirconia (Zr) probe

  A well established boiler technology that is relatively cheap. A zirconia probe is an electrochemical device that can be easily installed into a flue by using a currently available access port, or alternatively drilling a small hole in the flue and placing it in with suitable fitting. The drilling of a small hole into the flue will have no impact on boiler performance.

- Paramagnetic oxygen analyser

  Oxygen could also be measured using a paramagnetic oxygen analyser. This technology could yield more accurate results than a Zr probe (a Zr probe may have an uncertainty of 0.5% where a paramagnetic sensor may have an uncertainty of 0.1%). This device utilises the fact that oxygen has a magnetic susceptibility greater than most other gases to measure oxygen concentrations. This kind of analyser could also be easily installed to monitor flue gas oxygen levels; however this is more akin to an extractive CO_2 analyser with its attendant high costs and maintenance requirements.

A paramagnetic system would be much more expensive, of the order of a few thousand pounds, in contrast to a Zr probe which is available for much less than £1000. Paramagnetic oxygen sensors are typically less robust than a zirconia probe, hence; Kiwa suggest using a zirconia probe as the preferred method of flue gas oxygen concentration analysis as it is a relatively cheap, reliable and robust technology.

The calculated CO_2 measurement will feed directly into the indirect losses efficiency calculation to allow calculation of the loss due to sensible heat in the flue gas and also losses due to unburned gases in the flue gas.

Recommendation

Use of a zirconia oxygen probe for continuous flue gas oxygen concentration monitoring. The oxygen values will then be used to calculate carbon dioxide concentrations.

6.1.5 Flue gas temperature

Flue gas temperature is important as it enables the calculation of the main heat loss from the system – the sensible heat in the flue gas. This can be conveniently measured using an industrial thermocouple, which is standard boiler technology, and relatively inexpensive.

Knowledge of the flue gas temperature also gives information on boiler cycling and possibly on modulation as the ramping up and down of the boiler output will be reflected in the flue gas temperature. The information available on boiler modulation from flue gas temperature is investigated in section 8 of this report.

Flue gas temperature measurements will be used in the calculations to find losses due to sensible heat in the flue and losses due to the enthalpy in the water vapour in the flue gases.

Recommendation

Use of an industrial thermocouple for continuous measurement of flue gas temperature.

6.1.6 Ambient temperatures

Boiler house temperature, heated space temperature, and outside air temperature measurements can greatly aid analysis of data. For example outside temperatures can be used to give an indication of the heat demand of the building following a degree day analysis. This will be measured using a standard thermocouple.

Ambient air temperatures are used as the temperature of the air input to the boiler, this figure is used to calculate losses due to sensible heat in dry flue and also losses due to enthalpy in the water vapour in the flue.

Recommendation

Use of a suitable external temperature thermistor to continuously monitor ambient temperature.

6.1.7 Heat produced

The standard method of measuring heat produced in a low temperature hot water boiler is to install a heat meter which measures the heat transfer fluid (usually water) flow rate circulating around the heating system along with flow and return temperatures. Knowing the specific heat capacity of the fluid, the heat supplied can be calculated. This is usually displayed on the meter as cumulative energy supplied (in kWh), or as the instantaneous rate of energy supply (in kW). Some meters can be used to log flow and return temperatures separately, alongside cumulative heat delivered.

The method for steam boilers is similar, but an additional meter is required to measure the energy returning to the boiler in the condensate.

A requirement of participating in the non-domestic RHI scheme is the use of a heat meter to record eligible heat generated. Although not absolutely essential this information (ideally on a 5 minute basis) is very useful and will increase the quality of the result. If a meter is not in place one could be easily fitted. However, as mentioned above, heat meters can be erroneously installed and therefore must be surveyed to ensure correct installation before readings are taken.

Recommendation

Continuously monitor the site heat meter, or if heat meter not present, install and monitor a MID class 2 heat meter suitable for RHI purposes.

6.1.8 Surface temperatures

Case losses, both radiative and conductive, can be calculated by measuring boiler surface temperatures at points which are representative of an area of boiler casing. By application of a literature heat transfer coefficient and measured surface and boiler house temperatures, the heat flux can be calculated.

An alternative method which is used in BS 845 part 1 is to estimate boiler heat loss as a percentage (usually around 1% or 2%).of boiler output. This is an acceptable method and is based on empirical data. However these estimated case losses do become disproportionately less accurate at lower daily utilisation factors. As we expect to see low daily low utilisation factors in a field trial we suggest using surface thermistors to directly measure case temperatures.

The cost of installing case thermistors is obviously greater than not installing any equipment and estimating using empirical data, however this is still a relatively cheap technology hence the recommendation.

Recommendation

Use of surface thermistors for continuous monitoring of boiler case temperatures to allow calculation of case losses.

6.1.9 Combustion air flow rate

Air flowrate to the boiler could theoretically be used to infer flue gas flowrate and then be used with flue gas properties in a carbon balance to calculate fuel feed rate to the boiler.

Combustion air flow rate could be measured using:

- Pitot tubes

  This would be an acceptable method of measuring air flow in inlet ducts as the pitot would be installed in a clean air duct, therefore it would not suffer blockage.

- Fan power monitoring

  An alternative method to calculate the combustion air flow rate would be to monitor fan power through the electrical consumption data, then find the fan speed and from known fan properties the amount of combustion air supplied could be calculated.

- Miniature anemometers.

  Similar to Pitot tubes, anemometers can be used to measure the flow rate of air to the boiler.

However, all of the above measurement techniques are difficult for two reasons:

1. Many biomass boilers have several air inlets and forced draft fans, which would require multiple flow measurement devices.
2. Many boilers have additional air in-leakage from doors, inspection hatches, or under-grate, so the measured air flows represent the minimum air input to the boiler.

Therefore we do not recommend trying to measure input air flow rate as this would not only require measuring the air input through all fans but also accounting for leakage through other areas, which is impractical as tracing all possible air inlets would be time consuming and monitoring all these points may even be impossible, for example monitoring air leakage under grate.

Although knowledge of combustion air flow rate would allow information on flue gas flow rate (and subsequently fuel feed rate), purge times and boiler cycling, it is **not** required for measuring emissions or calculating efficiency through the indirect losses method hence we suggest not measuring combustion air flow rate.

Recommendation

We recommend not measuring combustion air flow rate.

6.1.10 Flue gas flow rate

Flue gas flowrate can theoretically provide information about boiler cycling and modulation. It can also be used along with fuel and flue properties in a carbon balance to calculate the fuel fed to the boiler, which can in turn be used in the case losses calculations of the indirect losses efficiency calculation. The flue gas flow rate (m^3) can also be used in conjunction with particulate measurements from obscuration (mg/m^3) to calculate absolute particulate measurements (mg).

Therefore flue gas flow rate can be a useful parameter to measure in a field trial. However it is not essential for efficiency calculations or emissions measurements via obscuration. This is because the flue gas flow rate does not enter into the indirect losses method calculations or particulate measurements via obscuration.

Some of the techniques available for measuring the flow rate of gases in the flue are as follows:

- Pitot tube

  Measurement of flue gas flowrate is usually done by measuring velocity at one or several points in the flue / chimney and then multiplying by duct area to give a flue gas volumetric flowrate. Velocity is usually measured using a pitot tube. This method is not suitable for long term velocity measurement due to the inevitability of blockage by smoke / particulates in the flue gas. (During the demonstration phase of this programme at the National Trust property, we installed a pitot tube in the flue gas duct. This was in a relatively ‘dirty’ part of the plant, before the multi-cyclone, however the pitot blocked within 24 hours). As a minimum, weekly cleaning / checking and recalibration of the pitot would be necessary, even if installed in a ‘clean’ area of the plant.

- Miniature anemometers

  Kiwa have also investigated the use of miniature anemometers for flue gas flow measurements, however, the material that these devices are produced from is not suitable for use for a large enough time period in the flue. It is possible that alternative anemometers could be designed and developed for use in a hostile environment such as the flue of a biomass boiler, using materials that can tolerate high temperatures and are coated with surfaces which shed particulates and moisture. However the development of such a device is out of the scope of this project and as it stands there are no suitable “off the shelf” products available.

- Thermal anemometer

  Another alternative “off the shelf” technology for measuring flue gas flow rate is a thermal anemometer. This technique relates the convective heat loss from an electrically heated metallic element to the surrounding fluid, in this case air, if only the fluid velocity varies then the heat loss from the wire can be interpreted as a measure of the flow velocity. This technology has been discounted for use in this field trial as commercial hot-wire anemometers that operate within the typical flue gas temperature ranges are not available.

There are many other ways to measure gas flow rates including laser velocimetry techniques and injection of tracer gases, however they are expensive solutions that are not readily available “off the shelf”.

Because of this, Kiwa sought an alternative method of measuring flue gas flow rate using two obscuration meters placed a known distance apart across a length of the flue. The signal outputs produced by the obscuration meters are subject to time delay analysis by means of cross-correlation. This function will yield the time delay between the two signals. Because the distance between the obscuration meters and the dimensions of the flue are known the volume of this section of the flue is calculated and using the time difference between the two signals the flue gas flow rate can be calculated.

The instrumentation used for measuring flue gas flow rate through obscuration has been tested under laboratory conditions to investigate if accurate, repeatable results are achievable with this novel technology.

Laboratory investigation of the flue gas velocity obscuration meter has shown that the results are variable and due to the fact that modern biomass boilers, particularly those burning wood pellet, produce very little particulate matter per unit volume, this technology could not produce robust, repeatable results.

Although we have seen in the laboratory that wood pellet burning biomass boilers do not produce enough particulate matter to measure flue gas velocity via obscuration, we have also seen in the field that the use of Pitot tubes to measure flue gas pressure (from which velocity can be calculated) quickly block up due to the amount of particulates.

Therefore, if particulate emissions are required on an absolute mass basis (mg), Kiwa recommend using knowledge of the amount of fuel supplied to the boiler, along with flue gas O_2 concentrations and fuel analysis to calculate flue gas flow rates. However it is important to reiterate that flue gas flow rate, although a preferred method of calculating fuel feed rate, is not necessary for any efficiency calculations.

Finally, it may be possible to develop a technique for long term flue gas flow rate measurements suitable for a field trial, for example a Pitot tube with an automatically controlled air jet to clean the Pitot at regular intervals, however this is an R & D project out of the scope of this project.

Recommendation

We recommend not directly measuring flue gas flow rate, however we do recommend calculating flue gas flow rate from knowledge of fuel feed rate and fuel properties.

6.2 Ancillary measurements

6.2.1 Electricity

It is well known that biomass boilers tend to have higher electricity consumption compared with appliances burning other fuels. This can be due to electrical ignition systems commonly found in biomass boilers, the power consumption of forced and induced draught fans, heat exchanger shake / wash down systems as well as fuel feed mechanisms. On an energy basis, electricity input to a biomass boiler is usually less than 1% of the fuel input. However, due to the current electricity grid emission factors, the CO_2 emissions attributable to electricity use may start to become appreciable.

Electricity metering is relatively cheap and straightforward using standard single or 3-phase meters with a digital output. Careful retrospective analysis of this data will yield useful information on boiler cycling.

Recommendation

It is recommended that the electrical consumption of any boiler be monitored continuously. If a boiler does not have a dedicated electricity meter we recommend that a MID compliant meter be fitted for continuous monitoring.

6.2.2 Oil / gas flowrates

Some biomass boilers use oil or gas for start-up purposes. The flowrate of oil / gas to the unit is relatively cheap and straightforward to measure with a positive displacement meter or other suitably priced flowmeter designed for measuring fuel oil / gas flowrate.

Recommendation

We recommend metering any ancillary fuel supplied to the biomass boiler with a suitable flow meter.

6.2.3 Utilisation factor measurement strategy

As identified above, utilisation factor is a key parameter in the performance of biomass boilers, therefore it is important that this is measured in the field trial. Measurement of utilisation factor requires two inputs, maximum rated output of boiler and heat generated. The rated output of the boiler can be taken from the data nameplate or by contacting the manufacturer directly. Heat output can be measured using a heat meter. An electricity meter will be fitted to the boiler, analysis of the electricity meter data will allow confirmation of when the boiler is in operation.

Knowing the duration of boiler operational periods, maximum output and rated output will allow us to calculate accurate utilisation factors. In order to capture data with a suitable level of granularity and to enable analysis of on and off time, data should be collected at least every 5 minutes, possibly every minute, this would allow a reasonable compromise between accuracy and data volume.

Recommendation

We recommend electrical consumption be measured by an electricity meter, heat output by heat meter and accept the boiler nameplate to be accurate as rated nominal output and use this data to calculate the boiler utilisation factor.

6.3 Uncertainty of the direct and indirect losses methods.

The uncertainty of the direct method is a direct function of the knowledge of the mass of fuel, CV of the fuel and heat production. All of these have significant uncertainties. In contrast the losses method only requires knowledge of flue gas CO_2 / O_2, flue gas temperature, combustion air (ambient) temperature, moisture content and boiler surface temperatures. Most of these can be determined accurately and / or are not material losses. Likely relative uncertainties using real data are shown below.

Comparison for a gas boiler of 115kW in (gross) and 100kW out

By the direct method:

Energy in	*= 115kW ± 1.5% = 116.7 to 113.3kW*
Energy out	*= 100kW ± 2% = 102 to 98kW*
Energy efficiency	*= 84 to 90%*
Uncertainty	***= 6%***

By the indirect losses method:

Energy in		*= 115kW±1.5%*	*= 116.7 to 113.3 kW*
Losses:			
	From case	*= 2kW ± 25% = 2.5 to 1.5kW*	
	From flue gas	*= 13kW ± 3% = 13.4 to 12.6kW*	
	Total	*= 15.9 to 14.1kW*	
Energy efficiency		*= (116.7kW-15.9kW) / 116.7kW = 89%*	
		= (113.3kW – 14.1kW) / 113.3 = 92%	

Uncertainty = 3%

It can be seen that the indirect losses method reports a less uncertain value. For biomass boilers this difference is likely to be larger due to the uncertainties in fuel feed. The uncertainties above are indicative values for the combined uncertainty in gas flow and gas CV for energy in, and of a MID class 2 heat meter for energy out. The losses uncertainties are indicative uncertainties obtained from the use of a thermocouple, oxygen sensor and fuel analysis for flue losses, and estimated case losses. As the flue gas temperature, ambient temperature, oxygen concentration and fuel analysis are measured with very low percentage uncertainties (≤1%) the calculation yielding the heat lost in the flue is also very low (≈≤ 2%), particularly when compared to some heat meters that have a declared uncertainty of 5%.

6.4 Summary of parameters to measure

Individual uncertainties stated below are the type B uncertainties based upon data provided in calibration reports and manufacturer's data, measuring instruments directive class two device uncertainties are reported for heat meter and electricity meter.

Loss due to	Variables in equation	Will variable be measured?	How?
Sensible heat in the dry flue gases	• Carbon content of fuel • Flue gas temperature • Ambient temperature • Concentration of CO_2 in flue	• Yes • Yes • Yes • No	• Fuel analysis • Thermocouple • Thermistor • O_2 as a proxy measured using Zirconia probe
Enthalpy in the water vapour in the flue gases	• Moisture content of fuel • Hydrogen content of fuel • Calorific value of fuel • Ambient temperature • Flue gas temperature	• Yes • Yes • Yes • Yes • Yes	• Fuel analysis • Fuel analysis • Fuel analysis • Thermistor • Thermocouple
Unburned gases in the flue	• Concentration of CO_2 in flue • Concentration of CO in flue	• No • No	• O_2 as a proxy measured using Zirconia probe
Radiation, convection and conduction losses	• Case surface temperatures • Thermal properties of case material • Ambient temperature • Actual rate of heat input to boiler • *Alternatively these losses can be estimated from empirical data as prescribed in BS845-1*	• Yes • No • Yes • Yes	• Thermistors • Empirical values • Thermistor • Fuel logs

Parameter	Method	Resolution	Uncertainty (k factor = 2[5])	Cost per boiler (equipment and installation) £	Cost per boiler (annual) £
Heat generated	Heat meter	1 Wh	±5% of value	400 (using existing) 1000 (installing new)	-
Ambient temperature	K type thermocouple	0.1 K	±0.75% of value	500	-
Case temperature	Thermistor	0.1 K	±0.75% of value	1500	1000
Electrical consumption	Electricity meter	1 W	±2.5% of value	500	-
Fuel input	Fuel delivery audit	10 kg	±10 kg (approx.)	-	
Fuel moisture	Laboratory analysis	1%	±1% of value	-	7200
Fuel analysis	Laboratory analysis	1%	±1% of value	-	
Flue gas O_2	Zirconia probe	0.1 %	± 0.5% of value	700	-
Flue gas temperature	K type thermocouple	0.1 K	±0.75% of value	400	-
Flue gas particulate	Obscuration meter	1 mg/m^3	±50% of value (up to specific optical density=0.25m^{-1}) ±25% of value (specific optical density >0.25m^{-1})[6]	2500	-
Flue gas NO_x	Portable gas analyser	1 ppm	±1% of value	17000	-
Flue gas CO_2	Portable gas analyser	0.1 %	±5% of value	6000	-
Oil flowrate	Flowmeter	0.5 l	±2% of value	500	-

[5] A 95% confidence level in the measurement assuming a Gaussian distribution

[6] We expect to see optical densities < 0.25 m^{-1} in pellet fired boilers, however this may be significantly higher in chip fired appliances or during start-up and shut down.

6.5 Data logging and handling

The choice of data logging equipment will be based on several possible systems. Possible methods include those used in most DECC sponsored field trials over the past decade, or the RHPP measurement programme. The following briefly describes the types of data logging equipment available.

6.5.1 Communication between sensors and data logger

The sensors can be:

- directly connected via cabling to a data logger (a wired system), or
- connected to one or more sensor transmitters which communicate wirelessly with the data logger a short distance away (a wireless system).

In a wireless system, the sensor transmitters send readings from the sensors to the data logger at pre-determined time frames. Data is then stored on the data logger (typically at 1-5 minute intervals) until it is sent/collected remotely.

Most trials have used a wireless system as this has the distinct advantage that very little wiring is required within a property, and so the installation process is quicker and less disruptive, requiring less remedial work on completion of the study. On large industrial sites, however, there may be issues with interference from other equipment, or distances between the sensor transmitters and data logger may be too large to enable wireless communication without repeaters – therefore a wired system may be preferred. Wired systems also have the advantage that there is no need to replace batteries in remote sensor transmitters, unlike a wireless system. Wireless transmitter battery life is dependent on the frequency of data gathering (e.g. every 1 minute or every 5 minutes). Recent field trials carried out for DECC have shown battery lives of at least one year.

6.5.2 Communication between data logger and office

Remote communication between the data logger and office is generally either:

- via the voice network (using the mobile phone voice network), or
- via the internet, either:
    - using the mobile data network, or
    - using an existing broadband connection.

Using the voice network, the data logger is ‘called up’ from the office at regular intervals (e.g. weekly). During the call, data is downloaded from the data logger. In case of connection issues, data loggers store their data, generally for up to 4 weeks, which can be downloaded in one batch once connection is re-established. In addition, the data logger can be easily ‘called up’ on an ad hoc basis for re-configuration or troubleshooting.

Using the internet, the data logger ‘pushes’ or uploads data to the office at regular intervals (e.g. daily, hourly or more frequently). In case of connection issues, data loggers store their data, and will retry uploading until successful. Using this method, it is possible to choose much more frequent data transmission intervals, i.e. almost continuous streaming of data. It is generally more difficult to communicate with the data logger on an ad hoc basis for re-configuration or troubleshooting.

Both the mobile phone voice network and mobile data network are subject to signal strength issues depending on location. However, depending on the site, a broadband connection may also be absent or inaccessible, e.g. larger sites often have security policies which prevent introduction of new un-vetted equipment onto the network. Mobile network solutions would then be preferred as they allow the data monitoring equipment to be completely isolated from the site’s own network.

6.5.3 Recommendations

For a study of this type, covering a range of installation sizes, we would recommend a wireless system. In terms of communication between the data logger and the office, the real time continuous streaming of data is not a priority. However frequent monitoring of data will allow any site issues to be flagged and prevented from cascading, if data is to be downloaded on daily basis an internet based transmission system would perform best. Therefore, both a voice network and an internet based solution would be workable – the choice mainly being based on what the manufacturer of the equipment supports. Issues with battery life will need to be addressed either by hard wiring power supplies or adding extra battery packs to sensors / transmitters which need very frequent data acquisition.

6.6 Data analysis

Apart from just collecting the data, if it is to be useful it needs to be expertly analysed. In an extensive field trial there will inevitably be problematic sites where solving the problem of interaction of the heating system and boiler is very contentious. Therefore analysis must be performed by knowledgeable individuals with strong understanding of biomass heating systems, without this understanding solutions are unlikely to be forthcoming i.e. the project will only produce outputs not successful outcomes.

6.6.1 Site details, breakdowns and data quality

The site details will be tabulated along with breakdowns reported by sites via their log books and data quality issues that occurred on site during the trial period.

6.6.2 Efficiency data

The various losses associated with each biomass boiler will be calculated from the flue gas, boiler case, fuel and ambient properties to assess the ways in which the boiler is losing heat. This data will then be handled to provide useful efficiency measurements for the operation of the boiler.

6.6.3 Particulate emissions data

Readings from the obscuration meter will be processed to eliminate noise and optical density values for the flue gas will be calculated, these optical densities will then be used to find particulate emissions values based on empirical relationships. This data will then be compared to heat output, flue gas temperatures and power consumption data to understand how and when particulate emissions arte highest.

6.6.4 Heat output data

The data will be first graphed to show the daily heat output from biomass boiler and/or thermal store, electricity used by the boiler, and oil or gas use where applicable.

If the system supplies energy to a heating system, a degree day heating (DDH) analysis will be undertaken. The DDH is a measure of the heating or cooling requirements based on the difference between the ambient temperature and a base temperature (which is normally taken as 15.5°C in the UK). DDH is calculated for each site on a daily basis using the methods described on the degree-days direct website (Vesma Degree Days, 2015) and summed over a month. This will be calculated using the local ambient (external) temperatures logged on each site for each day. The monthly DDH figures will be plotted against the monthly heat output from the biomass boiler. Well controlled sites with a normally controlled heating load would generally produce a linear trend with energy use proportional to the DDH figure. Deviations from a straight line trend show variation in plant operation or other inconsistencies in load or operation (such as breakdowns).

If the system supplies energy to a process, then the analysis will focus on the energy supplied to the process, per unit of production. Basically, the performance will be analysed in terms of the system drivers.

The utilisation factor will also be calculated and graphed for the trial period. The will produce information about the way in which the boiler was sized compared to the demand on site; it also shows breakdown periods and periods when the data quality was poor.

7 Conclusions from sections 3 to 6

This section of the report has described the differences between the direct and indirect losses methodologies for measuring boiler efficiency. We have proposed that the indirect losses method is a more robust method for measuring the in-situ efficiencies of biomass boilers as the impact of the large uncertainty (which varies from system to system) in measuring the fuel feed rate to the boiler does not have such large impact on results as with the direct method, it also provides information on boiler cycling and modulation through the flue gas properties and can help indicate where the largest thermal losses are found. To assess thermal performance via this method we must measure:

- Flue gas temperature
- Flue gas CO_2 **or** O_2 concentration
- Ambient air temperature
- Case temperatures (If empirical relationships are used fuel input is not required)
- Moisture, carbon and hydrogen content of fuel.

In addition we also recommend measuring:

- Fuel input
- Electrical power consumption.

We must also measure emissions of particulate matter and oxides of nitrogen to monitor the environmental impact of biomass combustion. We suggest measuring particulate emissions using the principle of obscuration to give indicative readings of particulate emissions. Techniques for measuring NO_x have been described although we suggest that the cost and time required to measure NO_x will not be suitable for a field trial. However, if required, the NO_x measurement techniques described above can be used.

Three monitoring regimes have been defined for biomass boiler field trials (Appendix A); each regime defines a different level of monitoring, complete, intermediate and minimal.

- “complete metering” where all parameters of interest would be measured with a high degree of accuracy enabling the performance of the boilers to be well characterised in terms of real life efficiency, mode of operation, and smoke and NO_x emissions;

- “intermediate metering” which would be a cost effective way of determining real life efficiency and smoke emissions with some compromise on measurement accuracy;

- “minimal metering” which would allow estimates of real life efficiency and smoke emissions with the lowest degree of accuracy.

The regimes are flexible and can be tailored to a bespoke regime as required. These monitoring regimes have been costed in terms of equipment costs, installation and annual ongoing costs. Each monitoring regime is applicable for both domestic and non-domestic biomass boiler installations of any size.

The proposed methodology will allow the thermal efficiency of biomass boilers of any scale to be calculated, overall energy efficiency including electrical consumption and indicative emissions of particulate matter.

In addition to calculating efficiencies and emissions, the data collected will allow interpretation of results to assess how utilisation factors, fuel quality and control strategy influence boiler performance. What this methodology will not permit is precise measurements of emissions of particulate matter, actual CO_2 values as O_2 is being used to calculate CO_2 concentrations, or emissions of NO_x.

8 Testing and Piloting of Methodology

8.1 Laboratory test work

Introduction

Laboratory test work was performed in order to assess the suitability and uncertainty of the instrumentation described above and to assess the reasons for good and poor performance. As identified above, utilisation factor could be a key parameter influencing the efficiency of biomass boilers. As part of this project, analysis has been performed to categorise the kinds of boilers installed under the domestic and non-domestic RHI. A conclusion drawn from that work was that a 20-30 kW pellet boiler producing central heating and domestic hot water would be representative of the boilers currently being installed under the domestic RHI. We therefore suggested that an accurate way to assess the performance of a domestic scale boiler under various utilisation factors is to perform laboratory analysis under different utilisation factors.

This laboratory work was performed in order to assess the following factors:

- Validate the use of the indirect losses method for measuring boiler efficiency under non-steady state and low load conditions;
- Validate the methodology for assessing the reasons for good and poor performance of the biomass boiler being tested;
- Measure how boiler efficiency varies with utilisation factors;
- Validate the use of obscuration as a method for particulate measurements.

The tests were performed under ~ 30% 10% and 5% load to see how the boiler performed under these low load conditions. The parameters that were measured under 30%, 10% and 5% load using a 26kW boiler were:

- Heat output – via high accuracy platinum resistance thermometers and ultrasonic flow meter
- Fuel input – record the mass going into the boiler using weighing scales (fuel analysis also performed)
- Flue gas CO_2 – measured using extractive gas analyser (CO_2 was measured in the laboratory rather than O_2 to validate measuring O_2 in the field.)
- Flue gas flow rate - using a calibrated pair of obscuration meters, signal processing and data logging equipment (this technique has subsequently been shown to be unsuitable for use in biomass boilers).
- NO_x – using extractive gas analyser
- Particulate emissions – Measured using obscuration and electrostatic precipitator (ESP)
- Flue gas temperature – measured using a thermocouple
- Ambient temperature – measured using a thermocouple.

Performing this test work in a controlled laboratory environment allowed equipment to be used in the field to be tested, calibrated and validated by secondary measurement techniques. For example, a novel method of measuring flue gas flow rates via obscuration was tested and found wanting in this test work. By performing full measurements, as will be performed in the field for a non-domestic sized boiler, any technical issues were raised in a setting that will not have a material impact on the outcome of the pilot field trial.

In summary the following work was completed:

Efficiency testing of a 26 kW pellet fuelled biomass boiler under 30%, 10% and 5% utilisation factors under unimodal operation. In addition we also measured:

- particulate emissions,
- flue gas flow rate,
- flue gas temperature,
- flue gas CO_2,
- flue gas O_2,
- heat output,
- fuel input, and
- ambient temperature.

8.1.1 Method

The boiler tested in this investigation is a pellet fed, automatic ignition 26kW boiler, a free-standing water heating boiler with a nominal heating output of 26kW. This boiler was chosen as it is typical of the type of boiler installed under the domestic RHI and is considered to be representative of the kind of boiler found in the wider biomass boiler population of the UK, hence suitable for testing the performance methodology upon. The boiler consists of a fabricated tube heat exchanger and a combustion burner with a forced draught fan designed to burn wood pellet fuel. The boilers flue outlet is fitted with a variable speed induced draught fan. The flue section fitted to the top of the boiler after the fan is fitted with a flue draught stabiliser. The boiler has separate fuel hopper that feeds fuel to the burner via an auger and drop tube feed system.

The boiler was installed by Kiwa staff. To assess the performance of the boiler in accordance with the indirect losses method proposed in this report the following parameters were measured:

- Flue gas temperature with k-type thermocouple
- Flue gas CO_2 and CO concentrations with high accuracy laboratory extractive gas analyser
- Ambient temperature with k-type thermocouple

Due to a draught stabiliser at the base of the flue the gas sampling was performed from a sample point on the boiler body.

As this investigation was performed in a laboratory with highly accurate equipment by trained engineers the direct method of efficiency measurement was used to validate the indirect losses method.

It is critical for the purpose of this report to state to the reader that the reason the direct method is used to validate the indirect losses method in this instance is that in the laboratory the direct method can yield highly accurate results, due to the highly accurate laboratory equipment operated by trained engineers and the simple process of measuring fuel feed rate. In a field trial the direct method could not yield such accurate and reliable results for reasons discussed previously.

To evaluate the accuracy of the efficiency measurement made through the indirect losses method a direct measurement of efficiency was also made using:

- high accuracy platinum resistance thermometers (PRTs) placed in the flow and return of the boiler
- an electromagnetic inductive flow meter in the boiler return
- electronic weigh scales to measure fuel feed rate. As indicated elsewhere this is simply impossible in a field environment. While such load cells can be fitted, these require mechanical isolation of the hopper with major implications on the dust integrity of the unit and possible ATEX explosive dust ratings.

In order to validate the obscuration PM readings addition to the measurements required to perform an indirect losses assessment of the thermal performance of the boiler, an electrostatic precipitator (ESP) was installed in the flue to enable a gravimetric measurement of particulate emissions from the boiler throughout the test. The mass of the ESP was recorded before the test and again after drying out overnight in a conditioned room, the increase in mass of the ESP is due to the accumulation of particulate matter.

A novel device based upon the principle of obscuration was installed on the flue to assess if this device could be used to measure both flue gas velocity and particulate emissions. This device measures the attenuation of a light beam whose path length is the diameter of the flue, this is performed at two positions a known separation across the flue. The attenuation in light can be shown to be proportional to the particulate emissions collected in the ESP, this was investigated in this study. Signal processing was performed to attempt to calculate the time of flight of particulate matter between the two light beams and hence allow calculation of flue gas flow rate.

The load on the boiler was determined by controlling the flow rate of cold water to the plate heat exchanger. This flow rate was controlled using both coarse and fine control valves installed in the cold inlet flow to the plate heat exchanger. Efficiency measurements were performed on the boiler operating with utilisation factors of 5%, 9% and 28%.

The boiler control panel was used to control the set point temperature of the boiler, this is a parameter that is designed to be controllable by the end user and can be between 55°C and 75°C. For the tests performed here the set point was 70°C, as per manufacturer's installation.

For the duration of the tests (four to six hours) all temperatures, flue gas concentrations and water flow rate were logged at either 1 or 5 second intervals using software designed by Kiwa. The mass of fuel was recorded at the beginning and end of the test to calculate a fuel feed rate for the duration of the test.

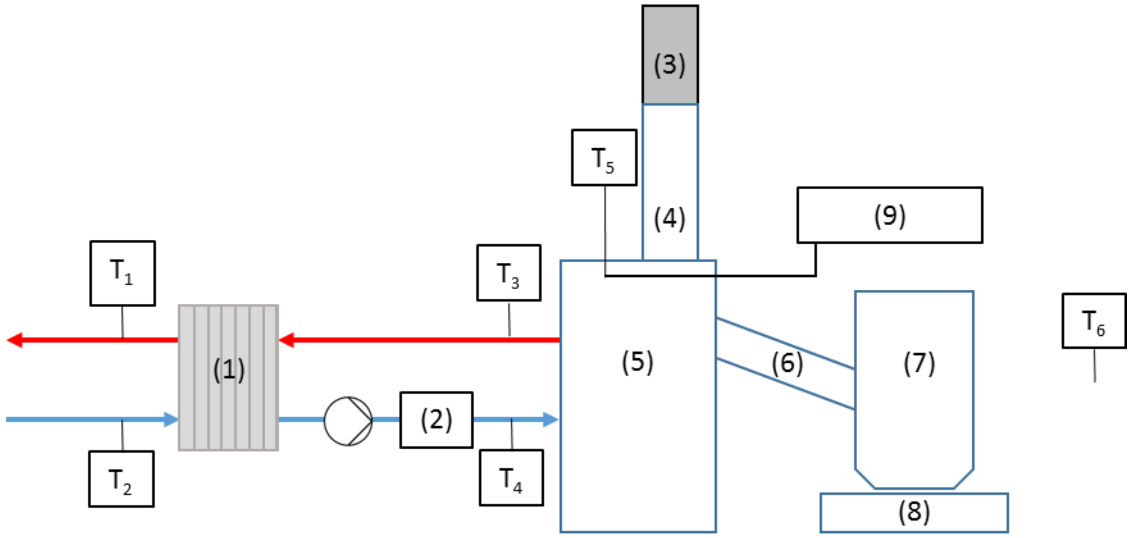

Figure 18: Schematic showing installation of boiler in Kiwa laboratory. (1) Plate heat exchanger, (2) flow meter, (3) ESP, (4) flue, (5) boiler, (6) screw feed, (7) fuel hopper, (8) balance, (9) gas analyser, T_1 PRT in demand side flow, T_2 PRT in demand side return, T_3 PRT in boiler flow, T_4 PRT in boiler return, T_5 thermocouple in flue, T_6 ambient thermocouple.

8.1.2 Results

Thermal efficiency

Data logged during this investigation was used to calculate the direct heat output per second of the boiler by using the following formula:

Heat output = (volumetric flow rate)*(density of water)*(specific heat capacity of water)*(temperature difference between boiler flow and return)*(test time)

Which in terms of units is:

kWh = (l/s)*(kg/l)*(kJ/kg/K)*(K)/(s/h)

A fuel analysis, Table 12, was performed to provide information on the carbon, hydrogen, nitrogen, oxygen, sulphur (C, H, N, O, S), moisture and ash percentage content of the fuel and also the calorific value. The moisture and hydrogen content of the fuel along with the calorific value are required for efficiency calculations by the indirect losses method and calorific value is required to calculate efficiency through the direct method.

The sum of the heat output of the boiler over the time of the test yields the total useful heat output of the boiler during the test period. Dividing the total heat output by the test time gives the load during the period, this can then be expressed as a percentage of the boiler nominal output to give a utilisation factor.

The energy supplied to the boiler was found by multiplying the fuel feed rate by the calorific value of the fuel and the direct thermal efficiency of the boiler found from the useful heat output from the boiler and the energy input to the boiler.

The indirect losses method of assessing thermal efficiency of the boiler was also performed. A detailed explanation of this can be found earlier in this report. Using the ambient and flue temperatures along with the CO_2 concentration in the flue, moisture content, hydrogen content and calorific value of the fuel the losses due to sensible heat in the flue, losses due to enthalpy in flue water vapour and losses due to unburned gases in the flue were calculated. Along with case losses these losses were subtracted from 100% to find the instantaneous thermal efficiency of the boiler. As this method is designed for assessing the performance of boilers operating at steady state, weighted averages of the instantaneous efficiencies were combined to give the overall efficiency of the boiler for the period. Case losses were assumed to be a percentage of the nominal output of the boiler as prescribed in BS-845:1(1987). At about 675W this then becomes the dominant loss as full output, but this not unexpected as keeping a large (and inevitably modestly insulated) metal box at 60°C is fairly energy intensive. The firing door, as well as other surfaces, will be at even higher temperatures.

Results of both the direct and indirect losses efficiency measurements are shown in Table 13. The final row in the table shows the percentage closure of the measurements made through each method at each utilisation factor. The percentage closure is calculated as the indirect losses efficiency value divided by the direct efficiency value and expressed as a percentage.

This agreement of the direct and indirect losses methods (so called Energy Balance Validation, EBV) is encouraging, it validates the indirect losses method as the indirect losses method is producing results in close agreement with the direct method. Further analysis of fan speed, and fan power demand do lead us to believe we may be able further refine flue loss estimates during the purge, early phases of start-up combustion and shut-down, as this is the period which we believe the largest losses are found.

Table 12: Wood pellet fuel analysis

	Units	As received	Air dried	Dry basis
Total moisture	%	8.1		
Free moisture	%	1.3		
Moisture analysis in sample	%		6.85	
Ash	%		0.3	0.3
Gross calorific value	MJ/kg	18.439		20.184
Net calorific value	MJ/kg	17.074		18.854
Carbon	%			52.1
Hydrogen	%			6.11
Nitrogen	%			0.08
Sulphur	%			0.02
Oxygen	%			41.4

Table 13: Gross thermal efficiency calculated through indirect losses and direct methods

Gross efficiency (%)					
5% load		9% load		28% load	
Indirect losses	Direct	Indirect losses	Direct	Indirect losses	Direct
24	26	69	64	72	74
Closure %					
107		107		97	

8.1.3 Uncertainty in efficiency calculations

BS845-1 contains methods for the establishment of uncertainties for the losses method, **under completely steady state** and for the sake of completeness these are detailed below, Unfortunately when operating at these low loads there is strong evidence (Figure 19) **that this not the case**, in which case (in the extensive experience of Kiwa) the uncertainties will be much larger and sometimes very much larger. However over long periods (24 hours) averages dominate. We have found in the case of Energy Balance Validation (the technical term for closure of the direct and indirect losses efficiencies), on previous work, this was typically good to better than 2.5% (Carbon Trust mCHP field trial) at low domestic utilisations. There are many similarities between mCHP units and biomass boiler e.g. their slow response and high thermal mass. As the uncertainties presented in this sections are calculated using the method described in BS845-1 it must be emphasised that the result of the calculations here will give maximum possible uncertainty; the actual uncertainty will be much less.

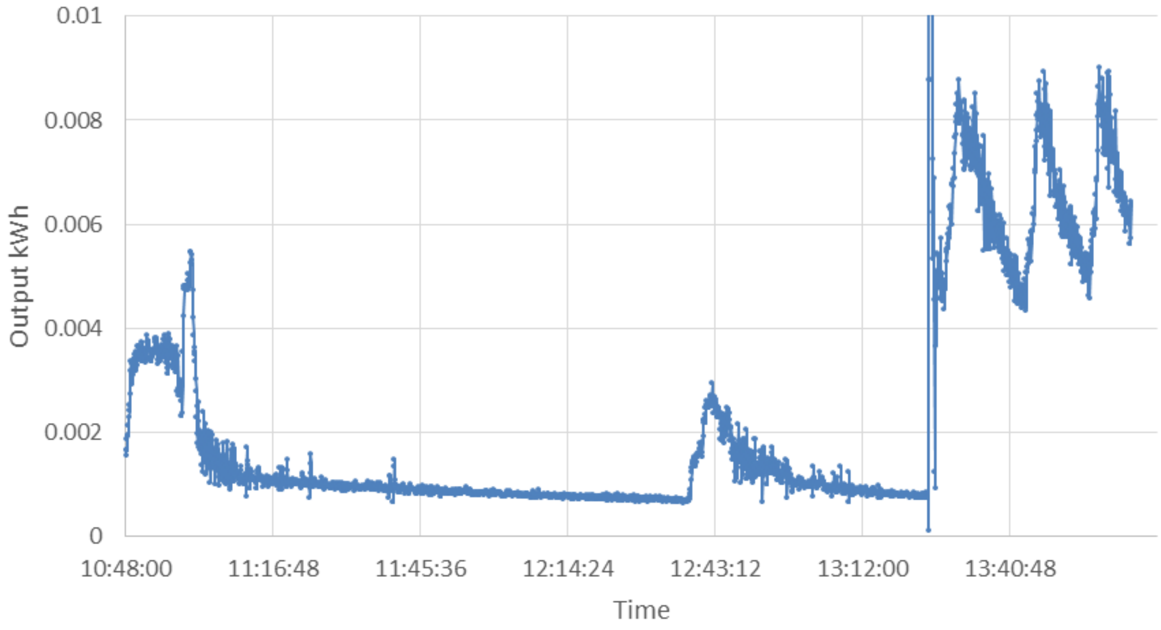

Figure 19: Plot of output against time for a section of the 5% load test. This illustrates the fact that the boiler was clearly not at steady state.

8.1.4 Direct method uncertainties

The uncertainty in the direct method is found from the uncertainties in the measurement equipment and combining these uncertainties. The uncertainties attributed to the measurement equipment is based on a standard uncertainty multiplied by a coverage factor k=2, providing a level of confidence of approximately 95%.

$$\begin{aligned}\Delta\eta &= [(\Delta flow)^2 + (\Delta fuel\ feed)^2 + (\Delta calorific\ value)^2 + (\Delta T)^2]^{0.5} \\ &= [(1\%)^2 + (2\%)^2 + (1\%)^2 + (1.4\%)^2]^{0.5} \\ &= 2.82\%\end{aligned}$$

Table 14: Gross efficiency including uncertainties

Gross efficiency (%)					
5% load		9% load		28% load	
Indirect losses	Direct	Indirect losses	Direct	Indirect losses	Direct
24±3	26±1	69±3	64±2	72±2	74±2

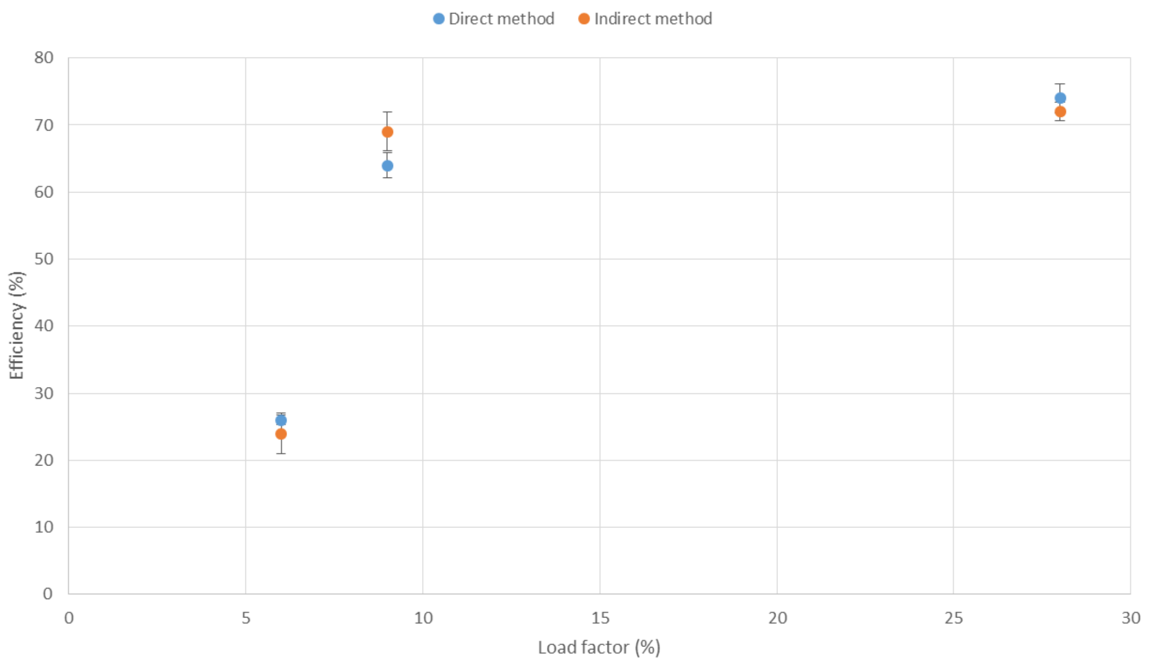

Figure 20: Plot showing gross efficiency variation with load utilisation factor for both the direct and indirect losses methods, including uncertainty

8.1.5 Emissions

The raw data that is recorded by the obscuration device is an electrical potential difference in mV. The un-attenuated beam produces a 50mV signal at the photo-receptor, attenuation of the beam by the particulate matter produces a voltage less than this. The specific optical density is then found by taking the base ten log of the ratio of the initial intensity beam to the attenuated beam and dividing through by the path length, i.e. the flue diameter. Data acquired from the obscuration device is shown in Figure 21, the average specific optical density achieved for the duration of the test is 0.046 m^{-1}.

An electrostatic precipitator (ESP) was placed in the flue, this device uses electric fields to charge the particulate matter and use electrostatic interactions to collect this matter. The mass of the ESP prior to the test was 8245.5 g, the final mass was 8252.8 g, and therefore the mass of particulate matter collected during this test was 7.3 g. This translates to a value of 1.55 g/h. By utilising the fuel analysis, fuel feed rate, flue temperature and the CO_2 concentrations in the flue over the duration of the test it is possible to find the volumetric flow rate of the flue gases. These calculations have been performed which yield a volumetric flow rate of 302 litres over the entire test period, when combined with the particulate matter measured by the ESP the mass per volume particulate emissions are found to be 24 mg/m³. This falls very close to the trend line in Figure 21, an interesting result as it agrees with previous data from the Kiwa laboratory and historical sources.

Measurement of flue gas flow rate via the obscuration flow meter was not possible for a number of reasons. Primarily the level of obscuration, hence particulate emissions, from this boiler was consistently too low to gather data frequently enough to perform correlation of the signals to calculate a flow rate. Therefore the level of obscuration (from the test appliance) remains too low and the device resolution was not great enough for us to be optimistic regarding using two obscuration meters to measure average flue velocity.

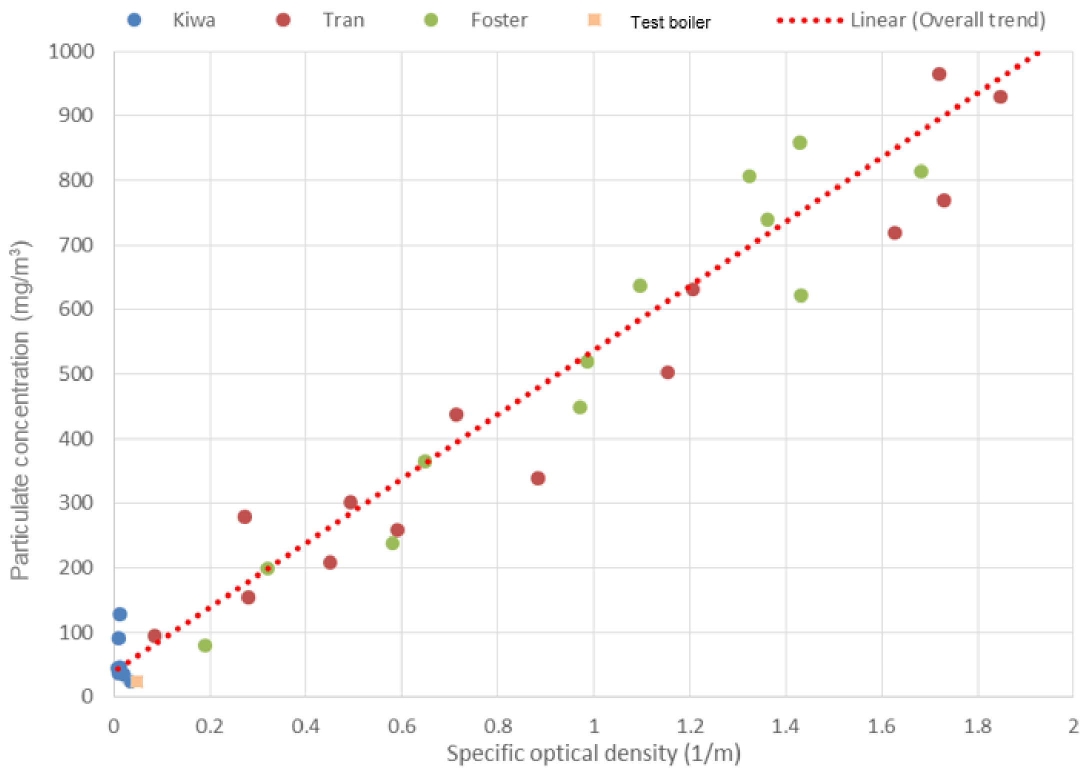

Figure 21: Wood smoke particulate matter data from various sources, showing the test boiler point.

8.1.6 Discussion

Validation of methodology

The agreement within the calculated uncertainties of the indirect losses and direct efficiency measurements performed in the laboratory shows that the indirect losses methodology proposed in this report can provide accurate results in agreement with a highly accurate laboratory method.

By using the indirect losses methodology we have been able to not only find the efficiency of the boiler under different load conditions, in agreement with the direct method, but we have also been able to identify where the greatest losses in efficiency come from. This is a distinct advantage of the indirect losses method, as more measurements are taken than the direct method, more can be learned about the way in which the boiler is performing. For example we have found in these laboratory tests that the major losses are from the enthalpy in the water vapour of the flue gas, the sensible heat in the dry flue gas and at low lower loads the case losses become a major factor, therefore fuel moisture content has a significant impact on boiler efficiency.

We were able to calculate the contribution from the case losses on a kilowatt and percent basis by using our knowledge of the contribution from the other losses, the heat transferred to the water, and the energy supplied to the boiler and performing an energy balance. It is however suggested that in a field trial surface thermistors are used to log case temperatures and directly measure the case losses, as the method used here could not be accurately performed in a field trial. An example of the mean average contribution from each of the losses during the 9% load test is show Figure 22.

Therefore due to the agreement between each of the methodologies used in this laboratory work, the extra information available from and the simplicity of performing the indirect losses methodology we suggest that this methodology is robust enough to be used in a further field trial.

The technique of using paired obscuration meters for measuring flue gas flow rate was unsuccessful, however, we have shown in this laboratory investigation that obscuration can be used to give indicative measurements of particulate emissions and that the pellet boiler tested was a low emitter. As taking flue gas flow measurements with paired obscuration meters was unsuccessful, the field pilot of this methodology tested the use of a Pitot tube and manometer as an alternative to this.

The obscuration meter did however give meaningful results when used to measure the emissions from the boiler. Plotting flue gas temperature against obscuration enabled analysis to reveal that the boiler emitted the greatest amount of particulate emissions during start up and shut down periods. This therefore reveals that multiple start-ups and shut downs do not only lead to low efficiency but also high particulate emissions. Therefore obscuration as a technique for particulate measurements can give useful data on good or poor performance of a biomass appliance.

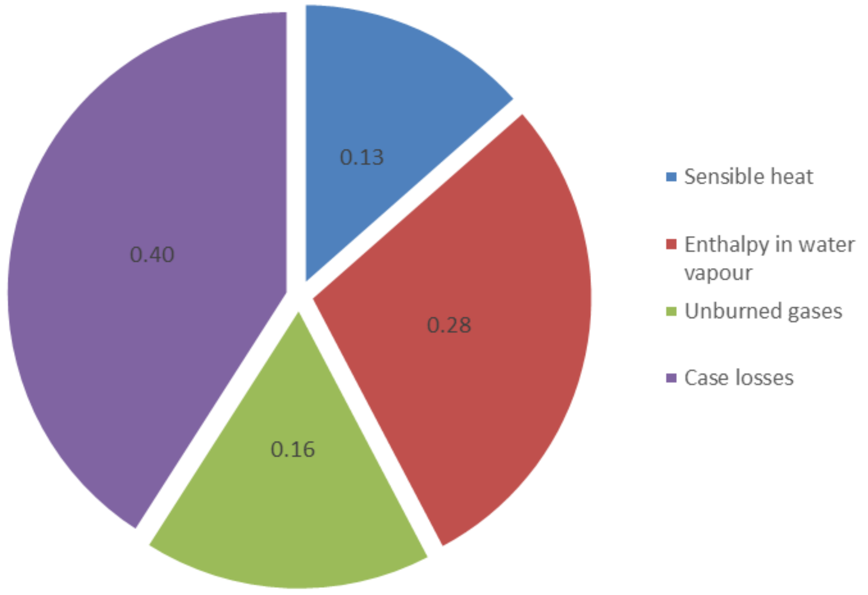

Figure 22: Average kilowatt contribution from each loss associated with the 9% load test

Interpretation of results

The results shown in Table 14 show that efficiency decreases significantly as utilisation factor decreases for this boiler. This is a trend that was postulated earlier in this report, a trend that we expect to see exhibited with boilers of all sizes. If a continuous utilisation factor of 5% produces a gross efficiency of around 25% and a continuous 9% Utilisation factor mid 60's% then it is understandable how extended demands (especially without a buffer vessel) of less than 10% will produce very modest annual efficiencies unless the firing cycle of the boiler is carefully managed. These low values are believed to be little known (and certainly not discussed) in the biomass industry.

If heat is demanded at say 5% continuously the control strategy will typically 'hunt about' looking for a solution; this produces low efficiencies. This is not unsurprising when it is appreciated that typically an oil or gas boiler has less than 1 seconds burn of fuel under fire compared to a biomass boiler of (about) 20 minutes. Oil and Gas boilers are tested 3 minutes ON and 7 minutes OFF, in great contrast it is usually barely possible to even light a biomass boiler in 20 minutes. This explains the better results obtained if the boiler is run batch-wise when the boiler can run for an hour (or more) to heat a buffer vessel and then this heat is used to slowly feed the heat distribution system. This inherently occurs (to a degree) if the heating is only run daily (say 7am to 10 pm) as bringing the heat emitters up to temperature inherently produces the extended run needed to improve efficiency.

Qualitatively (for the first time) it is now possible to see how a mixture of some extended firing periods (at 30% UF) and some 9% firing and 5% firing can give the overall anecdotal gross efficiencies of the 50% to 60% seen in the field.

The gross efficiency measurements for the direct and indirect losses methods under the three utilisation factors are in close agreement with each other, only differing by a maximum of 5%, as shown in Table 14.

The emissions collected with the ESP show 24±5 mg/m^3 and the specific optical density measurements show an optical density of 0.04 m^{-1}.This fits very well with the data shown in Figure 21 suggesting that there is a strong indicative relationship between optical density and gravimetric particulate emissions. Using the trend line shown in Figure 21 this specific optical density of 0.04 m^{-1} corresponds to a value of 57±28 mg m^{-3}, which agrees with the ESP value within uncertainties.

It should be noted that the ESP used in the laboratory employs total filtration of all the flue gases. This technique is believed to be unique in the world in collecting all the particulate emissions made by the boiler during the whole operating / test period. All of other emission techniques sample the flue gases and then employ assumptions to calculate total particulate flows. These assumptions can be of greater or lesser validity depending upon turn down, the flue temperature and nature of the particulate emissions. In light of this the particulates reported by the ESP often exceed those reported by these other sampling techniques. Unfortunately it is only suitable for laboratory use.

As mentioned previously in this report, particulate emissions are expected to be highest during start up and shut down periods. Therefore testing the boiler with multiple start up and shut downs not at steady state will be expected to produce higher emissions.

Conclusions from laboratory work

1. Indirect losses and direct thermal efficiency measurements yield results that are in close agreement. This is very encouraging with regard to using the indirect losses method as a technique for on-site monitoring.

2. Thermal efficiency can be measured successfully by only knowing flue gas temperature, ambient temperature, and fuel analysis and flue CO_2 concentration (which will be calculated from O_2 readings in the field).

3. Efficiencies in the low 30’s% at 5% continuous Utilisation factor (UF) and low 60’s% at 9% load factor explain the efficiencies of between 50 and 60% anecdotally reported from the field at low utilisation factor values. There is not a direct correlation here as daily firing and small buffer tanks can improve the situation (e.g. from 30’s% to 55’s%) even at extremely low utilisation factor values. This is first the authors are aware of these figures being measured in the UK. They are certainly little known.

4. Particulate emissions measurements via obscuration can be used to yield quantitative mg/m^3 values. Whilst uncertainties for these values may be high this is a common problem for all biomass emission measurements.

5. Low utilisation factors lead to low thermal efficiencies of wood pellet boilers.

8.2 Testing and piloting of methodology in the field

Piloting of the methodology described in this report along with data logging techniques was performed at a non-domestic site that has been identified by Kiwa. This site uses one 220 kW pellet fuelled boiler and one 250 kW pellet fuelled boiler.

It was decided to monitor the 220 kW wood pellet boiler. This boiler is installed at a National Trust site south of Bristol, it has been in place for approximately five years and is used to provide space heating and hot water to a visitor's centre, café and offices. The boiler is installed with a building management system in a brick built boiler house separate to the main building, this building also contains solar thermal and solar photovoltaic technologies. The solar thermal system has its own dedicated thermal store.

The boiler has a power range reported by the manufacturer to be 54 kW – 220 kW (25% - 100%), the boiler can be operated on either wood pellet or wood chip, this particular model has been configured to operate with wood pellets. The flue connects to an ash cyclone before extending out the roof of the building to atmosphere, there is a draught stabiliser situated in the vertical flue after the cyclone. The fuel is stored in an adjacent building and is fed to the boiler via an inclined screw feed system. There are also two 85 kW LPG back up boilers installed in the boiler room which feed the same 3000 litre thermal store as the biomass boiler. There is a heat meter installed in the flow from the biomass boiler to the thermal store, however it is printed on the meter that it should be installed in the return pipe.

The aim of piloting this methodology in the field was to test the suitability for the methodology developed in the laboratory to assess the performance of a biomass boiler in-situ and to identify difficulties in using this methodology in the field to enable solutions to be found to issues prior to any larger field trial roll out.

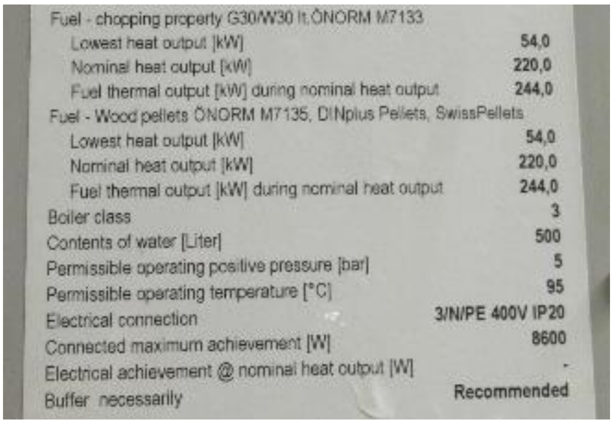

Figure 23: Field trial pilot boiler data plate (cropped for manufacturer anonymity)

8.2.1 Methodology

The equipment installed on this system was as described in the intermediate monitoring regime with case temperatures also measured. The equipment was installed as follows:

- **Flue temperature thermocouple** (placed in flue before cyclone), Figure 24, this was a standard 3mm k-type thermocouple with an uncertainty of 0.75% of the recorded value. A small hole was drilled through the double walled flue and the thermocouple was fixed in this place using a compression fitting. The thermocouple was connected to a wireless data transmitter specifically designed for reading the output voltage from a k-type thermocouple.

- **Pitot tube** and manometer (placed in flue before cyclone), Figure 24. The Pitot tube was placed in the flue in the same manner as the thermocouple and connected with flexible hosing to the manometer which was manually read over a 30 minute period.

- **Zirconia based oxygen sensor** (placed in flue before cyclone), Figure 24. This device measures the partial pressure of O_2 using a zirconium dioxide ZrO_2 sensor cell and has an accuracy of <0.5%. This sensor is calibrated to measure oxygen concentrations ranging from 0% to 5% and produces a linear output over this range of 0 V to 10 V DC.

  A mains power supply was connected into the power meter housing (Figure 25) to a transformer providing the 24 V DC power supply required for this probe. The 0 V– 10 V output of this probe was connected to a wireless data transmitter designed to accept a 0 V – 10 V input.

  A 12.5 mm hole was drilled into the flue to accept the Zr probe, which was fixed in place using a compression fitting.

- **Case surface temperature thermistors** (four thermistors used, fire-door, side, back and top of boiler casing), **Error! Reference source not found.**. The case temperatures of the boiler were surveyed using an infra-red thermometer in order for the thermistors to be placed in an area that gave a representative temperature of that part of the casing. Each thermistor was then connected to a wireless data transmitter designed to accept up to four thermistor inputs. The surface mounted thermistors were fixed to the boiler casing with aluminium tape. The uncertainty of the thermistors used was ±0.2°C.

- **Ambient temperature thermistor**. This was a wireless data transmitter with a self-contained thermistor that wirelessly transmitted data. The uncertainty of the thermistor used was 0.2°C.

- **Three phase electricity meter** (installed prior to biomass boiler isolator switch), Figure 25. A three phase meter which provided a pulse output for every kWh measured. This was placed in a housing fixed to the boiler room wall. The current was measured using current transformers which utilise electromagnetic induction to produce a current directly proportional to the measured current, this was then connected to the power meter along with voltage inputs from each of the three phases to calculate power supplied to the boiler.

  The pulsed output of the boiler was connected to a wireless data transmitter that accepts pulse outputs. The uncertainty of the power meter is 0.5% of the measured value and the uncertainty of the current transformers is also 0.5% of the measured value.

- **Obscuration meter** in flue (placed in flue before cyclone), Figure 26. Ideally this would have been placed after the cyclone, however this was not possible on this installation. This instrument is as described in 8.14. The obscuration meter was connected to an instrument box containing the power supply for the light source and an Arduino microcomputer used to process the data, this data was sampled every ten seconds and transferred via USB to a laptop computer where the data was logged and written to a .CSV file using a script written in Python programming language. This was placed prior to the cyclone as fitting it post cyclone was not possible without disruption to the boiler operation of which the site could not tolerate.

- **Fuel analysis** was not performed as, due the design of the fuel store, it could not be accessed during the short period of this trial. A direct door to the fuel store gains access, as the store was full opening this door would result in fuel pouring out and was therefore unsafe. For a longer field trial a fuel sample port could be installed in the access door, screw feeder or similar. As the fuel used at this site was from the same manufacturer as the fuel used in the laboratory investigation, the same fuel analysis was used for the field trial, see Table 12: Wood pellet fuel analysis.

- **Data logger transmitter and modem**, Figure 27. Each of the wireless data transmitters sampled every 30 seconds and transmitted data to the data logger every minute. This logger was connected to a modem containing a SIM card that was used to transmit data to the Kiwa office over the (analogue) circuit switched data network. Data was automatically downloaded from the data logger at 03:30 each morning.

  All wireless data transmitters were powered using four or six AA batteries and the data logger was powered via mains supply. Kiwa have experience of using this data logging / transmission on many field trials where we have found the battery power supply for these wireless transmitters sufficient enough to provide at least one year of data transmission.

- **Site heat meter.** Data was not logged from the site heat meter as this was connected to the BMS. A device known as a pulse splitter could be used to split the pulse output from the heat meter and provide an output to the BMS and a data logger, however, It is also thought that the heat meter may have been installed incorrectly as it was placed in the boiler flow yet stated on the casing that it should be placed in the return. If longer term monitoring was to be provided a heat meter could be fitted by a suitably qualified installer. However heat meter readings were visually taken at the beginning and end of the logging period to perform energy balance validation.

- **LPG meter**, for the same reason as the heat meter the LPG meter was not metered, however a system is available to split the output from this meter for extra logging. This could be installed on a longer field trial.

The boiler was operated under normal conditions, no changes were made to the boiler operation for the duration of the investigation.

Figure 24: Oxygen probe, thermocouple and Pitot tube installed in flue

Figure 25: Three phase power meter (power supply for Zr probe also installed in the box)

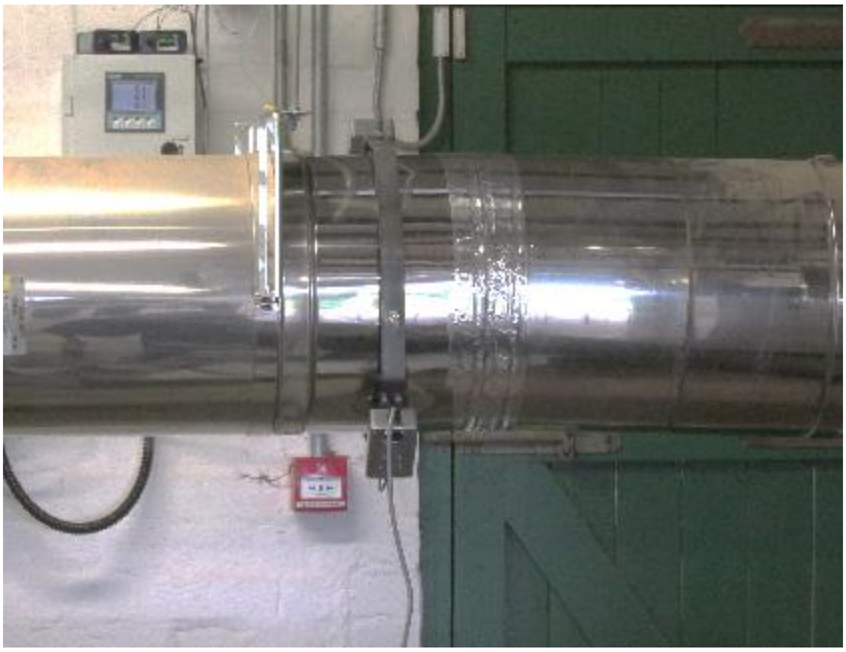

Figure 26: Obscuration meter installed in flue

Figure 27: Data logging and transmission modem, the wire at the bottom is the power supply connection and the other wire is a connection to an antennae.

8.2.2 Results from field trial pilot

Efficiency

Figure 28 shows four days of flue gas data that were remotely collected from the National Trust site, from this point on the analysis will focus on the 14/05/2015 in order to simplify the analysis for the reader

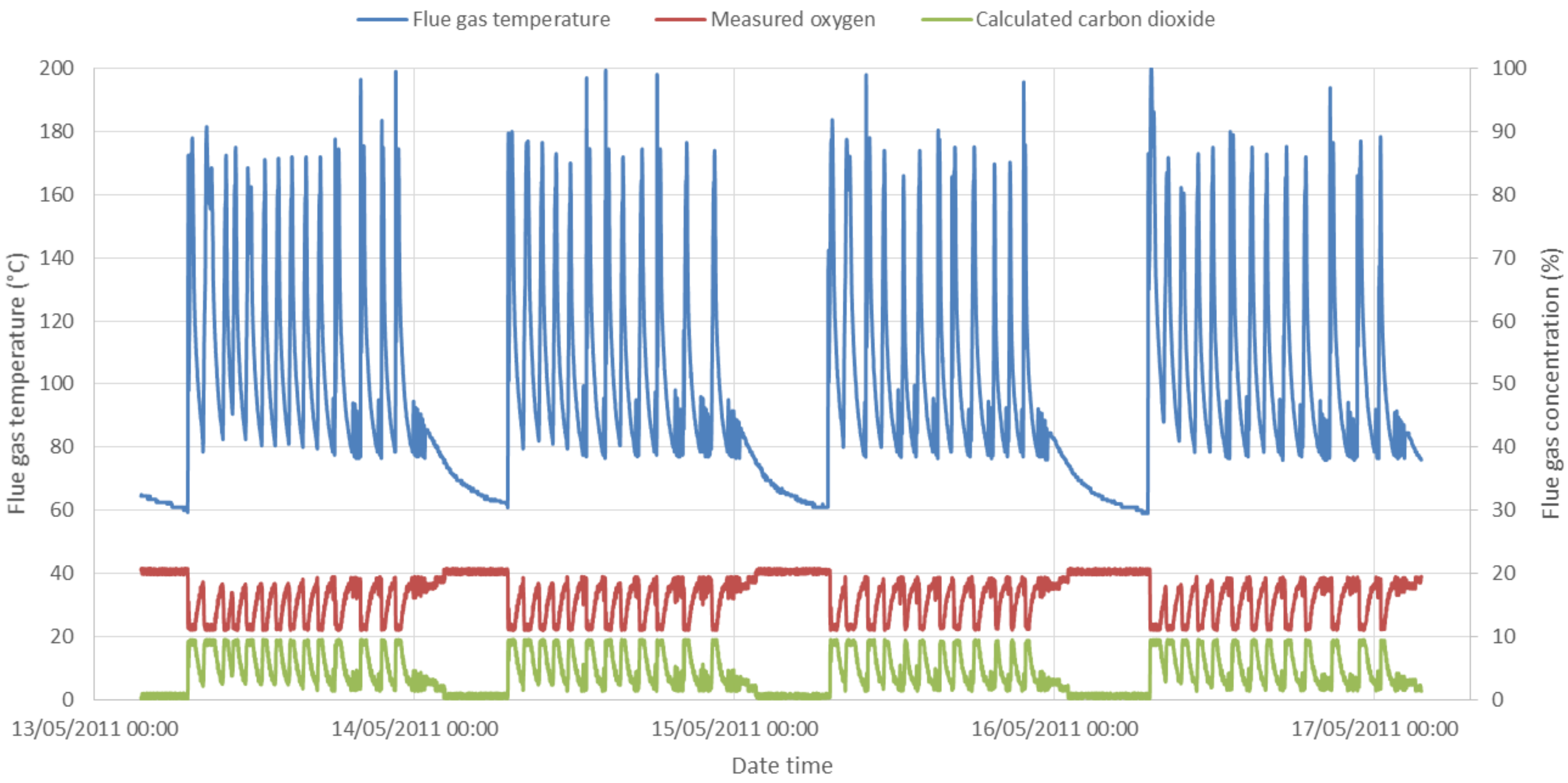

Figure 28: Four days of data collected for the period 14/05/2015 03:30 to 18/05/2015 03:31

A sample of the raw data collected during the field trial pilot is shown in Table 10: Sample of raw data collected during the field trial pilot.

Table 15: Sample of raw data collected during the field trial pilot

Date time	Ambient °C	Flue Gas °C	Case A °C	Case B °C	Case C °C	Case D °C	Power pulse	Oxygen V
14/05/2015 03:30	25.3	64.5	47.6	29.05	22.4	33.9	0	8.61
14/05/2015 03:31	25.3	64.5	47.6	29.05	22.4	33.9	0	8.7
14/05/2015 03:31	25.3	64.5	47.6	29	22.4	33.85	0	8.71
14/05/2015 03:32	25.3	65	47.6	29	22.4	33.85	0	8.62
14/05/2015 03:32	25.3	64.5	47.6	29	22.4	33.85	0	8.59

Figure 29 to Figure 34 show the data collected for one twenty four hour period of the investigation, 14/05/15 03:36 to 15/05/15 03:36. All of these figures show cyclical variation in readings which clearly show the cycling of the boiler over this period. A total of fifteen firing periods can be seen in these figures, these can be seen from the peaks in the flue gas temperature and carbon dioxide percentages.

Figure 35 shows that between the start of the day and 18:00 there were ten periods of high fire, this is indicated by the peak flue gas temperatures of approximately 175°C. This also reflected in the carbon dioxide concentrations shown. The carbon dioxide concentrations shown here are calculated from the oxygen values measured with the zirconia oxygen sensor. This calculation was performed using the formula shown in Equation 2.

Equation 2

$$CO_2 = \left[1 - \frac{O_2}{20.9}\right] CO_{2_{max}}$$

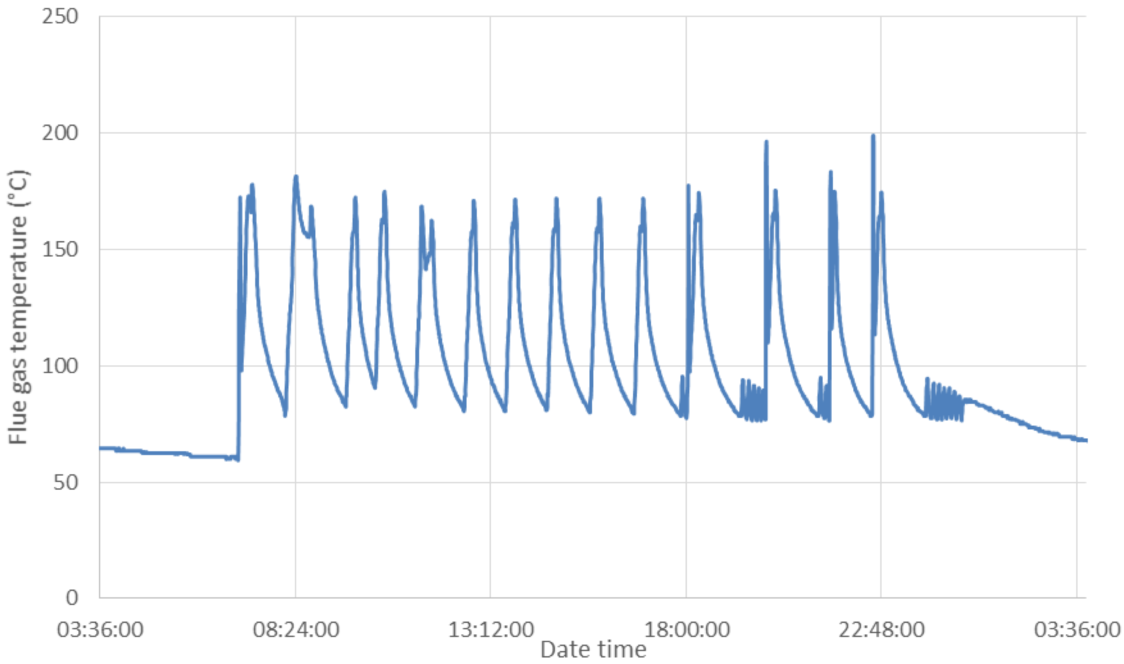

Figure 29: Flue gas temperature over the 24 hour period 14/05/2015 03:36 to 15/05/2015 03:36

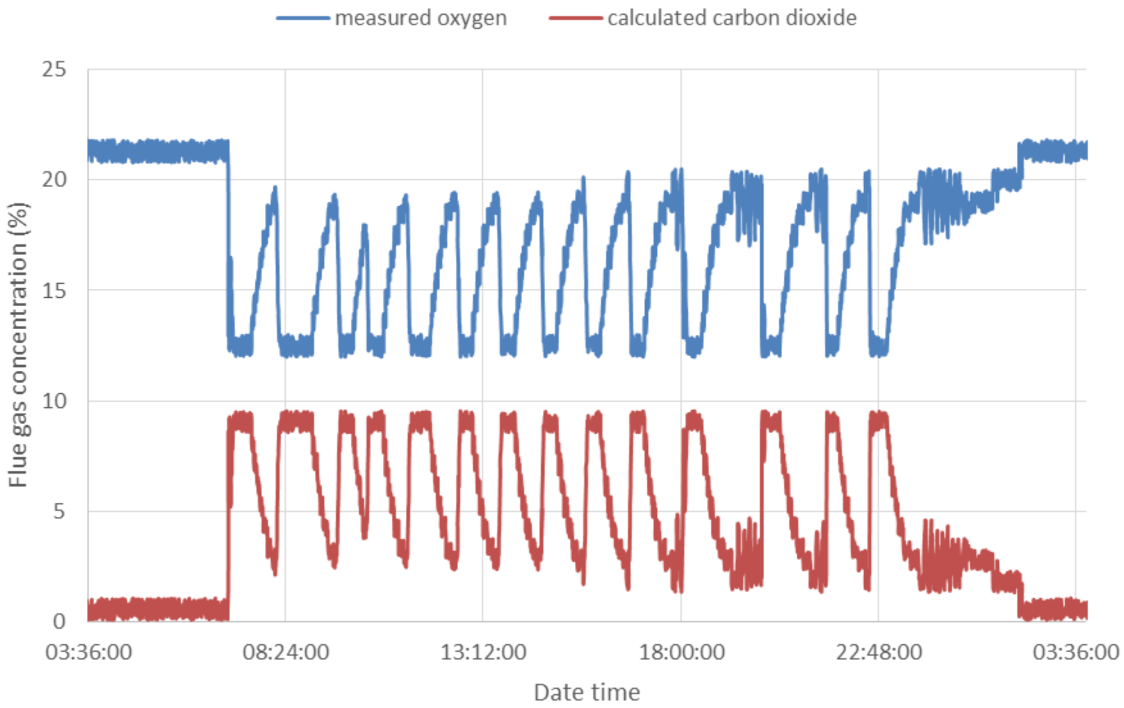

Figure 30: Measured oxygen values using the Zirconia probe and calculated carbon dioxide values for the period 03:36 to 15/05/2015 03:36.

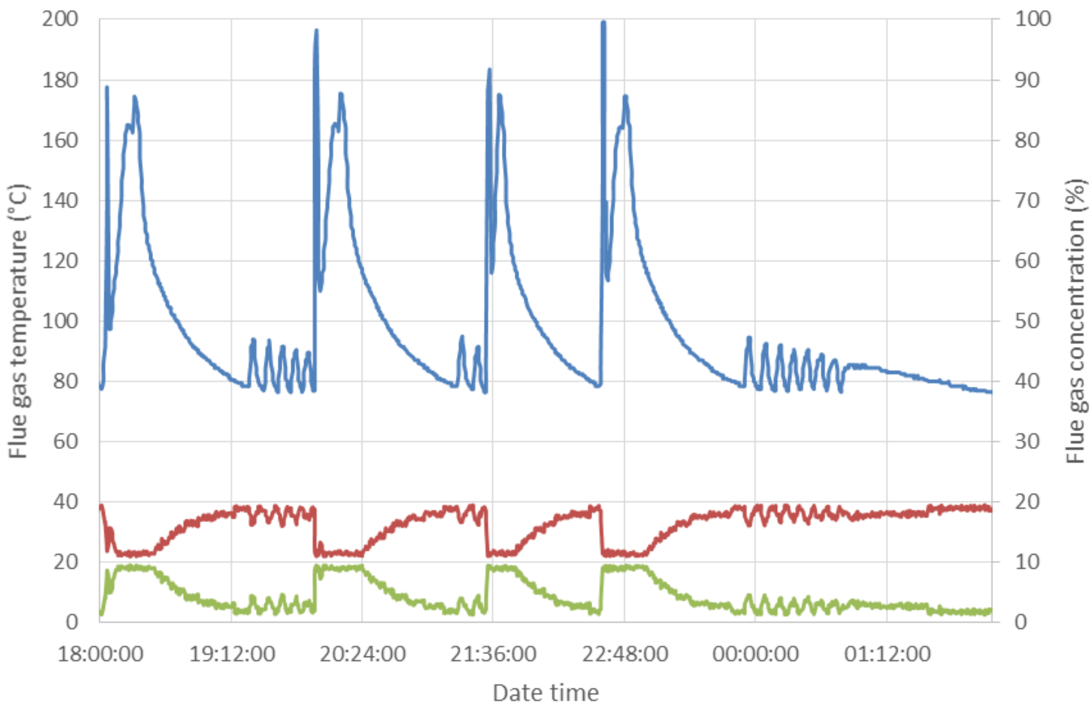

Figure 31: Plot showing period of the 14/05/15 18:00 onwards to illustrate the cycling under both low and high fire.

Figure 32 shows the measured case temperatures that were used along with the case surface areas and the equations governing convection and radiation to calculate the case losses. To calculate the radiative losses Equation 3 was used with an emissivity ε of 0.8, this is an efficiency factor with relation to a black body (perfect) emitter, σ is the Stefan-Boltzmann constant, A surface area and ΔT the temperature difference between case and ambient. Convective losses were calculated using Equation 4 where C is the convective heat loss coefficient of 1.2, η is a coefficient of 1.36. Using these formulae the total heat loss from convective and radiative losses for were found to be 0.8% of heat input (based on fuel calorific value) to the boiler. This value of 0.8% is in good agreement with the 1 % – 2 % suggested value stated in BS:845-1.

Figure 32: Case temperatures for the period 14/05/2015 03:36 to 15/05/2015 03:36.

Equation 3

$$q = \sigma \epsilon \Delta T^4 A$$

Equation 4

$$q = C \Delta T^{\eta} A$$

The electrical power demand of the boiler is illustrated in Figure 33, along with the flue gas carbon dioxide emissions. There is a relatively constant power demand of the boiler throughout the stand-by periods between firing. The peaks in boiler power demand appear as the carbon dioxide emissions start to peak and again as they diminish, this is most likely due to the increase in power from ignition sources and purge fans.

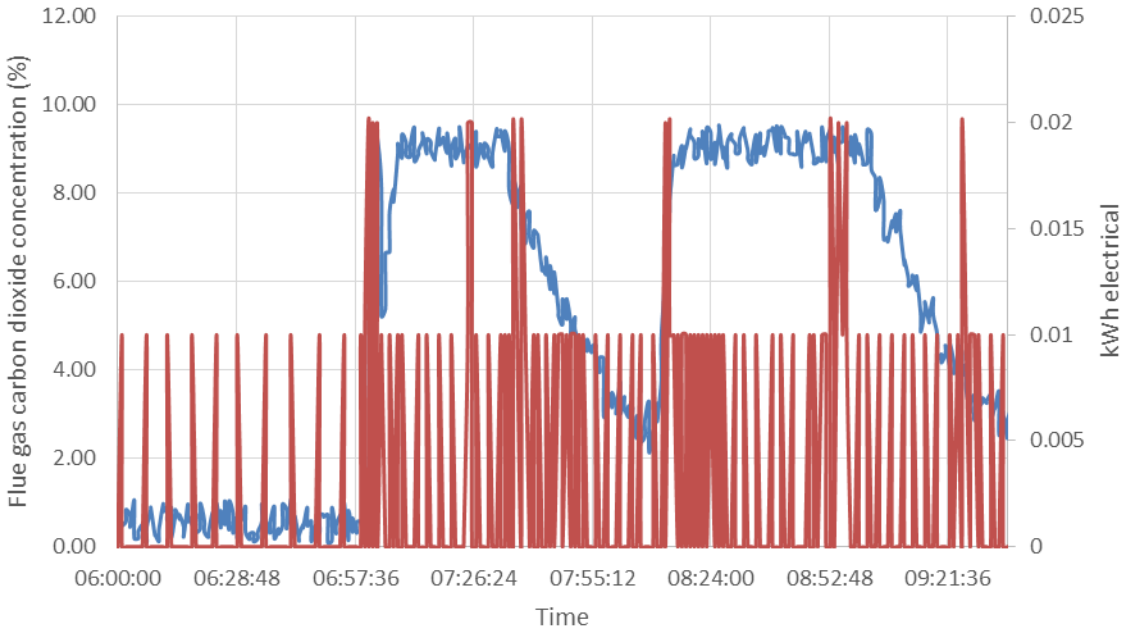

Figure 33: Electrical consumption shown with flue gas carbon dioxide concentration for the two initial firing periods of the 14/05/2015

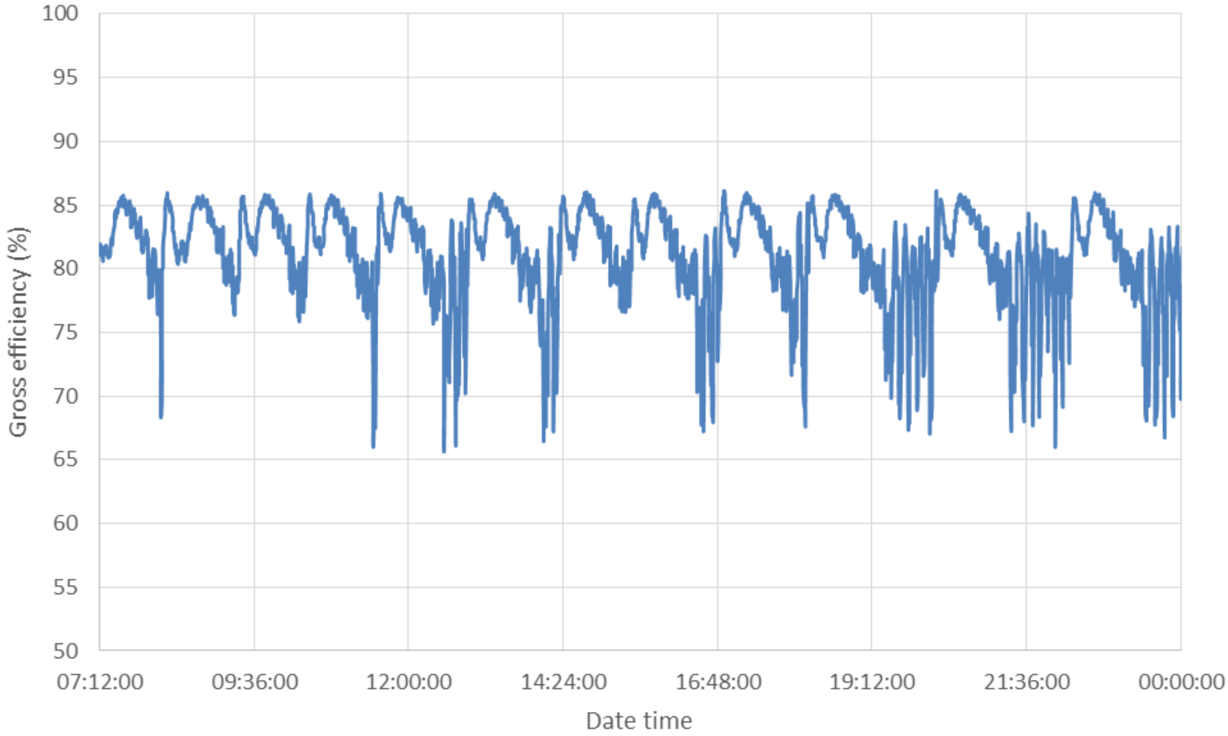

Figure 34: Gross efficiency data for the period the boiler was firing 15/05/2015 07:12 to 15/05/2015 00:00.

8.2.3 Utilisation factor / Energy balance validation

As mentioned above, the data from the heat meter was not logged due to the connection to the BMS system. This is a problem that could be easily overcome for a longer field trial as the signal from the heat meter could be split to provide an output to a data logger whilst still providing an output to the BMS system. However it was also noted that the heat meter appeared to be installed in the wrong location, nevertheless heat meter readings were taken at the beginning and ending of the data logging period in order to calculate an utilisation factor and perform an energy balance validation of the indirect losses efficiency calculation. Fuel feed rate to the boiler was estimated from fuel delivery information given by the site operator.

The heat meter data enabled a utilisation factor to be calculated, this was found to be 55%. Based on the results presented in Table 5 this is a high utilisation factor for the time of year, undoubtable due to a contribution from the thermal store.

The uncertainty in the net efficiency has been calculated as prescribed by BS845-1 as with the laboratory trial. The uncertainty in the efficiency calculated from the direct method is estimated from the uncertainties in the heat meter, fuel analysis and fuel feed rate and combining them in quadrature to find the overall uncertainty. As previously mentioned, the heat meter is suspected to be incorrectly installed, however, for the purpose of this calculation we have assumed the uncertainty to be as declared by the manufacturer for correct installation.

Table 16: Efficiency calculated through the indirect losses method for the period 14/05/2015

	Indirect losses	**Direct**
Efficiency (Gross)	68.9±3.5%	62.7±19%[7]
Closure	110%	

[7] Such high uncertainty in this measurement due to the large uncertainty in the fuel feed rate.

8.2.4 Emissions data

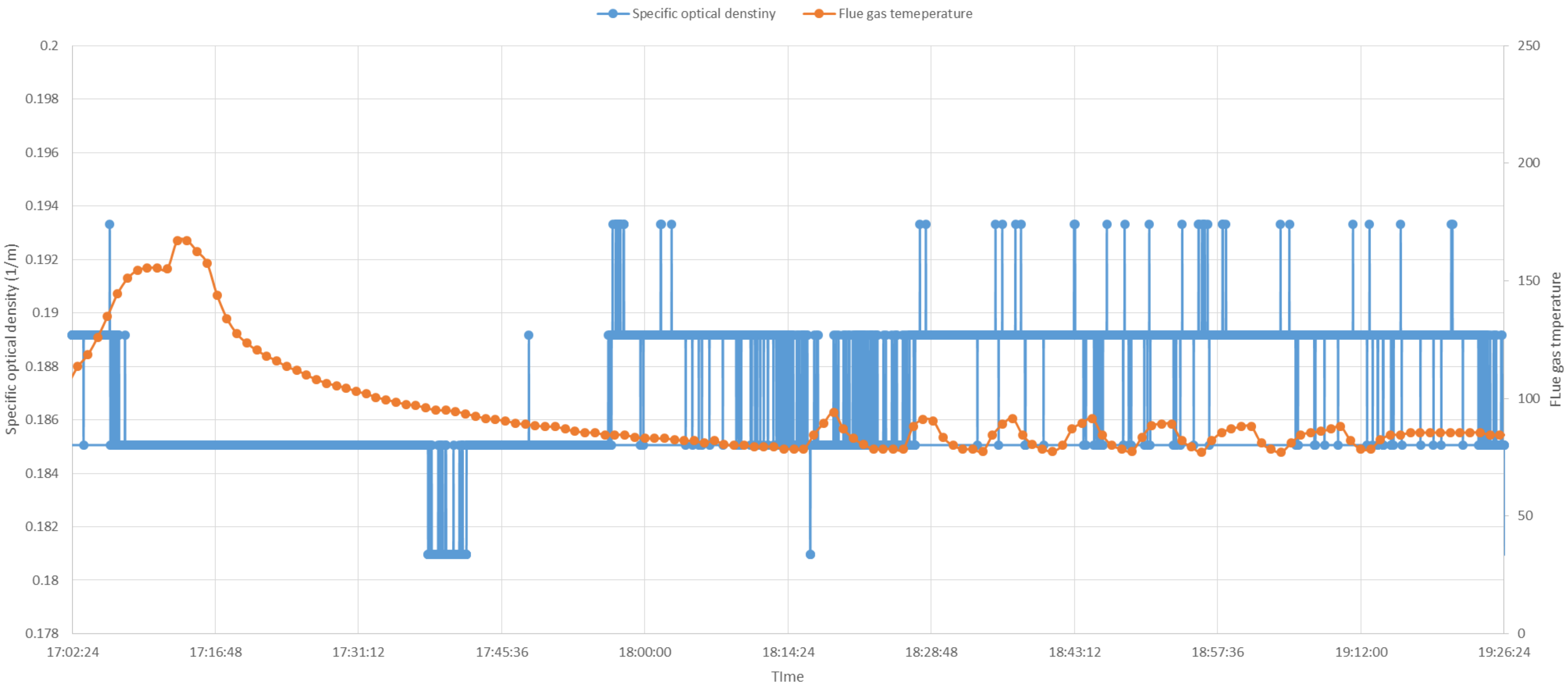

Figure 35: Data collected from the obscuration meter along with flue gas temperature

Figure 35 shows a window of obscuration data collected during the field pilot along with flue gas temperature for the same period. The resolution of the obscuration data collected is not sufficient to gain detailed insight into the particulate emissions, however it does allow calculation to be made and an indicative value of the emissions to be found in accordance with trend line illustrated in Figure 21. Using this data the emissions have been calculated to be 480g/h over the entire test period.

The data shown in Figure 35 also shows the peaking of emissions approximately coinciding, before and after the peaks in flue gas temperature. This reinforces the findings from the laboratory that emissions peak at start up and shut down of the boilers.

It must be noted here that due to the arrangement of this particular site the obscuration meter could not be placed after the cyclone so the emissions to atmosphere will be much less than this as the efficiency of cyclones is typically greater than 80%.

8.2.5 Discussion of the field investigation

The results presented here show that the indirect losses methodology proposed in this report along with remote data logging and transmission can be successfully used to evaluate the in-situ performance of biomass boilers.

Closure between the efficiency calculated via the indirect losses and direct methods could not be performed on this site. This is because the heat supplied by the LPG boilers was also metered by the heat meter. There are a number of ways that this issue could be resolved in a longer field trial:

- Analysis of data logged from the heat meter could be compared to the time that the biomass boiler was seen to be running for (from flue / power analysis), and any heat generated during times when the biomass boiler was not firing could be subtracted to provide the heat recorded by the heat meter from the biomass boiler only.

- By measuring the fuel flow rate to the LPG boilers, LPG calorific value and efficiency of the LPG boilers, the energy supplied by the LPG boilers could be subtracted from the heat meter reading.

- Additional heat meters could be placed on the LPG boilers for subtraction from the site heat meter.

These methods could then be used to gain a heat meter reading from only the biomass, which would allow an energy closure to be performed as in the laboratory investigation in section 15 of this report.

Pressure readings were taken at the time of installation of the Pitot tube, and again a day later. Within this day the Pitot tube had become blocked due to particulate emissions from the boiler and no reading could be made with the manometer. This clearly informs us that a standard Pitot tube is not suitable for measuring the flue gas flow rates in biomass boilers for any appreciable time period.

This site was not metering the power demand of the boiler prior to this trial, therefore Kiwa were required to install a power meter. To measure the current being supplied to the boiler current transformer coils were installed. The location of the isolation switch to the boiler made it simple to disconnect the switch and thread the current transformers around the live cables. The current transformers were then placed in the cable trunking which contained all electronics for the boiler room. Installation on this site was relatively straightforward, however difficulties could arise in other sites in which the electrical wiring of the boiler cannot be so easily accessed.

Mains power supplies were for the power supply to the data logger, obscuration meter, laptop for obscuration data logging and oxygen probe. For future field obscuration readings the obscuration meter could be adapted to allow for real time wireless data logging as with the other instrumentation, hence eliminating the requirement for a mains power supply for a laptop computer.

This site had few mains power supply sockets and Kiwa were required to occupy a number of these for the equipment described in the previous paragraph. This was not a major issue in this field trial but it could become an issue in other sites where there are fewer mains power supplies or if the mains sockets are a large distance away from instrumentation. In this case extension cables may need to be carefully installed to supply power without becoming a hazard.

The transmission of data from the logger to the Kiwa office was performed using a mobile SIM card installed in a stand-alone modem using the analogue circuit switched data network. The mobile phone coverage at this site was strong and no problems were had with downloading data from the logger. Alternatively a system based upon a wireless or Ethernet based broadband system could be used. A problem with using a sites own internet connection is that the site owner / householder may not wish to give access to this service, therefore use of a stand-alone SIM card modem has a distinct advantage.

The installation of the obscuration meter was initially planned to be installed in the existing flue by drilling diametrically opposite holes in a piece of flue and fixing the lamp and photoreceptor mountings with screws, however this was not possible due to the flue orientation. Instead, a section of flue identical to a small section at the site was purchased and the obscuration meter was mounted on this in the laboratory, this section of flue was then installed in place of the existing section. The original flue section will be replaced upon the end of the trial.

The fuel was delivered to this site by blowing the pellet to the fuel store through a delivery tube. The only way a fuel sample could be taken from the store was to access the fuel store through a split level access door. The door contained viewing windows at three levels in the door. Due to the level of fuel in the store, the door could not be safely opened to acquire a fuel sample. As the fuel used in the laboratory trial was from the same manufacturer as the fuel used at this site, the fuel analysis from the laboratory trial was used to perform calculations. We suggest that for a further long term field trial that a sampling strategy, including the frequency of and location of where samples are to be taken from, is specified for each site during a site assessment.

The overall gross efficiency measured for the boiler over the entire period was found to be 69.1% and 68.9% for the one day period illustrated above. The reported steady state output efficiency of this boiler at 100% output is 89.5%. By measuring the efficiency using the indirect losses methodology proposed in this report we can suggest the reason for the good performance of this boiler:

- Unlike the boiler tested in the laboratory, the boiler installed at this site is fitted with an appropriately sized thermal store. Kiwa would recommend a slightly larger tank than the 3000 litre one in place. Based on estimated values and the formula for minimum thermal store volume specified in BS EN 303-5 we recommend a tank of ~4000 litres, however this boiler is operating well with this tank in the system.

- As a result of the accumulator tank, the boiler operates at full output for 70% of the operating time, the remaining time at reduced output. As revealed in the laboratory work, operating at high output results in higher efficiency when compared to modulated operation.

- The largest losses associated with this boiler were due to the sensible heat contained in the dry flue gases. This is a typical result for a well performing boiler operating with a suitable fuel.

- The losses due to enthalpy in the water vapour made up 7.5% of the losses from the boiler. This is indicative of the fuel quality, as a higher moisture content fuel would result in greater enthalpy losses.

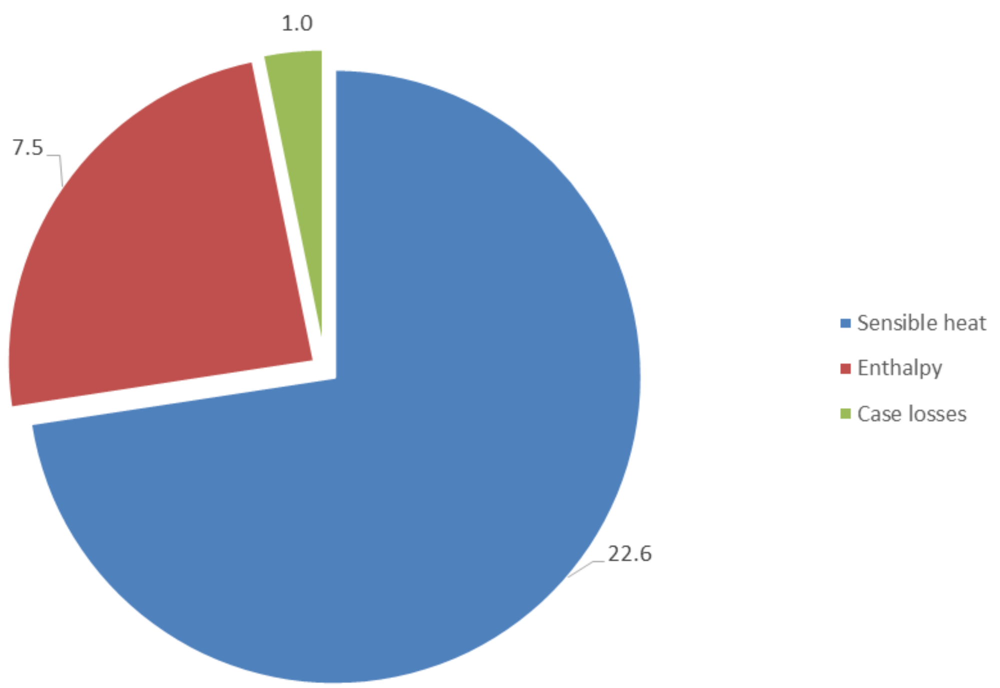

Figure 36: Percentage losses from the boiler tested in the field trial pilot

8.2.6 Conclusions from field work

- Efficiency calculations can be made using the indirect losses method by using flue gas temperature thermocouple, zirconia oxygen sensor, ambient temperature thermistor, case temperature thermistors and fuel analysis.

- Data can be successfully received and wirelessly transmitted from battery powered transmitters to a local mains powered data logger which can then use a modem with an analogue circuit switched data SIM card to transmit the data at regular intervals to a data logging computer connected to another modem.

- Sampling of fuel can be difficult and a sampling strategy should be agreed with the site prior to starting any field trial to ensure access is available for frequent sampling.

- Calculated uncertainties from the field data, using the BS845-1 uncertainty assessment, yield values comparable to those measured in the laboratory. This shows that the indirect losses methodology of calculating efficiency proposed in this report is suitable for use in a field trial.

- The strong closure between the direct and indirect losses efficiency measurements and agreement within uncertainties confirms that the methodology proposed in this report is capable of providing information on the thermal efficiency of biomass boilers in situ.

- The information provided by the proposed methodology enables investigation in to the reasons why a biomass boiler may have good or poor performance by permitting analysis of the way in which the boiler loses heat, the cycling and modulation of the boiler through flue gas analysis and indicative particulate emission values are provided via obscuration.

9 Project Conclusions

This project has successfully analysed all available data on biomass boilers installed under the RHI in the UK. Trends in the installations have been identified and categorised dependent upon domestic or non-domestic status and the key parameters shown in Table 13 and Table 14. Based upon this categorisation, two biomass boilers were chosen for the piloting of a field trial. A domestic scale wood pellet boiler and a non-domestic wood pellet boiler.

The domestic scale biomass boiler that was tested in the Kiwa laboratory successfully showed that efficiencies calculated via both the direct and indirect losses methods yield results that are in close agreement. This is very encouraging with regard to using the indirect losses method as a technique for on-site monitoring.

The laboratory work performed in this project has also investigated the effect of low loads on the efficiency of biomass boilers. We have shown in this work that low load does directly and negatively affect the efficiency of the wood pellet boiler tested. A continuous utilisation factor of 5% has shown efficiencies in the low 30% range and a 9% continuous utilisation factor has shown an efficiency of approximately 60%, these numbers fit well with anecdotal evidence reported in the field.

The laboratory work has also shown a relationship between optical density of emissions from a wood pellet biomass boiler and the mass concentration collected using an electrostatic precipitator. Particulate emissions measurements via obscuration can be used to yield quantitative mg/m^3 values. Whilst uncertainties for these values may be high this is a common problem for all biomass emission measurements, an issue which has been reported in recent, currently unpublished work, performed for DEFRA.

The piloting of the indirect losses methodology proposed in this work has shown that thermal efficiency calculations can be made using the indirect losses (losses) method by using flue gas temperature thermocouple, zirconia oxygen sensor, ambient temperature thermistor, case temperature thermistors and fuel analysis.

The field work also successfully demonstrated that data can be successfully received and wirelessly transmitted from battery powered transmitters to a local mains powered data logger which can then use a modem with an analogue circuit switched data SIM card to transmit the data at regular intervals to a data logging computer connected to another modem.

Although the laboratory gas analysis was performed with instrumentation with a much lower uncertainty than the oxygen sensor used in the field, the calculated uncertainties from the field data, using the BS845-1 uncertainty assessment, yield values comparable to those measured in the laboratory. This shows that the indirect losses methodology of calculating efficiency proposed in this report is suitable for use in a field trial.

In summary; if the methodology proposed in this report is to be used in an extensive field trial to analyse the in-situ performance of biomass boilers, the following reasons for good and poor performance can be understood:

- Utilisation factor – by measurement of heat output and fuel input

- Boiler efficiency, including the pathways that heat is lost from the boiler – through ambient temperature, flue gas and fuel analyses

- Boiler modulation – by analysis of flue gas O_2 and temperature

- Boiler cycling – through analysis of flue gas temperature, O_2 and electrical power consumption of the boiler

- Indicative particulate emissions values can be understood through obscuration measurements which can be analysed in conjunction with flue gas temperature, O_2, and power consumption to understand when and why emissions are highest.

9.1 Metering regimes

From the previous sections it is clear that there are many measurements that can be used to characterise boiler performance with varying degrees of detail and accuracy. Three levels of metering complexity are defined below. The proposed metering methodologies are suitable at any scale, covering all domestic and non-domestic RHI sites and also outside the RHI scheme. Metering will become simpler as site size increases above 1 MW as these sites will be operated by professional engineers and as a result will already be monitoring a lot of the required parameters, e.g. flue gas oxygen. These are:

- "complete metering" where all parameters of interest would be measured with a high degree of accuracy enabling the performance of the boilers to be well characterised in terms of real life efficiency, mode of operation, and smoke and NO_x emissions;

- "intermediate metering" which would be a cost effective way of determining real life efficiency and smoke emissions with some compromise on measurement accuracy;

- "minimal metering" which would allow estimates of real life efficiency and smoke emissions with the lowest degree of accuracy.

The parameters to be measured under each scenario are detailed in the sections below. This is not a strict set of metering regimes and options can be chosen from each metering regime to create a new one if required.

The uncertainty associated with each piece of measurement equipment is stated above and also below within each monitoring regime. By only considering the uncertainties associated with measurement equipment, and not the techniques, we have combined them in quadrature to give an illustrative figure for the measurement uncertainty associated with the efficiency calculated from each monitoring regime.

In order to perform a complete uncertainty analysis for the combined uncertainty in each measurement regime an analysis in line with the guidance set out in the Guide to Uncertainty Measurement (BIPM, 2008) must be followed, this accounts for all types of uncertainty such as, but not limited to:

- non-representative sampling
- finite instrument resolution or discrimination threshold
- inexact values of constants and other parameters obtained from external sources

- inexact values of measurement standards and reference materials
- Approximations and assumptions incorporated in the measurement method and procedure.

Therefore the actual uncertainties for each measurement regime stated below will not be entirely correct but will suffice to give an indicative value of the total uncertainty associated with the efficiency calculations associated with each regime.

The estimated overall uncertainties presented in this section are presented as percentage of the measured value. For example if the boiler efficiency is measured to be 50% and the associated overall uncertainty is 10% of the value the efficiency should be stated as 50 +/- 5% (i.e. between 45% and 55 %). Similarly if the efficiency is 30% with an overall uncertainty of 10% of the value the efficiency should be stated as 30 +/- 3% (i.e. between 27% and 33 %).

9.1.1 Complete metering

Parameter	Comment	Uncertainty
Heat output	a) Take signals from existing heat meter b) Install new heat meter if necessary	±5% of value
Fuel input	Site to record all deliveries by mass or volume.	±10% of value
Fuel Quality	Representative sampling (Cone & quarter) every delivery for analysis of moisture content. Ultimate analysis and CV of monthly fuel samples. All this subject to appropriate Health and Safety reviews.	±1% of value
Flue gas CO_2	Measured using extractive gas analyser, filters changed / cleaned daily, calibrated weekly, and serviced every 3 months. CO_2 will be used to cross check fuel information closure. Ordinary oil and gas flue gas analysers are insufficiently robust for extended duty with biomass plant.	±0.5% of value
Flue gas NOx	Measured using extractive gas analyser, filters changed / cleaned daily, calibrated weekly, and serviced every 3 months.	±0.5% of value
Flue gas particulate	A. Repeated onsite stack sampling (discounted as prohibitively expensive) B. Measured using obscuration (still to be quantitatively proven)	A. ±1% of value B. ±50% of value (up to specific optical density=0.25m-1) ±25% of value (specific optical

		density >0.25m-1)
Flue gas temperature	Measured using a thermocouple	±0.75% of value
Air flow rate to boiler	Not measured	N/A
Ambient temperatures	Measured using thermocouple / transmitters	±0.75% of value
Case losses	(a) Calculated using surface temperature sensors, area of case, and temperature difference case to boiler house (b) Estimated using boiler rated output	(a) ~ 2% of value (b) ≈10% of value
Electricity	Measured using standard meter: (a) 3-phase meter (b) Single phase meter	±2.5% of value
Oil flowrates	Measured using standard meter	±2% of value

Uncertainty assessment

The parameters and associated uncertainties (u_i) from the complete metering regime that will lead into an efficiency calculation by the indirect losses (losses) method are:

Fuel quality (moisture, hydrogen content, carbon content): 1%

CO_2: 0.2%

Flue gas temperature: 0.75%

Ambient temperature: 0.75%

Case losses: 2%

Electricity: 2.5%

Oil flow rate: 2%

Total uncertainty ≈ 4%

9.1.2 Intermediate metering

Parameter	Comment	
Heat output	a) Take signals from existing heat meter b) Install new heat meter if necessary	±5% of value
Fuel input	Site to record all deliveries by mass or volume.	±10% of value
Fuel quality	Sample some deliveries for analysis of moisture content. Ultimate analysis and CV of first and last fuel samples. Practical experience shows this approach is very possible for pellet given appropriate support. It is probably impractical for chip.	±1% of value
Flue gas CO_2	Not measured	N/A
Flue gas oxygen	Measured using zirconia probe	±0.5% of value
Flue gas NOx	Not measured	N/A
Flue gas particulate	Measured using obscuration	±50% of value (up to specific optical density=0.25m-1) ±25% of value (specific optical density >0.25m-1)
Flue gas temperature	Measured using a thermocouple	±0.75% of value
Air flow rate to boiler	Not measured	N/A
Ambient temperatures	Measured using thermocouple / transmitters	±0.75% of value
Case losses	Estimated using boiler rated output	±10% of value
Electricity	Measured using standard meter: (a) 3-phase meter (b) Single phase meter	±2.5% of value
Oil flowrates	Not measured	N/A

Uncertainty Assessment

The parameters and associated uncertainties (u_i) from the intermediate metering regime that will lead into an efficiency calculation by the indirect losses (losses) method are:

Fuel quality (moisture, hydrogen content, carbon content): 1%

O_2: 0.5%

Flue gas temperature: 0.75%

Ambient temperature: 0.75%

Case losses: 2%

Electricity 2.5%

Oil flow rate: 2%

Total uncertainty ≈ 4%

9.1.3 Minimal metering

Parameter	Comment	
Heat output	a) Take signals from existing heat meter b) Install new heat meter if necessary	±5% of value
Fuel input	Site to record all deliveries by mass or volume.	±10% of value
Fuel Quality	Moisture content, ultimate analysis and CV of one fuel sample. This is possible for pellet. The data for chip is unlikely to be meaningful.	±1% of value
Flue gas CO_2	Not measured	N/A
Flue gas oxygen	Measured using zirconia probe	±0.5% of value
Flue gas NO_x	Not measured	N/A
Flue gas particulate	Measured using obscuration (this technique is currently quantitatively unproven).	±50% of value (up to specific optical density=0.25m-1) ±25% of value (specific optical density >0.25m-1)
Flue gas temperature	Measured using a thermocouple	±0.75% of value
Air flow rate to boiler	Not measured	N/A
Ambient temperatures	Not measured	N/A
Case losses	Estimated using boiler rated output	≈10% of value
Electricity	Measured using standard meter: (c) 3-phase meter (d) Single phase meter	±2.5% of value
Oil flowrates	Not measured	N/A

Uncertainty assessment

The parameters and associated uncertainties (u_i) from the intermediate metering regime that will lead into an efficiency calculation by the indirect losses (losses) method are:

Fuel quality (moisture, hydrogen content, carbon content): 1%

O_2: 0.5%

Flue gas temperature: 0.75%

Ambient temperature: 0.75%

Case losses: ≈10%

Electricity 2.5%

Oil flow rate: 2%

Total uncertainty ≈ 10%

9.2 Costs of metering regimes

The estimated costs of each metering regime are shown in Table 17. Costs are per boiler. The large annual costs for the complete metering regime are particularly high when compared to the intermediate and minimal metering regimes as the complete regime includes measurement of flue gas CO_2 and NO_x concentrations, whereas the others do not. As mentioned earlier in this report, the ongoing calibration and maintenance of CO_2 and NO_x analysers are very high, hence the high ongoing costs of the complete metering regime. Detailed cost breakdowns including ongoing annual costs are shown in Appendix A. It will be possible to choose measurement strategies from any of the three scenarios to compile a bespoke metering strategy.

However, costs do not include data analysis and rational consideration of the results. Apart from just collecting the data, if it is to be useful it needs to be expertly analysed. Kiwa appreciate the difficulties associated with this and have worked on several problematic sites where solving the problem of interaction of the heating system and boiler is very contentious, and yet without this understanding solutions are unlikely to be forthcoming i.e. the project will only produce outputs not successful outcomes. This is especially the case if the boiler is too large, buffer tank too small or other fundamental problem which requires innovative site specific consideration.

Most biomass sites are large and / or non-domestic so the generic problem solving used in similar work regarding heat pumps is unlikely to be successful. It must be remembered that most heat pump manufacturers are very large companies with in depth expertise from in house R&D divisions. This is not the case with biomass boilers installed by small installers as if they were oil or gas units. A site visit is usually essential to allow for meaningful data analysis.

Table 17: Summary of costs for various metering regimes

	Equipment Cost, £	Installation Cost, £	Ongoing Costs, £ (annual)	Totals, £	Uncertainty in efficiency
Complete	28,500	6,350	28,340	**63,190**	4%
Intermediate	5,700	2,650	2,780	**11,130**	4%
Minimal	4,400	1,950	1,280	**7,630**	10%

9.3 Recommendations

Following on from the investigation and analysis performed as part of this report we put forward the following recommendations for a large scale field trial to assess the performance of in situ biomass boilers:

1) That the efficiency of currently installed and new biomass boilers are calculated by the losses method on a 5 minute basis using the following data:

- Flue oxygen concentration
- Flue gas temperature
- Flow and return water temperatures
- Instantaneous heat output
- Boiler house temperature.

This integrated efficiency being displayed both as % loss and real energy flows (kW). The calculation being carried out intelligently and diligently to allow for uncertainties in measurement values.

This performance to be compared with direct efficiency on an interval conveniently determined by frequency of fuel delivery.

2) That the above data be intelligently analysed for patterns and trends such that that causes of any inefficiencies on plants can be determined. For example rapid changes in demand or very low demand that causes the biomass boiler to wish to fire in a pattern incompatible with its minimum firing cycle. There is a substantial short fall in knowledge in the biomass sector as to the technical reasons why some sites perform poorly. There is strong anecdotal evidence this is leading to some installers offering designs which are of low capital cost but are more likely to underperform, in a fashion too complex for the market to resolve without independent research.

3) That the particulate emissions from the above range of instrumented boilers are also estimated by obscuration. It is appreciated this method has significant uncertainties, but there is substantial evidence that some designs of biomass boiler are emitting significant quantities of particulates when operated to real world demand cycles. These designs need to be identified and action taken to improve their operation. It is appreciated many of these designs will have very low emissions when measured under test conditions, but this conflict between performance during type testing and under real use is well known especially in the transport sector.

4 Additional information to be gathered for a field trial should be: biomass controls, control strategy (automatic and manual), details of the heat use (building type, what the heat is used for e.g. hot water, heating etc.), system configuration including any thermal stores or buffer tanks, load profiles and any other available supplementary information.

5) Use the above to produce practical advice for DECC and the biomass industry to improve the level of knowledge as to what factors create underperformance and real techniques as to how these can be overcome e.g. use of thermal stores, use of a secondary fuel to take very light summer load. Only in this structured fashion can the necessary knowledge be established and disseminated through the industry.

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Appendix A Detailed breakdown of metering costs

Complete Metering				
Parameter	**Comment**	**Equipment Cost, £**	**Installation Cost, £**	**On-going Costs, £ (annual)**
Heat output	a) Take signals from existing heat meter	200	200	-
	b) Install new heat meter if necessary	500	500	-
Fuel input	Site to record all deliveries by mass or volume. Sample every delivery for analysis of moisture content. Ultimate analysis and CV of monthly fuel samples.	-	-	7,200
Flue gas CO_2	Measured using extractive gas analyser, filters changed / cleaned daily, calibrated weekly, and serviced every 3 months. CO_2 will be used to cross check fuel information closure	5,000	1,000	9,280
Flue gas O_2	Not measured	-	-	-
Flue gas NO_x	Measured using extractive gas analyser, filters changed / cleaned daily, calibrated weekly, and serviced every 3 months.	15,000	2,000	10,080
Flue gas particulate matter	Measured using obscuration	2,000	500	-
Flue gas temperature	Measured using thermocouple	200	200	-
Air flow rate to boiler	Not measured	-	-	-
Ambient temperatures	Measured using thermocouple	500	-	-
Case losses	a) Calculated using surface temperature sensors, area of case, and temperature difference of case to boiler house	1,000	500	1,000
	b) Estimate using boiler rated output	-	-	-
Electricity	Measured using single or three phase meter (as required)	300	200	-
Oil flow rates	Measured using standard oil flow meter	300	200	-
Data logging		3,000	850	780
Totals		**28,000**	**6,150**	**28,340**
Grand Total				**62,490**

Intermediate Metering				
Parameter	**Comment**	**Equipment Cost, £**	**Installation Cost, £**	**On-going Costs, £ (annual)**
Heat output	a) Take signals from existing heat meter	200	200	-
	b) Install new heat meter if necessary	500	500	-
Fuel input	Site to record all deliveries by mass or volume. Sample some deliveries for analysis of moisture content. Ultimate analysis and CV of first and last fuel samples.	-	-	2,000
Flue gas CO_2	Not measured	-	-	-
Flue gas O_2	Measured using Zirconia probe	500	200	-
Flue gas NO_x	Not measured	-	-	-
Flue gas particulate matter	Measured using obscuration	2,000	500	-
Flue gas temperature	Measured using thermocouple	200	200	-
Air flow rate to boiler	Not measured	-	-	-
Ambient temperatures	Not measured	-	-	-
Case losses	Estimate using boiler rated output	-	-	-
Electricity	Measured using single or three phase meter (as required)	300	200	-
Oil flow rates	Not measured	-	-	-
Data logging		2,000	850	780
Totals		**5,700**	**2,650**	**2,780**
Grand Total				**11,130**

Minimal Metering				
Parameter	**Comment**	**Equipment Cost, £**	**Installation Cost, £**	**On-going Costs, £ (annual)**
Heat output	Take signals from existing heat meter	200	200	-
Fuel input	Site to record all deliveries by mass or volume. Moisture content, ultimate analysis and CV of one fuel sample	-	-	500
Flue gas CO_2	Not measured	-	-	-
Flue gas O_2	Measured using Zirconia probe	500	200	-
Flue gas NO_x	Not measured	-	-	-
Flue gas particulate matter	Measured using obscuration	2,000	500	-
Flue gas temperature	Measured using thermocouple	200	200	-
Air flow rate to boiler	Not measured	-	-	-
Ambient temperatures	Not measured	-	-	-
Case losses	Estimate using boiler rated output	-	-	-
Electricity	Not measured	-	-	-
Oil flow rates	Not measured	-	-	-
Data logging		1,500	850	780
Totals		**4,400**	**1,950**	**1,280**
Grand Total				**7,630**

Appendix B Indirect losses methodology losses calculations

Percentage loss due to sensible heat in dry flue gas:

$$Loss_{\text{sensible heat}} = \frac{k(t_{flue} - t_{ambient})}{V_{CO_2}}$$

Siegert constant

$$k = \frac{255C}{C.V._{gross}}$$

Volume of CO_2 from direct measurement of O_2

$$V_{CO_2} = \left[1 - \frac{V_{CO_2}}{20.9}\right] CO_{2\ \max}$$

Percentage loss due to enthalpy in the water vapour in the flue gases

$$Loss_{\text{enthalpy}} = \frac{(m_{H_2O} + 9H)(2488 - 4.2t_{ambient} + 2.1t_{flue})}{C.V._{gross}}$$

Case temperature losses

These equations yield absolute values, which must be divided through by the energy supplied to the boiler to give a percentage value.

$$Loss_{\text{radiative}} = \sigma T^4 A$$

$$Loss_{\text{convective}} = h_c A(t_{surface} - t_{ambient})$$

Thermal efficiency

$$\text{Thermal efficiency} = 100 - \Sigma Percentage\ losses$$

Table 18: Equation nomenclature

Symbol	**Definition**
k	Siegert Constant
t_{flue}	Flue gas temperature (K)
$t_{ambient}$	Ambient temperature (K)
V_{CO2}	Volume of carbon dioxide in flue gas (%)
C	Carbon content of fuel as fired (%)
$C.V.\ gross$	Gross caloric value of fuel (kJ/kg)
$CO_2\ max$	Stoichiometric maximum possible CO_2 value (%)
m_{H2O}	Moisture content of fuel as fired (%)
H	Hydrogen content of fuel as fired
σ	Stefan-Boltzmann constant (W m^{-2} K^{-1})
T	Case temperature (K)
A	Case surface area (m^2)
h_c	Conductive heat transfer coefficient (W m^{-2} K^{-1})
$t_{surface}$	Surface temperature (K)

Appendix C Indirect losses method uncertainty calculations

The method used to calculate the uncertainties in the indirect losses method measurements are as described in this appendix and as in the BS845-1 standard. The uncertainties found in these calculations are the maximum possible uncertainty; the actual uncertainty will be less than this.

Loss due to sensible heat in the dry flue gas

This is the most variable and important loss given by the formula:

$$\Delta L_{sensible\ heat} = \frac{k(t_3 - t_a + e_t)}{V_{CO_2 - e_{CO_2}}}$$

If O_2 is measured instead of CO_2 the volume of and uncertainty in this measurement should be used in place of CO_2.

Loss due to enthalpy water vapour

This is not very variable; the uncertainties are likely to be in the measurements of calorific value, hydrogen content of the fuel, t3 and ta. The greatest uncertainty is likely to occur from these sources combined is below 0.1 percentage points. It will therefore be sufficient to add 0.1 percentage points to the calculated value as follows:

$$\Delta L_{H\ water\ vapour} = L_H + 0.1$$

Losses due to convection, radiation and conduction

These are assessed losses and there will be errors due to assumptions made and to changes in environmental conditions. An allowance of 25 % is made as follows:

$$\Delta L_{case} = 1.25 L_{case}$$

Overall uncertainty

The total uncertainty in the total loss is given as:

$$\Delta L_{total} = \Delta L_{sensible\ heat} + \Delta L_{H water\ vapour} + \Delta L_{case}$$