Department for
Business, Energy
& Industrial Strategy

Measurement of the in-situ performance of solid biomass boilers

Summary of findings

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Commercial in confidence

Preface

This report is a summary of the findings of “Measurement of the in-situ performance of solid biomass boilers”, a report prepared for BEIS which details work carried out from 2015 to 2018 where the real-life efficiencies and pollutant emissions of a range of biomass boilers were measured.

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

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1 Introduction

The Renewable Heat Incentive in Great Britain (the RHI) was the world's first long-term financial support programme for renewable heat. Since its launch, the RHI has supported many solid biomass boilers, with biomass boilers comprising 89% of total non-domestic installations and 21% of domestic installations [1, 2]. Financial support is provided for 7 years for boilers on the domestic RHI and 20 years for the non-domestic RHI scheme.

Government supported technologies are tested in laboratories to assess performance in terms of efficiency and pollutant emissions based on British and European standards, however it is unclear how biomass boilers perform outside the laboratory i.e. installed in a boiler house and responding to a real-world, variable load.

In March 2014, the Department of Energy & Climate Change (DECC) – now the Department for Business, Energy & Industrial Strategy (BEIS)[1], began an evaluation of the RHI, focussed on the delivery of the scheme against its objectives and lessons for the future. In late 2015, after conducting a desk-based study [3] and researching a viable methodology [4], DECC commissioned a field trial to gather further data on the performance and emissions of a selection of boilers over a minimum of 12 months. The field trial was designed to gain a greater understanding of the performance of the population of boilers installed in Great Britain under the RHI and the reasons for good and poor performance. The work was carried out by a consortium led by Kiwa Gastec and including Ricardo Energy & Environment, Energy Saving Trust, HETAS and Optimum Consultancy.

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

This report outlines the key results and conclusions of the programme. The full technical report and annexes are provided with this summary report.

1.1 Project objectives

The objectives of the project were:

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

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

1.2 Summary of work carried out

The work carried out under this contract is summarised below:

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

2 Background

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

Phase 1
Preparatory work
November 2015 – March 2016

- Sample and recruit sites, procure equipment
- Survey sites, install equipment, set-up data storage
- Coordinate with DECC IT partner
- Literature review & develop lab trial methodology

Phase 2
Monitoring & Analysis
April 2016 – July 2017

- Field trial data collection
- Laboratory trials – efficiency and pollutant emissions
- Data analysis
- Social research

Phase 3
Interventions
August 2017 – July 2018

- Interventions and continued monitoring (selected sites)
- Guidance documents
- Laboratory trials – heavy metals

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

2.1 Field trial

The field trial studied the operation of 67 solid biomass boilers installed around Great Britain. The boilers were fired by either wood pellet, wood chip or wood log and had rated outputs between 10 kW and 800 kW. All the boiler installations qualified for either non-domestic or domestic RHI.

Data from these boilers was collected from April 2016 until July 2017. Factors affecting the performance of the boilers were analysed and the efficiency of the boilers was calculated using the losses/indirect method. The focus of this field trial was on the performance of the biomass boiler itself, and the factors affecting this. Measuring heat output and the losses from the boiler gave a more robust measure of efficiency than a direct calculation based on an estimation of fuel use. The outputs from this work included a series of case studies which illustrated specific effects on a boiler-by-boiler basis.

2.2 Laboratory trials

Data on pollutant emissions was collected during the field trial, however it is very difficult to collect pollutant data in a cost effective and robust manner. Therefore, the field trial results were supplemented with a laboratory test programme to investigate air quality and pollutant emissions. This work was carried out at two scales: laboratory tests on a small boiler, supplemented by the in-situ emissions measurements at a large boiler site. Measurements of NO_x and particulate emissions were undertaken with the boilers operated to satisfy a defined, variable heat demand.

A 25 kW wood pellet biomass boiler was tested in the laboratory using Kiwa's dynamic heat load test rig (DHLTR). The DHLTR has been designed to enable the performance of wet heating appliances to be measured under repeatable dynamic demand conditions. This allows the performance of the boiler to be evaluated under real-world conditions typical of the way in which they are operated in normal use. The rig was configured to provide a repeatable heat demand consistent with those observed in the field trial data.

Testing a large biomass boiler in the lab was not possible due to the requirement to install the boiler and equipment capable of removing the heat produced during the tests work, so emissions and efficiency measurements were carried out at one of the field trial participant's sites. An 800kW boiler was used to investigate the effect of start-ups and shutdowns on boiler performance. The operator controlled the boiler onsite and the measurements taken were comparable to the laboratory measurements.

As well as the emissions of NO_x and particulates, there is interest in the emission of heavy metals from biomass boilers. Therefore, further laboratory tests on the combustion of fuels under controlled conditions were carried out. The purpose was to gain an understanding of the fate of heavy metals after combustion, and the extent to which they may be emitted to atmosphere and/or retained in the ash.

2.3 Social research

An analysis and evaluation of behaviours, motivations and satisfaction of trial participants was carried out. It had three objectives:

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

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

2.4 Interventions

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

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

3 Summary of key findings

3.1 Efficiency

The average (median) efficiency of the all boilers in the field trial was **77% net** and **70% gross,** see Figure 2. The best performing boiler had an efficiency of 84% gross. This was within the range of values expected in standard laboratory tests at steady state, which are 77–86% gross. However, over three quarters of boilers fell below the bottom of this range. The efficiency distribution indicates that there is a performance gap of on average 15 percentage points between standard laboratory efficiency and real-world efficiency.

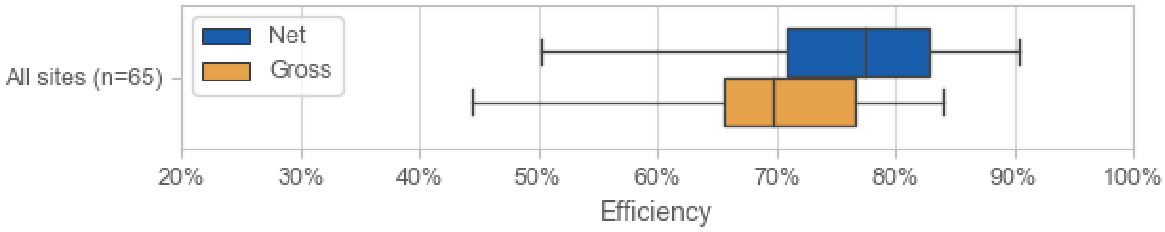

Figure 2: Efficiencies measured at all sites in the field trial, from July 2016 – July 2017

This performance gap was mirrored in the in-situ tests on the larger boiler. Part of the test work was carried out at steady state, and under these conditions the boiler had an efficiency of 78% gross. In contrast, the real-world efficiency observed from the same boiler in the field trial was 66% gross, i.e. a performance gap of 12 percentage points.

The average boiler efficiency of the wood pellet boilers in the field trial (78% net, 72% gross) was higher than the average boiler efficiency of the wood chip boilers (75% net, 67% gross). The wood log boilers had the highest boiler efficiency (81% net, 74% gross). There was greater variation in the efficiencies of the wood chip and pellet fired boilers, and in the gross efficiencies over the net efficiencies. This is shown in Figure 3.

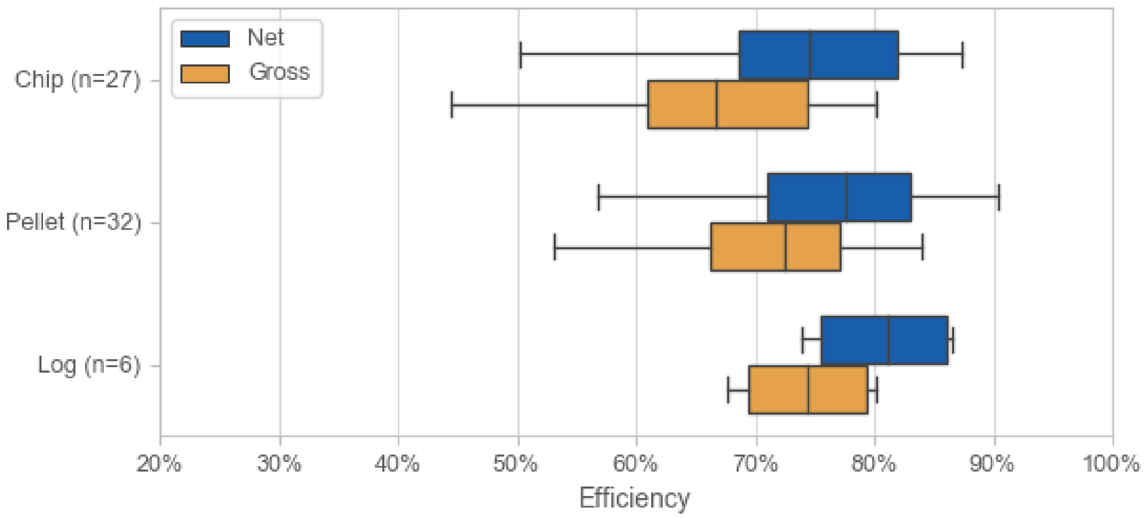

Figure 3: Efficiencies measured at all sites in the field trial over one year, split by fuel type

The average efficiencies of boilers below 100kW (around 81% net, 75% gross) were higher than the average efficiencies of the boilers between 100kW and 1MW (around 71% net, 65% gross). Boilers with rated outputs greater than 100kW had efficiencies that were spread over a larger range – some large wood chip and wood pellet boilers showed high efficiencies, but equally some showed the lowest efficiencies measured (Figures 4, 5). During stakeholder engagement events, many industry representatives believed this was primarily due to boiler oversizing.

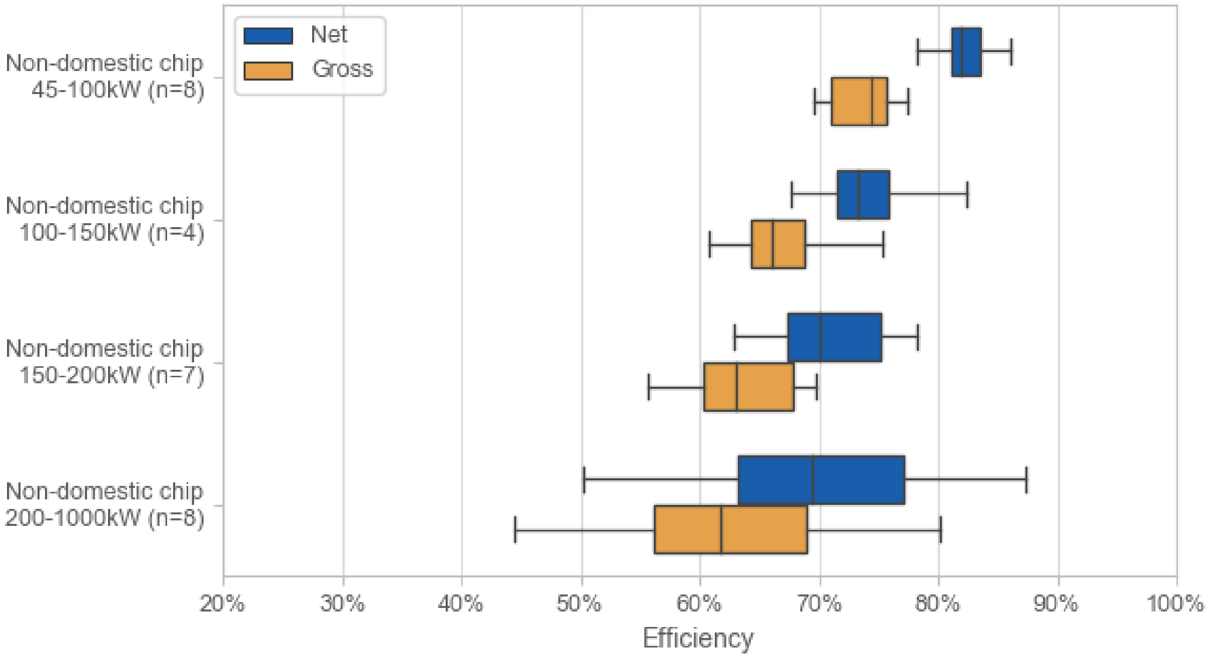

Figure 4: Efficiencies measured at wood chip sites in the field trial over one year, split by rated output

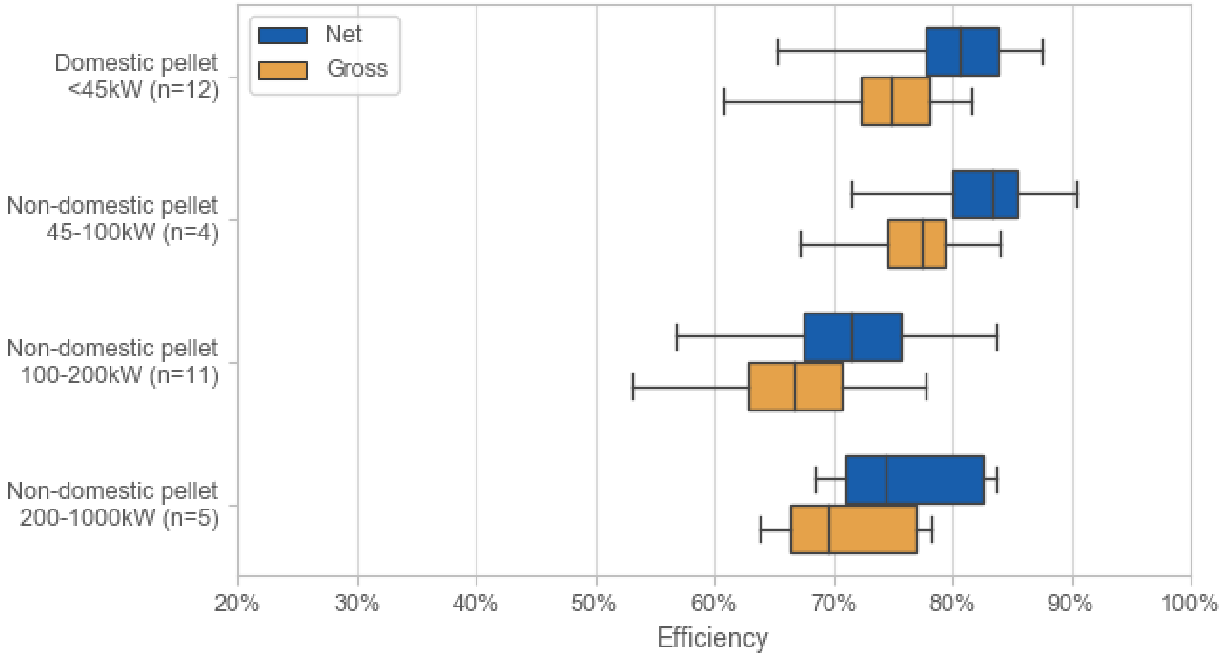

Figure 5: Efficiencies measured at wood pellet sites in the field trial over one year, split by rated output (the 100-150kW and 150-200kW wood pellet strata have been merged, as there were only two boilers operating in the 100-150kW wood pellet group)

3.2 Greenhouse gas emissions

SAP 2012, Table 12 [5, p. 199] provides emissions factor for various fuels in kgCO_2 emitted per kWh (gross energy content) of fuel burned. The efficiencies measured during the field trial were used to calculate emission factors on an output basis, i.e. kgCO_2 emitted per kWh useful heat generated. These are shown in Table 1.

Table 1: Emission factors for wood biomass (using GHG Protocol Scope 3 [6, 7])

Fuel	Rated output	Emission factor – input basis (kgCO_2e[2]/kWh gross input) *from SAP 2012* [5]	Emission factor – output basis (kgCO_2e/kWh output) *from efficiency measurements*
Wood pellet	<100kW	0.039	0.052
	>100kW		0.058
Wood chip	<100kW	0.016	0.022
	>100kW		0.025
Wood log	<100kW	0.019	0.025

3.3 Pollutant emissions

All the boilers in the field trial were eligible for RHI payments. Therefore, all boilers in the field trial would have demonstrated compliance with the RHI air quality requirements, which are:

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

The RHI regulations require that the boilers operate at least 85% of rated output when demonstrating compliance with these limits. This is in effect the same as the steady state testing that would be conducted in a laboratory to determine efficiency. During the laboratory trials two boilers were tested; a 25 kW wood pellet boiler and a 800 kW wood chip boiler. The boilers were tested at steady state to evaluate their emissions, mimicking the standard laboratory testing used to issue their emissions certificates. Both the 25 kW and 100 kW boilers were found to have NO_x and particulate emissions that were compliant with the RHI air quality requirements.

The RHI air quality limits do not require boilers to be compliant during non-steady state operation. The effect of non-steady state operation on biomass boiler emissions was tested using a range of real world cycling regimes which were determined via the in-situ monitoring. These real-world cycling regimes were designed to test the boilers in conditions that they would typically see when running during normal use. The real-world testing was similar to the standard steady state testing but with three main differences:

- Low daily load factors of 5%-30% were used to replicate the load factors that were identified from analysis of the field trial data.
- The flow and return temperatures were not fixed.
- As testing was not at steady state start-ups and shutdowns were also included in the test work. The effects of boiler cycling were therefore also included in the test results.

[2] These are CO_2 equivalent figures which include the global warming impact of CH_4 and N_2O as well as CO_2.

3.3.1 NO_x emissions

The NO_x emissions were measured using chemiluminescence as outlined in standard reference method EN 14792 [8]. The boilers tested during the laboratory trials had NO_x emissions of 70–130 g/GJ net input, independent of the test performed. The RHI emissions limit of 150 g/GJ net input was therefore not exceeded. This demonstrated that NO_x formation was not strongly dependent on the operation for biomass boilers. NO_x emissions were found to be dependent on fuel quality.

3.3.2 Particulate emissions

Particulate emissions were measured using standard gravimetric measurement techniques as outlined in standard reference methods EN 13284-1 [9] / ISO 9096 [10] (isokinetic extractive sampling) or PD 6434:1969 [11] (electrostatic precipitator). During the tests that mimicked real-world operation, emissions of around 50-160 g/GJ net input were measured. These were around 2–8 times higher than the steady state emission rates and exceeded the RHI emissions limit by a factor of around 2–5. This demonstrates that particulate formation was strongly dependent on boiler operation. The poor operational performance that was observed at many boilers in the field trial, suggests that there are likely to be a large number of biomass boilers which do not meet expected particulate emission levels during their normal operation. However, there were examples of well-operated boilers in the trial which ran for long periods at steady state and were likely to be meeting the RHI limits. Particulate emissions were also dependent on fuel quality

3.4 Causes of poor performance

The predominant factors causing poor performance were rapid cycling, poor fuel or lack of operator knowledge. However, the root cause(s) of these factors was a complex combination of issues specific to each biomass boiler. The common themes observed are summarised below and in Figure 6.

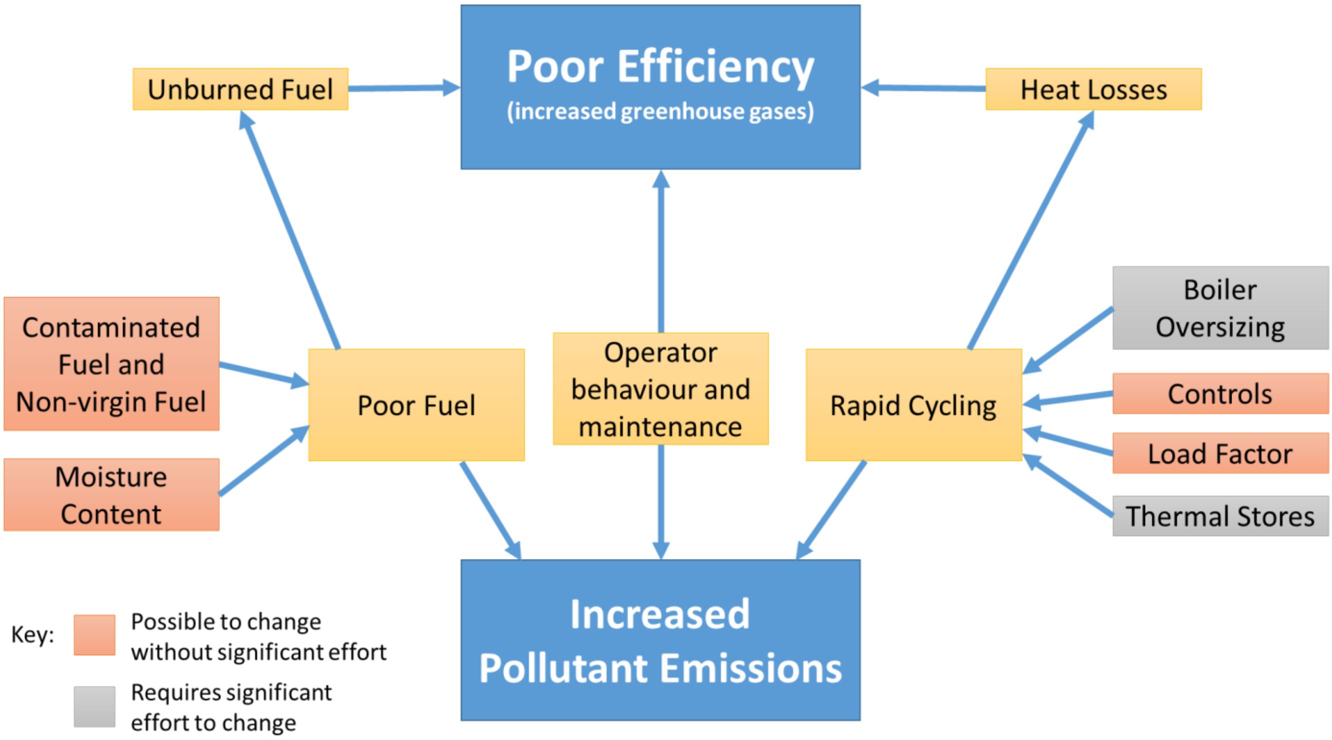

Figure 6: Root causes of the predominant factors impacting biomass boiler performance

The following sections summarise the main causes of poor performance.

3.4.1 Rapid cycling

Boiler efficiency was higher during prolonged periods of operation at high output. During startup and shutdown the boiler efficiency was significantly lower. When the demand for heat was low, boilers tended to cycle on and off frequently and in some cases unburned fuel was left in the grate. This led to large drops in efficiency. It is useful to draw parallels with gas boilers where the amount of unburned fuel in the combustion chamber is very low and the time that the fuel spends in the boiler is less than a second. This compares with a biomass boiler which may contain large quantities of unburned fuel and have fuel residence times of 20 minutes or more. Start-up and shutdown times are also much longer in a biomass boiler (10 to 30 minutes) compared with a gas boiler (a few seconds).

Similarly, emissions of particulates were significantly worse during startup and shutdown periods compared with periods of steady operation. Each cycle of the boiler was equivalent to between 1 and 5 additional hours of steady state operation.

The root causes of many of the rapid cycling issues were:

- Low load factor (14% over the year rather than an ideal design value of 20% [12]) due to the boiler being significantly oversized for the demand. Modulation is often used to address low load factors, however if boilers are not able to modulate down quickly enough, either during or shortly after the startup sequence, then they will continue to cycle rapidly.
- Controls (either of the boiler or the system) that cause frequent boiler operation, such as:
    - Bandwidth of thermostat too narrow
    - Set points unnecessarily high
    - Accumulators kept hot unnecessarily when there is no load
- The lack of a large enough accumulator tank, however this is difficult to change and often constrained by the physical space available.

3.4.2 Poor fuel

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

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

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

3.4.3 Lack of operator knowledge and boiler maintenance

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

In some cases, operators had failed to take basic energy saving steps. This might be due to a combination of lack of incentive to reduce usage due to the low cost of heat provided by the biomass boiler, and lack of understanding of the principles of biomass boiler operation.

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

3.5 Interventions to improve performance

Out of the total 67 biomass boilers in the Phase 2 field trial, 16 boilers with performance issues and a further 6 control boilers were chosen for intervention visits in Phase 3.

They were a mix of:

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

Visits were made to all 22 boilers, with interventions made at 16 “Poorer performers”. The typical site intervention process is shown in Figure 7.

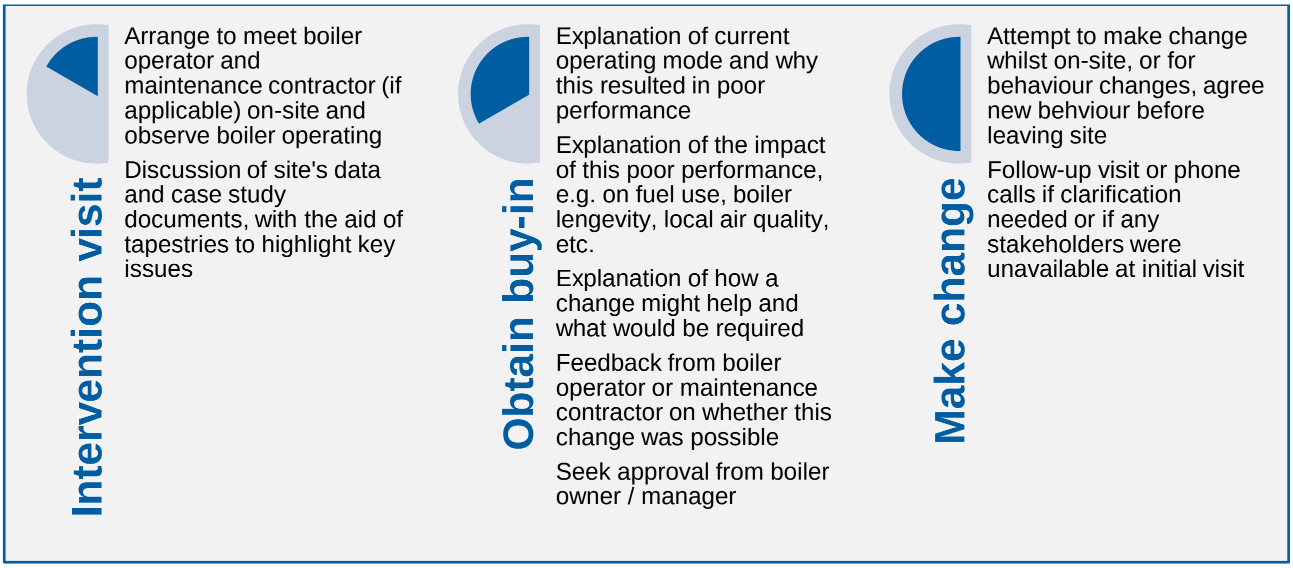

Figure 7: The site intervention process in Phase 3

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

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

Another common issue was ***operation of the boiler when either not required, or when another source of heat should be used instead*** (33% of sites).

The most effective method of improving efficiency was to check that the flue gas oxygen set point of the boiler was set correctly, that the boiler’s oxygen sensor was serviced, and checking that the smoke tubes were cleaned to extract the maximum energy from the flue gases.

For some of the interventions, a maintenance company (contractor) assisted with the change in some way. Their assistance did not guarantee that the change would be successful, however in all cases where there was a successful change, a maintenance company had been involved. Of the maintenance contractors engaged during the interventions, most would only normally visit the biomass boiler once per year for an annual service. It was common that the site would switch off the boiler beforehand so that it was cool ready for the maintenance. When the boiler was switched on after the maintenance, the system would have cooled, so boiler cycling would not start straight away. A side effect of this was that the maintenance companies never observed the boiler operating under normal conditions for an extended period. Without remote monitoring of boiler operation, some had been previously unaware of the boiler cycling.

4 Conclusions

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

This work found a performance gap, both in terms of energy efficiency and emissions of particulates, when biomass boilers are operated under real-world conditions. Many of the biomass boilers observed were oversized for the heat demand they were supplying, and this was one of the causes of frequent cycling.

The average efficiency of biomass boilers under real-world conditions (which were determined via the in-situ monitoring) was ***77% net*** or ***70% gross***. This indicates there is a performance gap of on average 15 percentage points, between standard laboratory efficiency and real-world efficiency.

The particulate emissions were ***50-160 g/GJ net input*** under real-world conditions. These exceeded the RHI emissions limit of 30 g/GJ net input for particulate emissions by 2-5 times, although they may not have been visually noticeable.

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

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

4.1 Rapid cycling

When the demand for heat was low, boilers tended to cycle on and off frequently. This led to large drops in efficiency. Similarly, emissions of particulates were significantly worse during startup and shutdown periods compared with periods of steady operation. Each cycle of the boiler was equal to an equivalent extra number of hours of operation (between 1 and 5 hours extra operation per cycle for the boilers tested). The root causes of many of the rapid cycling issues were:

- Low load
- Controls (either of the boiler or the system) that cause frequent boiler operation.
- The lack of a large enough accumulator tank.

4.2 Poor fuel

Poor fuel impacted both efficiency and pollutant emissions.

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

- High moisture leading to low efficiency.
- Non-virgin wood or contamination of the fuel – this led to increased particulate emissions.
- If there was an increased nitrogen content in the fuel it also led to increased NO_x emissions.

4.3 Lack of operator knowledge and boiler maintenance

The level of operator knowledge and training, and therefore the boiler maintenance untaken, varied widely. It was unclear whether the best practice advice was consistent, as several operators did not identify symptoms of poor operation, such as visible smoke or rapid cycling. Around half of operators suggested that more information could have been provided to help ensure the smooth operation of their boiler.

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

Maintenance personnel who undertook work on the boilers were often unaware of the normal pattern of operation of the boiler. The annual service takes place at most sites when the boiler is switched off (for example, over the summer). Without witnessing poor behaviour maintenance personnel did not correct issues which could otherwise have been prevented.

5 Recommendations and further work

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

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

Key recommendations are:

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

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

Key areas of further work are:

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

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

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

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