Department for
Business, Energy
& Industrial Strategy

Measurement of the in-situ performance of solid biomass boilers

kiwa

Annex F: Case Studies

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26 July 2018
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Preface

This report is a compilation of case studies produced from the measurement of in-situ performance of solid biomass boilers 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

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B046 was monitored from 16 March 2016 to 31 May 2018. This case study contains information on performance and efficiency of the biomass system and recommendations on how to improve operation. Information on performance of all systems across the trial is also included.

2 Background

B046 was one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip or log.

B046 was also part of further year of monitoring where 21 sites were monitored for a further year. Interventions were made at 15 of these sites to improve the site performance in terms of both efficiency and pollutant emissions.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. This data was used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data that was kindly provided by trial participants was used (along with the compositional analysis we had carried out) to give a picture of energy input and, combined with heat output and oxygen consumption, to provide an indication of the overall efficiency.

3 Description of the boiler and system

The monitoring was completed on an 800 kW wood chip biomass boiler located in its own boiler house. During the field trial there were several faults reported on the boiler. However, most faults resulted in the boiler being inoperable for only a few hours. The most serious faults occurred in January 2017 when the boiler was offline for 12 days due to faults with gear boxes, software on the control panel, and feed augers. A fault with the flowmeter attached to the heat meter led to a loss of heat meter data between October 2016 and January 2017. The heat between these two periods was calculated from the flow and return temperatures and the known system flowrate. Heat data that was calculated has been coloured differently in the graphs presented below.

The boiler was fired by self-supplied virgin wood chip stored in a fuel bunker which was on the side of the boiler house. The boiler itself incorporated an underfeed stoker type burner. Primary combustion air was fed under the fuel bed by rows of air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and the residual ash was thus pushed across the floor of the combustion chamber to the ash removal channel/screw.

Table 1 About the site

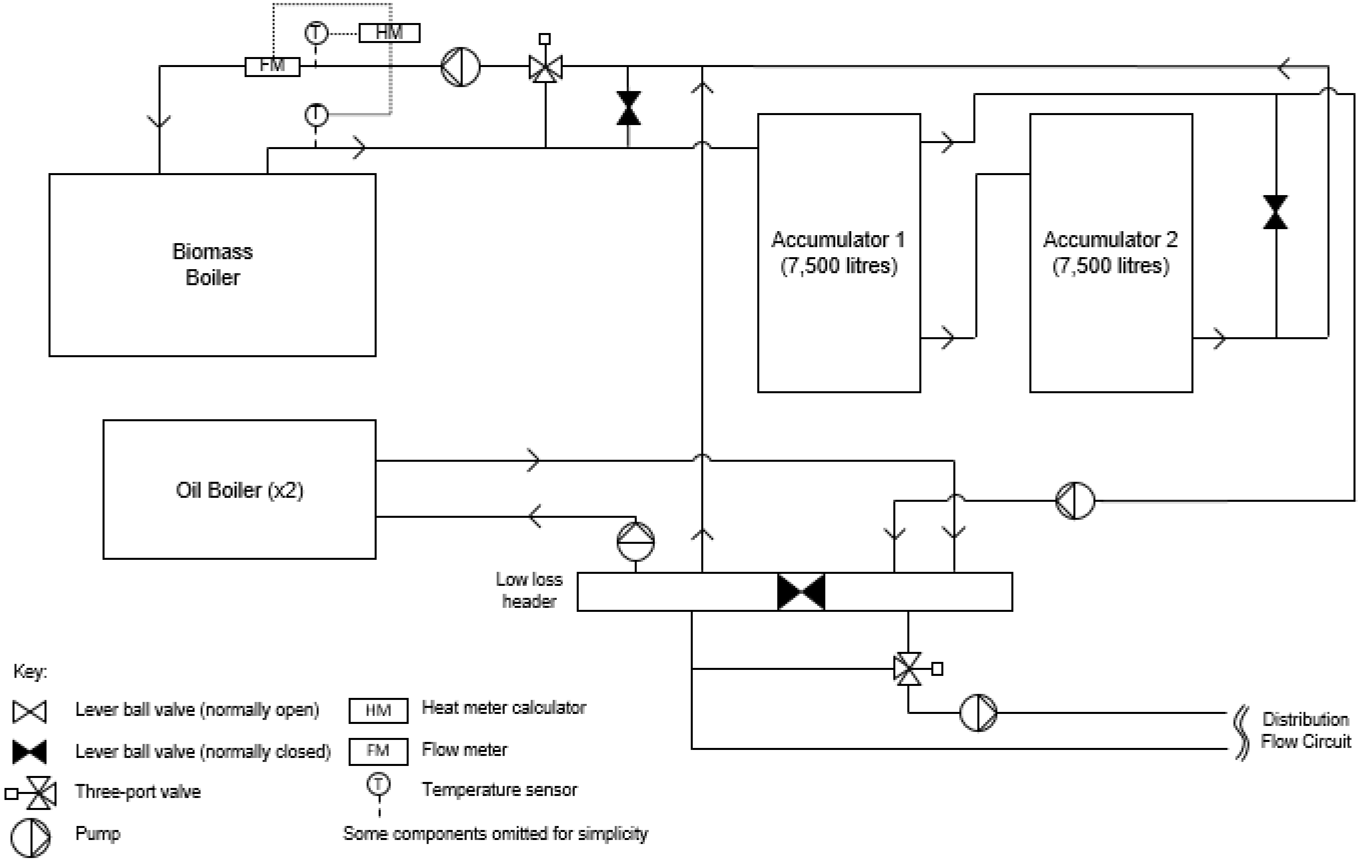
Building description	Estate
Fuel storage issues	Fuel storage was in a separate area of the boiler house.
Heat losses	All of the pipework observed was well insulated.
Issues raised by operator at time of installation	The owner commented on the time it took to resolve a lot of issues during the first year to 18 months of operation. A number of which, such as fuel quality, they have resolved themselves. The estate has made a significant investment in biomass in both time and money.

The boiler's primary use was to provide space heating and hot water to commercial and domestic properties through a district heating system. Two 7,500 litre accumulation vessels were fed directly by the biomass boiler and they formed the first part of the installation in the boiler house which fed the district heating system. The boiler house itself also contained equipment used to move heat around the district heating system as well as two oil fired boilers which provided back up heat generation. This resulted in a large amount of piping connecting the boiler to the accumulation vessels and district heat network, all of which had been well insulated to reduce the heat losses.

Table 2 About the biomass boiler

Rated output	800 kW
Fuel type	Wood chips
Thermal store	Yes
Draught diverter	None
Dilution components	The system used flue gas recirculation, which was recirculated after the dust abatement
Fans	Forced draft, induced draft, flue gas recirculation
Cyclones	Yes separate unit
Filters	None
Boiler faults	No faults displayed

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

This section shows how the boiler performed between 16 March 2016 to 31 June 2017. In accordance with EN standards, the efficiencies have been calculated on a Net basis using efficiency equations outlined in BS 845-1.

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 3

Data collection period was from	16 March 2016 to 31 July 2017	
Heat output over this period	1,870,616	kWh
Estimated fuel use over this period	750,219	kg
Electricity consumption over this period	19,996	kWh
Hours of operation over this period	6,791	hours

5.2 Annual equivalent use

Table 4

	Annual equivalent use		**Typical winter month (Feb 2017)**		**Typical summer month (Sep 2016)**	
Heat output	1,424,826	kWh	229,520	kWh	46,610	kWh
Estimated fuel use	555	tonnes	85	tonnes	21.5	tonnes
Electricity consumption	15,550	kWh	2,186	kWh	532	kWh
Efficiency	74	%	76	%	68	%
Hours of operation	5,178	hours	604	hours	229	hours
Load factor	20	%	43	%	8	%
Average starts per day	1.8	starts	1.0	starts	2.4	starts

5.3 Overall boiler efficiency

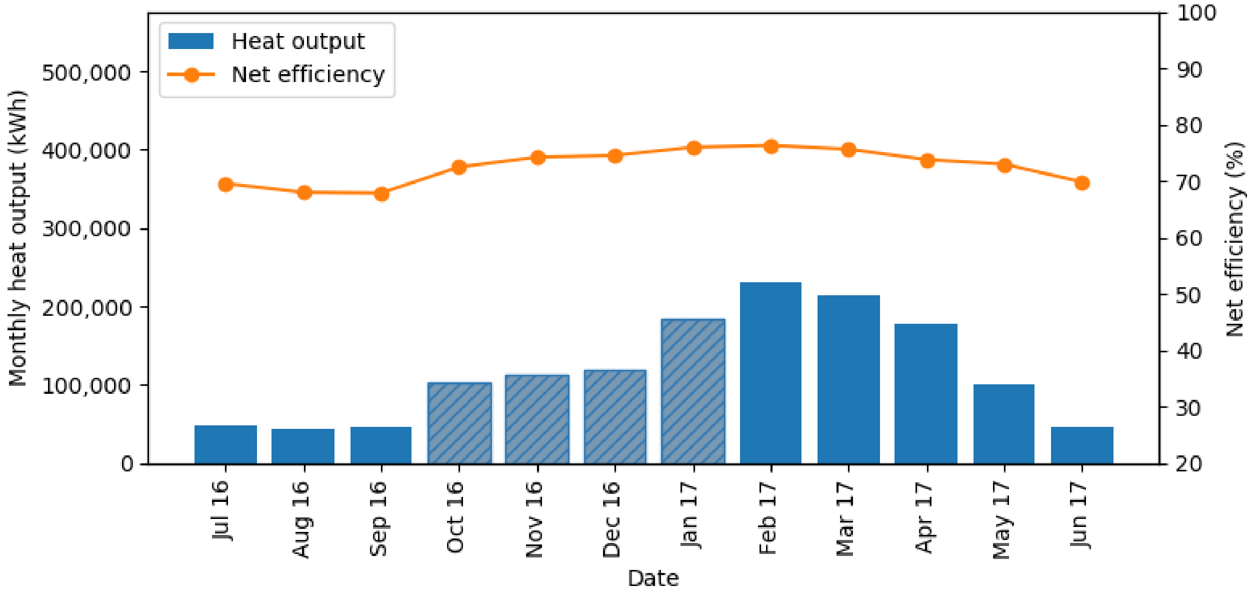


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler. Figure 1 shows hashed bars from October 2016 to January 2017 which correspond to the period where the heat meter was faulty. Heat has been calculated during this period based on the operation of the boiler.

The net efficiency was calculated for the boiler by specifically looking at and how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, will have their own heat losses which will decrease the net efficiency of the system as a whole. If the system had large accumulator tanks in unheated spaces, or long lengths of underground distribution pipes (as was the case with this boiler), then the overall system efficiency could be much lower. This is explored further in the published field trial report.

The calculated annual equivalent efficiency of the boiler over the field trial averaged at 74 % (over the period for which we had data), however this changed depending on the time of year. It is important to note that the efficiency is for the boiler only and uses the heat meter shown between the boiler and the accumulator in the schematic. Although the effects of the system on boiler performance have been discussed, the data monitored for the site was from the boiler only and therefore is only a measurement of boiler performance. This is particularly important at this site as the boiler fed a large district heating main which provided heat to many properties. The losses from the district heating main were likely to be significant.

The graph shows that the efficiency of the boiler was higher in the colder winter months (the period in which the most heat was supplied) and lower in the summer months when the boiler was used for domestic hot water only. For example, it averaged 76% in February 17 and 68% in September 16. The exact cause of these lower efficiencies in summer have been investigated and are detailed in section 7.

5.4 Boiler efficiency from on-site testing

B046 was also tested by Kiwa on site and the more accurate measurements taken during testing have allowed for more accurate efficiencies to be calculated. The testing was done over two days and focused primarily on start-up, shutdown, and steady state efficiencies. The results of the testing are shown in table 1.

Table 5: Results of the on-site testing.

Test No.	Test Type	Test duration (h)	Fuel Energy in (kJ)	Fuel In (kg)	Heat out (kJ)	Dust emission (g/GJ)	NOx emission (g/GJ)	HC emission (g/GJ)	Efficiency net (%)
1	Full cycle	1.38	1,308,406	76.9	993,003	218	91	2,529	76
2	Full Cycle	0.88	706,328	41.5	516,000	107	127	1,325	73
3	Full cycle	0.80	845,306	49.7	666,000	67	89	891	79
4	Start up	0.48	241,479	14.2	150,000	844	214	19,446	N/A
5	Steady state	0.50	939,667	55.2	717,000	27	73	86	76
6	Shut down	0.60	588,951	34.6	453,000	114	111	3,234	N/A
7	Start up	0.35	291,474	17.1	207,000	102	100	1,518	N/A

The tests above show the pollutant emissions from the boiler during on-site the testing. The average net efficiency of the boiler during the tests was around 76%. The boiler produced a high level of dust and hydrocarbon emissions during start up and shut down, however during steady state operation the pollutant emissions were very low. Comparing tests 4, 5, and 6, start-up and shut downs produced most of the dust and hydrocarbon emissions. It can clearly be seen that limiting the cycles the boiler completes in a 24-hour period would improve boiler performance with regards to pollutant emissions. It may be possible to achieve this to a modest extent by adjusting the control of the boiler. However, due to the complexity of the system and the competing backup oil boiler, this may be very difficult to achieve. The boiler also performed better when starting from a warm state. Igniting the boiler from cold gave significantly more emissions than when warm. This can be seen from tests 1, 2 and 3 where the boiler gets progressively warmer from the heat of the previous test, and tests 4 and 7 show the difference between a cold start-up and a warm start-up.

Another observation we made of the site was that the boiler itself was very well maintained and that the operators would go beyond manufacturers maintenance recommendations to ensure that the boiler operated with optimum performance. This can be seen in the performance and efficiency results in Table 5 and in the data for a full year as the boiler had very few maintenance issues apart from problems with using different fuels.

5.5 Heat output vs. degree day heating requirement

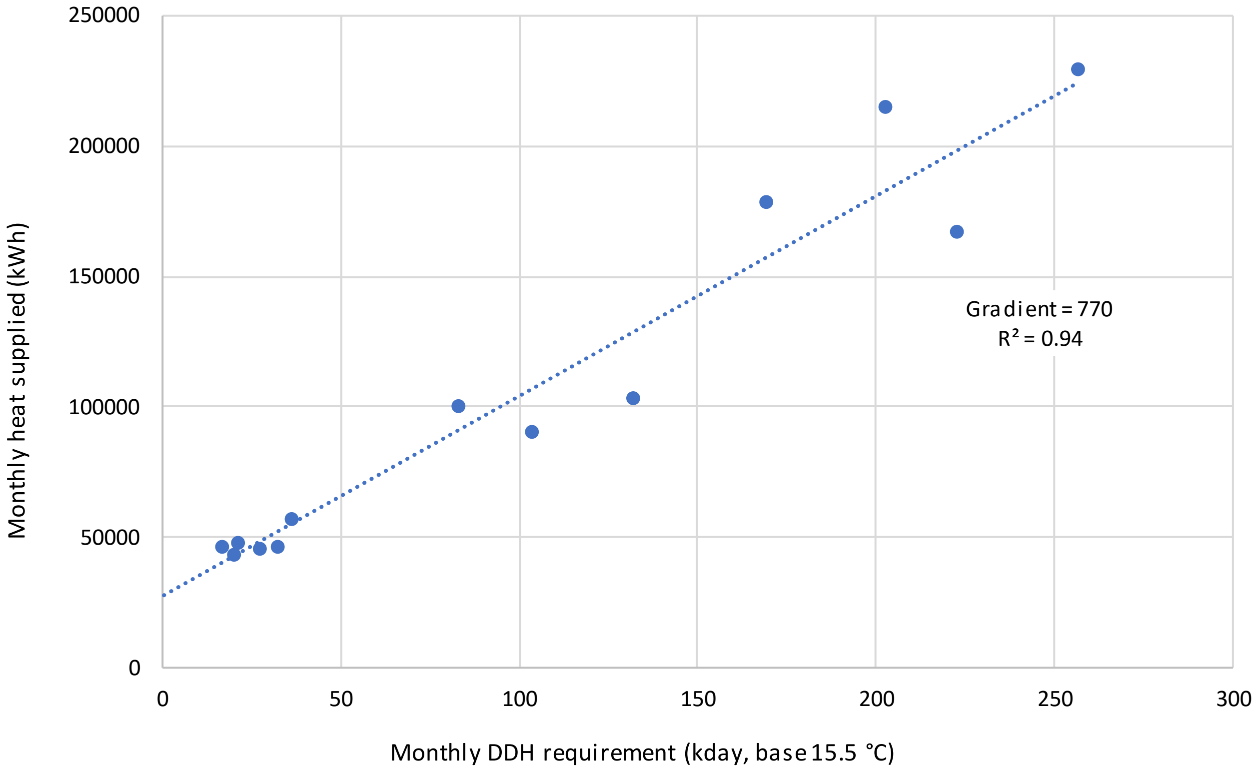


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

For B046 there is good correlation between degree day requirement and heat output of the boiler. In the summer, the load was mainly used for Domestic Hot Water (DHW) which is around 50,000 kWh per month which can be seen from figure 2.

An output of 50,000 kWh equated to the 800kW boiler operating for just 2 hours a day. In the winter, the monthly load was around 200,000 kWh which was 4 times the summer value. This equated to a run time of around 8 hours per day. In practice, we saw longer run times in both summer and winter as the boiler could modulate its output down to around 40% of capacity. This modulation had the effect of allowing the boiler to operate for longer run times.

The losses in the district main had been seen to be around two degrees however without information on flow rates the exact losses could not be estimated. To understand how much the losses from the system impact the overall efficiency it is suggested that the site investigates the losses in the distribution system when heat is supplied to the properties for DHW in the summer months. If they form a significant part of the heat supplied by the boiler it is suggested that for summer operation another source of heat could be found for DHW such as point of use electric heaters.

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

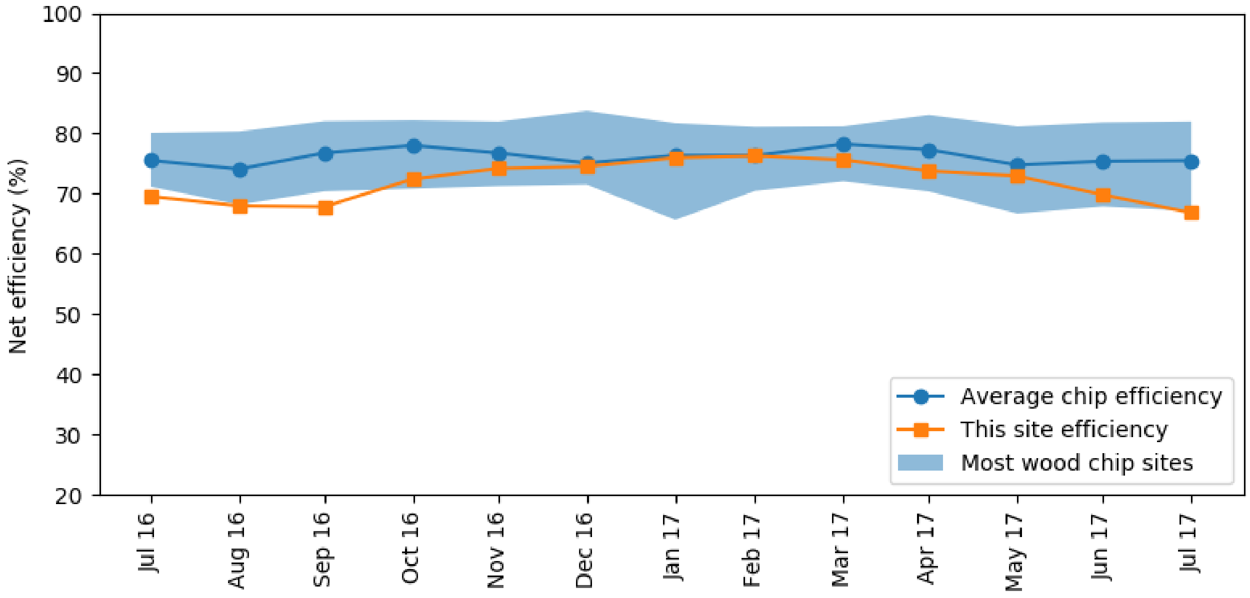


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B046.

The net efficiency of the boiler (in orange) is shown along with the average boiler efficiency (in blue). The light blue band on the graph shows the efficiency range of most of the boilers in the field trial (the middle 75%).

If the boiler fell above this band, it was performing particularly well compared with the other boilers of this type in the field trial. If the boiler fell below this band, it was performing particularly badly compared with the others.

7 Heat use and patterns of heat demand

To understand how the boiler operated throughout the field trial, data collected by the monitoring equipment installed on site has been used to plot the daily load factor.

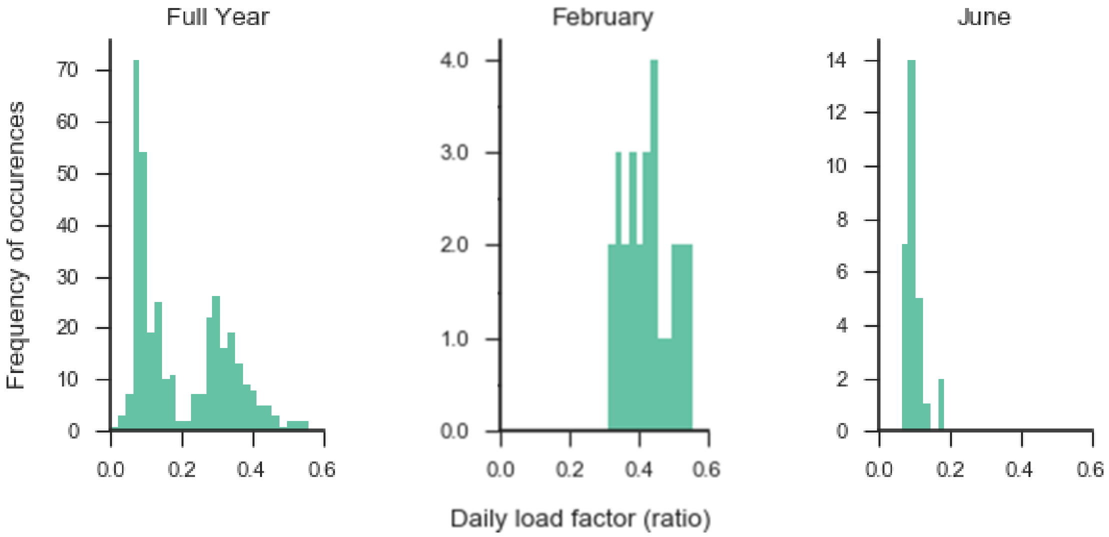


Figure 4: Daily load factors B046 for a full year, the month of February and June

In the summer, space heating was no longer required, and domestic hot water production became the major use of the boiler which provided a significantly lower demand. Figure 4 shows the reduction in daily load factor that occurred in summer (June) compared with winter (February). The distribution in the histogram for the full year shows the variation between the seasons as two distinct areas on the graph either side of the 20% daily load factor. The reduced load factors in summer months may also have been caused by the boiler modulating down its output as heat demand reduced. This modulation was seen during testing of the boiler where the boiler limited its fuel input to modulate down to around 40% of its rated output.

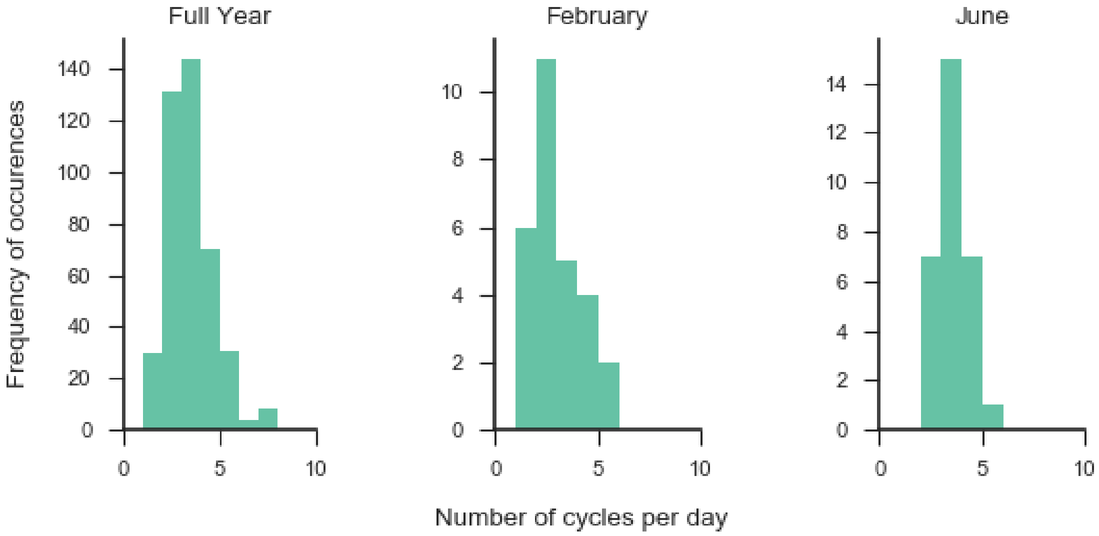


Figure 5: Number of cycles per day at B046 for a full year, the month of February and June

The number of cycles the boiler completed per day did not change much over the year as load factor changed (Figure 5). There was only a small difference between summer and winter, with fewer cycles in the winter months. The main effect of the seasonal variations on the boiler was the reduction of cycle length as average cycle length in summer fell to a quarter of the run time it was in winter. We have already shown the cause of this was due to the much lower demand for heat in the summer where the boiler was required to operate for just 2 hours per day (at full output) to meet demand. The efficiency was therefore reduced during summer months as the boiler modulated its output and operated for shorter periods of time, where it no longer remained warm between runs.

8 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial we analysed fuel from every site. The table below gives the results of the fuel analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 6: Fuel analysis for the site compared with the average from the field trial

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Site sample	Wood chips	11.211	35.7	33.1	4.1	26.9	0.2	0.10
Average in field trial	Wood chips	12.619	27.8	37.0	4.4	29.9	0.4	0.15
Minimum		10.524	8.1	-	-	-	-	-
Maximum		17.025	39.2	-	-	-	-	-

8.1 Ash issues arising from fuel quality

For B046 it was understood that when using fuels other than virgin woodchip, excessive build-up of ash deposits in the combustion chamber occurred periodically. This prevented boiler operation and required shutdown and manual removal of the deposits. The ash deposition incidents were thought to be associated with the combustion of the forest residue. In contrast with clean woodchip. Forest residue can contain significant adventitious material (dirt, stones, leaves etc.). Deposits removed from the boiler were examined visually and inferences drawn about the characteristics of the deposits and the mechanisms of formation.

Photos of the burner pot and combustion chamber were taken and the burner pot was seen to be generally clear of deposits (Figure 6). The walls of the combustion chamber had visible layers of ash deposit. Figure 7 shows a section of deposit removed from the burner pot on a previous visit after the boiler was fed with “lop and top” fuel. Layers of sintered material were covered with fine particles which were likely to have arrived during the close-down phase as the temperatures fall and thus had not been fused into the deposit. Holes through the deposit had also been maintained by the primary combustion air flows, however the flow regime was being affected and this interference with the air distribution was likely to cause the boiler to operate sub-optimally.

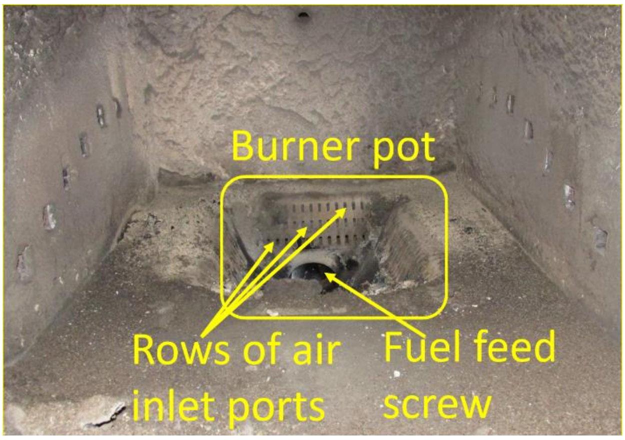


Figure 6: Interior of boiler combustion chamber

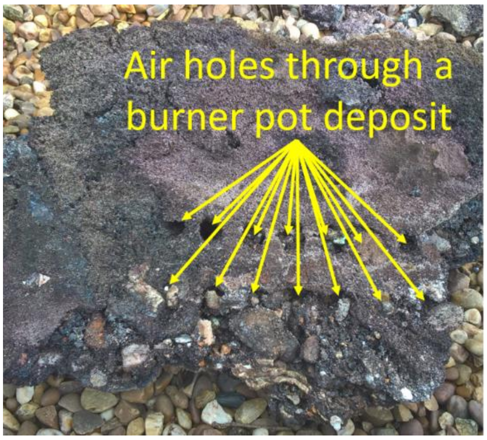


Figure 7: Deposits from a face of the burner pot

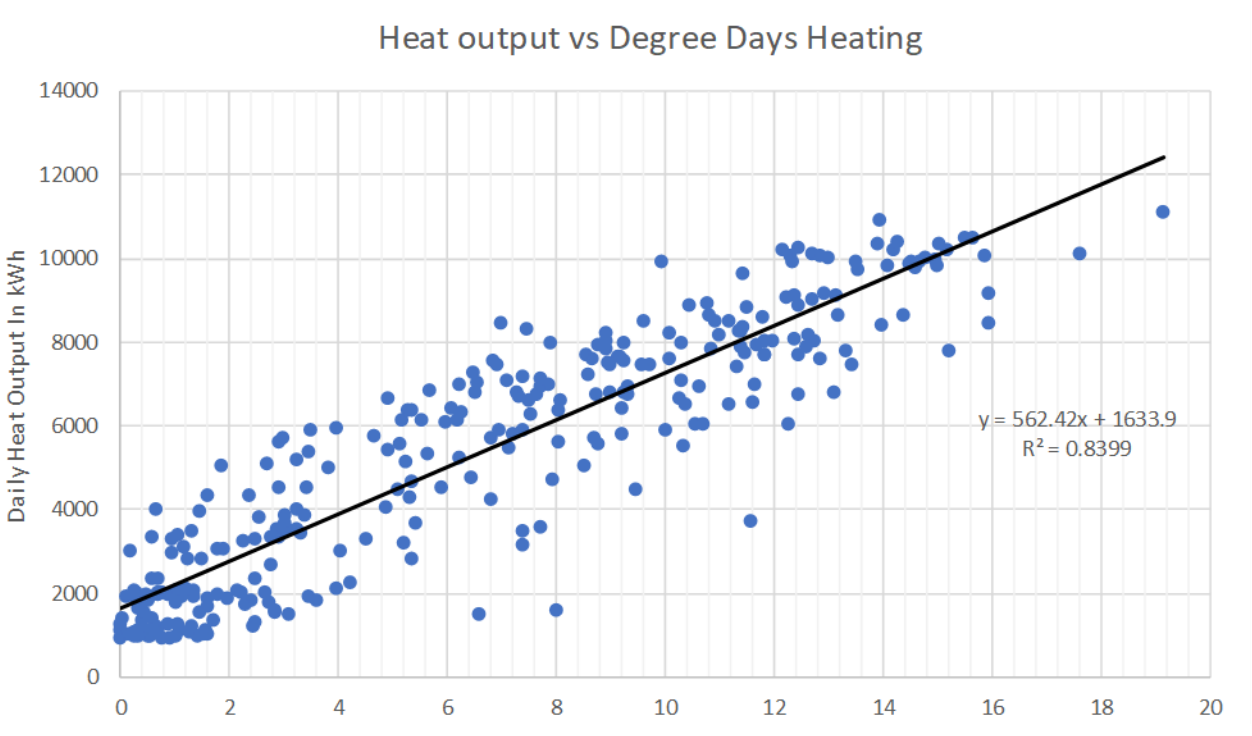
It is not recommended that “lop and top” fuel should be used with this boiler as the ash fusion issues which it causes have a detrimental effect on performance.

9 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31st of June 2017 and the 31st of May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring described in the previous sections of this case study.

9.1 Summer use and DHW load

One of the main findings from the first period of monitoring was the use of the boiler during the summer to provide only DHW, and no heating for buildings. It is known that there are large losses in the summer due to DHW as the heat is circulated to the plant rooms around the site via an underground heat main.



Daily Degree Day Heat (DDH) requirement (kday, base 15.5°C)

Figure 8: Heat output vs degree day heating

The heat output vs degree day plot shows good control of the biomass boiler with a large R^2 value showing good correlation between degree days and heat output. The graph can be used to infer the DHW load on the boiler where the degree day values are low and space heating is not required. The intercept on the y axis gives the background load which is independent of temperature. This intercept is usually indicative of the DHW load however at this site the value is much larger than the possible DHW usage at the site. At low degree day values there is a cluster of points between 1,000 and 2,000 kWh with an actual intercept of 1634 kWh per day; this is equivalent to around 650 showers per day (2.5 kWh per shower), which is not a feasible quantity of hot water use for this site. At this site, it is inferred that the intercept shows the background load of DHW combined with the losses from the underground heat main.

As part of the intervention the DHW use was investigated further to understand their summer usage and to find a solution which would enable the biomass system and heat main to be turned off during the summer. We found that hot water was used in two buildings; a small office block (hand washing and showers), and a large domestic property to provide hot water for a family of four. This level of consumption does not match the amount of heat produced by the boiler each day for DHW. The intervention therefore focussed on educating the operators on the site about this issue as initially they appeared to have limited understanding that by continuously pumping heat around the heat main that the system is constantly losing heat to the ground. Kiwa attribute the decision to use the biomass boiler in the summer to a misapprehension on the part of the decision makers on the site, in that they believed it was financially beneficial to do so because of the Renewable Heat Incentive payments for heat consumption. However, the decision makers did not appear to understand that the payments are for metered heat consumption, and not for heat production, and therefore the RHI payments for the small amount of hot water consumed in the summer would be much smaller than the costs associated with operating an 800 kW boiler to produce the heat maintain the temperature in a district heating system. It is important to note that the site does not receive financial incentives for heat lost in its underground heat main and only benefits from heat supplied through each plant room. It is Kiwa’s belief that if a costlier fuel was used such as oil then the boiler would not be used in the summer due to the cost and the DHW load would be supplied by other means.

The planned intervention was to use immersion heaters that were present in the DHW tanks which supply the hot water from the plant rooms. This was initially agreed upon by the site so that the biomass could be deactivated. The planned intervention failed after discussions at the site indicated that although the office block could be switched to immersion it was not possible to do so at the domestic property. A compromise was made where the site would run the heat main to charge the DHW tank only when required. This allowed the biomass boiler to remain off for the summer period as oil was used to satisfy the DHW load.

The boiler was deactivated on the 01 June 2018. It is planned to remain off for a 3-month trial period which, if successful, will be repeated every year when there is no space heating demand. For the same 3-month period in 2017 the boiler produced 140,000 kWh of heat and used 58,000 kg of fuel. It would seem counterintuitive for sites to deactivate biomass in the summer and to use fossil fuels or electricity however, because boilers are oversized for DHW loads (they mainly supply heat for space heating) then the emissions of hydrocarbons, carbon monoxide and NOx will be reduced by supplying DHW using other means. To provide DHW for a family of 4 would require the biomass boiler to run for a very short period. The pollutants produced during startups and shutdowns for this boiler are shown in Table 1.

Biomass boilers need a fixed minimum length of time to startup and to shutdown safely. This results in a minimum burn time for this boiler of 1.2 hours. When small amounts of heat are required the emissions of the air pollutants NOx and particulate matter produced by the boiler will be much greater than the pollutants that would be emitted by using gas or oil fossil fuelled boilers to supply the same amount of heat, because gas or oil boilers can start up and shut down in a matter of minutes. This is best illustrated by the onsite testing work where readings were taken which show the total pollutants produce by 1 cycle. The results show the emissions from the biomass boiler for one cycle were 216 grams of dust, 90 grams of NOx, and 2,500 grams of hydrocarbons. With the average number of starts in the summer at 2.5 per day this can be as much as 540 grams of dust, 225 grams of NOx and 6250 grams of hydrocarbons being produced unnecessarily.

9.2 Fuel quality

After the work completed in phase 3 with the site operators on fuel quality, and issues with the formation of clinker, further work was done to support the site operators to use good quality fuel. The site operators were keen to improve their fuel and made improvements to their fuel at the beginning of the extended monitoring period. This is shown in the first analysis in Table 7 below where efforts were made to lower the moisture content of the fuel (which is significantly lowered compared to the site average).

Table 7:Two fuel analysis results for samples taken in the extended monitoring period compared with the site and field trial average

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
1st Analysis	Wood chips	13.923	23.3	41.1	4.66	30.5	0.3	0.08
2nd Analysis	Wood chips	12.922	29.2	37.6	4.31	28.7	0.1	0.12
Average site	Wood chips	12.246	30.5	35.6	4.26	28.6	0.3	0.13
Average field trial	Wood chips	12.619	27.8	37.0	4.40	29.9	0.4	0.15

Table 8: Heavy metal analysis results of ash taken in the extended monitoring period.

	Cadmium (mg/kg)	Zinc (mg/kg)	Lead (mg/kg)	Copper (mg/kg)	Chromium (mg/kg)	Nickel (mg/kg)	Arsenic (mg/kg)	Mercury (mg/kg)
B046 Wood Ash	31.5	572	280	186.7	282	119	6.3	< 0.01

Table 9: Two heavy metal analysis results for wood samples taken in the extended monitoring period.

	Cadmium (mg/kg)	Zinc (mg/kg)	Lead (mg/kg)	Copper (mg/kg)	Chromium (mg/kg)	Nickel (mg/kg)	Arsenic (mg/kg)	Mercury (mg/kg)
1st Analysis	0.09	10.04	3.13	3.10	1.06	1.19	< 0.10	< 0.01
2nd Analysis	0.20	12.13	2.86	1.50	2.14	1.63	< 0.10	< 0.01

Having made this improvement to their fuel the site the site decided to make further improvements in December after receiving the results of their fuel analysis. This is the second analysis shown in Table 7 and was the result of the site trying to reduce the heavy metal content of their fuel and ash by sourcing wood from other areas of their site. Table 8 shows the heavy metals present in the bottom ash of the boiler which concerned the site. The levels of all heavy metals tested were higher than expected apart from mercury. The changes made to the fuel were an attempt to reduce the levels present in the self-produced chip. As can be seen from the analysis results in Table 9 there is no material change in the heavy metal content of the fuels. The change to the fuel that the site made was to introduce virgin wood chips from another tree species from another area of the site into the fuel. The moisture content increased in the second analysis because this wood had not been left to dry for as long a period as the previous wood fuel. There was no impact on the boiler performance from switching between the two different fuels that could be measured by our monitoring equipment however the site did suggest that the “performance on the boilers is suggesting it may be wetter“. This was down to changes in the consistency of the ash and the weight of the fuel that was being used. It should also be noted that the site no longer has issues with clinker and ash fusion since they started to take greater care in the type of fuel that they were using in the boiler.

9.3 Oxygen adjustment

One of the findings from the intervention visit with the site was the oxygen levels in the boiler were higher than would be expected. Biomass boilers must supply enough air to the fuel to ensure clean combustion, excess air must be supplied to prevent high levels of CO and smoke being produced.

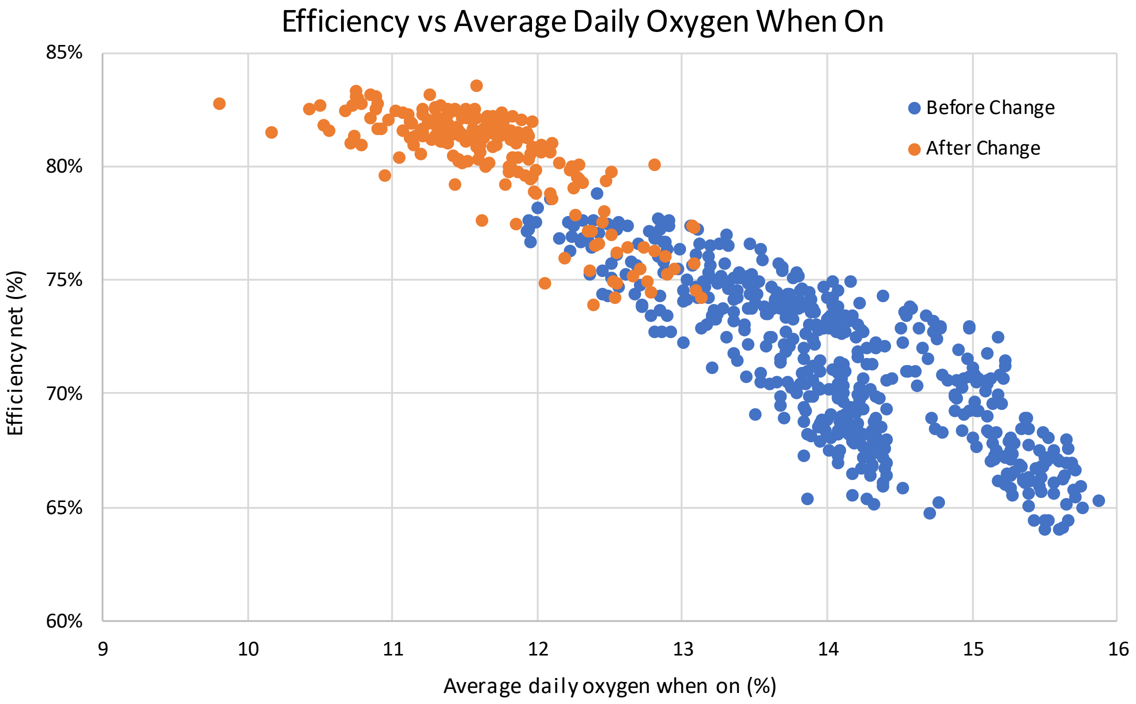


Figure 9: Efficiency vs average daily oxygen when on before and after the oxygen set point

Typically, biomass boilers are operated with 10% oxygen in the flue gases. High oxygen levels will cause the boiler to run with high excess air which causes energy to be lost in the flue gases which will decrease boiler efficiency. Figure 9 shows that the oxygen content varied between 12 and 16 %, before the intervention. The site agreed to have the oxygen set point changed when they had a commissioning visit from their maintenance provider. Figure 9 shows the result of the change and as expected the lowering of the oxygen set point increased the efficiency of the boiler significantly.

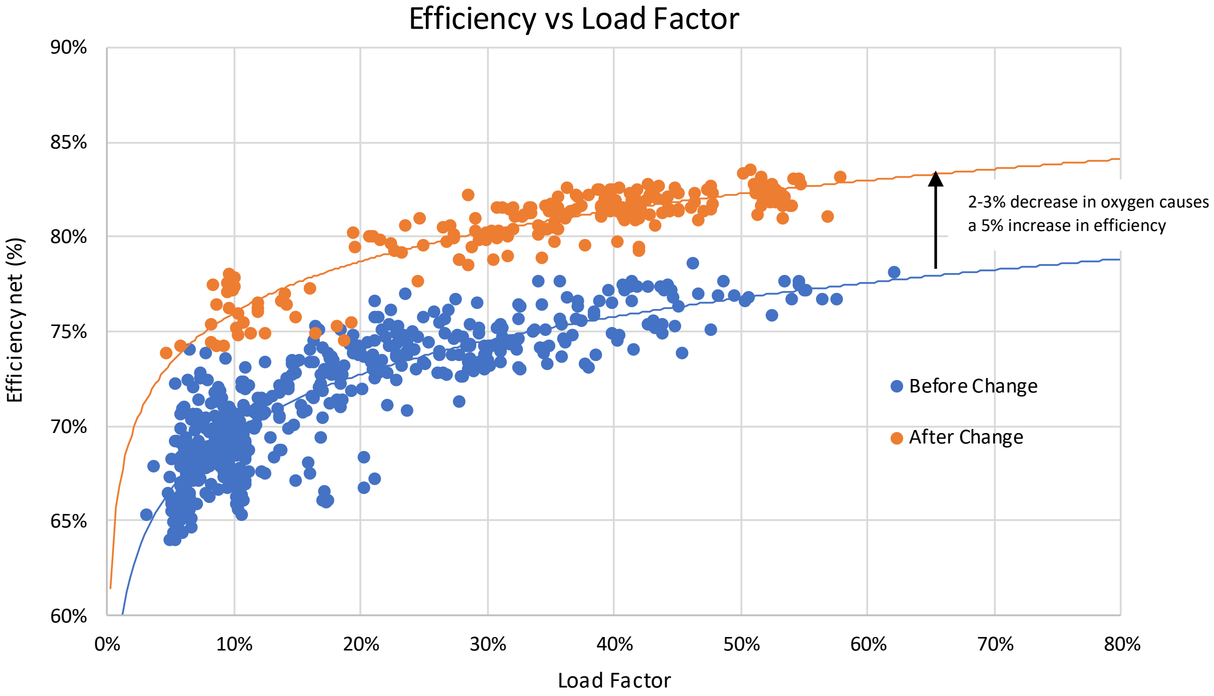


Figure 10: Efficiency vs load factor before and after the oxygen set point

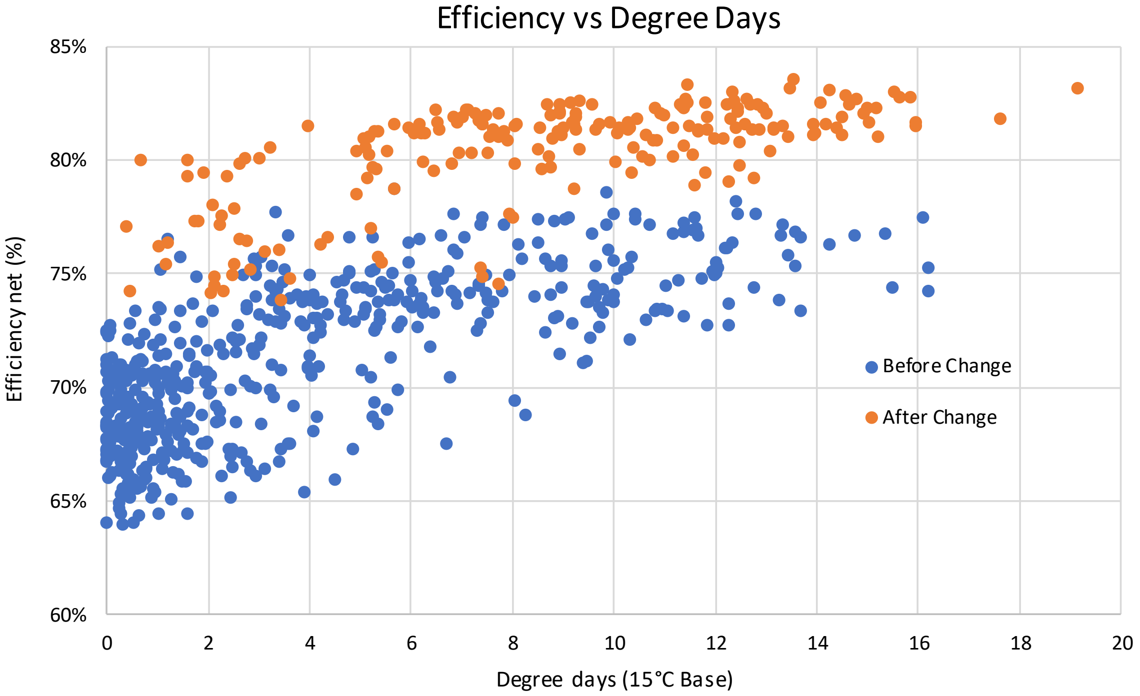


Figure 11: Efficiency vs degree days before and after the oxygen set point change

Figure 10 and Figure 11 shows efficiency plotted against load factor and degree days to show that the increased efficiency is not dependent on the load or external temperature and is caused by the lower oxygen set point. The overall increase in efficiency was 5% which can be seen in Figure 10 as the difference between the logarithmic best fit lines

10 Boiler performance summary

The boiler operated well throughout the first year of the trial with an annual equivalent net efficiency of 74%, although there were differences in winter and summer efficiencies. In the second year the efficiency was increased through a site intervention to lower the oxygen set point. The efficiency was raised by around 5%. This is a significant increase in the efficiency of the boiler which was achieved by ensuring that it was set up correctly.

As expected, the onsite testing showed that the start-up and shut down periods were the most polluting. Steady state operation for the boiler resulted in low emissions of hydrocarbons and particulates. Therefore, start-ups and shut downs should be limited as far as reasonably practicable to reduce pollutant emissions. The DDH plot showed good correlation between heat provided and outside temperature suggesting there was good control of the boiler ensuring that heat produced related well to demand. There were differences between summer and winter demand at the site. The site experienced lower efficiencies in the summer due to shorter run times which would also result in higher pollutant emissions. It should be noted that only the boiler efficiency was calculated, and not the efficiency of the whole heating system, which would have been very much lower. Summer use of the boiler was primarily DHW supplied by plant rooms fed via an underground heat main. Calculations showed that there were high losses in the main in the summer and to reduce boiler pollutant emissions the boiler should be turned off. This was achieved in June 2018 when the site agreed to trial turning the boiler off.

Finally, the ash deposits that can occur when burning a different fuel to the design fuel were examined in detail at this site. It was shown that a small change to the fuel had a large impact on performance and could cause damage to boilers. It is not recommended that boilers burn fuel for which they have not been commissioned as it can cause serious issues, as seen at this site. The improvements that this site continued to make were also monitored. Although these had no major improvement of boiler performance it should be noted that the boiler had no down time in the second year due to breakdowns caused by poor fuel.

Department for
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Biomass boiler field trial
Case studies – B445

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1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B445 was monitored from 19 February 2016 to 31 July 2017. This case study contains information on the performance and efficiency of the biomass system and recommendations on how to improve its operation. Information on the performance of all systems across the trial is also included.

2 Background

B445 was one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip, or log.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data that was kindly provided by trial participants was used (along with the compositional analysis we had carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall efficiency.

3 Description of the boiler and system

The monitoring was completed on a 75 kW wood chip biomass boiler located in its own boiler house. During the field trial, no faults were reported and the only times the boiler was not in operation for extended periods was a period when the boiler was turned off during the summer. The boiler was fired by pellet stored in a fuel bunker which was on the side of the boiler house.

Table 10 About the site

Building description	Sports Pavilion
Fuel storage issues	None reported
Heat losses	Some un-insulated pipework in boiler house
Issues raised by operator at time of installation	None reported

The boiler itself incorporated an underfeed stoker type burner with a tipping grate for ash removal. Primary combustion air was fed under the fuel bed by air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and so the residual ash was thus pushed towards the side of the burner pot to the ash removal screw.

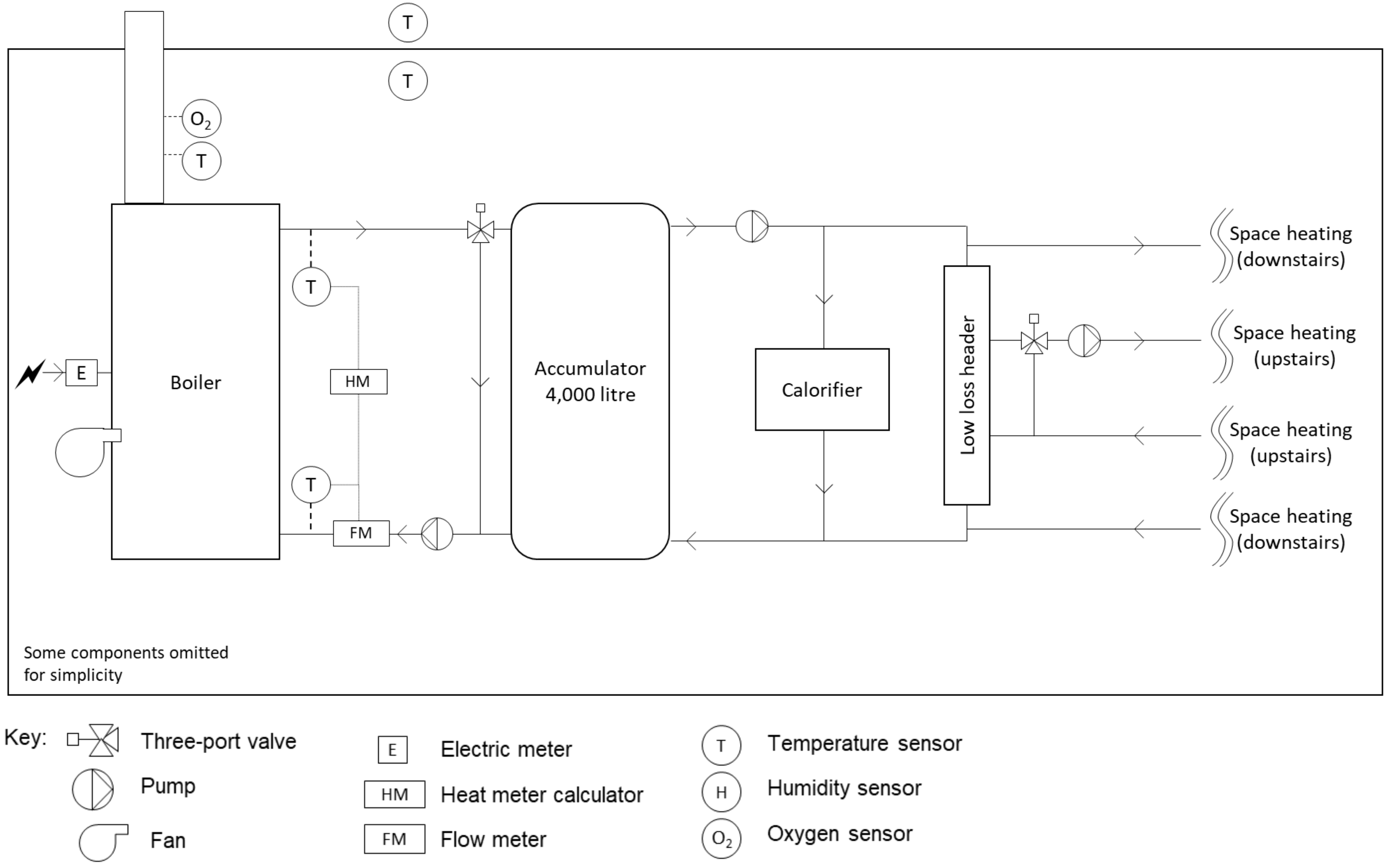
Table 11 About the biomass boiler

Rated output	75 kW
Fuel type	Wood chips
Thermal store	Yes
Draught diverter	approx. 1 metre from boiler
Dilution components	None reported
Fans	Forced and induced draft
Cyclones	None
Filters	None
Boiler faults	None reported

The boiler’s primary use was to provide space heating and hot water to a sports pavilion which was also used as a community centre throughout the year. One 3000 litre accumulation vessels were fed directly by the biomass boiler and formed the first part of the installation in the boiler house which fed the system used for hot water and space heating. The building was used primarily as a sports pavilion, however internally it was split into two areas: a community area and the area used for sports. The boiler provided energy to the sports area through two sets of piping, one set fed a large calorifier and the other was used for space heating. One other set of piping which came from a common header was used by the community area for space heating only - point of use heaters generated hot water use.

The boiler house did not contain back up equipment for heat generation when the boiler was not in operation, however the calorifier used for sports activities contained two immersion heaters which provided backup for hot water production. The central heating water was piped to radiators which resulted in a large amount of piping. Apart from the piping directly to the accumulator, pipework in the building was well insulated to reduce the heat losses.

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

During the field trial, no serious faults were reported on the boiler, there was good communication between the logging equipment and there were no prolonged periods of data loss. This section shows how the boiler performed over length of the field trial

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 12: main measurements during the field trial

Data collection period was from	19 February 2016 to 31 July 2017	
Heat output over this period	92,810	kWh
Estimated fuel use over this period	25	tonnes
Hours of operation over this period	1,780	hours

When calculating the efficiency, the data collected was for the performance of the boiler specifically and how well it transferred energy to the water in the accumulator. Other components of the heating system, such as water tanks and distribution pipework, will have their own heat losses which will decrease the efficiency of the whole system, so their impact on system efficiency can only be considered qualitatively.

At this site, the accumulator vessel, calorifier and pipework were internal to the heated building and any energy losses would contribute to the heating of the building. The accumulator was well insulated and most of the pipework was also well insulated. The piping in the boiler house was quite complex with a large number of valves, pipes, and pumps used to distribute heat around the building. The large amounts of equipment increased the area of hot surfaces exposed within the boiler house which were large for an installation of this size. Although not calculated, these losses were thought to be high as there was evidence of wet sports equipment being stored in the room next to the boiler house so that it dried quickly due to the heat. As stated previously, the losses from the accumulator piping and calorifier were likely to reduce overall system efficiency, however in this case study data has been recorded for the boiler only.

5.2 Annual equivalent use

Table 13: Annual equivilent and typical use for summer and winter

	Annual equivalent use		Typical winter month **(Feb 2017)**		Typical summer month **(Sep 2016)**	
Heat output	64,297	kWh	8,651	kWh	1,246	kWh
Estimated fuel use	24	tonnes	3	tonnes	0.5	tonnes
Efficiency	83	%	79	%	76	%
Hours of operation	1,715	hours	278	hours	49	hours

Load factor	9.7 %	17.2 %	2.3 %
Average starts per day	2.1 starts	2.5 starts	2.2 starts

5.3 Overall boiler efficiency

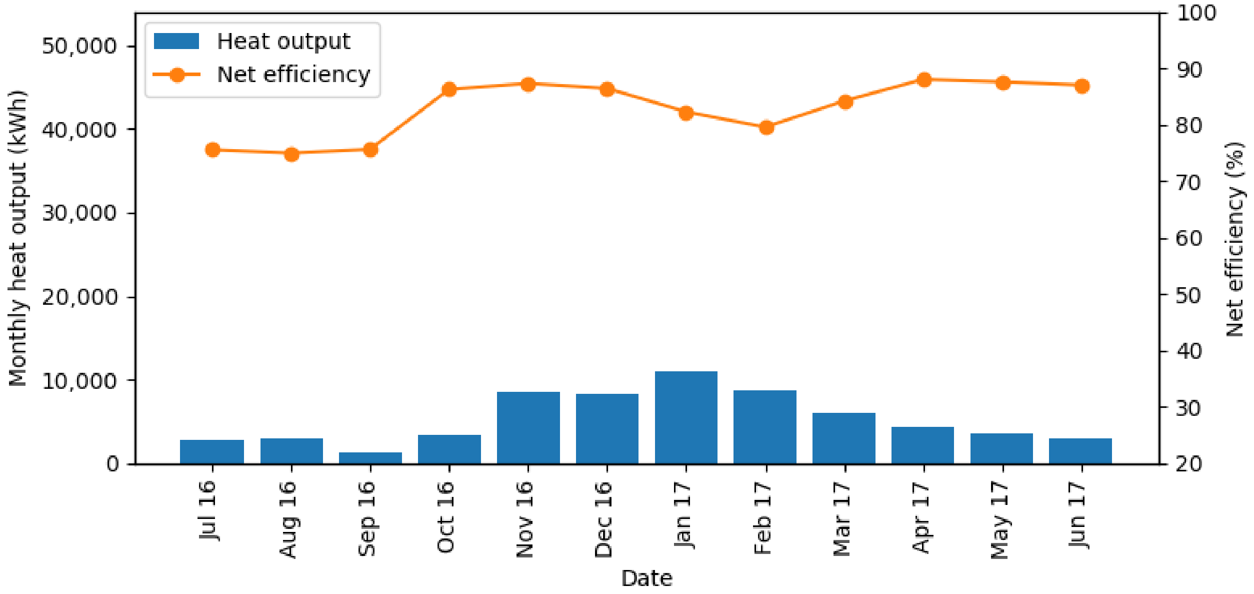


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the efficiency of the boiler over a 1 year period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The measured efficiency of the boiler averaged 84%, however this changed depending on the time of year. The highest efficiencies occurred in the winter when the load on the boiler was greatest, however the boiler did not strictly follow this trend as the operating pattern also influenced the efficiency. This will be explored further in section 7.

5.4 Heat output vs. degree day heating requirement

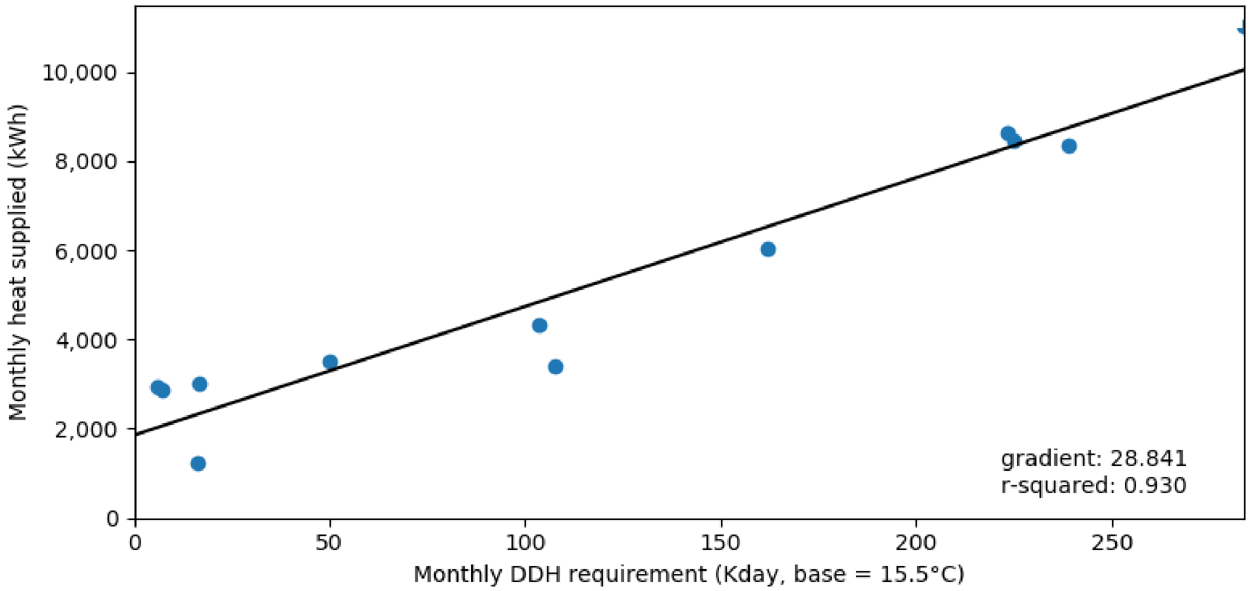


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

The r^2 value calculated for the system is displayed in Figure 2. The value of 0.930 shows good response to temperature.

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

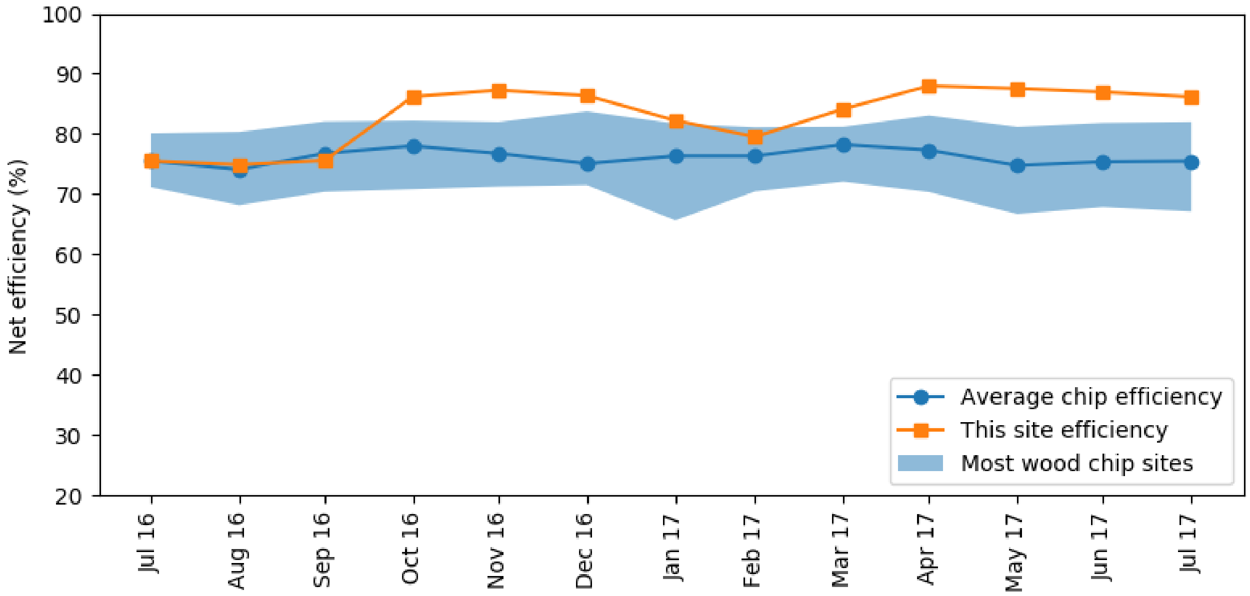


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B445. The efficiency of this boiler lies towards the top of the range of efficiencies.

7 Operating pattern

Operating pattern at this site changed with building use throughout the year. The building had three main operating patterns throughout the year; a unimodal pattern in summer months, a tri modal pattern in the winter months which moved to a bimodal pattern in spring. Furthermore, the three operating patterns occur alongside changes in the efficiency of the boiler.

7.1 Unimodal operation

This pattern occurred predominantly in July 2016 and August 2016. The boiler came on at around 8am and supplied heat to the accumulator for around 4 hours. Weekend usage of the building also increased the heat output from the boiler. Saturdays during this time switched to bimodal operation supplying heat during two periods; in the morning and the afternoon.

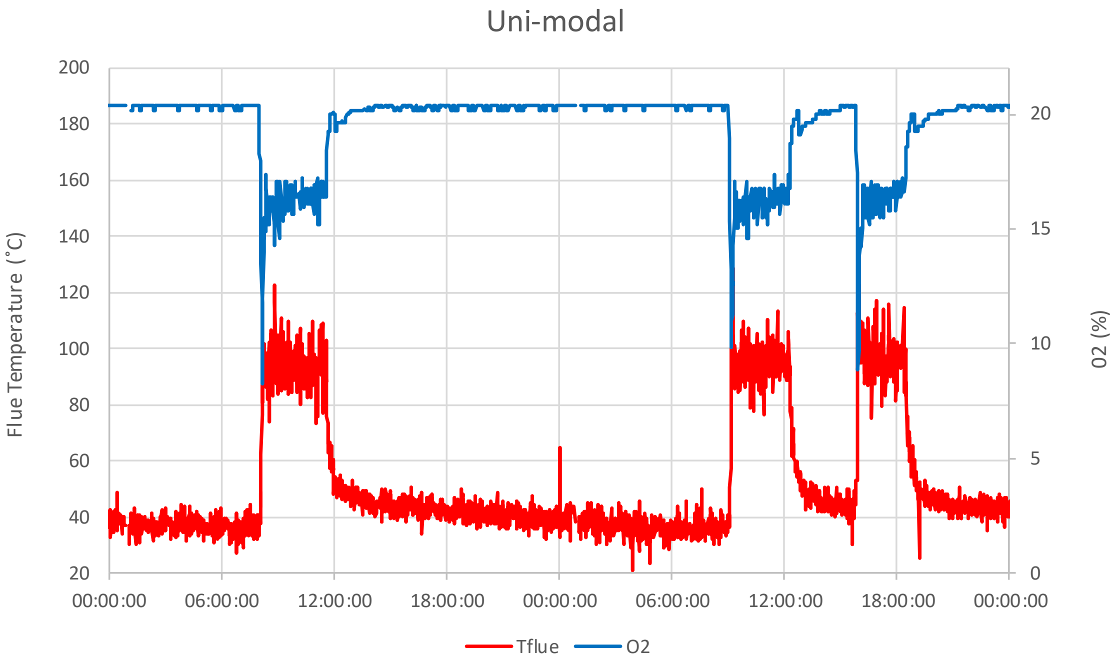


Figure 4: Graph showing efficiency of boilers in the field trial

Figure 4 shows a typical two-day period in July and August. The two days shown are a Friday and Saturday. Unimodal operation can be seen on Friday and was typical of operation during the week where the boiler only operated for four hours in the morning. The changeover to bimodal operation on Saturday can be seen as two peaks in flue gas temperature and decreases in oxygen as the boiler had an additional run period in the evening. The efficiency of the boiler during this period of unimodal operation was 75% which was the lowest efficiency during the field trial.

7.2 Trimodal operation

This pattern occurred predominantly from October 2016 to the end of January 2017. The boiler came on at around 6am and supplied heat to the accumulator. The boiler operated again 6 hours later at around 12:00 and then again, another 6 hours later, at 18:00. Weekend usage of the building did not change the operating pattern during this period.

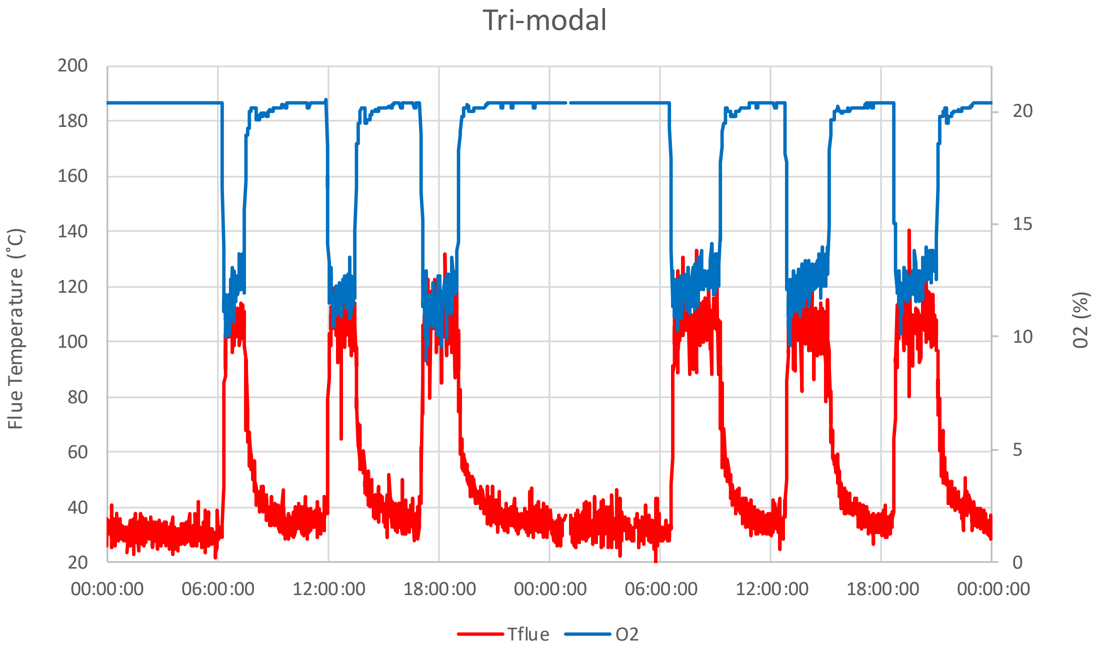


Figure 5: Graph showing efficiency of boilers in the field trial

Figure 5 shows a typical two-day period of trimodal operation. The efficiency of the boiler during this period of trimodal operation was 85% which was the highest efficiency that was seen from the boiler during the field trial.

7.3 Bimodal operation

This pattern occurred predominantly from February 2017 to March 2017. The boiler came on at around 6am and supplied heat to the accumulator for around 9 hours. Later at around 18:00 the boiler came on again for a run in the evening. Weekend usage of the building did not change the operating pattern during this period.

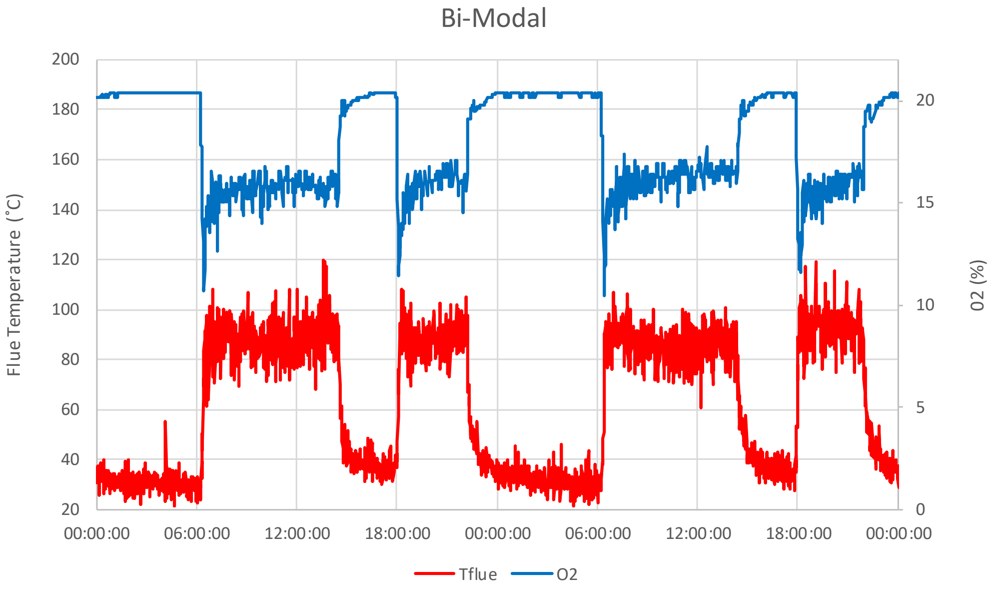


Figure 6: Graph showing efficiency of boilers in the field trial

Figure 6 shows a typical two-day period of bimodal operation. The efficiency of the boiler during this period of bimodal operation was 80%.

8 Modulation

The boiler modulated its output during the field trial which can be seen from the differences in flue gas oxygen concentration while running in figures 4, 5 and 6. This provides an explanation for why the efficiency seemed to change with operating pattern (as boilers are not necessarily designed to run at different load factors and lower outputs). In July and August when the load was low, the boiler modulated to its lowest output, this can be seen by the oxygen being above 16% in figure 4. In February to March the bimodal pattern ran with a higher modulated output and ran at an oxygen of around 15% (figure 5). When operating in a trimodal pattern the boiler was at its most efficient as it did not modulate and had three burns a day at maximum output.

The modulation of the boiler may have reduced the efficiency but it also prevented the boiler cycling throughout the day. Cycling will reduce the performance of a boiler much more dramatically than modulation and should be avoided and cycling should therefore be reduced to as much as possible. It can therefore be said that by modulating this boiler had good control.

9 Heat Use

During the summer, the boiler was not required for space heating and its main use is to provide hot water for the sports pavilion. It was noted that the boiler would run and keep the accumulator hot, regardless of the requirement for heat. For example, the heat use of the boiler was dependent in the summer on the use of the facilities. If there was no requirement for the heat the boiler should not have been operated. There were immersion heaters which could provide heat to the calorifier in periods of low usage and it was suggested that this may be the most effective way to provide heat in the summer.

10 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial we analysed fuel from every site. The table below gives the results of the fuel analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 14

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Site sample	Wood chips	11.474	33.1	34.1	3.9	27.6	1.1	0.16
Average in field trial	Wood chips	12.619	27.8	37.0	4.4	29.9	0.4	0.15
Minimum		10.524	8.1	-	-	-	-	-
Maximum		17.025	39.2	-	-	-	-	-

It can be seen that the fuel analysis was very close to the average of the analyses in the trial. This is unsurprising given the manufacturing process for pellets which tends to result in a very consistent product.

11 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 30 June 2017 and the 31 May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring highlighted in the previous sections of this case study.

11.1 Time clocks and heat requirement

The intervention at this site was twofold to limit the operating hours of the boiler and to ensure that it was not operated when heat was not required. The site was designed to be occupied during daylight hours with a small site office on site where staff would oversee the sports facility. However, changes to how the site was managed meant this was no longer how the site was operated during the field trial.

There were no staff permanently based at the site and none who had oversight of how the biomass boiler operated or was controlled. This caused numerous issues when the boiler had issues with faults or as happened on one occasion the boiler ran out of fuel. The people who used the facility would notify when there had been an issue with the boiler. Obviously, this was an issue when trying to implement the intervention at the site as there was no one available to deactivate the boiler when it was not required. The use of a remote connection to the boiler was suggested to the site and it was agreed that remote monitoring and control of the boiler was required if there was none on site. Figure 7 shows the boilers runtime per day. As you can see there is no prolonged period of downtime from the boiler except for in January where the boiler ran out of fuel. The intervention was therefore not effective as the remote monitoring was not installed during the monitoring period because of the high capital cost for the site. It is understood that the site will implement this in the coming months to allow the boiler to be deactivated during periods where the site is not used.

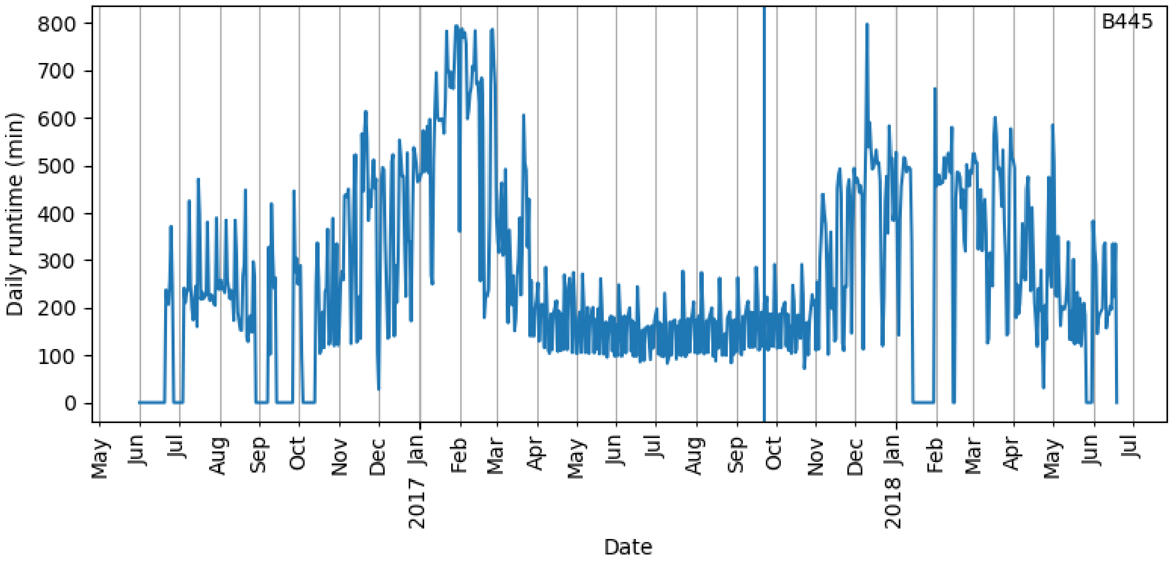


Figure 7: Graph showing daily runtime durning the entire monitoring period

Having someone onsite to look after biomass boilers is important to ensure that they have high performance. It is not usual to have a site with a biomass boiler of this size operated without somebody on site actively looking after the boiler. Findings from previous work found that having an onsite “boiler champion”, somebody who actively tries to understand how the boiler should be run is important to ensure that a biomass system performs well.

Although the boiler has a high efficiency compared with field trial sites its performance in terms of useful heat delivered is very low. This is because the building is not occupied for most of the week and there are high system losses due to an uninsulated calorifier which is kept at high temperature. Adjusting the time clock on the boiler was also suggested as the boiler operated between the hours of 6 am to 10 pm. It was suggested to the site that this was outside the time that the building would be expected to be occupied. The main use of the heat was for hot water and it was not expected that people would need to use the facility before these times. There was no artificial lighting for sport so during the night there was no need for hot water usage. It was suggested that the site limit the hours the boiler can be activated in the winter to daylight hours. The plan from the site was to do this using the remote monitoring control of the boiler but as this was not installed during the field trial the changes were not made.

12 Summary

The boiler had an average net efficiency of 84% which was above average for wood chip fuelled biomass boilers. The DDH plot showed good correlation between heat provided and outside temperature suggesting there was good control of the boiler.

This case study looked at different operating patterns throughout the year and the effect on the performance of the boiler. A Trimodal operating pattern was found to give the highest efficiencies for this site. A Bimodal operating pattern was also found to efficient and it is suggested the boiler keeps to one of these operating patterns in the winter months.

Modulation was also found to affect the efficiency and, in general, lowered the running efficiency, however it also prevented the boiler from rapid cycling in the winter months and therefore showed good control.

It was suggested that although the efficiency was high and the cycling rate was low the actual performance in terms of heat used by the end user was low. The boiler operates when the building is not occupied. The boiler should also be limited better by the time clock in the winter as the boiler can operate up to 10 pm at night which is after the last requirement for heat which is only in daylight hours.

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Biomass boiler field trial Case studies – B445

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B445 was one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip, or log.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data that was kindly provided by trial participants was used (along with the compositional analysis we had carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall efficiency.

3 Description of the boiler and system

The monitoring was completed on a 75 kW wood chip biomass boiler located in its own boiler house. During the field trial, no faults were reported and the only times the boiler was not in operation for extended periods was a period when the boiler was turned off during the summer. The boiler was fired by pellet stored in a fuel bunker which was on the side of the boiler house.

Table 15 About the site

Building description	Sports Pavilion
Fuel storage issues	None reported
Heat losses	Some un-insulated pipework in boiler house
Issues raised by operator at time of installation	None reported

The boiler itself incorporated an underfeed stoker type burner with a tipping grate for ash removal. Primary combustion air was fed under the fuel bed by air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and so the residual ash was thus pushed towards the side of the burner pot to the ash removal screw.

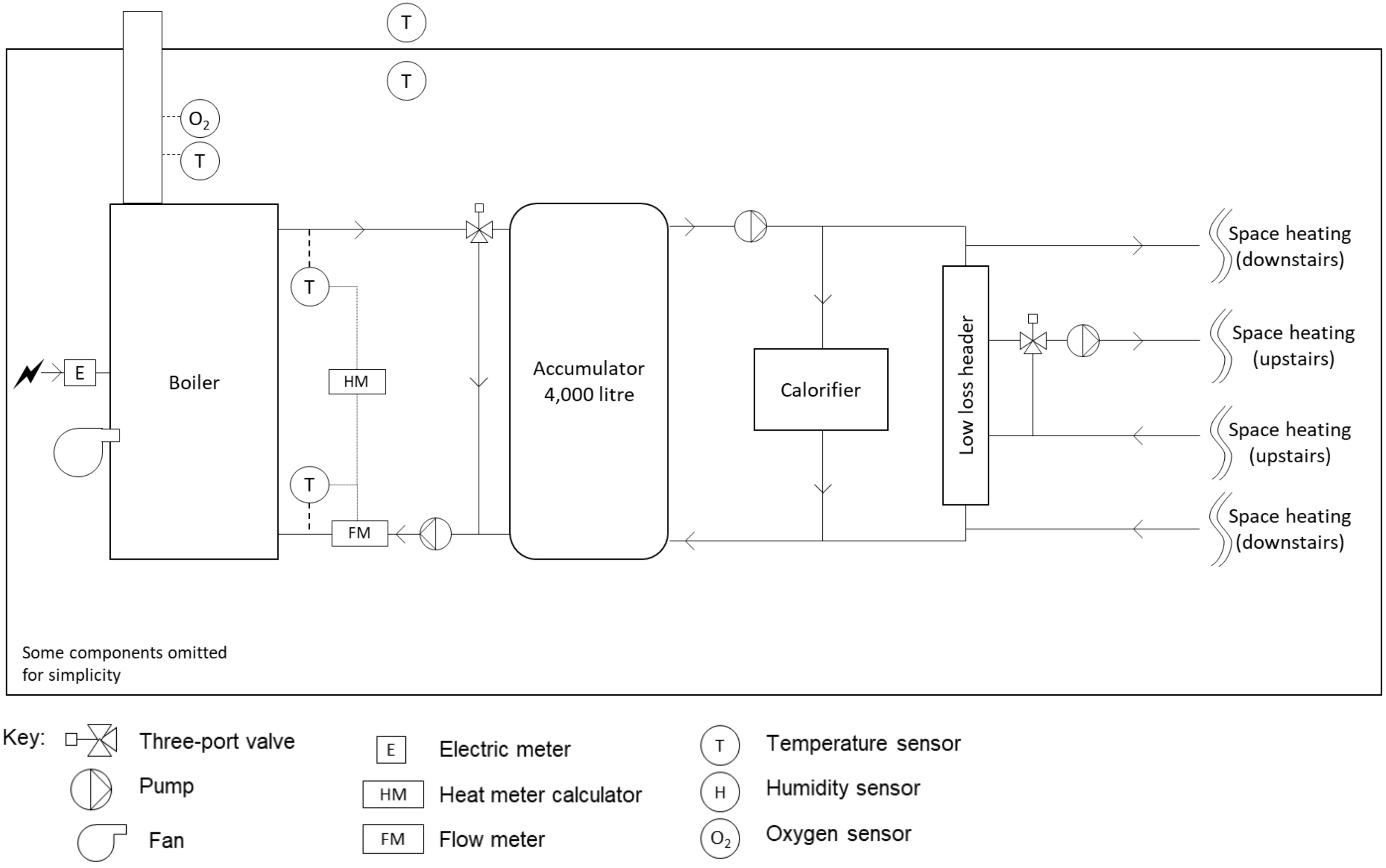
Table 16 About the biomass boiler

Rated output	75 kW
Fuel type	Wood chips
Thermal store	Yes
Draught diverter	approx. 1 metre from boiler
Dilution components	None reported
Fans	Forced and induced draft
Cyclones	None
Filters	None
Boiler faults	None reported

The boiler's primary use was to provide space heating and hot water to a sports pavilion which was also used as a community centre throughout the year. One 3000 litre accumulation vessels were fed directly by the biomass boiler and formed the first part of the installation in the boiler house which fed the system used for hot water and space heating. The building was used primarily as a sports pavilion, however internally it was split into two areas: a community area and the area used for sports. The boiler provided energy to the sports area through two sets of piping, one set fed a large calorifier and the other was used for space heating. One other set of piping which came from a common header was used by the community area for space heating only - point of use heaters generated hot water use.

The boiler house did not contain back up equipment for heat generation when the boiler was not in operation, however the calorifier used for sports activities contained two immersion heaters which provided backup for hot water production. The central heating water was piped to radiators which resulted in a large amount of piping. Apart from the piping directly to the accumulator, pipework in the building was well insulated to reduce the heat losses.

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

During the field trial, no serious faults were reported on the boiler, there was good communication between the logging equipment and there were no prolonged periods of data loss. This section shows how the boiler performed over length of the field trial

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 17: main measurements during the field trial

Data collection period was from	19 February 2016 to 31 July 2017	
Heat output over this period	92,810	kWh
Estimated fuel use over this period	25	tonnes
Hours of operation over this period	1,780	hours

When calculating the efficiency, the data collected was for the performance of the boiler specifically and how well it transferred energy to the water in the accumulator. Other components of the heating system, such as water tanks and distribution pipework, will have their own heat losses which will decrease the efficiency of the whole system, so their impact on system efficiency can only be considered qualitatively.

At this site, the accumulator vessel, calorifier and pipework were internal to the heated building and any energy losses would contribute to the heating of the building. The accumulator was well insulated and most of the pipework was also well insulated. The piping in the boiler house was quite complex with a large number of valves, pipes, and pumps used to distribute heat around the building. The large amounts of equipment increased the area of hot surfaces exposed within the boiler house which were large for an installation of this size. Although not calculated, these losses were thought to be high as there was evidence of wet sports equipment being stored in the room next to the boiler house so that it dried quickly due to the heat. As stated previously, the losses from the accumulator piping and calorifier were likely to reduce overall system efficiency, however in this case study data has been recorded for the boiler only.

5.2 Annual equivalent use

Table 18: Annual equivilent and typical use for summer and winter

	Annual equivalent use		Typical winter month **(Feb 2017)**		Typical summer month **(Sep 2016)**	
Heat output	64,297	kWh	8,651	kWh	1,246	kWh
Estimated fuel use	24	tonnes	3	tonnes	0.5	tonnes
Efficiency	83	%	79	%	76	%
Hours of operation	1,715	hours	278	hours	49	hours

Load factor	9.7 %	17.2 %	2.3 %
Average starts per day	2.1 starts	2.5 starts	2.2 starts

5.3 Overall boiler efficiency

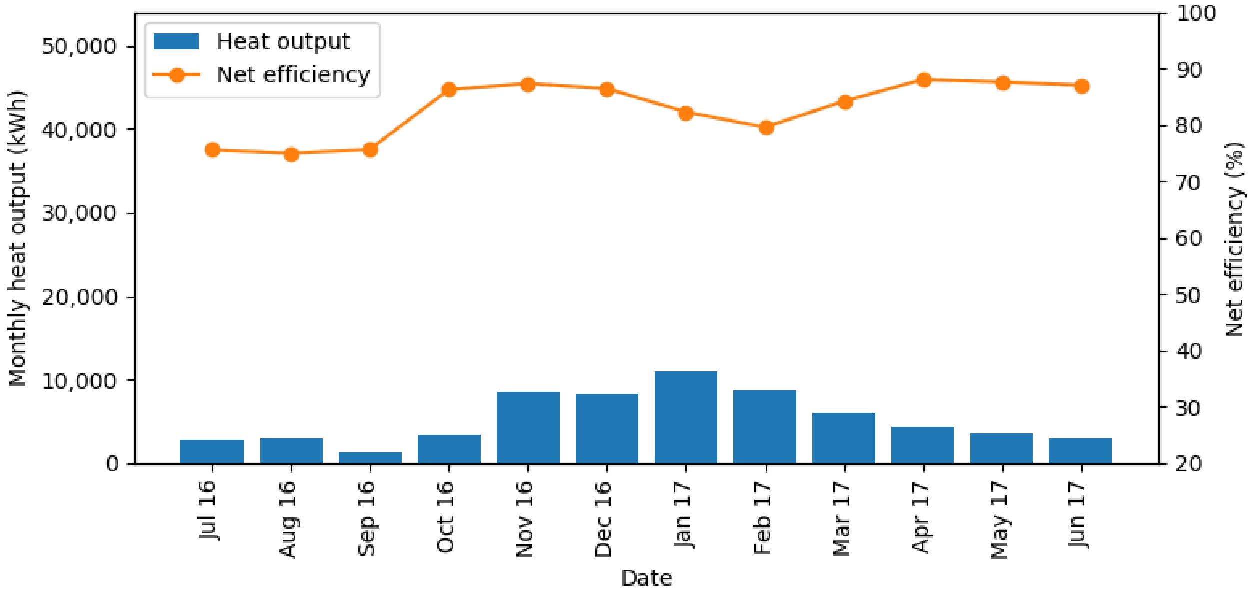


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the efficiency of the boiler over a 1 year period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The measured efficiency of the boiler averaged 84%, however this changed depending on the time of year. The highest efficiencies occurred in the winter when the load on the boiler was greatest, however the boiler did not strictly follow this trend as the operating pattern also influenced the efficiency. This will be explored further in section 7.

5.4 Heat output vs. degree day heating requirement

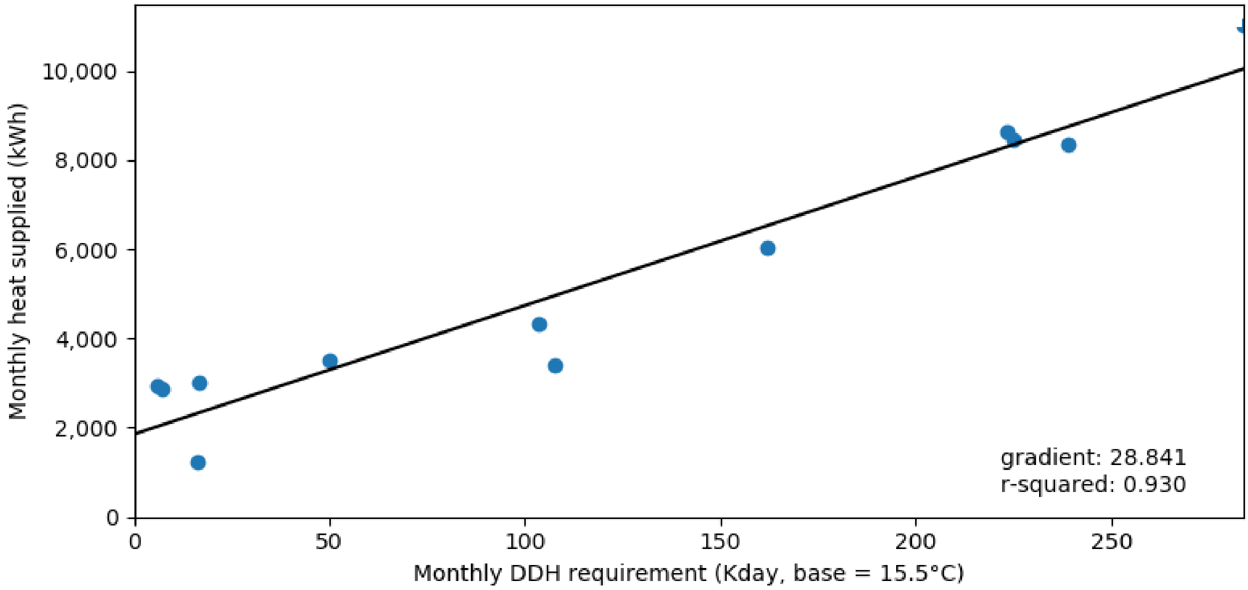


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

The r^2 value calculated for the system is displayed in Figure 2. The value of 0.930 shows good response to temperature.

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

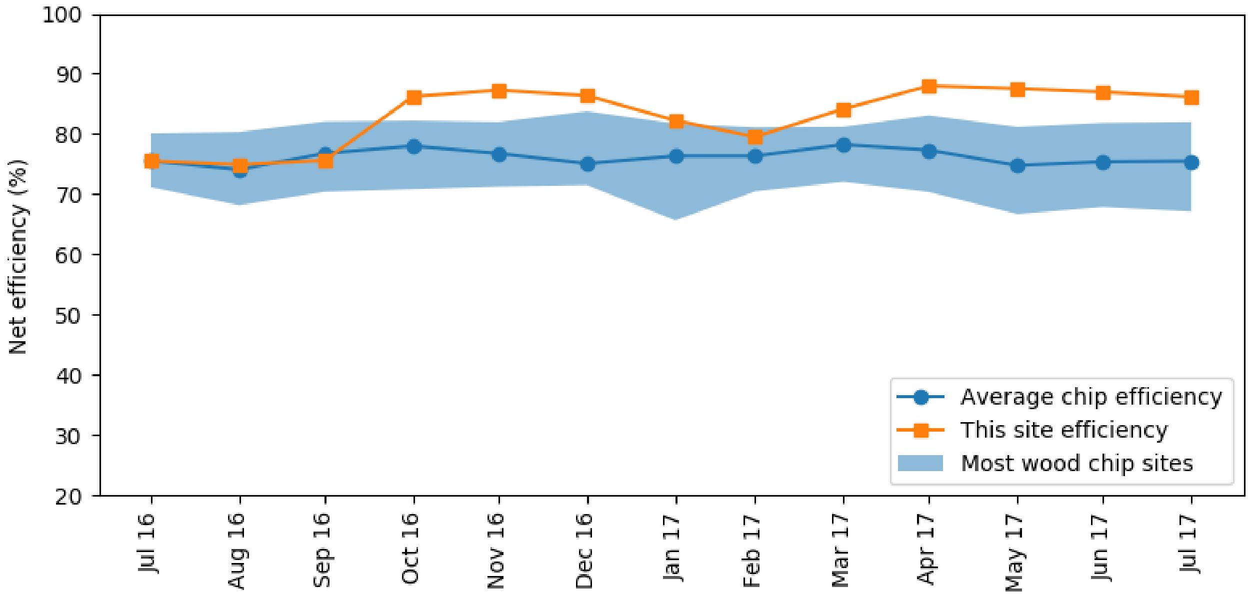


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B445. The efficiency of this boiler lies towards the top of the range of efficiencies.

7 Operating pattern

Operating pattern at this site changed with building use throughout the year. The building had three main operating patterns throughout the year; a unimodal pattern in summer months, a tri modal pattern in the winter months which moved to a bimodal pattern in spring. Furthermore, the three operating patterns occur alongside changes in the efficiency of the boiler.

7.1 Unimodal operation

This pattern occurred predominantly in July 2016 and August 2016. The boiler came on at around 8am and supplied heat to the accumulator for around 4 hours. Weekend usage of the building also increased the heat output from the boiler. Saturdays during this time switched to bimodal operation supplying heat during two periods; in the morning and the afternoon.

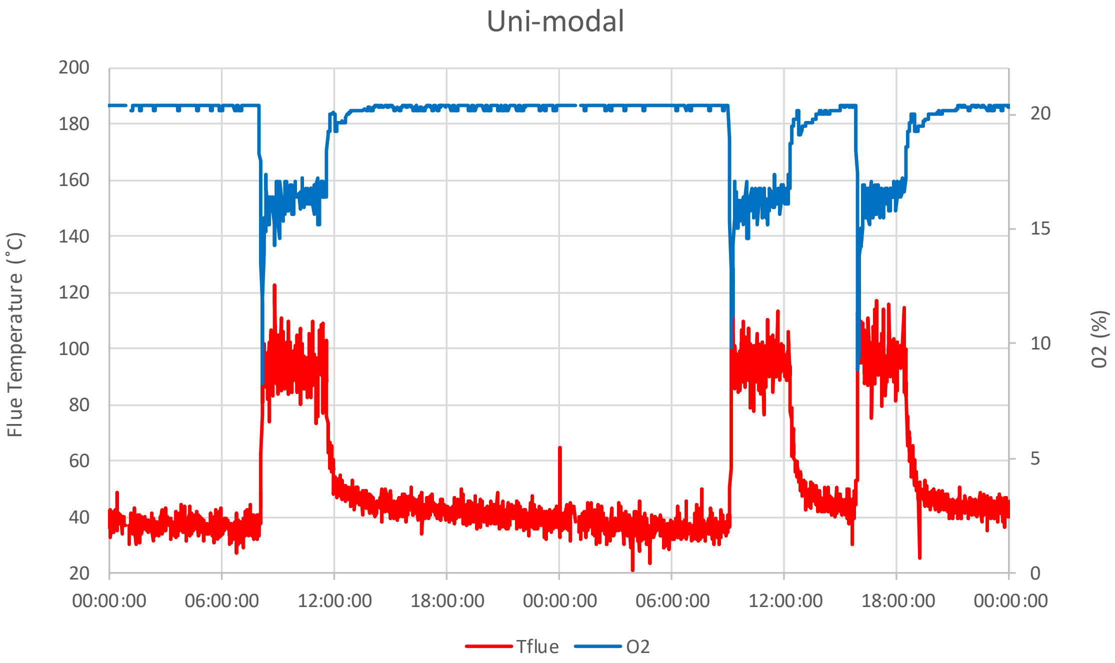


Figure 4: Graph showing efficiency of boilers in the field trial

Figure 4 shows a typical two-day period in July and August. The two days shown are a Friday and Saturday. Unimodal operation can be seen on Friday and was typical of operation during the week where the boiler only operated for four hours in the morning. The changeover to bimodal operation on Saturday can be seen as two peaks in flue gas temperature and decreases in oxygen as the boiler had an additional run period in the evening. The efficiency of the boiler during this period of unimodal operation was 75% which was the lowest efficiency during the field trial.

7.2 Trimodal operation

This pattern occurred predominantly from October 2016 to the end of January 2017. The boiler came on at around 6am and supplied heat to the accumulator. The boiler operated again 6 hours later at around 12:00 and then again, another 6 hours later, at 18:00. Weekend usage of the building did not change the operating pattern during this period.

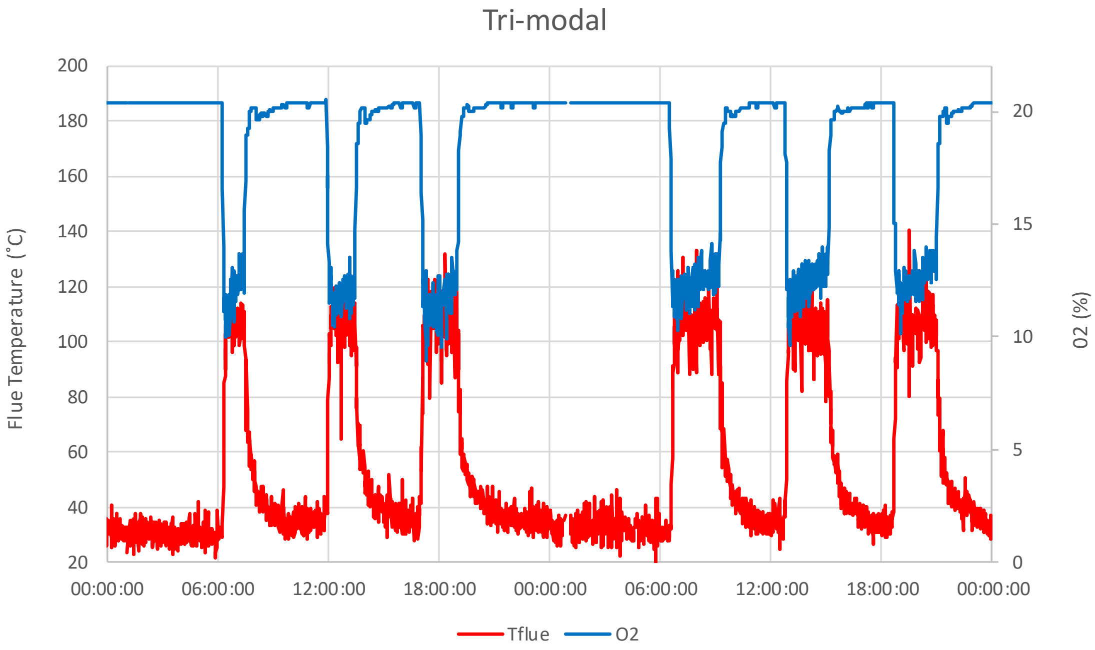


Figure 5: Graph showing efficiency of boilers in the field trial

Figure 5 shows a typical two-day period of trimodal operation. The efficiency of the boiler during this period of trimodal operation was 85% which was the highest efficiency that was seen from the boiler during the field trial.

7.3 Bimodal operation

This pattern occurred predominantly from February 2017 to March 2017. The boiler came on at around 6am and supplied heat to the accumulator for around 9 hours. Later at around 18:00 the boiler came on again for a run in the evening. Weekend usage of the building did not change the operating pattern during this period.

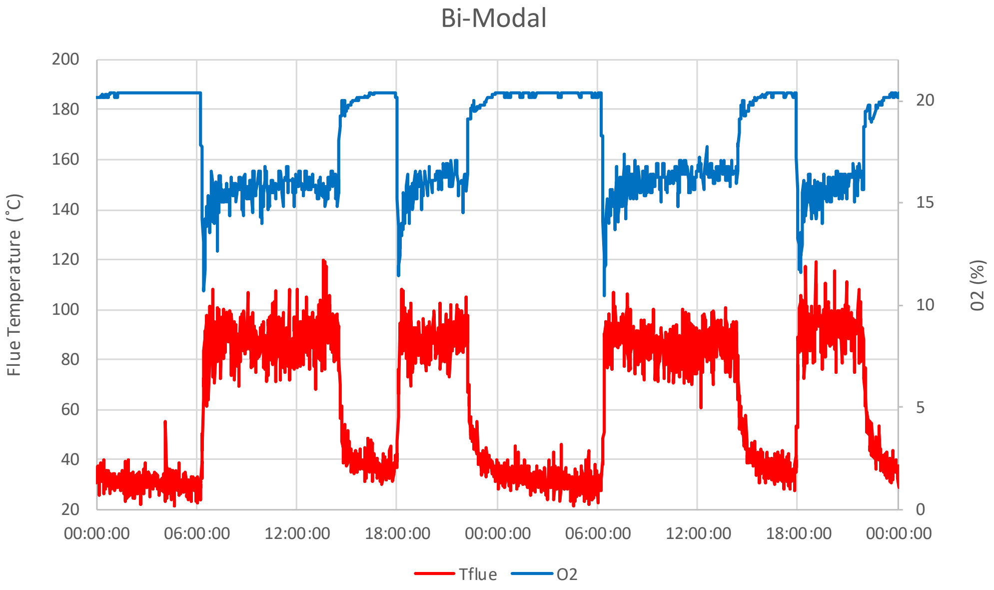


Figure 6: Graph showing efficiency of boilers in the field trial

Figure 6 shows a typical two-day period of bimodal operation. The efficiency of the boiler during this period of bimodal operation was 80%.

8 Modulation

The boiler modulated its output during the field trial which can be seen from the differences in flue gas oxygen concentration while running in figures 4, 5 and 6. This provides an explanation for why the efficiency seemed to change with operating pattern (as boilers are not necessarily designed to run at different load factors and lower outputs). In July and August when the load was low, the boiler modulated to its lowest output, this can be seen by the oxygen being above 16% in figure 4. In February to March the bimodal pattern ran with a higher modulated output and ran at an oxygen of around 15% (figure 5). When operating in a trimodal pattern the boiler was at its most efficient as it did not modulate and had three burns a day at maximum output.

The modulation of the boiler may have reduced the efficiency but it also prevented the boiler cycling throughout the day. Cycling will reduce the performance of a boiler much more dramatically than modulation and should be avoided and cycling should therefore be reduced to as much as possible. It can therefore be said that by modulating this boiler had good control.

9 Heat Use

During the summer, the boiler was not required for space heating and its main use is to provide hot water for the sports pavilion. It was noted that the boiler would run and keep the accumulator hot, regardless of the requirement for heat. For example, the heat use of the boiler was dependent in the summer on the use of the facilities. If there was no requirement for the heat the boiler should not have been operated. There were immersion heaters which could provide heat to the calorifier in periods of low usage and it was suggested that this may be the most effective way to provide heat in the summer.

10 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial we analysed fuel from every site. The table below gives the results of the fuel analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 19

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Site sample	Wood chips	11.474	33.1	34.1	3.9	27.6	1.1	0.16
Average in field trial	Wood chips	12.619	27.8	37.0	4.4	29.9	0.4	0.15
Minimum		10.524	8.1	-	-	-	-	-
Maximum		17.025	39.2	-	-	-	-	-

It can be seen that the fuel analysis was very close to the average of the analyses in the trial. This is unsurprising given the manufacturing process for pellets which tends to result in a very consistent product.

11 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 30 June 2017 and the 31 May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring highlighted in the previous sections of this case study.

11.1 Time clocks and heat requirement

The intervention at this site was twofold to limit the operating hours of the boiler and to ensure that it was not operated when heat was not required. The site was designed to be occupied during daylight hours with a small site office on site where staff would oversee the sports facility. However, changes to how the site was managed meant this was no longer how the site was operated during the field trial.

There were no staff permanently based at the site and none who had oversight of how the biomass boiler operated or was controlled. This caused numerous issues when the boiler had issues with faults or as happened on one occasion the boiler ran out of fuel. The people who used the facility would notify when there had been an issue with the boiler. Obviously, this was an issue when trying to implement the intervention at the site as there was no one available to deactivate the boiler when it was not required. The use of a remote connection to the boiler was suggested to the site and it was agreed that remote monitoring and control of the boiler was required if there was none on site. Figure 7 shows the boilers runtime per day. As you can see there is no prolonged period of downtime from the boiler except for in January where the boiler ran out of fuel. The intervention was therefore not effective as the remote monitoring was not installed during the monitoring period because of the high capital cost for the site. It is understood that the site will implement this in the coming months to allow the boiler to be deactivated during periods where the site is not used.

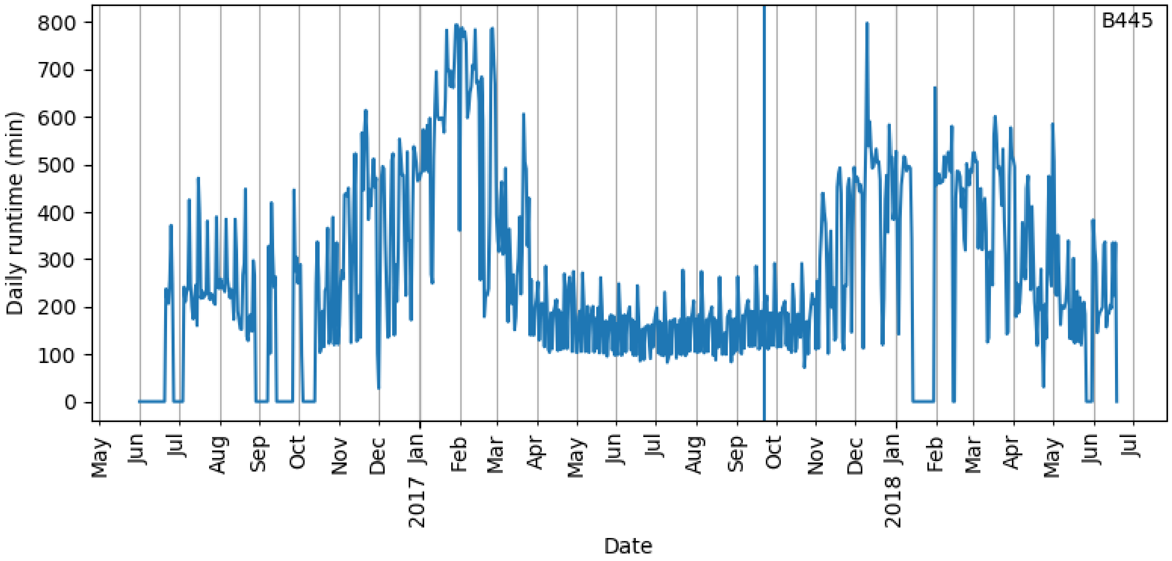


Figure 7: Graph showing daily runtime durning the entire monitoring period

Having someone onsite to look after biomass boilers is important to ensure that they have high performance. It is not usual to have a site with a biomass boiler of this size operated without somebody on site actively looking after the boiler. Findings from previous work found that having an onsite “boiler champion”, somebody who actively tries to understand how the boiler should be run is important to ensure that a biomass system performs well.

Although the boiler has a high efficiency compared with field trial sites its performance in terms of useful heat delivered is very low. This is because the building is not occupied for most of the week and there are high system losses due to an uninsulated calorifier which is kept at high temperature. Adjusting the time clock on the boiler was also suggested as the boiler operated between the hours of 6 am to 10 pm. It was suggested to the site that this was outside the time that the building would be expected to be occupied. The main use of the heat was for hot water and it was not expected that people would need to use the facility before these times. There was no artificial lighting for sport so during the night there was no need for hot water usage. It was suggested that the site limit the hours the boiler can be activated in the winter to daylight hours. The plan from the site was to do this using the remote monitoring control of the boiler but as this was not installed during the field trial the changes were not made.

12 Summary

The boiler had an average net efficiency of 84% which was above average for wood chip fuelled biomass boilers. The DDH plot showed good correlation between heat provided and outside temperature suggesting there was good control of the boiler.

This case study looked at different operating patterns throughout the year and the effect on the performance of the boiler. A Trimodal operating pattern was found to give the highest efficiencies for this site. A Bimodal operating pattern was also found to efficient and it is suggested the boiler keeps to one of these operating patterns in the winter months.

Modulation was also found to affect the efficiency and, in general, lowered the running efficiency, however it also prevented the boiler from rapid cycling in the winter months and therefore showed good control.

It was suggested that although the efficiency was high and the cycling rate was low the actual performance in terms of heat used by the end user was low. The boiler operates when the building is not occupied. The boiler should also be limited better by the time clock in the winter as the boiler can operate up to 10 pm at night which is after the last requirement for heat which is only in daylight hours.

Department for
Business, Energy
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Biomass boiler field trial
Case studies – B542

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1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B542 was monitored from 14 April 2016 to 31 July 2017. This case study contains information on the performance and efficiency of the biomass system and recommendations on how to improve its operation. Information on the performance of all systems across the trial is also included.

2 Background

B542 was one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip, or log.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data that was kindly provided by trial participants was used (along with the compositional analysis we had carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall efficiency.

3 Description of the boiler and system

The monitoring was completed on a 15kW wood pellet biomass boiler located in a garage. The garage was attached to an annex building that was a short distance from the main house. There was a section of underground pipework that ran from the garage to the main house.

The boiler was fired by wood pellet which was supplied in bags that were stored in the garage, and was manually fed into the integrated storage hopper as required.

Table 20: About the site

Building description	Domestic Property
Fuel storage issues	None reported
Heat losses	Insulated pipework, some underground
Issues raised by operator at time of installation	None reported

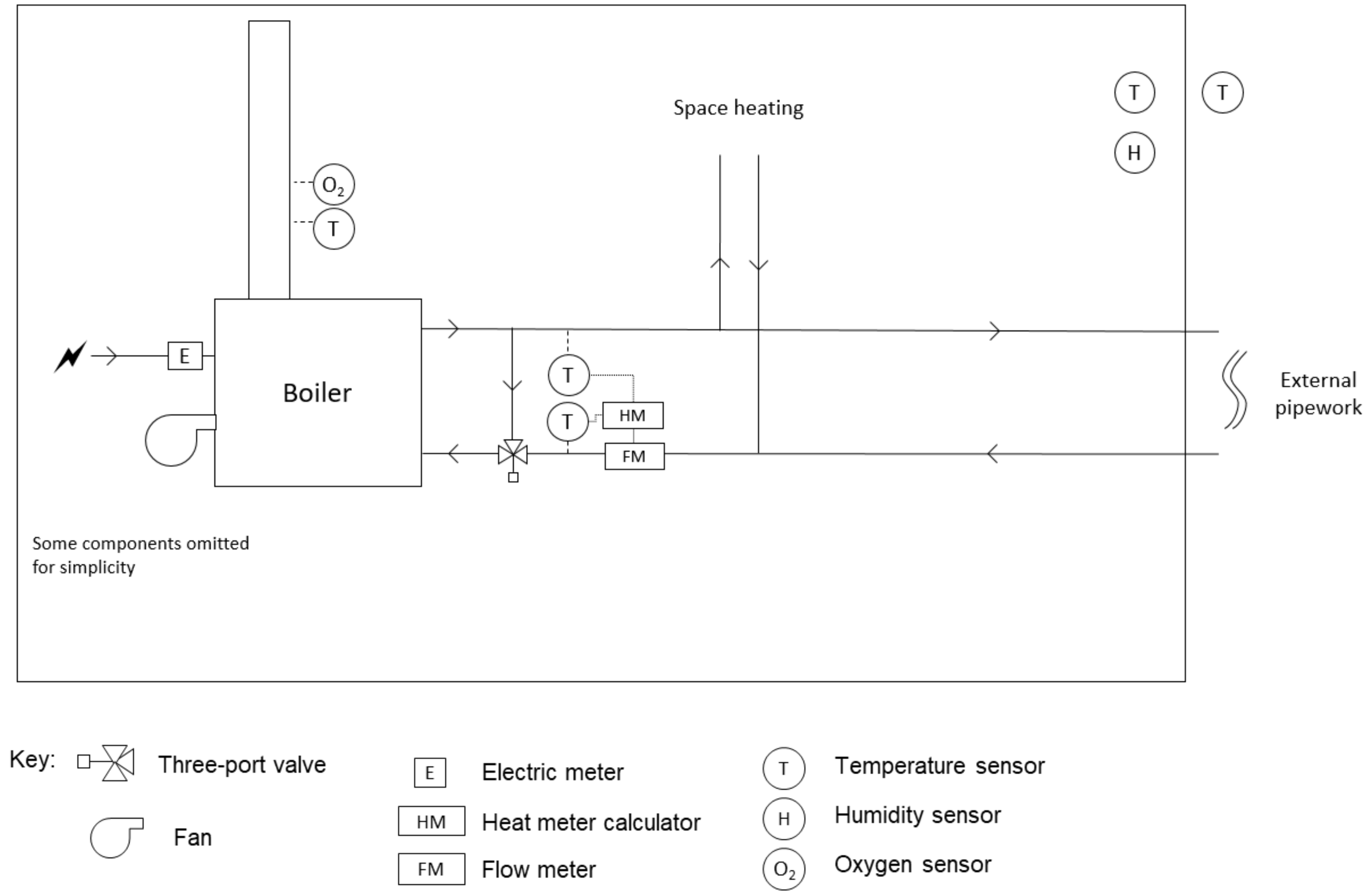
Table 21: About the biomass boiler

Rated output	14.9 kW
Fuel type	Wood pellets
Thermal store	No
Draught diverter	None reported
Dilution components	None reported
Fans	Forced draft
Cyclones	None reported
Filters	None reported
Boiler faults	None obeserved

The boiler's primary use was to provide space heating and hot water to the domestic property and annex building. There was a short section of buried pipework between the garage and main house which was assumed to be properly insulated and from which there were likely to have been some heat losses.

There was no accumulation vessel present on the system.

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

During the field trial, no serious faults were reported on the boiler, there was good communication between the logging equipment and there were no prolonged periods of data loss. This section shows how the boiler performed over length of the field trial. The efficiencies have been calculated on a net basis using efficiency equations outlined in BS 845-1.

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 22: Main parameters measured

Data collection period was from	14 April 2016 to 31 July 2017	
Heat output over this period	18,036	kWh
Estimated fuel use over this period	5	tonnes
Hours of operation over this period	1,948	hours

5.2 Annual equivalent use

Table 23:Annual equivalent use and summer and winter usage

	Annual equivalent use	**Typical winter month (Feb 2017)**	**Typical summer month (Sep 2016)**
Heat output	15,532 kWh	2,060 kWh	494 kWh
Estimated fuel use	4.5 tonnes	0.5 tonnes	0.1 tonnes
Efficiency	71 %	75 %	74 %
Hours of operation	1,663 hours	192 hours	67 hours
Load factor	12 %	20 %	4.6 %
Average starts per day	3.5 starts	4.2 starts	2.5 starts

5.3 Overall boiler efficiency

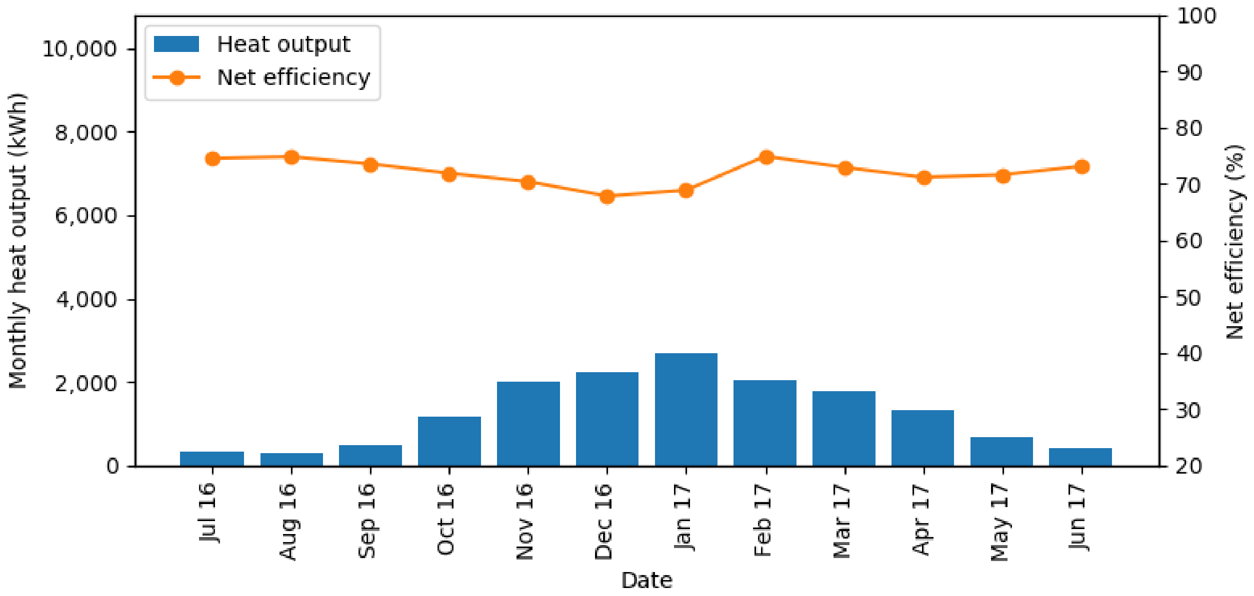


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

When calculating the net efficiency, the data used was specific to the boiler and how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, will have their own heat losses which will decrease the net efficiency of the system as a whole. If large water tanks (such as accumulator tanks) are installed in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency could be much lower. This is explored further in the published field trial report.

The annual equivalent net efficiency of the boiler averaged 71%.

5.4 Heat output vs. degree day heating requirement

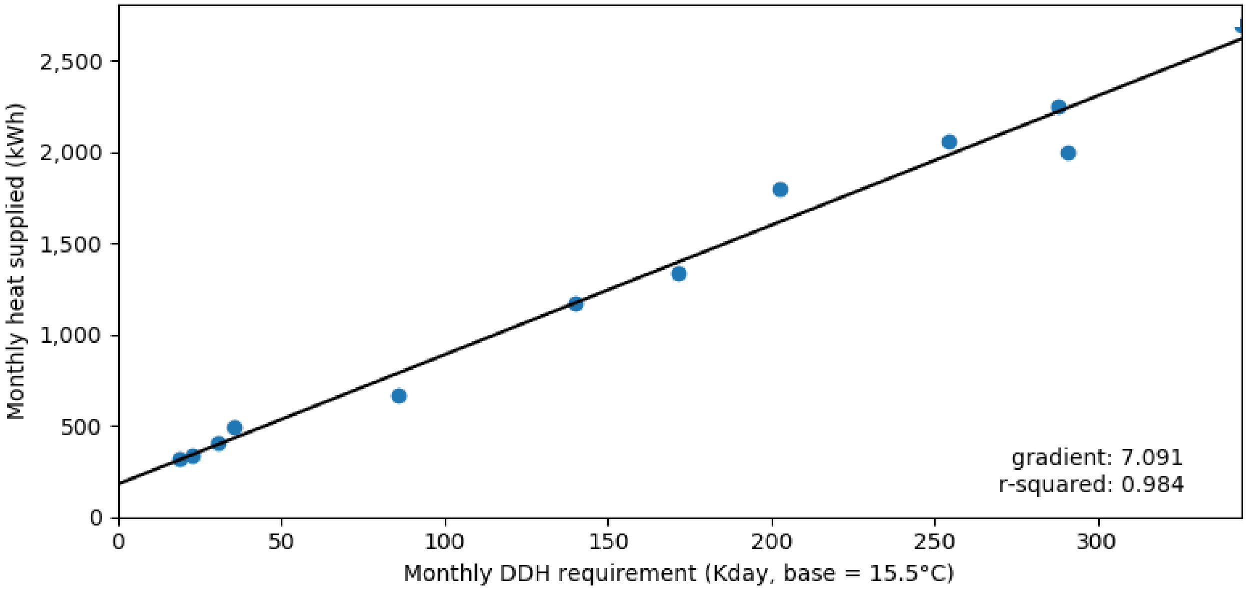


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

For B542 there was a good correlation between degree day requirement and heat output of the boiler, reflected by the r^2 value being very close to 1. In the summer, load was mainly used for DHW which was roughly 300 kWh per month which can be seen in Figure 2. However, there was uncertainty in this number as there may have been considerable losses from the DHW cylinder which was of an unknown specification. 300 kWh equated to the 15kW boiler operating at full output for just under an hour a day. In the winter, the monthly load was around 2,200 kWh per month which was around 7 times the summer value and which equated to a full load run time of around 5 hours per day.

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

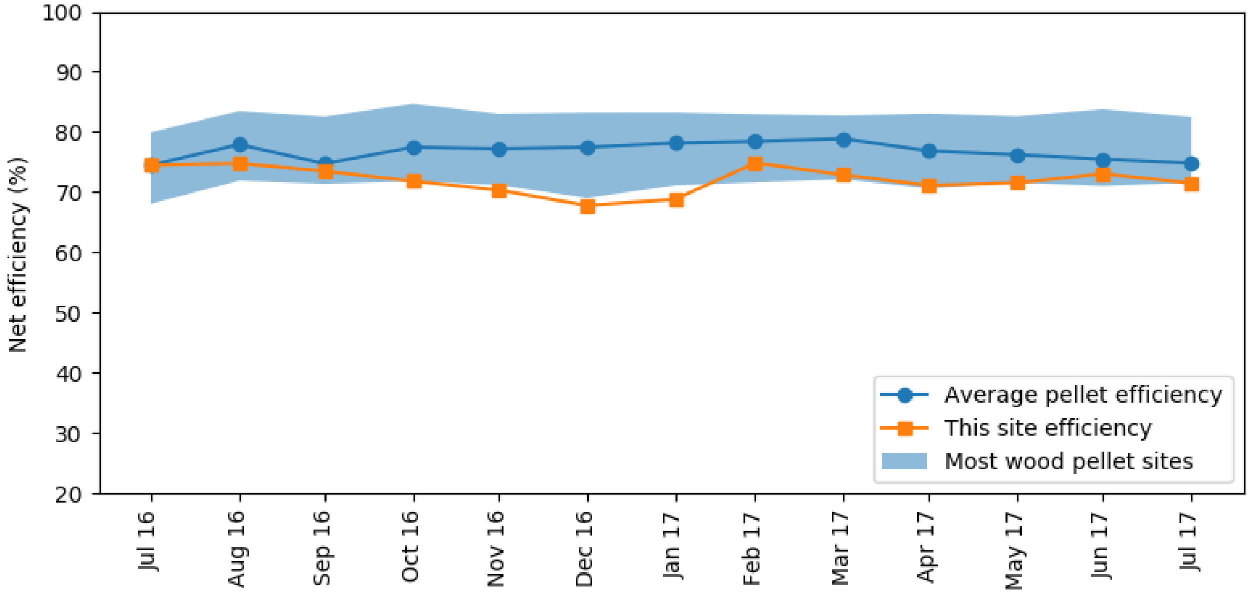


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B542.

The net efficiency of the boiler (in orange) is shown along with the average boiler efficiency (in blue). The light blue band on the graph shows the efficiency range of most of the boilers in the field trial (the middle 75%).

If the boiler falls above this band, it is performing particularly well compared with the other boilers of this type in the field trial. If the boiler falls below this band, it is performing particularly badly compared with the others.

During the winter months, the efficiency of the boiler fell. The winter was the period where we would expect the boiler to perform with the highest efficiency as this was when the boiler was normally able to run for longer and more continuously (both types of behaviour have been shown from the laboratory testing to increase efficiency). The boiler at B542, however, displayed the lowest efficiency during these months. Some possible explanations for this occurrence are discussed in the following sections.

7 Seasonal heat use and cycling

7.1 Summer heat use and cycling

The boiler at B542 showed two distinct patterns of operation, a bimodal pattern during summer and a unimodal pattern during winter. The boiler was switched on at the same time every day throughout the year suggesting that a time clock controlled it. Figure 4 shows the use of the boiler on a typical July day. The boiler was switched on around 4am and fired for a short period of approximately 1 hour. It then fired again at around 3pm and there was another short burn. During the summer, there was no space heating load on the system, so the heat produced during these burns was most likely being used to maintain the temperature within a DHW cylinder in the main house or annex building. The boiler appeared to be operating with a relatively poor efficiency during the summer months so the use of alternative systems to provide DHW could be considered.

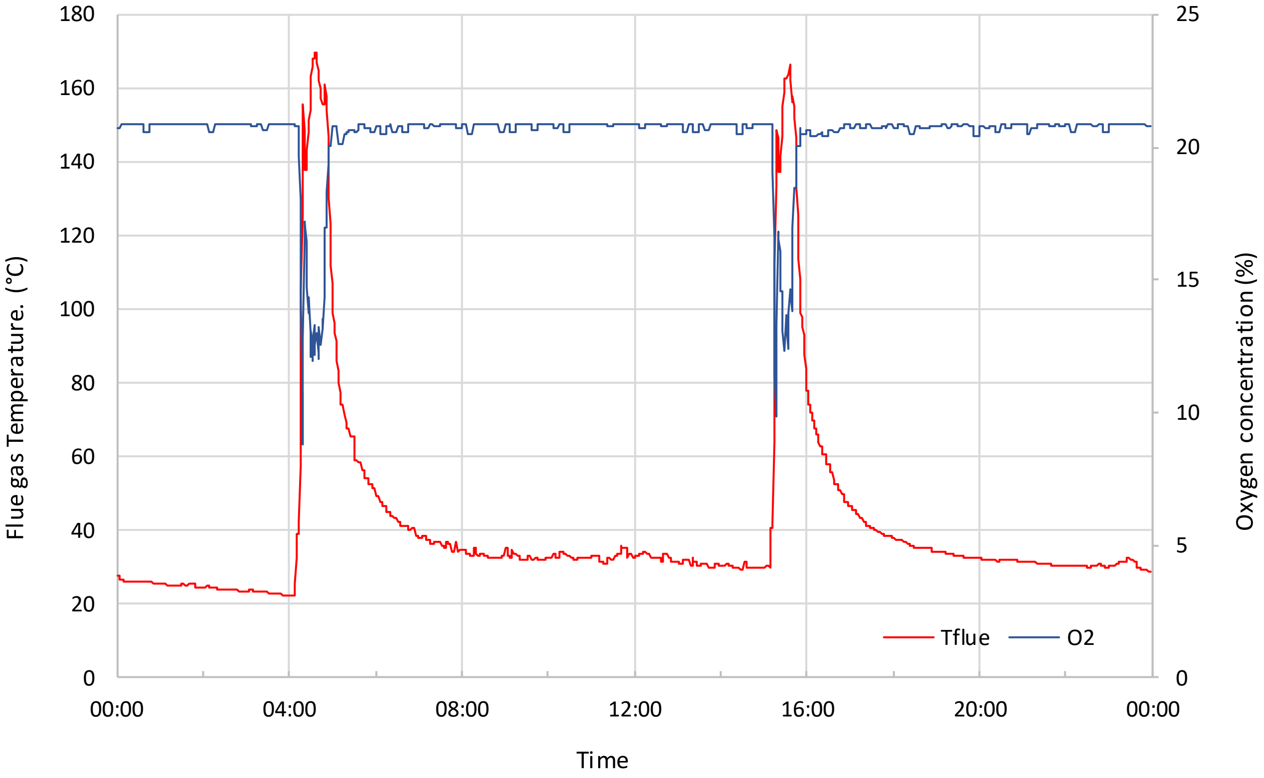


Figure 4: Oxygen and flue gas temperature for B542 on a typical July day

7.2 Winter use and cycling

Figure 5 shows the use of the boiler on a typical December day. The boiler switched on around 4am and operated continuously until it turned off at around 11:30pm. During this period, there were between 6 and 7 on/off cycles. The average number of cycles during December was 5.1, and each burn was approximately 1.3 hours in duration.

The laboratory testing showed that cycling in biomass boilers increased the hydrocarbon and particulate emissions and reduced efficiency. It may be possible to reduce the number of cycles during the day by installing an appropriate sized accumulator tank. However, the downside of installing an accumulator tank will be that the system’s heat losses will increase, particularly during the summer. If an accumulator is fitted then it is recommended that it is bypassed during the summer months when there is no space heating requirement.

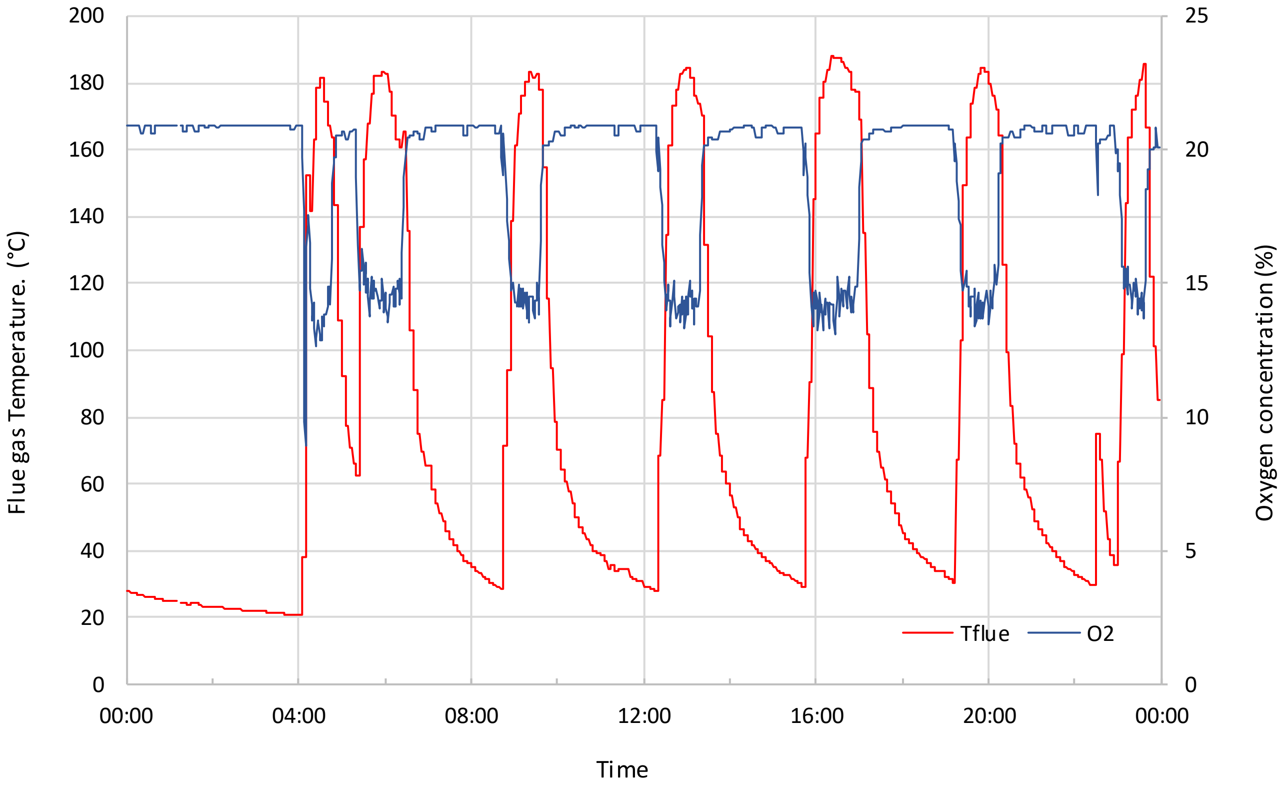


Figure 5: Oxygen and flue gas temperature for B542 on a typical December day

8 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial we analysed fuel from every site. The table below gives the results of the fuel analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites.

Table 24: Fuel quality at the site

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Site sample	Wood pellets	17.399	6.2	50.9	6.4	36.0	0.4	0.10
Average in field trial	Wood pellets	17.469	6.8	49.9	5.7	37.0	0.3	0.13
Minimum		16.482	4.4	-	-	-	-	-
Maximum		18.061	9.3	-	-	-	-	-

The fuel analysis was very close to the average of the analyses of other fuels in the trial. This is unsurprising given the manufacturing process for pellets which results in a very consistent product.

9 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31 June 2017 and 31 May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring highlighted in the previous sections of this case study.

9.1 Patterns of heat use

The intervention visit to this site identified that the boiler operated throughout the day when the property was unoccupied. During the visit the operator adjusted the boilers time clock settings to limit the times the boiler is used for space heating at the property. It was expected that this would let the boiler fire for longer as the house would need heating up from a lower starting temperature. As there is no accumulator there is no advantage to allowing the boiler to fire when the building is not occupied as this heat is effectively lost.

This site does not have an accumulator however the biomass boiler does supply a small DHW tank which is used for hot water in the domestic property. The control of the biomass boiler is also affected by this DHW load and the boiler is set up to fire and satisfy the DHW tank when it requires heat. The site was able to adjust the space heating supply clock, it was not possible to limit the boiler turning on to heat the DHW tank.

The intervention to limit use was unsuccessful as although the site made changes to the control of the boiler the DHW tank load ensured that the boiler still fired throughout the day when the property was not occupied. It is interesting that the site had little control over when the boiler fired.

9.2 Oxygen set points and maintenance

One of the findings from the intervention visit with the site was the oxygen levels in the boiler were higher than would be expected. Biomass boilers must supply enough air to the fuel to ensure clean combustion, excess air must be supplied to prevent high levels of CO and smoke being produced. Typically, biomass boilers are operated with 10% oxygen in the flue gases. High oxygen levels will cause the boiler to run with high excess air which causes energy to be lost in the flue gases which will decrease boiler efficiency. The oxygen set point for the boiler was at 13% which can be seen in Figures 4 and 5. This is higher than would be expected and would have a negative impact on boiler performance. The site was advised that during their next maintenance visit that they should ensure that the engineer recommissioned the boiler to run at a lower oxygen concentration in the flue. The site did have yearly maintenance visits to fully service the boiler. During the visits the boiler heat exchanger tubes were cleaned to ensure that they removed the maximum amount of heat from the flue gasses. Drops in flue gas temperature show this maintenance work being undertaken as can be seen in Figure 6 where the work can be seen in January and November 2017. A further visit was also undertaken in March 2018. The red lines show when the visits took place during the monitoring period. What one see from Figure 7 is that these visits have a corresponding step change in the data showing an adjustment of oxygen when a visit takes place. The efficiency of the boiler also increases after the visits shown in Figure 8 which is to be expected as reducing oxygen content and flue gas temperatures will reduce the two largest losses from biomass boilers increasing efficiency. After the maintenance visit in March 2018 the oxygen increases showing that the set point has been incorrectly adjusted. There is no corresponding efficiency increase after this adjustment as the efficiency gains from reducing flue gas temperature is offset by the increased oxygen concentration which reduces efficiency.

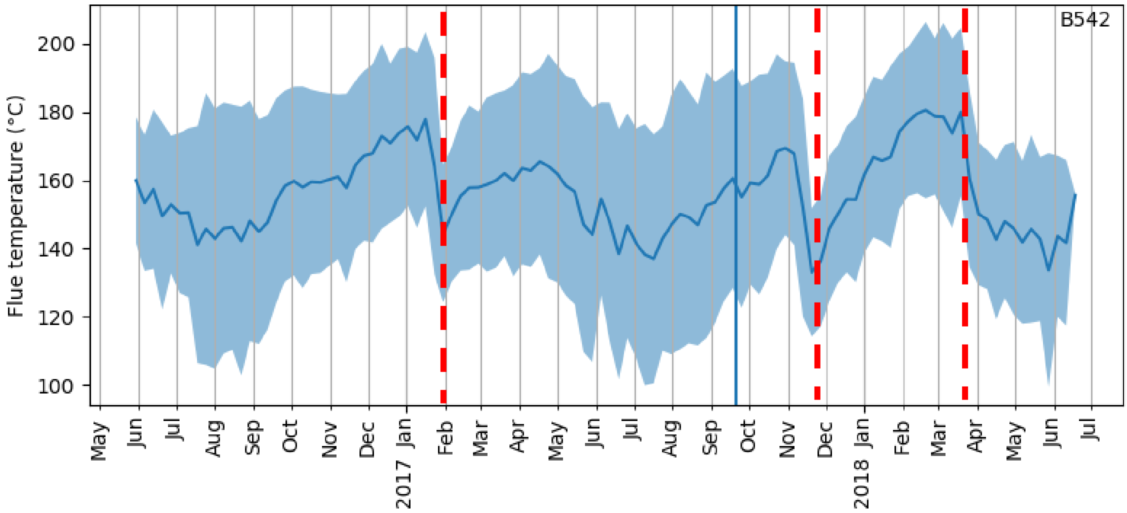


Figure 6: Flue gas temperature for B542 for the entire monitoring period.

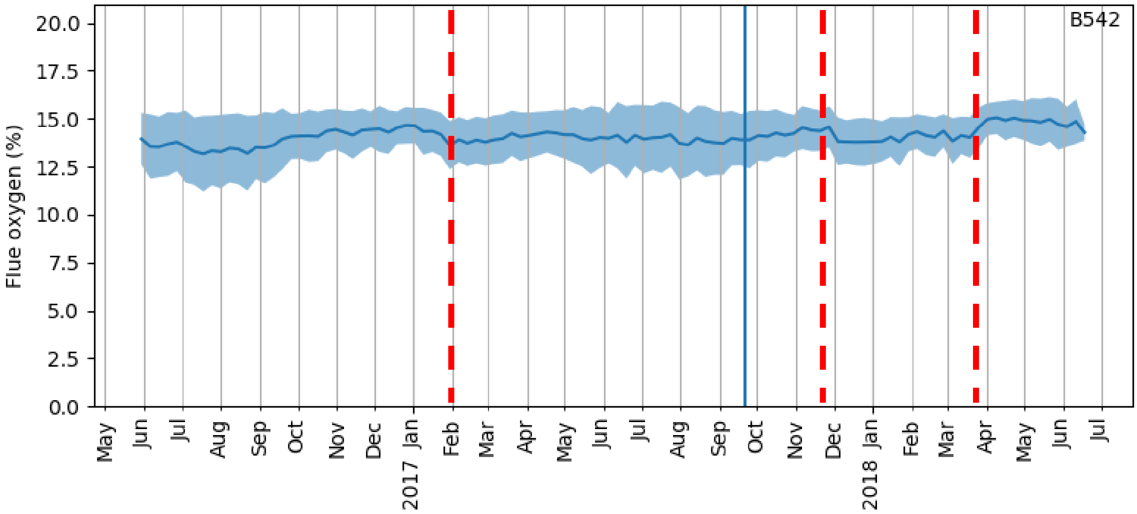


Figure 7: Flue oxygen in flue gasses for B542 for the entire monitoring period.

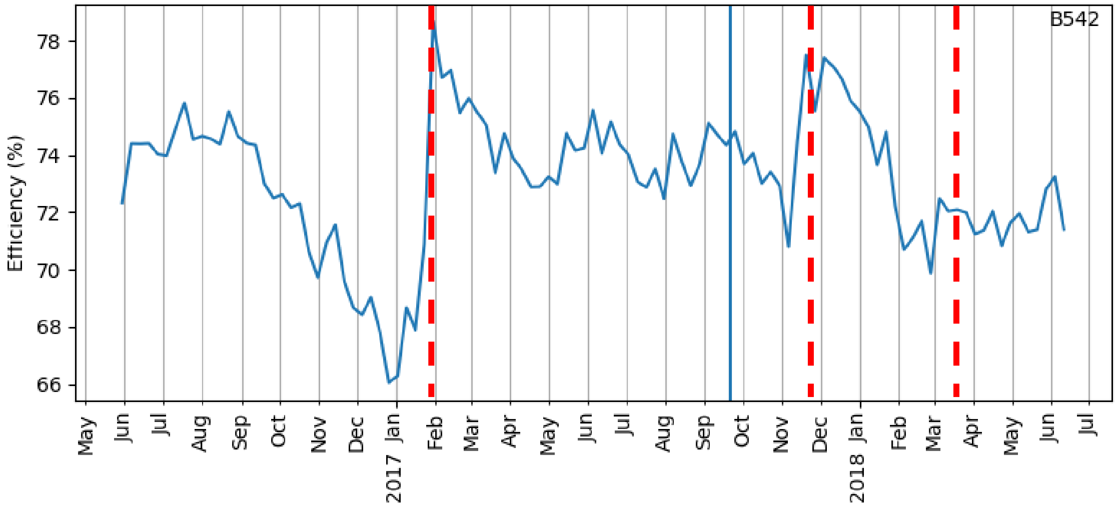


Figure 8: Net efficiency for the boiler at site B542 for the entire monitoring period.

The intervention to reduce the oxygen in the flue gasses at this boiler site did not have the desired effect as the attempts to adjust the oxygen did not bring the oxygen level down closer to 10%.

There were two opportunities after the intervention visit to make the changes required however the site was unable to get their maintenance provider to make the change. It is unknown why the adjustments were not undertaken correctly. The operator of the boiler at this site is fully dependent on their maintenance provider to make these changes on their behalf. During these visits the oxygen content in the flue should be measured when the boiler is running and the boiler oxygen set point adjusted as appropriate. The site is unable to measure the oxygen content in the flue without investment in expensive monitoring equipment. They are also not capable of making the required adjustments to the flue gas oxygen. Without the maintenance provider making this change the site have no indication that the oxygen set point is too high as the boiler otherwise ran well.

10 Summary

The boiler at B542 operated well throughout the year although the efficiency was lower than expected. Comparing the site with other pellet sites the winter and summer efficiencies were in the middle of the range

The DDH plot showed good correlation between heat provided and monthly degree days, suggesting that the boiler was controlled well in response to outside temperature.

The case study looked at operation during both summer and winter and it was suggested that a reason the site experienced cycling during the winter was due to the DHW tank requiring heating. It was suggested that fewer cycles of longer duration could be achieved by installing an appropriately sized accumulation vessel which would allow the boiler to fire for longer with longer periods between burns.

In the summer, the boiler showed a different cycling behaviour with two distinct burn periods during the day. The efficiency was still relatively low, and it may be worth considering alternative ways of supplying DHW during the summer

It was also suggested to the site’s owners that they should limit the boiler operation when the property is not occupied. This was attempted by the site however it was not successful due to the limited control over the boilers operation.

The oxygen set point of the boiler was too high and it was suggested that it should be reduced. Despite three maintenance visits where it was attempted to lower the set point, it was not set correctly and therefore did not have a big impact on improving performance. It appeared that this was not a failure of the site’s owners but rather of the engineers servicing the boiler, not having the capability to set the oxygen correctly.

Department for
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Biomass boiler field trial
Case studies – B586

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1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B586 was monitored from 24 March 2016 to 31 May 2018. This case study contains information on performance and efficiency of the biomass system and recommendations on how to improve operation. Information on performance of all systems across the trial is also included.

2 Background

B586 was one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip, or log.

B586 was also part of further year of monitoring where 21 sites were monitored for a further year. Interventions were made at 15 of these sites to improve the site performance in terms of both efficiency and pollutant emissions.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data that was kindly provided by trial participants was used (along with the compositional analysis we had carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall efficiency.

3 Description of the boiler and system

The monitoring was completed on a 60kW wood log boiler located in a purpose-built container building located in the garden behind the guesthouse. There was a section of underground pipework that ran from the container to the guesthouse.

The boiler was fired by wood log which was self-supplied and seasoned to meet the quality required by the appliance. The wood was a mixture of hard and softwoods of different species including ash, beech and sycamore.

Table 25: About the site

Building description	Large guesthouse
Fuel storage issues	None reported
Heat losses	Insulated pipework, some underground
Issues raised by operator at time of installation	None reported

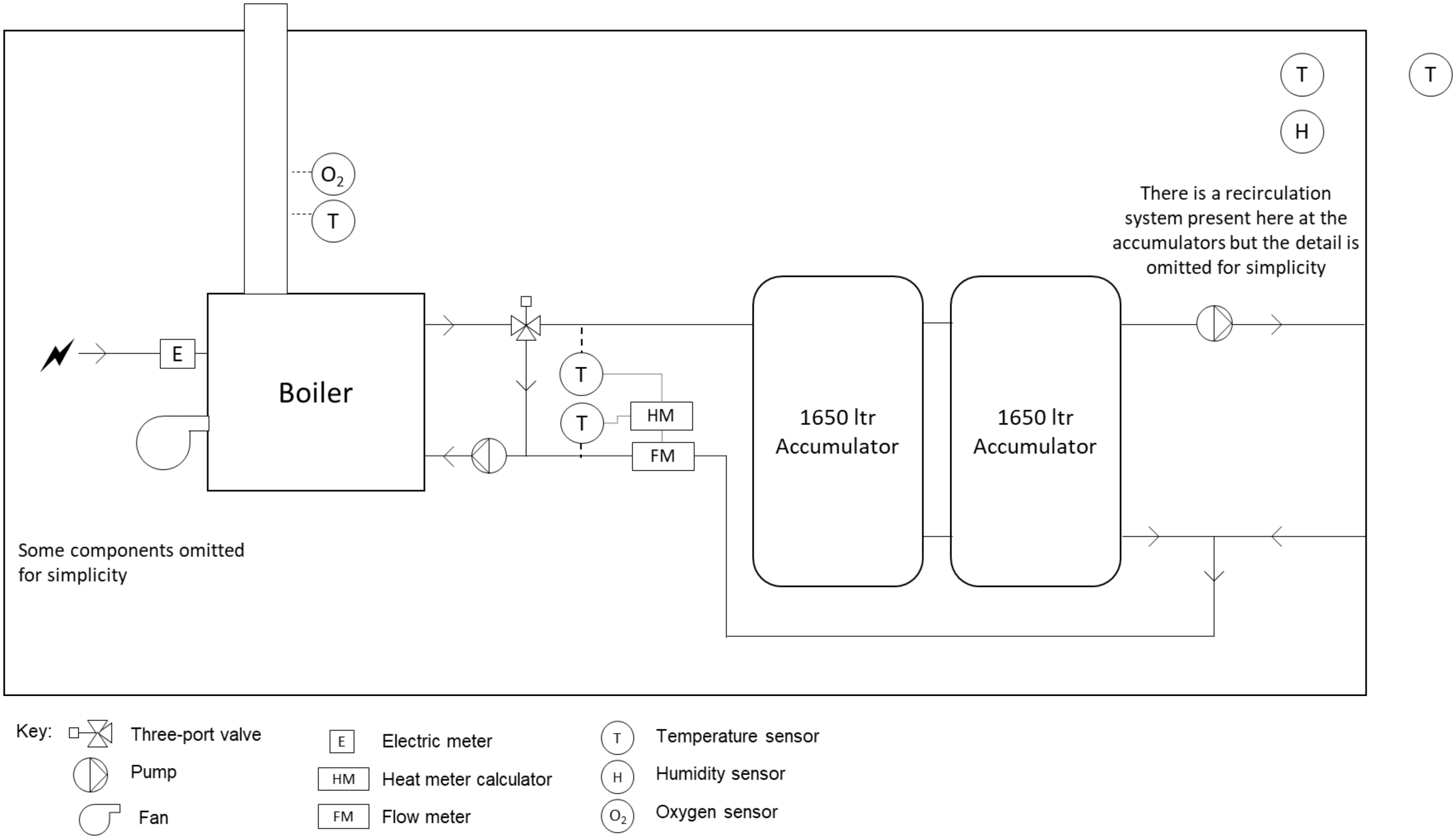
The boiler's primary use was to provide space heating and hot water to a large guest house. There was a short section of buried pipework between the boiler cabin and the main house which was assumed to be properly insulated and from which there would be some heat loss.

There were two accumulation vessels present on the system, with a combined capacity of 3,300 litres.

Table 26: About the biomass boiler

Rated output	60 kW
Fuel type	Wood logs
Thermal store	Yes
Draught diverter	On other branch of Y-junction about 2m from boiler exit
Dilution components	None reported
Fans	Forced draft
Cyclones	None
Filters	None
Boiler faults	None reported

4 System schematic



5 The performance and efficiency of the boiler

During the field trial, no serious faults were reported on the boiler, there was good communication between the logging equipment and there were no prolonged periods of data loss. This section shows how the boiler performed between 24 March 2016 to 31 July 2017. In accordance with EN standards, the efficiencies have been calculated on a net basis using efficiency equations outlined in BS 845-1.

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 27: Main measured parameters

Data collection period was from	24 March 2016 to 31 July 2017	
Heat output over this period	54,100	kWh
Estimated fuel use over this period	14	tonnes
Hours of operation over this period	1,287	hours

5.2 Annual equivalent use

Table 28: Annual equivilent use and summer and typical winter useage

	Annual equivalent use		**Typical winter month (Feb 2017)**		**Typical summer month (Sep 2016)**	
Heat output	42,130	kWh	5,230	kWh	1,640	kWh
Estimated fuel use	11	tonnes	1	tonne	0.4	tonnes
Efficiency	85	%	85	%	87	%
Hours of operation	1,005	hours	124	hours	37.8	hours
Load factor	8.0	%	13.0	%	3.8	%
Average starts per day	0.8	starts	1.3	starts	0.3	starts

5.3 Overall boiler efficiency

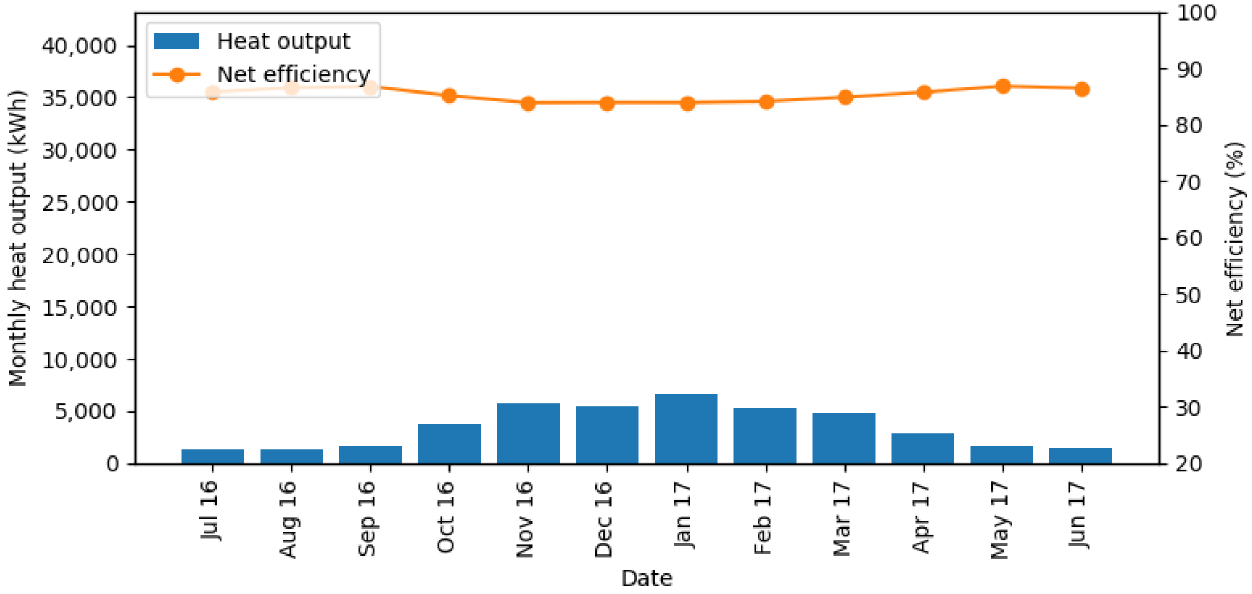


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The net efficiency was calculated for the boiler by specifically looking at how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, have their own heat losses which can decrease the net efficiency of the system as a whole. If the site had large water tanks (such as accumulator tanks) in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency may have been much lower. This is explored further in the published field trial report.

The measured annual equivalent efficiency of the boiler over the field trial averaged 85% (over the period for which we had data). There appeared to be a small seasonal variation in net efficiency of 3% with the efficiency slightly higher in summer than winter. However, the utilisation of the boiler during the summer was very low, so this increase in efficiency did not affect the overall efficiency greatly. Thus, over the trial period the efficiency of the boiler was broadly constant.

5.4 Heat output vs. degree day heating requirement

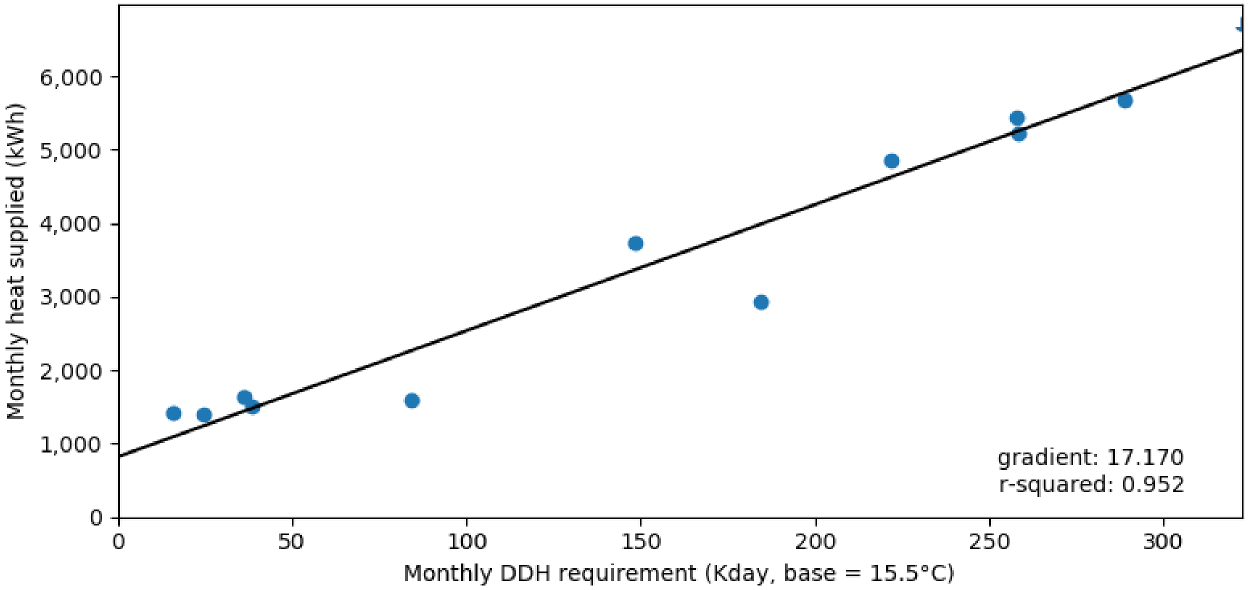


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

For B586 there was a good correlation between degree day requirement and heat output of the boiler, reflected by the r^2 value of 0.952. In the summer, load was mainly used to keep the accumulator charged to provide DHW, this was around 1,000 kWh/month.

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

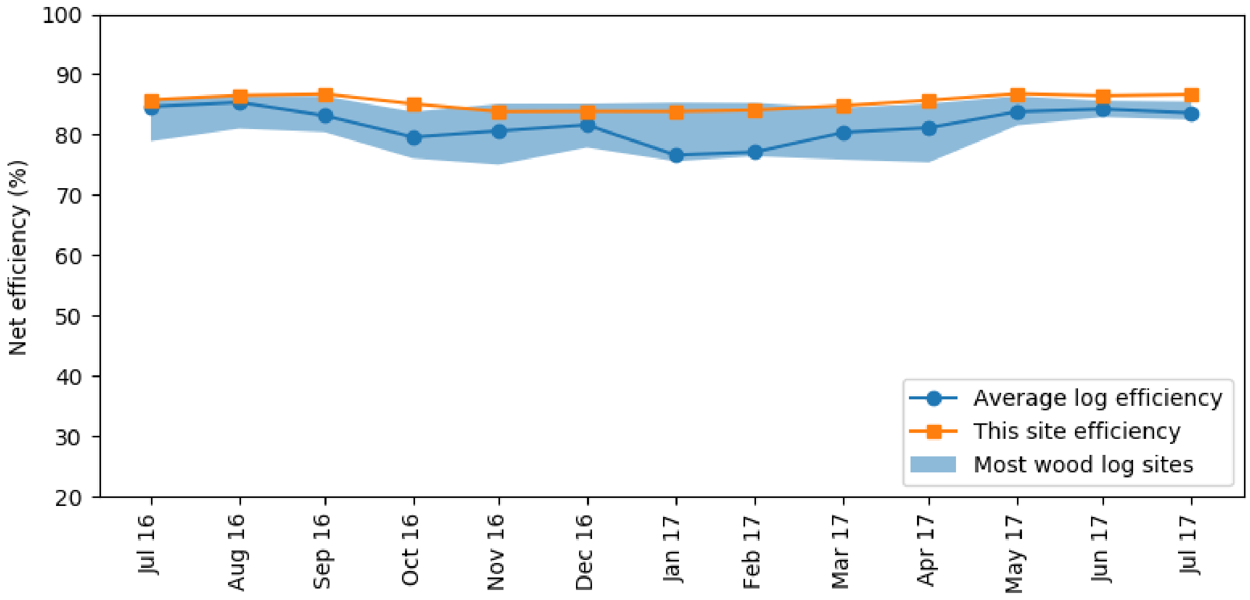


Figure 3: Graph showing net efficiency of boilers in the field trial

Figure 3 provides a comparison between net efficiency of the log boiler on this site and the average net efficiency of all the log boilers in the trial. It sets these in the context of the band of efficiencies achieved by most (the middle 75%) of the log boilers in the trial. This shows that this boiler performed well compared with the other boilers of this type in the field trial.

7 Seasonal heat use and occupancy

The boiler at B586 was a manually fed log wood boiler used to supply space heating to a large guest house. It was apparent that the boiler was fed as frequently as was necessary to maintain the accumulator vessel at the required temperature. The firing frequency varied throughout the year, from 1 load every 4 days in summer (for example 12th – 14th August 2016) to two loads each day (25th January). Once fed, the boiler burned uninterrupted until the fuel was used up (which is the most efficient way to run this type of boiler). The duration of the burn was very consistent throughout the year, reflecting the consistency in the quality of the fuel used.

The disadvantage of a manually batch fed boiler is that the operator must always be present to start a burn. Given the nature of a guesthouse, the operator may feel it necessary to fire the boiler and charge the accumulator at times where there is no demand (for example late at night in anticipation of the guests requiring heating in the morning). This may have led to an increase in losses from the accumulator and although the boiler itself appeared to operate efficiently, the efficiency of the system as a whole may suffer. In general

The operator should always endeavour to ensure the accumulator is charged as closely to the time that heat is required as possible, for convenience, in certain situations, this may mean leaving it charged overnight.

7.1 Summer firing

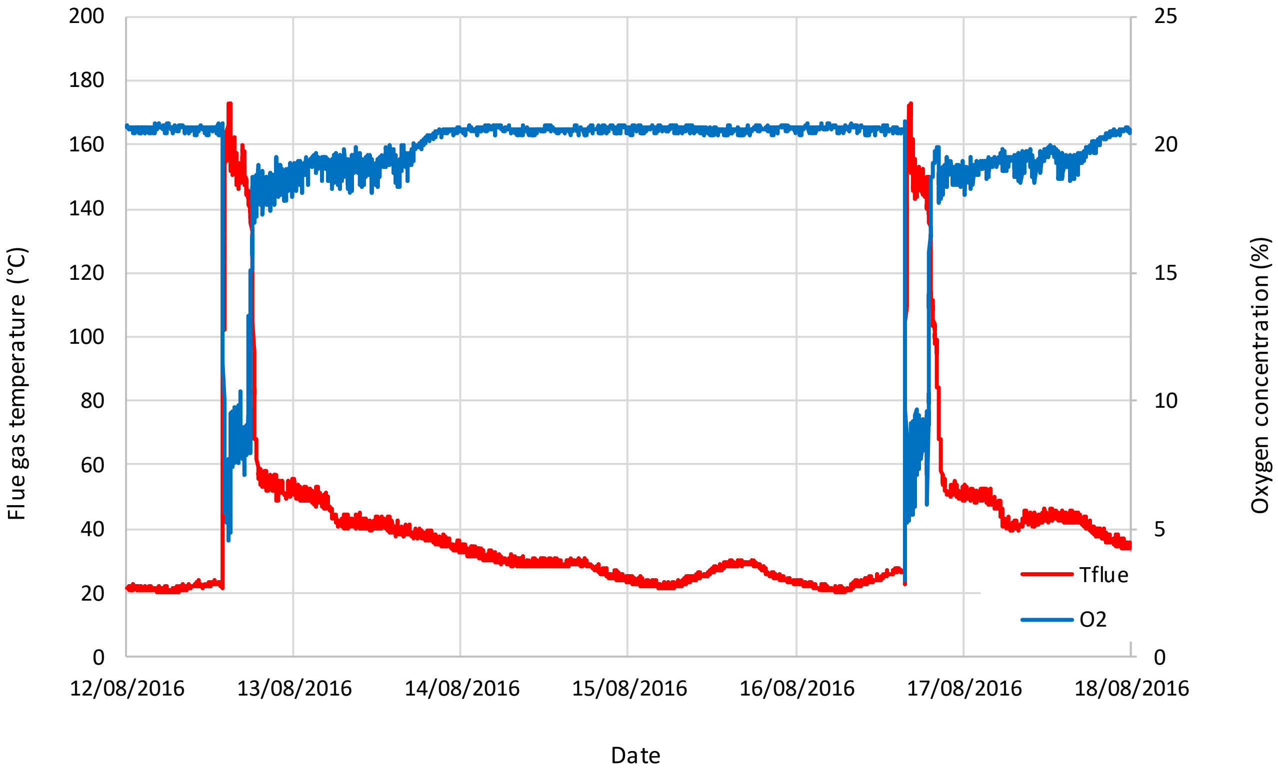


Figure 4: Operation of the boiler from 12-16th August

Figure 4 shows the operation of the boiler during a period in summer. It can be seen that the boiler was fired just after midday on the 12th August and the burn duration was approximately 4 hours. The boiler was not fired again until the 16th August. This type of behaviour repeated throughout the summer but the day on which the boiler was fired varied. The site operator explained that during the summer months electric immersion heaters were used to supply most of the DHW demand, however the boiler was occasionally fired to ensure that the accumulator contained heat should the guests require it on a cold evening or to dry clothes.

7.2 Winter firing

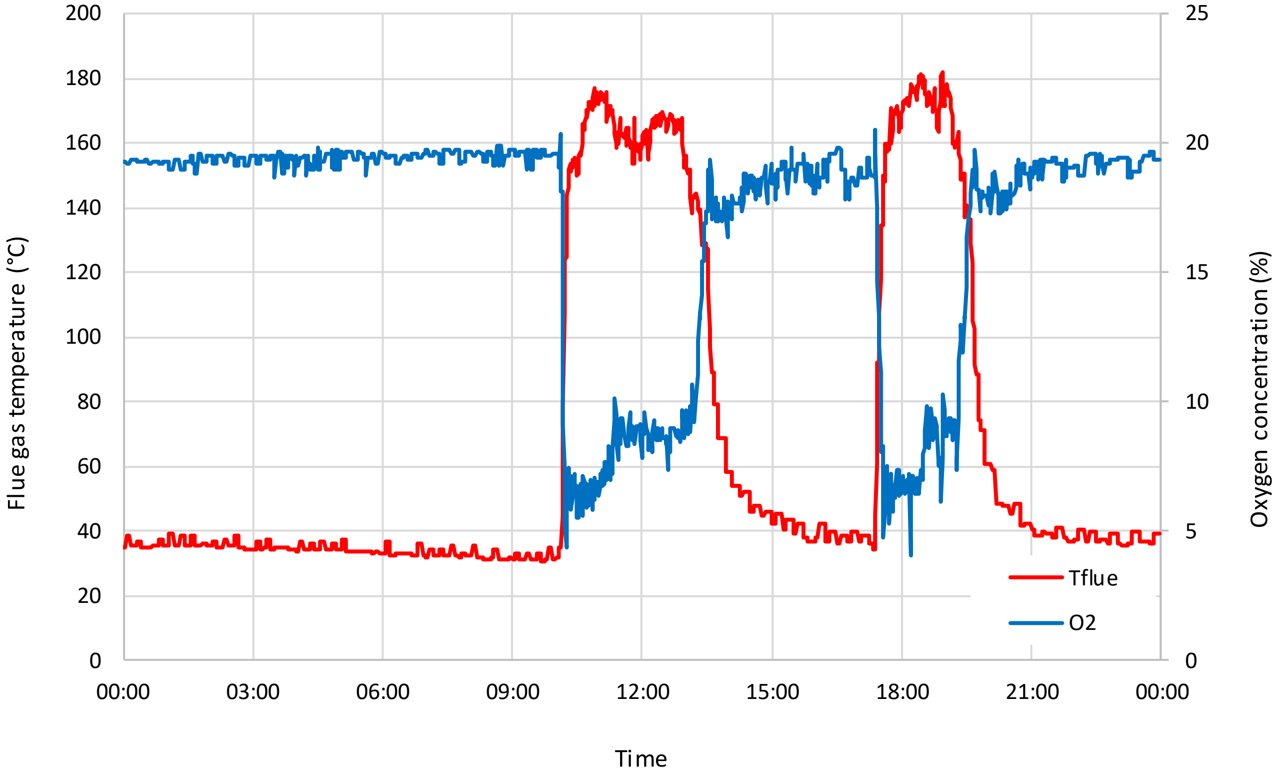


Figure 5: Operation of the boiler on the 25th January

Figure 5 shows the operation of the boiler during a cold day in winter. There were two distinct burns during the day, one at around 10am lasting for approximately 5 hours and another at around 17:30 that lasted for approximately 2.5 hours.

Despite the higher utilisation of the boiler during the winter, the efficiency of the boiler remained as high as it did in summer. This showed that the efficiency of each burn period was roughly constant and that there were simply more burns per day in winter. This is indicative of a correctly operated manually batch fed boiler.

8 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 30 of June 2017 and the 31 of May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring highlighted in the previous sections of this case study.

8.1 Accumulator adjustment

As part of the field trial the site interventions that were made to boilers were mainly focussed on making changes to controls, maintenance, and behaviour. However, for this site a physical change to the configuration of the heat accumulators was suggested.

During the intervention visit issues with the boiler operation indicated by the owner were investigated. These related to degradation of the refractory lining in the boiler. Discussions with the manufacturer indicated that degradation of this type was usually a sign of overheating in the boiler. During it was found that the overpressure valve had discharged onto the floor of the boiler house confirming that the water in the boiler was overheated producing excessive pressure.

Batch fed boilers are much more prone to overheating. They are loaded with a fixed amount of fuel per burn. This means that there is a fixed amount of energy that will be released during the burn. All this heat must be removed from the boiler or overheating will occur. The manufacturer suggested that the return temperatures were too high to remove heat effectively from the boiler. To reduce the return temperature (and improve heat removal from the boiler) more heat must be dissipated from the water as it passes through the heating system. This includes storing some of the heat in the accumulators.

The accumulators that were installed at the site were modular and two had been combined to provide a larger volume. This approach can enable more capacity to be installed in limited space. These accumulators were coupled at the top of the accumulators and at the bottom. The system set up can be seen in the schematic in section 4. In this configuration there are two types of flow through the system which will affect its operation depending on which of the pumps are active. The system configuration is designed to work with a stratified accumulator. However, with the tanks coupled at the top and bottom stratification doesn’t occur and the water is mixed by the flow through the coupling pipes. Also, there are dead zones that occur of water volume that is not fully utilised, and this effectively reduces the accumulator size.

Having more couplings across the accumulators will allow the water in both tanks to move freely between each other and allow them to stratify as one volume rather than separate mixed volumes. This will enable more heat to be retained in the accumulator, reducing the return temperature to the boiler helping to prevent overheating in the boiler.

During the intervention visit it was found that both the tanks have two unused ports which are designed to be coupled together. It is not clear why this was not done during installation however it was suggested to the site that this would improve the tanks ability to stratify by connecting them.

The site operator was interested in making the change however he was reluctant to do so unless the boiler manufacturer replaced the refractory material in the boiler. While the site was in dispute with the manufacturer the intervention was put on hold. Due to the delay the intervention at the site was not completed before the end of the monitoring period and therefore the effect that the change would have had on boiler performance is unknown.

9 Summary

The boiler operated well throughout the year with an average annual equivalent net efficiency of 85.2% and this was consistent during the summer (with low average daily output) and in the winter (a period of higher daily average usage). This consistency was due to the fact that each time the boiler was refuelled and fired it was allowed to burn to completion, thus, each burn period in summer or winter had approximately the same net efficiency. the operator had a good knowledge of the approximate energy content of the fuel being used and when the accumulator could accommodate another burn period. The site operator should continue to (as far as is realistically possible) fire the boiler close to the time where the heat is required. This will reduce the heat losses from the accumulator particularly in the summer where there are long periods between burns.

A maintenance intervention was carried out at the site to try to limit the boiler overheating and damaging boiler components. The plan to improve the accumulator as a heat store was not completed during the monitoring period due to an ongoing dispute with the manufacturer.

Department for
Business, Energy
& Industrial Strategy

Biomass boiler field trial
Case studies – B900

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Quality
Progress

1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B900 was monitored from the 01 June 2016 to 31 May 2018. This case study contains information on the performance and efficiency of the biomass system and recommendations on how to improve its operation. Information on performance of all systems across the trial is also included.

2 Background

B900 is one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip or log.

B900 was also part of further year of monitoring where 21 sites were selected for monitoring for a further year. Interventions were made at 15 of these sites to improve the boiler performance in terms of both efficiency and pollutant emissions.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data which was kindly provided by trial participants, was used (along with the compositional analysis Kiwa carried out) to give a picture of energy input, and combined with heat output and oxygen consumption to provide an indication of the overall boiler efficiency.

3 Description of the boiler and system

The monitoring was completed on a boiler over one large educational site. The boiler all had an output of 200kW and was fuelled using wood pellet. The boiler was used to provide heat for three buildings which were previously heated with individual oil boilers. The biomass boilers are installed in ISO-type containers (accumulators are also found within these containers) and under-ground pipes have been installed on site to provide the heat produced to where it is needed. The boiler was owned and operated by a third party, whom the site paid for the heat supplied. This meant that the maintenance and fuelling of the boiler and tasks such as emptying the ash was not the responsibility of the people working at the. The boiler incorporated an underfeed stoker type burner. Primary combustion air was fed under the fuel bed by rows of air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and the residual ash was thus pushed away as more fuel is fed and subsequently removed from the combustion chamber.

4 Performance and efficiencies of boilers

This section shows how the boiler performed between 13 April 2016 to 31 June 2017. In accordance with EN standards, the efficiencies have been calculated on a Net basis using efficiency equations outlined in BS 845-1.

4.1 Total data collected

The following tables present a summary of the main parameters measured during the trial for the boilers.

Table 29: Main measured parameters

Data collection period was from	01 February 2016 to 31 July 2017	
Heat output over this period	616,360	kWh
Estimated fuel use over this period	168,797	kg
Electricity consumption over this period	1,430	kWh
Hours of operation over this period	5,704	hours

4.2 Annual equivalent use

The following tables present an annual equivalent summary of the main parameters measured.

Table 30: Annual equivilent use and typical summer and winter usage

	Annual equivalent use		**Typical winter month (Feb 2017)**		**Typical summer month (Sep 2016)**	
Heat output	423,280	kWh	62,424	kWh	14,690	kWh
Estimated fuel use	115,314	kg	16,634	kg	4,179	kg
Electricity consumption	970	kWh	133	kWh	29	kWh
Efficiency	73.5	%	75.1	%	70.1	%
Hours of operation	3,902	hours	517	hours	180	hours
Load factor	24.3	%	46.7	%	10.2	%
Average starts per day	5.5	starts	6.4	starts	5.1	starts

4.3 Overall net boiler efficiency

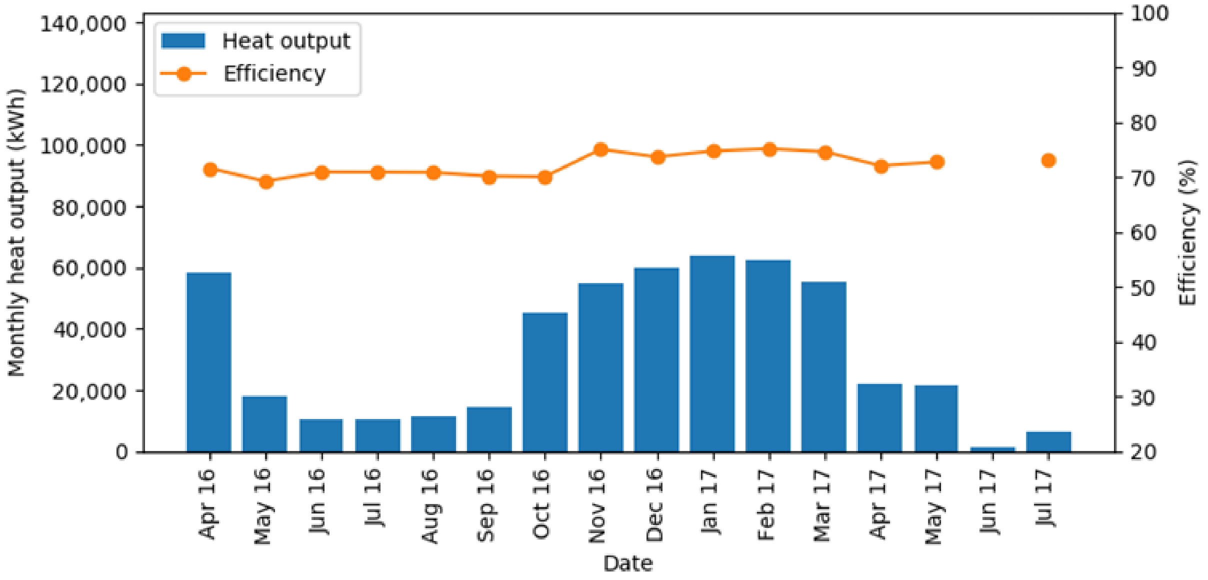

Figure 1: Graph showing the heat output and net efficiency of (B900)

Figure 1 shows the net efficiency of the boiler over the second period of monitoring. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The net efficiency was calculated for the boiler by specifically looking at how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, have their own heat losses which can decrease the net efficiency of the system as a whole. If the site had large water tanks (such as accumulator tanks) in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency may have been much lower. This is explored further in the published field trial report.

The measured net efficiency of the boiler was at 73.5%. The boiler had a steady efficiency throughout the year and higher outputs during the winter months. The summer has very low usage in comparison to the winter and the winter had slightly higher efficiencies.

5 Heat output vs. degree day heating requirement

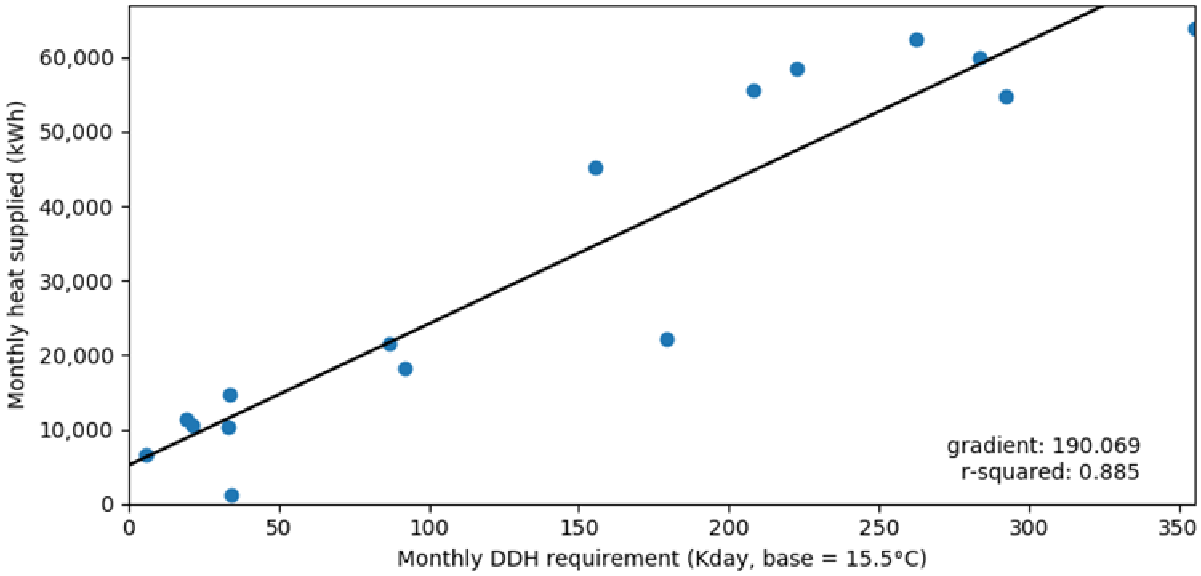

Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement for B900

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

The r^2 value calculated for the system is displayed in Figure 2. The value of 0.885 shows good control. There is a y axis intercept which is indicative that this boiler provides Domestic Hot Water (DHW) load in the summer of around 5,000 kWh per month.

6 Comparisons with other sites

Net efficiency of the boiler in relation to other boilers in the trial

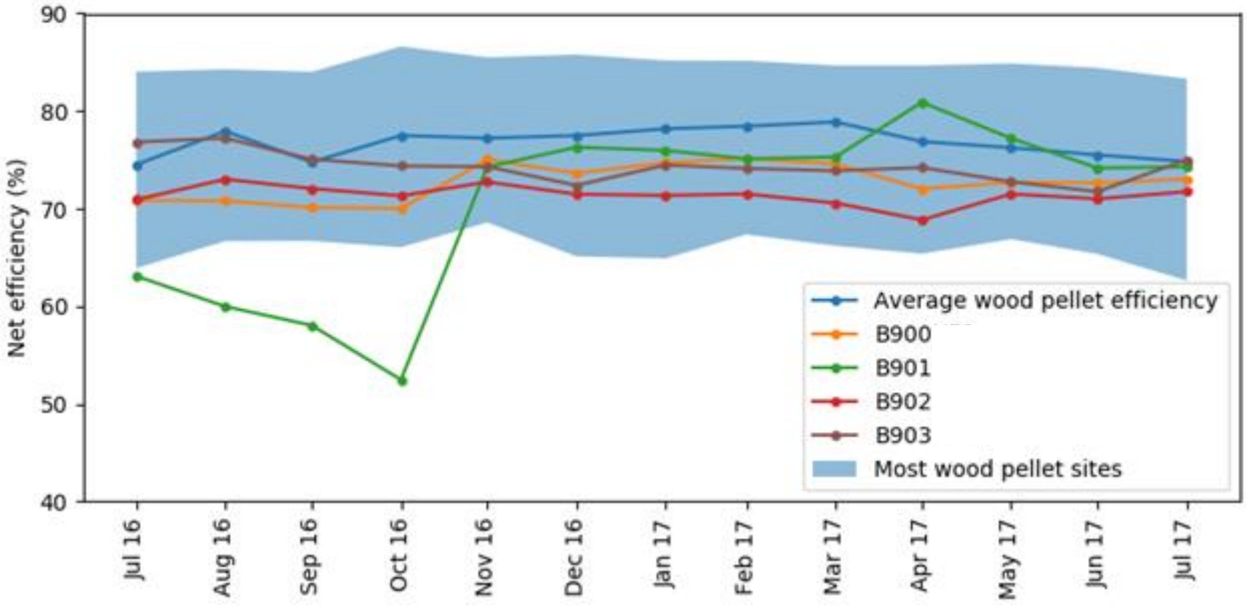

Figure 3: Graph showing net efficiency of B900, B901, B902, B903 and other boilers in the field trial

The above graphs show the net efficiency of all the boilers in the trial using the same fuel as B900.

The net efficiency of each boiler is shown along with the average boiler efficiency (in blue). The light blue band on the graph shows the efficiency range of most of the boilers of that fuel in the field trial (the middle 75%).

The graph compares the efficiency against four other boilers installed at the site providing heat to other buildings. All the boilers are identical in size and fuel used however they all provide buildings with different requirements and therefore the loads on the boilers are different. All the boilers fall within the middle 75% of pellet boilers in the field trial with the exception of B901 which performed badly from July to October 2016. The boilers shown in figure 9 also fall below the blue average net efficiency line.

7 High flow, return and flue gas temperatures

The heat from the boiler was used in college buildings used for offices and meeting rooms as well as buildings used for accommodation. The buildings use air heating coils to provide heating which require a high temperature to work correctly. The requirement to supply the heating coils with high temperature heat to operate correctly causes problems with the boiler operation. There are long pipe runs and equipment in the system which cause heat losses reducing the final temperatures delivered to the three buildings supplied by the boiler. The temperature that is delivered by the biomass boiler is set high to compensate for this heat loss and ensure that the delivered temperature does not fall too low.

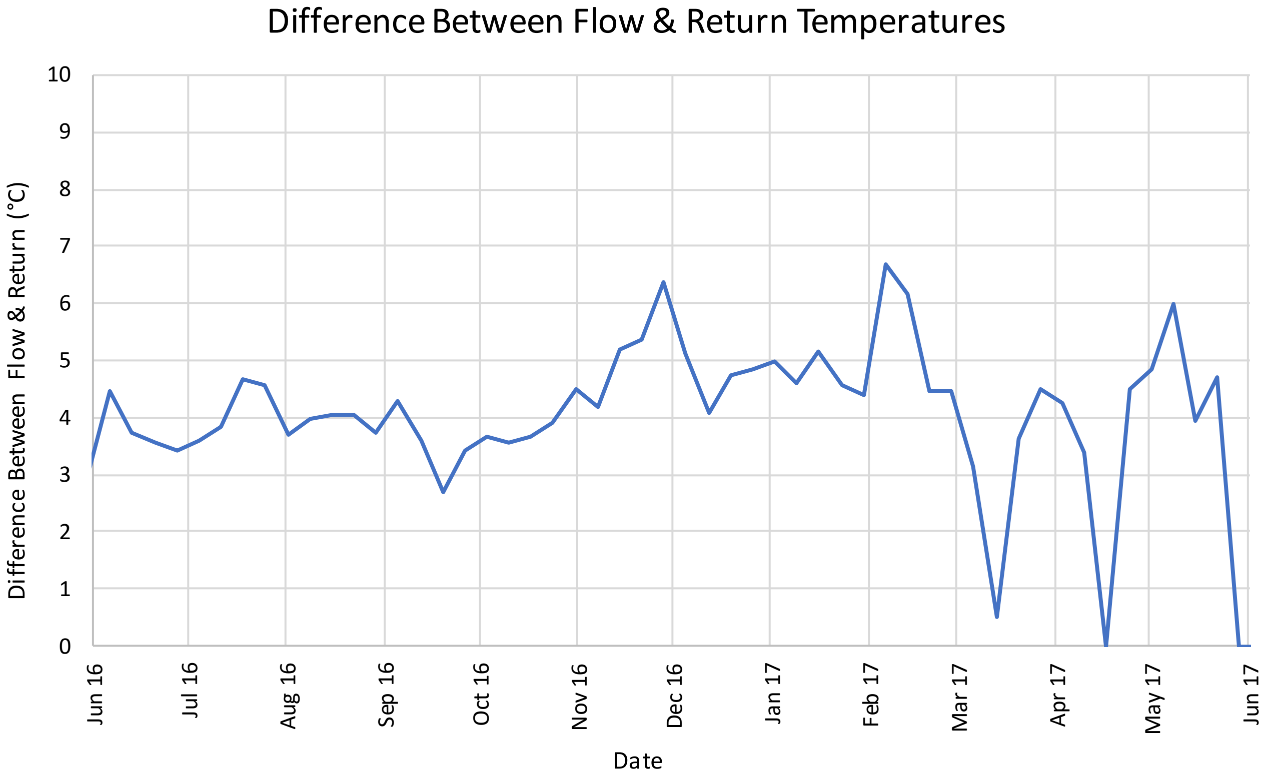

Figure 4: Graph showing the difference between flow and return temperatures

As the requirements of the system is a high temperature this limits the minimum flow temperature from the boiler. For safety reasons biomass boilers cannot allow water temperatures to exceed 100°C during operation. If they get close to this temperature they biomass boilers will shut down to stop producing heat to protect themselves. The temperature that a boiler will shut down at due to overheating depends on the boiler design, its size and type of fuel that it burns but it will usually be in the range of 85°C to 95°C degrees. As the minimum supply temperature delivered by the boiler at this site is high the boiler only has a small temperature difference between it safety shut off and the return temperature. Figure 4 shows the difference between the flow to and return from from the accumulator which is on average around 4 to 5 degrees less than the flow temperature. The difference between the flow and return is small because the boiler does not have much temperature range to operate in. The boiler was set to supply heat at 90°C to the accumulator which was the maximum that the boiler could supply before it shut down due to overheating. The temperature supplied to the site from the accumulator was set to a minimum of 83°C. To achieve this the boiler ran between 85°C and 90°C.

Increasing the bandwidth between the flow and return temperature by lowering the temperature supplied to the system would allow the boiler to operate for longer. Lowering the system supply would allow the boiler to run for longer and stay off for longer reducing the cycling rate. In the winter months the boiler has high load factors of around 46%. with long burn periods

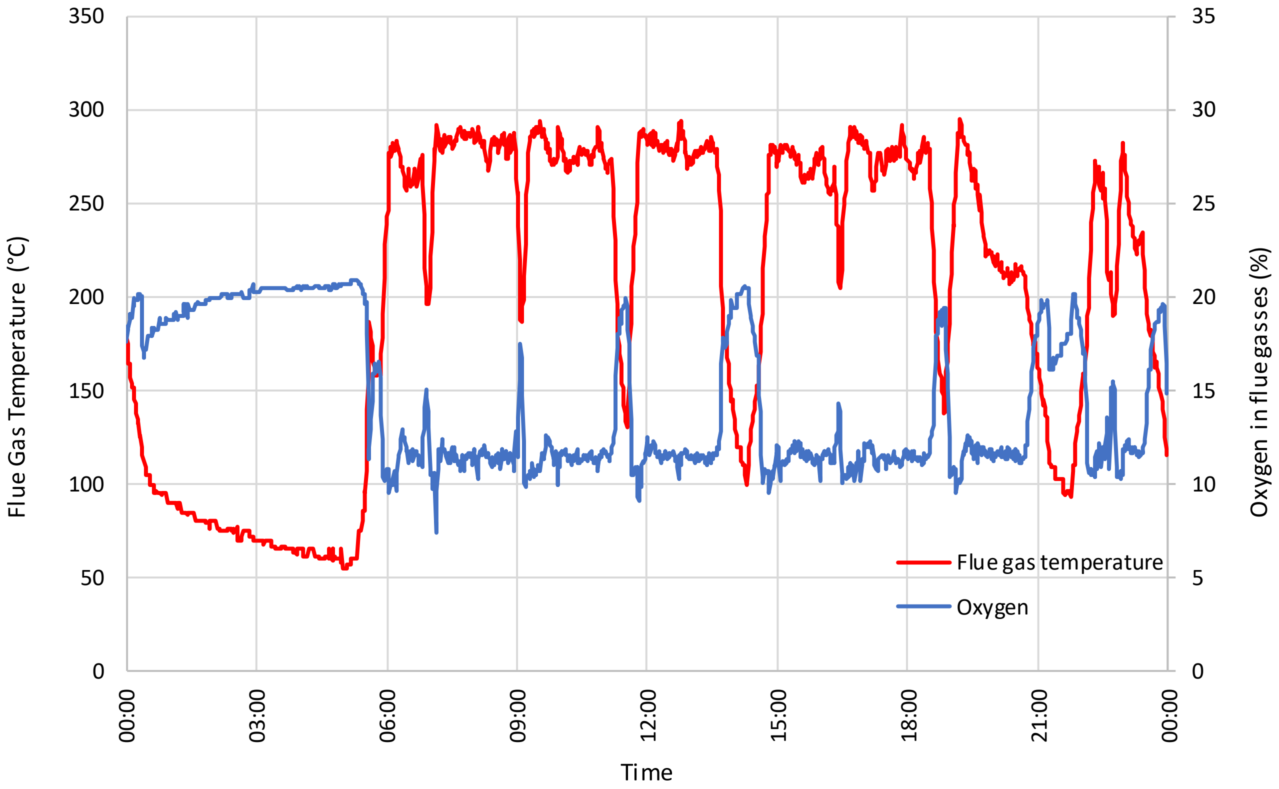

Figure 5: Graph showing the oxygen and flue gas temperatures on a typical winters day

Figure 5 shows the boiler on a typical winters day in February 2017 where the boiler was of during the night and ran for long periods during the day with short off periods. The load factor was 54% on this day and in total the boiler cycled 7 times during this period. Overall the operation of the boiler was good over this period however if possible the boiler should be made to fire continuously with fewer starts the operation would be improved.

The flue temperature is also high at this site most other boilers involved in the trial had flue gas temperatures of around 150°C. The flue gas temperature was consistently high when the unit was in operation, often above 250°C, as can be seen in Figure 7. This temperature was significantly higher than would be expected for this type of system. High temperatures in the flue increases the losses as energy to the atmosphere (this is energy which could have been transferred to the water in the boiler) and contributes to the comparatively low efficiency calculated. The exact causes of the high flue gas temperatures are not known. It could have been an issue with the boiler design or potentially a problem with heat transfer between the flue gases and the water in the boiler, due to fouling or deposits inside the boiler. If the problem was caused by fouling or deposits, a service could improve the operation.

8 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial fuel was analysed fuel from every site. The table below gives the results of the fuel analysis carried out on your fuel as well as the average values for all fuels of this type from other trial sites.

Table 31 Fuel quality at the site

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Your Fuel	Wood pellets	17.981	6.0	50.5	6.0	37.0	0.4	0.15
Average in field trial	Wood pellets	18.848	6.8	49.9	5.7	37.0	0.3	0.13
Minimum		16.482	4.4	-	-	-	-	-
Maximum		18.061	9.3	-	-	-	-	-

9 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31 June 2017 and the 31 May 2018. Interventions were proposed to improve the performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions proposed for this site followed the findings from the first year of monitoring highlighted in the previous sections of this case study.

9.1 High flow and return temperatures

An intervention was made to lower the system temperatures. A visit to the site was arranged to educate the team in charge of the heating system maintenance on biomass operation and to let them know how the boiler had operated during the first year of the trial. At first the site was reluctant to make any alterations to the heating operation as they did not fully understand how the system functioned. It was clear that the site had not set the supply temperature to match the heating system but that this was an artefact of the flow temperature from the previous oil fired system which was now used as a backup for the biomass boiler. The site was made aware of the increased pollutant emissions coming from the biomass during start-ups and were also alerted to the very high temperatures in the two underground pipe mains which would limit the lifetime of the underground pipes as they were not designed for 83°C heat. It was eventually agreed that a trial period where the system temperature was lowered by 5°C should be implemented to allow the effects on the system to be monitored.

This decision was made by the site but also required the third party to make changes to the boiler, whom the site paid for the heat supplied by the biomass. A visit was undertaken with the third party who owned and operated the boiler to asses if they could make the change. It was found that the third party had a very good understanding of how the boiler operated and how it was controlled. They had spent significant time optimising the boiler and ensuring that it worked the best it could with the limitation in system temperatures. It was interesting to find that the boiler operators had not previously asked the site to change the system temperature. They had spent resources trying to improve the boilers operation in the narrow temperature band where changes to the system would have allowed for the boiler to perform better. They agreed that they were happy to lower the boiler supply temperature when the site lowered the system temperature requirement.

To change the system temperatures the site was asked to adjust the system controls. It was discovered that the backup oil boilers were set to activate if the system temperatures fell below 80°C. The oil backups were set to activate when the temperature fell below 80 in the supply to a low loss header where connections to the three separate buildings were supplied. The oil boilers and low loss header were situated in a boiler room of one of the buildings which was around 80 meters from the ISO container housing the biomass boiler. The 80-meter pipe length connected the accumulator in the ISO container with another large accumulator in one of the buildings. The pipe lengths, accumulators and ancillary equipment between the low loss header and the oil boiler had losses of around 3°C. The minimum flow temperature setting of 83°C ensured that the water reaching the low loss header would be at 80°C and therefore the oil boilers would not activate.

It was clear that the problem with high flow temperatures was caused by the original system installation. The biomass boiler had been installed utilising the existing system which was designed for oil only. The controls had not been integrated with the new biomass system therefore the controls worked separately to provide heat. It was found that the existing controls which were outdated and could not be accessed by the site or the third party operating the biomass. This meant that the oil boilers could not be adjusted. Investment in a new control system to control the oil boilers was required which would allow the biomass boiler to operate at a lower temperature.

There was an interest from the biomass operator to supply the site with a new control system. However, the site was not interested in investing any money in the heating system control as they were satisfied with its current operation. It was clear that because they did not own or operate the biomass boiler they were not interested in its efficiency or performance.

A final suggestion was made to the site to try to implement the intervention. It was suggested that they could manually deactivate the oil boiler and reactivate it when the biomass boiler was not operating. The site was reluctant to do so as it would require the maintenance staff to monitor the biomass boiler to ensure that it was suppling heat.

9.2 High flue gas temperatures

There was a period during the field trial of high flue gas temperatures which would reduce boiler performance. The operator of the boilers was asked about the high flue gas temperatures and if there was anything that could be done to reduce the temperature and or improve the heat transfer to the water in the boiler to reduce the heat losses. The operator had a lot of expertise with biomass operation and explained the site had previously tried to reduce the losses in other boilers at the site but had not tried on this boiler as it was not known to be an issue. It was found that the high flue gas losses were not due to fouling or deposits on the boiler tubes which would affect the heat transfer as the boiler was well maintained. We did not expect the site to be able to make a change to the flue gas temperature as if a boiler is well maintained and with the correct oxygen in the flue gasses the flue temperature is usually very much dependent on the boiler design. The site operator was known to make adjustments to improve performance and made changes in early January during shut down for boiler maintenance

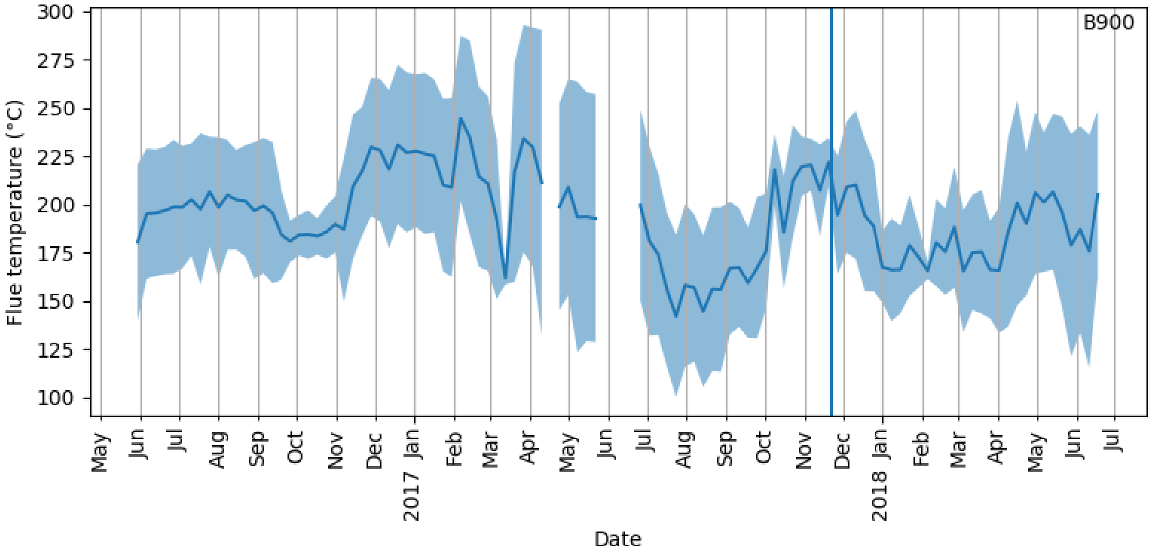

Figure 6: Graph showing the flue gas temperatures when the boiler is running. The blue band is the standard deviation.

Figure 6 shows the flue gas temperature at the site over the length of the field trial. The period of high flue gas temperatures which effected boiler performance is from November 2016 to April 2017 during which the flue gas temperatures are above 225°C. This period corresponds to the winter months where the load on the boiler is at its highest. Over the same comparable period in the winter of 2017 to 2018 the flue gas temperatures are around 50°C lower. The operator of the boiler recommissioned the boiler specifically to try to reduce the flue temperatures during this period.

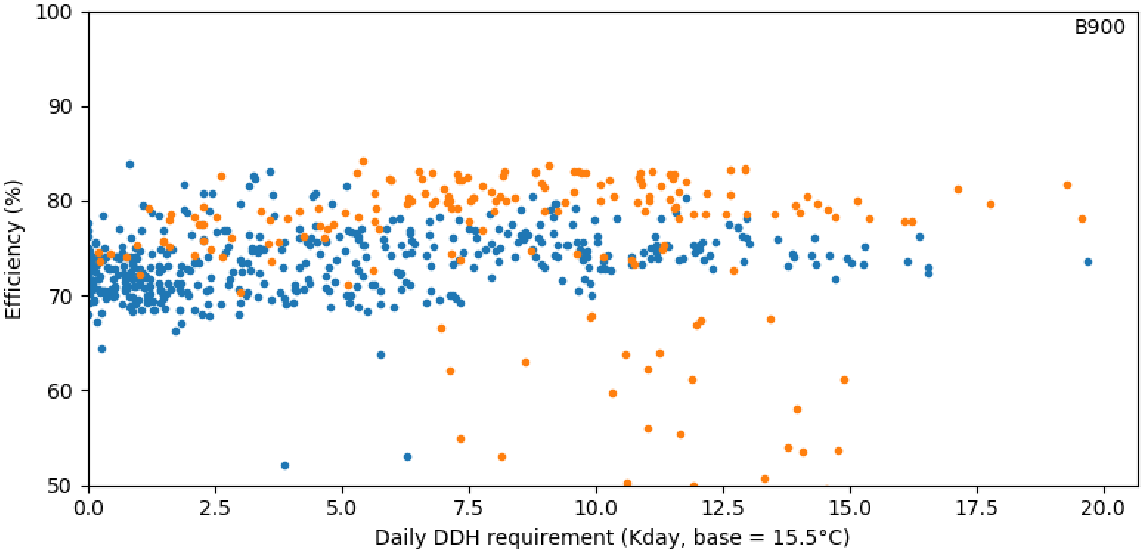

Figure 7: Graph showing efficiency against heating degree days. Orange points show the data after the intervention visit.

Figure 7 shows the effect of the reduced flue gas temperature on boiler efficiency. The orange points are higher on comparable heating days as the band has shifted up. The lower orange points show the efficiencies of two boiler malfunctions. The first at the end of December 2017 into early.

January 2018 occurred just before the boiler maintenance visit which improved performance on the 10 January. The second occurred in February which also effected boiler performance. Both can be seen below in the plot of average oxygen concentration as peaks in the flue oxygen. Despite these two periods of malfunctions the boilers improved efficiency can still be seen in Figure 7.

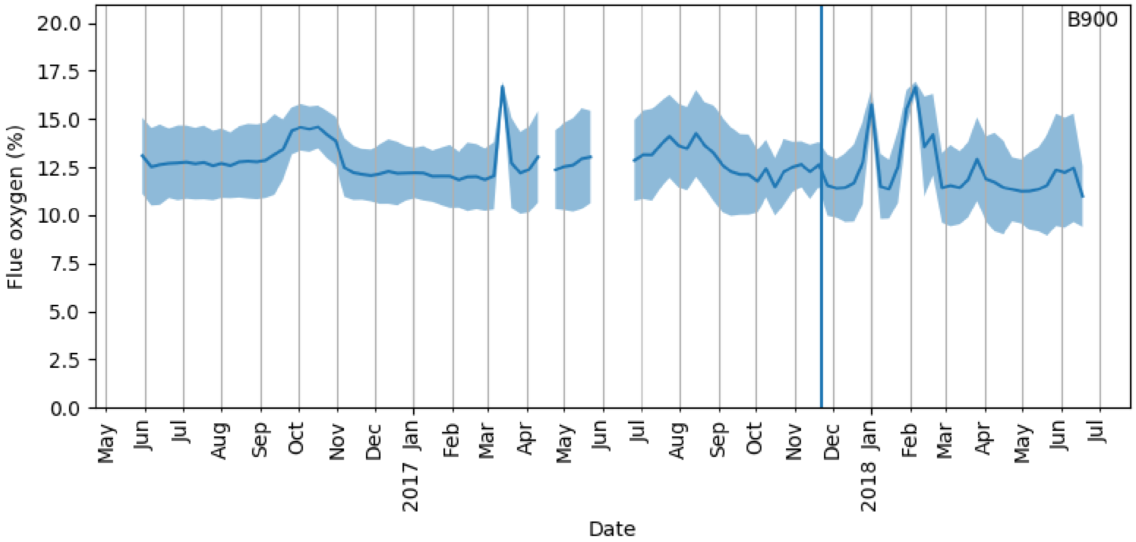

Figure 8: Graph showing flue gas oxygen when the boiler is on over the length of the field trial. The blue band is the standard deviation.

Figure 8 shows that the boilers oxygen is steady throughout the field trial at around 12%. The peaks on the line show boiler malfunctions where repair visits were required. The improvement made to the boiler did not affect the oxygen concentration which stayed relatively constant

10 Summary

Monitoring of the B900 boiler showed that the boiler performed well but had cycles which could be reduced due to its narrow temperature bandwidth. The efficiencies were comparatively low with other sites which was caused by high flue gas temperatures. The DDH plot showed good correlation between heat provided and monthly degree days suggesting the boiler was controlled well in response to outside temperature.

The case study looked at the temperature bandwidth of the boiler and attempted to investigate the effect of widening this would have on boiler performance. It was suggested to the site and the third-party boiler operator that simple changes to the system could be trialled in an attempt to improve performance. It was found that the high set points on the temperatures in the system were caused by the legacy settings of the previous heating system now utilised by the biomass as a backup. Changing the system proved to be impossible without investment from the site both in terms of time and money. The nature of the third-party arrangement to supply heat meant that the site did not see a problem boiler performance as they did not directly benefit from increased efficiency.

High flue gas temperatures were an issue at the site which was resolved through a recommissioning of the boiler. This had the effect of improving the boiler performance as there was reduced losses in the flue gasses form the boiler.

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Biomass boiler field trial
Case studies – B909

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1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B909 was monitored from 04 March 2016 to 31 May 2018. This case study contains information on performance and efficiency of the biomass system and recommendations on how to improve operation. Information on performance of all systems across the trial is also included.

2 Background

B909 is one of 67 biomass boilers across England, Wales and Scotland that were monitored by Kiwa via the logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip or log.

B909 was also part of further year of monitoring where 21 sites were monitored for a further year. Interventions were made at 15 of these sites to improve the site performance in terms of both efficiency and pollutant emissions.

The data collected from the site includes heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data that was kindly provided by trial participants was used (along with the compositional analysis carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall efficiency.

3 Description of the boiler and system

The monitoring was completed on a 25kW wood log biomass boiler located in a garage. The garage is attached to the rest of the property. During the trial, no faults were reported with either the boiler or the monitoring system, however, heat meter readings were only available after mid-April 2016 as a new meter had to be supplied and fitted.

The boiler was fired by virgin logs which had been split and were stored next to the boiler in an open crate. The boiler used a small amount of wood pellet for automatic ignition, supplied from an integrated hopper.

Table 32: About the site

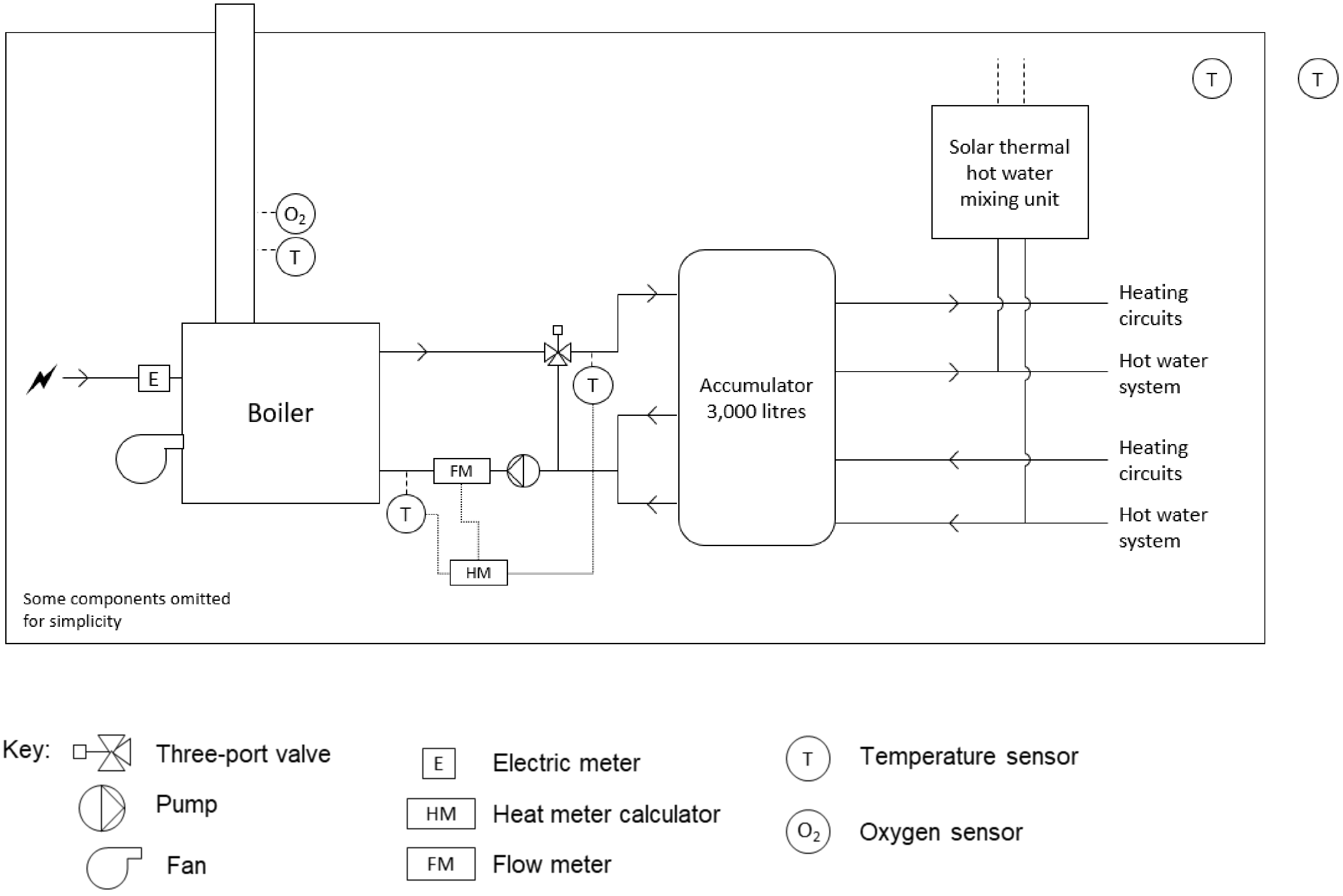
Building description	House
Fuel storage issues	None reported
Heat losses	Sections of pipework within the garage appear to be well insulated
Issues raised by operator at time of installation	None

Table 33: About the biomass boiler

Rated output	25 kW
Fuel type	Wood logs
Thermal store	Yes
Draught diverter	Approx. 1m from boiler exit, on vertical section
Dilution components	None reported
Fans	Integrated
Cyclones	None reported
Filters	None reported
Boiler faults	None reported

The boiler's primary use was to provide space heating and hot water to the domestic property. A well-insulated 2,500 litre accumulator vessel (also situated in the garage) was fed from both the biomass boiler and a solar thermal system (unmetered). Heat from the accumulator was distributed to the house via insulated pipes.

4 System schematic



5 The performance and efficiency of the boiler

During the field trial, no serious faults were reported on the boiler, there was good communication between the logging equipment and there were no prolonged periods of data loss. This section shows how the boiler performed between 04 March 2016 to 30 June 2017. In accordance with EN standards, the efficiencies have been calculated on a net basis using efficiency equations outlined in BS 845-1.

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 34: Main collected parameters

Data collection period was from	04 March 2016 to 30 June 2017
Heat output over this period	13,334 kWh
Estimated fuel use over this period	4 tonnes
Electricity consumption over this period	272 kWh
Hours of operation over this period	2,050 hours

5.2 Annual equivalent use

Table 35: Annual equivilent use and typical summer and winter usage

	Annual equivalent use	**Typical winter month (Feb 2017)**	**Typical summer month (Sep 2016)**
Heat output	11,583 kWh	1,548 kWh	444 kWh
Estimated fuel use	3.4 tonnes	0.4 tonnes	0.1 tonnes
Electricity consumption	224 kWh	26 kWh	13 kWh
Efficiency	77 %	77 %	80 %
Hours of operation	1,570 hours	201 hours	82 hours
Load factor	5 %	9 %	2 %
Average starts per day	0.8 starts	1.4 starts	0.4 starts

5.3 Overall boiler efficiency

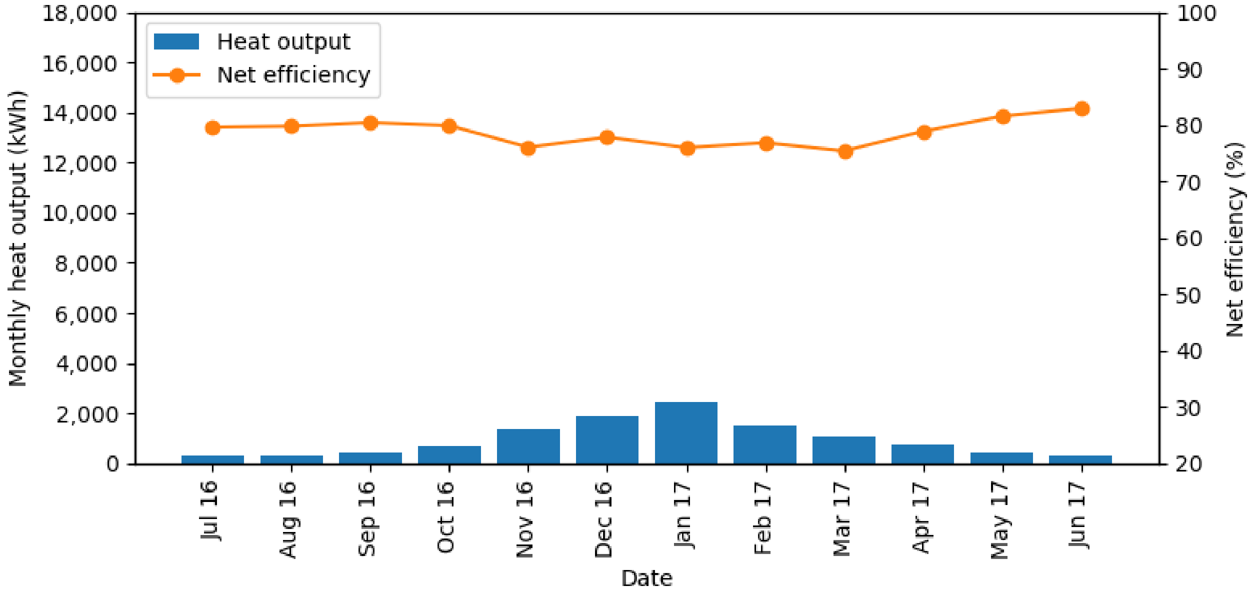


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The net efficiency was calculated by considering the boiler specifically and how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, will have their own heat losses which will decrease the net efficiency of the system as a whole so their impact on system efficiency can only be considered qualitatively.

At this site, the accumulator vessel was in the same unheated garage as the boiler, therefore any losses from the vessel will not contribute to heating of the property. However, the accumulator was well insulated with an approx. 10cm thick jacket which will minimise the heat losses. There were also many pipes and mixing valves, more than would be expected for an installation of this size. Again, these will contribute to heat losses in the system, however, the pipe runs were short, were all well insulated and all run above ground, which will minimise heat losses.

The measured annual equivalent net efficiency of the boiler averaged 77% (over the period for which we had data), however this changed depending on the time of year. Unusually, the boiler was more efficient in the summer, when the average outside temperature was higher and the demand was lower. The efficiency dropped from around 80% in summer to around 77% in winter when demand was highest (a fall of 3%).

5.4 Heat output vs. degree day heating requirement

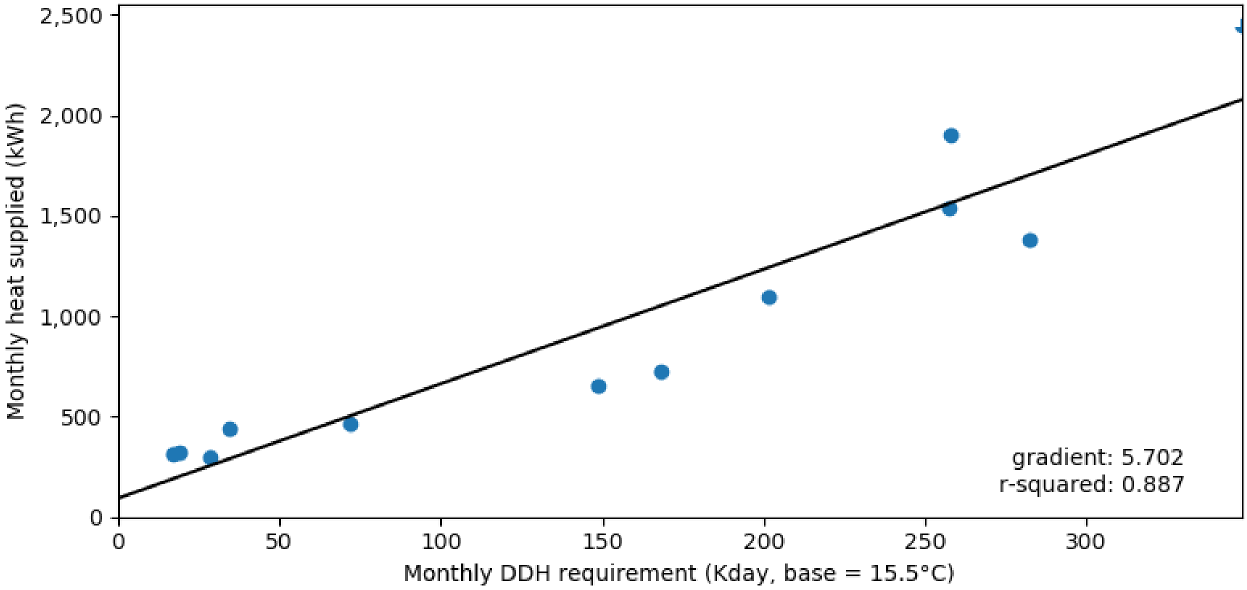


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

The r^2 value for this system is around 0.89. This is fairly high, which for a domestic property indicates a good level of system control. There is some scatter in the points at large monthly DDH (the colder months), which may indicate poorer temperature response at these times.

Sometimes an estimate of hot water consumption can be made from the graph, however in this case the picture is complicated by a solar thermal hot water system, which depending on the weather, could satisfy some of the demand instead of the biomass system. Therefore, it is not possible to estimate the hot water consumption of the site.

The seasonal variation in heat generated is explored in more detail in section 7

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

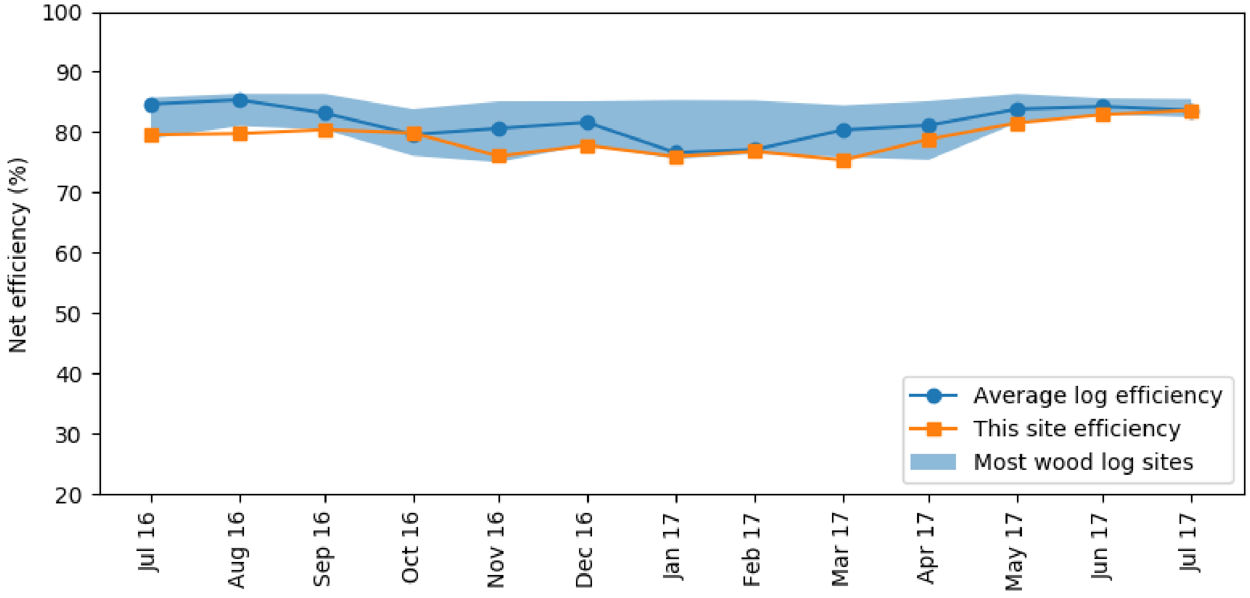


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B909.

The net efficiency of the boiler (in orange) is shown along with the average boiler efficiency (in blue). The light blue band on the graph shows the efficiency range of most of the boilers in the field trial (the middle 75%).

If the boiler falls above this band, it is performing particularly well compared with the other boilers of this type in the field trial. If the boiler falls below this band, it is performing particularly badly compared with the others.

This site appears to have an efficiency around the average for wood log-fuelled boilers (although there are only a small number of wood log boilers in the trial).

7 Seasonal heat use and cycling

The boiler was ignited automatically using a small supply of wood pellets. This allowed it to start at any time of day, as long as it was loaded with wood logs.

The data indicated that the boiler had two modes of operation. It operated with:

1. A flue gas temperature around 250°C and oxygen around 10%. This is the normal “high output” mode for the boiler and is seen at the start of each burn cycle.
2. A reduced flue gas temperature around 100°C and oxygen around 10%. This is a “reduced output” mode that is seen after the initial high output mode, in some but not all burns. It is more common in the summer than the winter.

7.1 Summer heat use and cycling

In a typical summer month, the biomass boiler generated 440kWh of heat. For a 25kW boiler, this is equivalent to around 0.6 hours of operation at full output per day which is a very short time. However, during the summer the boiler was used less frequently than once per day (one cycle every 3-3.5 days) and the average heat output was lower than the rated output. This meant that on average each burn period lasted around 8 hours and generated 44kWh of heat, which is equivalent to an average output of approx. 6kW.

The boiler operated in its more efficient, lower output mode for around 70% of the time in the summer.

7.2 Winter use and cycling

In a typical winter month, the biomass boiler generated 1,500kWh of heat. For a 25kW boiler, this is equivalent to around 2 hours of operation at full output per day which is a modest duration. Although the boiler was used around once per day during the winter, the average heat output was again lower than the rated output. This meant that on average each burn period lasted around 6.5 hours and generated 53kWh of heat, which is equivalent to an average output of approx. 8kW.

The boiler operated in its more efficient, lower output mode for around 45% of the time in the winter.

Unusually, the efficiency in the winter was around 6% lower than in the summer. This is believed to be for two reasons:

1. The boiler operated in its more efficient, lower output mode for around 70% of the time in the summer, compared with around 45% of the time in the winter.
2. Less importantly, the temperature in the boiler room was higher during the summer, so the flue losses were reduced slightly.

The load factor was low, however this is to be expected for a manually-fed wood log boiler, as the boiler will only operate if it is stocked with fuel. In the winter, when demand is highest, the operator may not be able to keep the boiler stocked at all times (e.g. if there is a burn in the evening, the boiler will not be re-stocked until morning). This was observed during the winter with a greater number of burns starting around 9:00am. These burns also started with a higher output, indicating the accumulator vessel was being re-heated more due to the boiler not running earlier in the morning.

8 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial we analysed fuel from every site. The table below gives the results of the fuel analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet). The fuel at B909 was close to the average specification of all the log fuel across the trial.

Table 36: Fuel analysis results at B909

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Site sample	Wood logs	15.166	16.5	41.6	5.1	36.4	0.3	0.10
Average in field trial	Wood logs	15.764	15.0	44.7	5.2	34.9	0.8	0.13
Minimum		11.062	9.8	-	-	-	-	-
Maximum		16.404	37.4	-	-	-	-	-

9 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31st of June 2017 and the 31st of May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring highlighted in the previous sections of this case study.

9.1 Winter boiler operation

Analysis of the data from the first year of the field trail identified two distinct modes of operation a high and low output mode. During the high output mode, the boiler ramped up quickly to produce heat with high flue gas temperatures. The low output mode as slower to produce heat as boiler started slowly and the flue gas temperatures were reduced. As the boiler was more efficient in the lower output mode the intervention that was proposed to the site was to ensure that the boiler ran in this mode more often than the lower output mode.

The intervention visit investigated the boilers operation further and identify the exact cause of the boiler entering a high fire or low fire mode. It confirmed the findings that the boiler entered its high fire mode if the accumulator temperature had fallen too low below its set point. If this occurs the boiler ramps up its heat output and tries to provide heat as soon as possible. This is the main mode of operation in the winter months where the accumulator temperature falls quickly and the boiler operates in high fire mode. This is due to the increased load on the boiler compared with the summer. In summer months the boiler fires every 3 days which provides ample time to refuel the boiler before the accumulator calls for heat again. When this occurs the accumulator, temperature is only slightly below the set point, so the boiler enters low fire mode. Conversely in the winter there is not enough time between loads to refuel the boiler. Therefore, the accumulator temperature falls much lower than the set point and the boiler works very hard once it is activated to quickly increase the accumulator temperature.

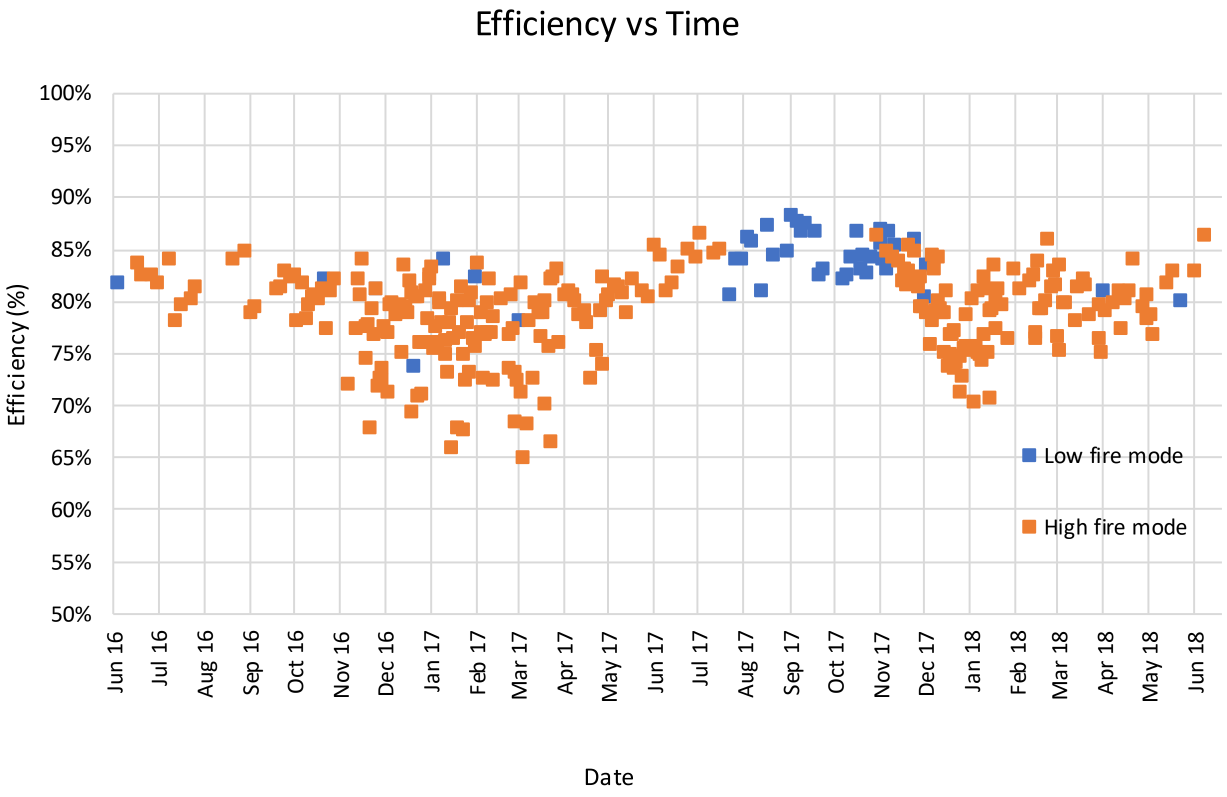


Figure 4: Graph showing efficiency over the entire monitoring period.

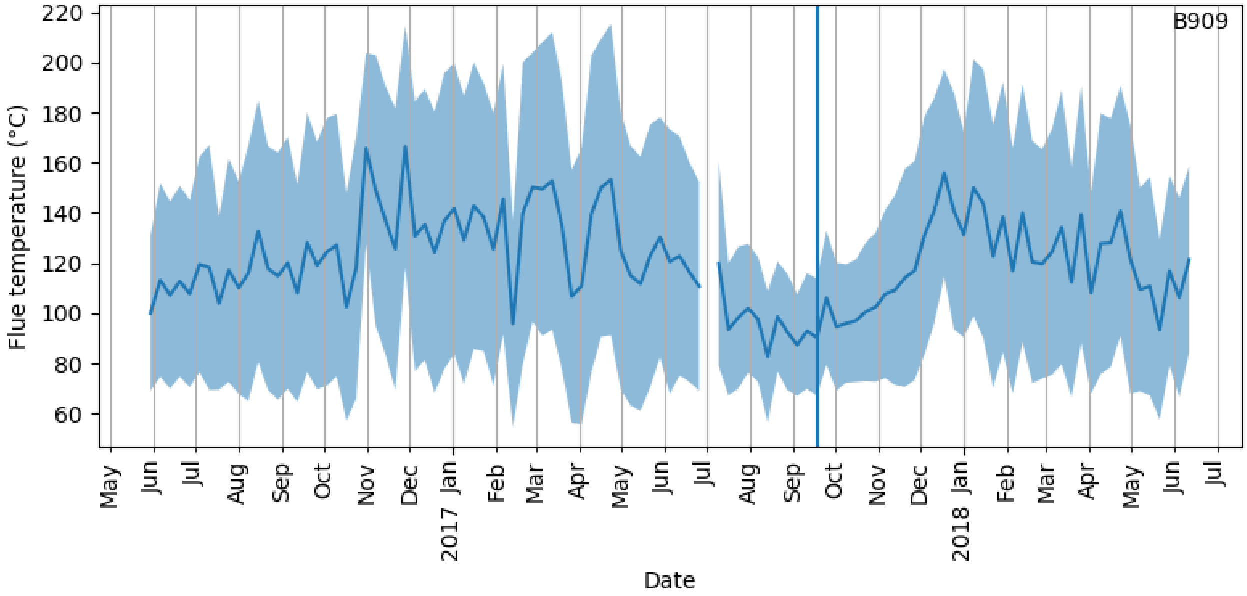


Figure 5: Graph showing average flue gas temperature with standard deviation over the entire monitoring period.

Figure 4 shows where the low fire modes occurred throughout the monitoring period. It was found to occur predominately in the summer months August 2017 to November 2017. Figure 5 shows the

flue gas temperature from the boiler over the monitoring period and the area that corresponds with low fire mode has lower flue gas temperatures. The efficiency across the whole field trial for the high fire burning mode was 79% with the low firing mode having an efficiency of 84%. This 5% difference would be the improvement if the boiler could be made to operate in the low fire mode. This low fire mode only contributed 11% of the total heat delivered to the accumulator over the field trial. The site was asked to change their behaviour around the way that they operate their boiler to ensure that the boiler was refuelled at regular intervals in the winter months to ensure that when the accumulator called for heat the boiler would turn on into low fire mode. The main change the site was asked to make was to refuel the boiler at night to ensure that it had fuel ready to burn when the heating system turned on and depleted the accumulator in the morning.

Both Figure 4 and Figure 5 show that the operator was unable to make the changes that would keep the boiler operating in the low firing mode. This was due to the need to constantly look after the boiler and plan to refuel at regular intervals. Once a burn was started the site would know roughly when the burn would finish as each time the boiler operated it ran for approximately the same period. The site was unable to refuel the boiler regularly as they were away from the property in the day which meant that the boiler often went unfuelled. The site owners also expressed that fuelling the boiler was unpleasant particularly at night in the winter and that ensuring this was completed was often not possible.

10 Summary

The boiler had an average annual equivalent efficiency (net) of 79.5%% which was about average for wood log fuelled biomass boilers. There was a good level of system control, however the picture was complicated by a solar thermal hot water system and the operator being unwilling to refuel the boiler during the night in winter.

Unusually, the efficiency in the summer was 5% higher than in the winter. This was in part due to a more efficient “low fire” mode that the boiler operated in during the summer of 2018. This mode was 5% more efficient due to reduced flue losses as the flue temperatures were reduced during this period. This period contributed just 11% of the total heat over the monitoring period.

The intervention at this site was not successful as the operator was unable/unwilling to make the changes required to improve the boiler performance.

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Biomass boiler field trial
Case studies – B912

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1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B912 was monitored from 17 March 2016 to 31 May 2018. This case study contains information on the performance and efficiency of the biomass system and recommendations on how to improve its operation. Information on performance of all systems across the trial is also included.

2 Background

B912 was one of 67 biomass boilers across England, Wales and Scotland which were monitored by Kiwa via logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip or log.

B912 was also part of further year of monitoring where 20 sites were selected for monitoring for a further year. Interventions were made at 15 of these sites to improve the boiler performance in terms of both efficiency and pollutant emissions.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data, which was kindly provided by trial participants, was used (along with the compositional analysis Kiwa carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall boiler efficiency.

3 Description of the boiler and system

The monitoring was completed on a 230kW wood pellet biomass boiler located in its own boiler house. During the field trial, the boiler suffered from breakdowns particularly in the first year of monitoring. This was caused by on-going mechanical failures of boiler components, such as the auger feed and the de-ashing mechanisms. The main down time occurred between August 2016 and November 2016. The boiler was used all year to provide heat for both heating and Domestic Hot Water.

The boiler was fired by pellet stored in a fuel bunker which was on the side of the boiler house. The boiler incorporated an underfeed stoker-type burner which fed fuel into the bottom of the combustion pot and forced the fuel bed upwards and the ash outwards to the removal screw. Primary combustion air was fed under the fuel bed via air ports.

Table 37: About the site

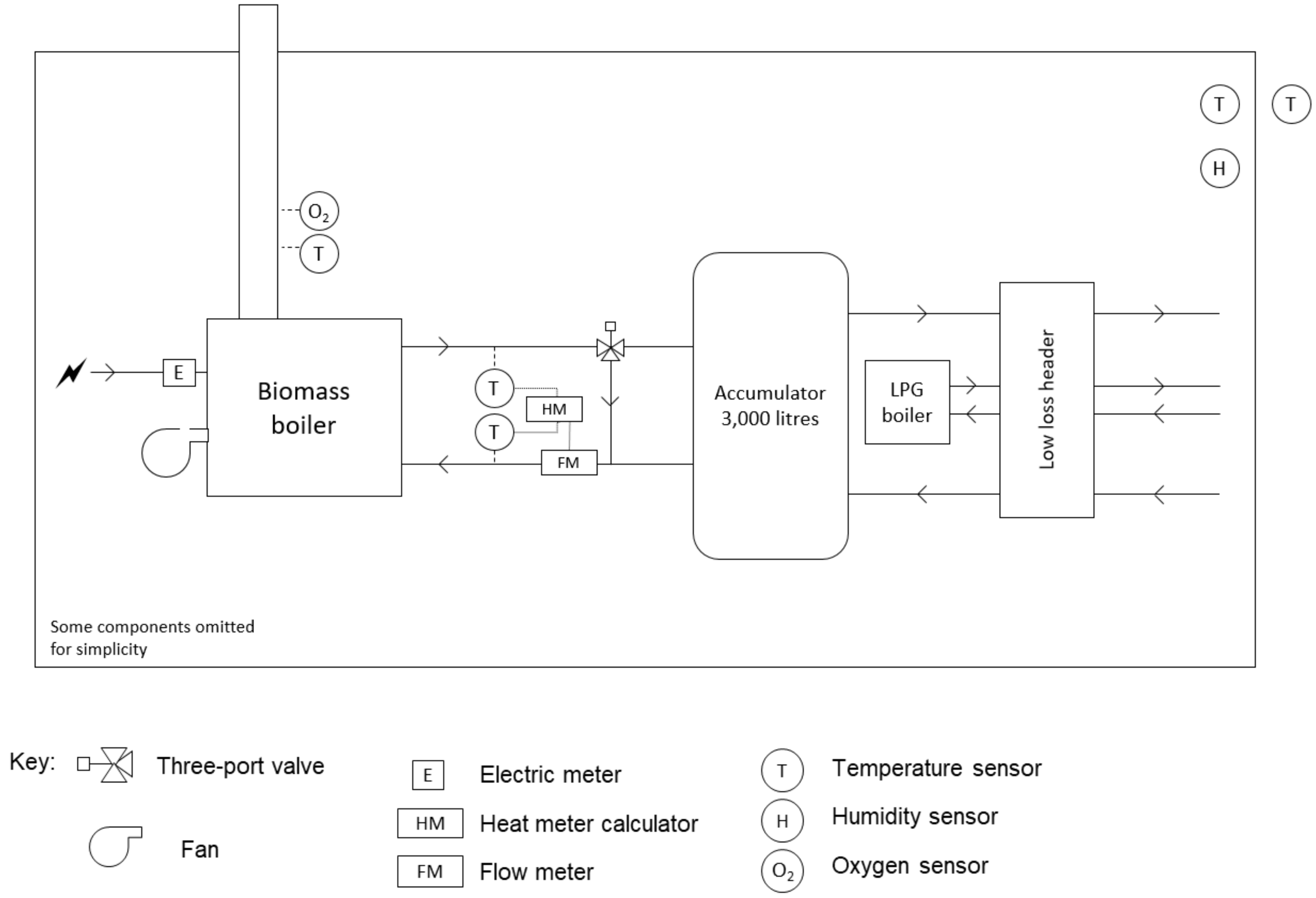
Building description	National Trust Property
Fuel storage issues	None reported
Heat losses	Sections of pipework within the boiler house appear to be well insulated
Issues raised by operator at time of installation	None reported

The primary use of the boiler was to provide space heating and hot water directly to a large property and surrounding buildings owned by a charitable organisation. A 3,000l accumulation vessel was fed directly by the biomass boiler and they formed the first part of the installation in the boiler house. The boiler house itself also contained two LPG boilers which provided backup heat generation. Solar energy was also incorporated in the system and fed a smaller accumulator vessel however, this was not operational during the length of the field trial. The biomass accumulator fed into a low loss header tank, which could also be heated by LPG boilers. The heat used for space heating and DHW was taken from the header tank.

Table 38: About the biomass boiler

Rated output	230 kW
Fuel type	Wood pellets
Thermal store	Yes
Draught diverter	None
Dilution components	Air recirculation
Fans	Induced draft fan in same unit as cyclone
Cyclones	Yes, separate unit
Filters	None reported
Boiler faults	Some mechanical failures throughout the trial

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

This section shows how the boiler performed between 17 March 2016 to 30 June 2017. In accordance with EN standards, the efficiencies have been calculated on a Net basis using efficiency equations outlined in BS 845-1.

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 39: Main parameters measured

Data collection period was from	17 March 2016 to 31 July 2017	
Heat output over this period	168,910	kWh
Estimated fuel use over this period	47	tonnes
Hours of operation over this period	2,050	hours

Figure 1 shows the efficiency for the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

When calculating the efficiency, the data collected was for the performance of the boiler specifically and how well it transferred energy to the water in the heating system, in this case to the accumulator. Other components of the heating system, such as water tanks and distribution pipework, have their own heat losses which decrease the efficiency of the system, and were not calculated.

5.2 Annual equivalent use

Table 40: Annual equivalent use and summer and winter usage

	Annual equivalent use		**Typical winter month (Feb 2017)**		**Typical summer month (Aug 2016)**	
Heat output	158,030	kWh	23,210	kWh	2,860	kWh
Estimated fuel use	44	tonnes	6.2	tonnes	0.8	tonnes
Efficiency	74	%	78	%	72	%
Hours of operation	1,902	hours	203	hours	38	hours
Load factor	7.8	%	13.6	%	1.7	%
Average starts per day	4.4	starts	2.6	starts	1.7	starts

5.3 Overall boiler efficiency

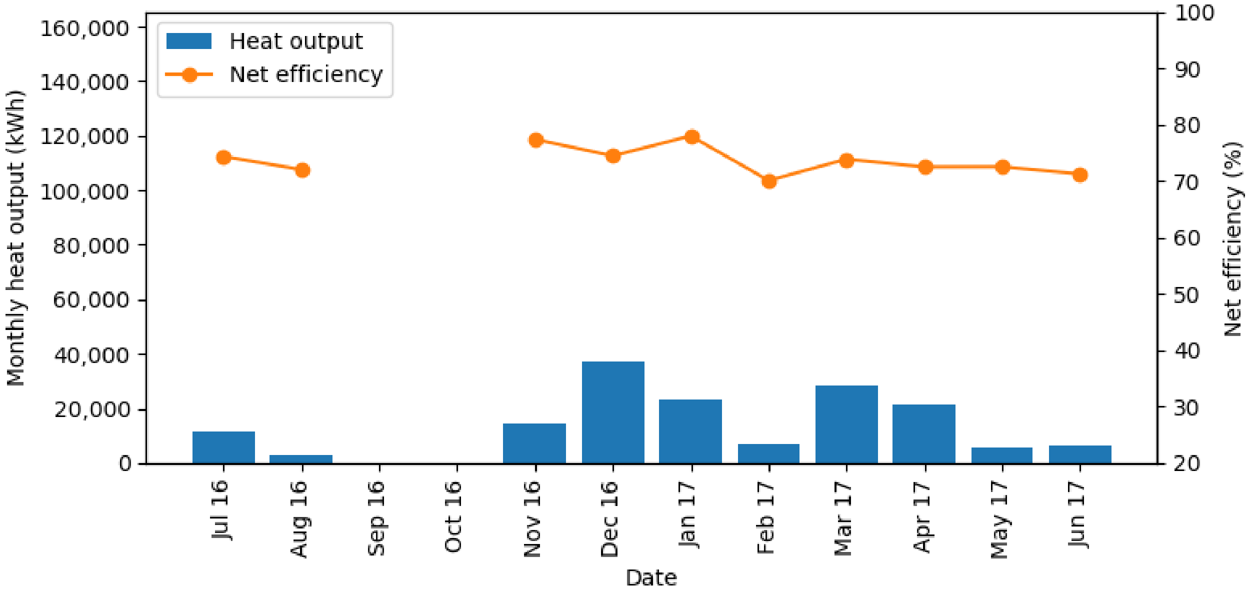


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

When calculating the net efficiency, only the boiler was looked at specifically and how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, will have their own heat losses which will decrease the net efficiency of the larger heating system. If large water tanks are present (such as accumulator tanks) in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency could be much lower. This is explored further in the published field trial report.

The measured annual equivalent net efficiency of the boiler averaged 74%. The graph shows that the efficiency of the boiler was higher in the colder winter months (the period in which the most heat was supplied) and lower in the summer months when the boiler was mainly used for domestic hot water. For example, it had an efficiency of 80% in January ‘17 and 72% in August ‘16. The exact cause of these lower efficiencies in summer have been investigated and are detailed in section 7.

5.4 Heat output vs. degree day heating requirement

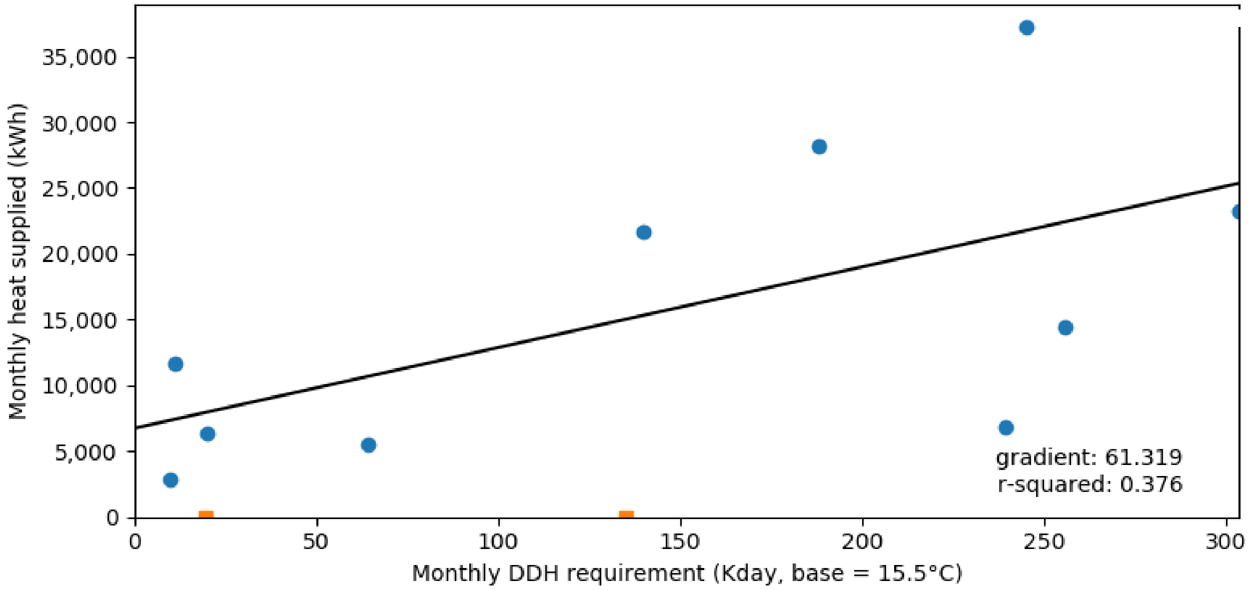


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

For B912 it could be expected that the r^2 value would be close to 1, as the boiler is used to supply space heating which is dependent on temperature. Outside of the heating season the boiler may only be for DHW.

There was missing data due to maintenance in January and February, however the available data shows that the heat supplied in kWh does not correlate well with degree days; a possible indication of an incorrectly configured system.

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

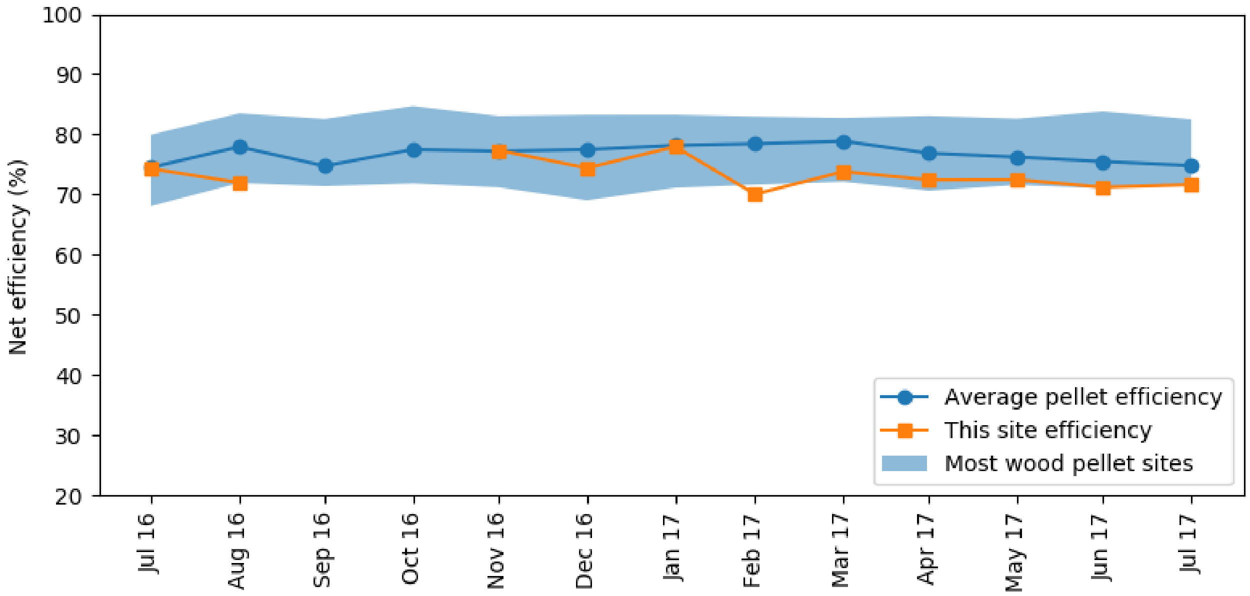


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B912.

The net efficiency of the boiler (in orange) is shown along with the average boiler efficiency (in blue). The light blue band on the graph shows the efficiency range of most of the boilers in the field trial (the middle 75%).

If the boiler falls above this band, it is performing particularly well compared with the other boilers of this type in the field trial. If the boiler falls below this band, it is performing particularly badly compared with the others.

The boiler at B912 lies towards the lower half of the range of efficiencies. The gap in the site efficiency data occurred during the summer months when the boiler was switched off and the load satisfied by either the solar system or the LPG boilers.

7 Summer heat use and cycling

In the summer the boiler was enabled to provide only DHW so the demand was much lower than during the winter months. Figure 4 shows the use of the boiler on a typical June day where the boiler came on just after 6 am and ran for around 30 minutes providing heat to the 3,000 litre accumulator vessel which was subsequently used to meet the DHW demand.

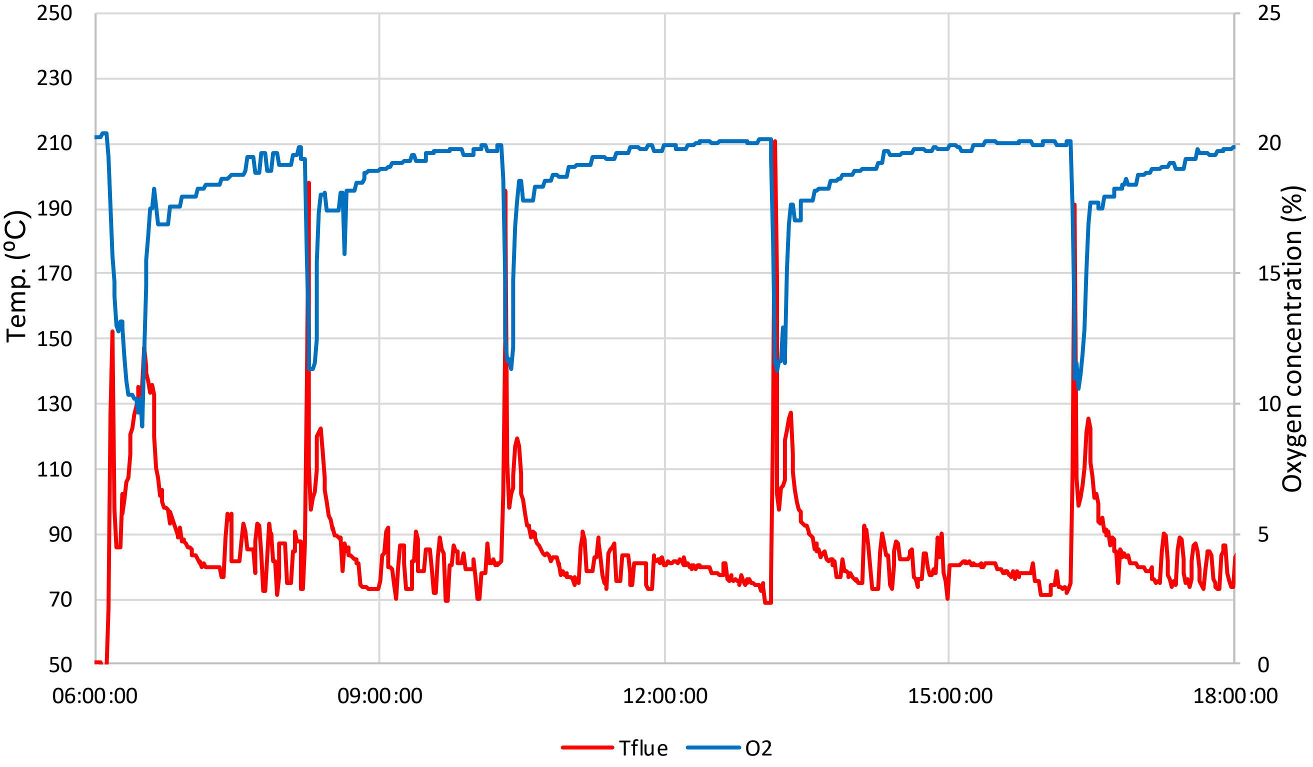


Figure 4: Oxygen and flue gas temperature for B912 on a typical June day

The load on the system was for DHW only and throughout the day the boiler provided heat to the accumulator a total of five times. In the summer, one can see that the efficiencies fell to around 74% and this was not caused by the number of cycles but rather the run time of the boiler during each cycle. The length of burn inside the boiler and therefore time it produced heat can be seen by looking at the oxygen level and temperature of the flue gases. In Figure 4 the length of a burn can be seen by the O_2 falling and rising and flue temperature rising and falling. Apart from the first burn of the day all subsequent burns lasted around 15 minutes. To run efficiently it is recommended that biomass boilers should maximise their run times and avoid very short cycle lengths. When the boiler operates in the regime shown above, the boiler will not reach the high temperature it needs to run efficiently. Furthermore, the long periods between cycles (typically two hours) would have caused energy to be lost due to fuel being wasted as the bed burned out, and heat transferred to the body of the boiler was also lost.

The boiler was controlled by a thermostat in the accumulator. To avoid the system operating as shown in Figure 4 the hysteresis (lag allowance) of the thermostat could be increased to stop the boiler turning on too frequently and increase the length of a burn periods. This would have to be managed such that the LPG boilers not called to run. Alternatively, the boiler could be switched off earlier in the year and other means of producing the heat required for DHW could be used such as the LPG boilers or point of use electric heating.

8 Winter heat use and cycling

By comparing Figure 4 and Figure 5 one can see that on a typical winter day the boiler ran for much longer than in the summer. The boiler was being used primarily for space heating and the load was much greater than in the summer. The boiler operated in a unimodal pattern all year round, where if the boiler was required to fire it would operate for roughly 12 hours. The boiler still showed cycling behaviour in the winter where it cycled more frequently than in summer but the run times were longer. Typically, the boiler cycled 8 times per day in winter. The laboratory testing of biomass boilers has shown that cycling in biomass boilers increases the hydrocarbon and particulate emissions and reduces efficiency This is described in the biomass field trial report.

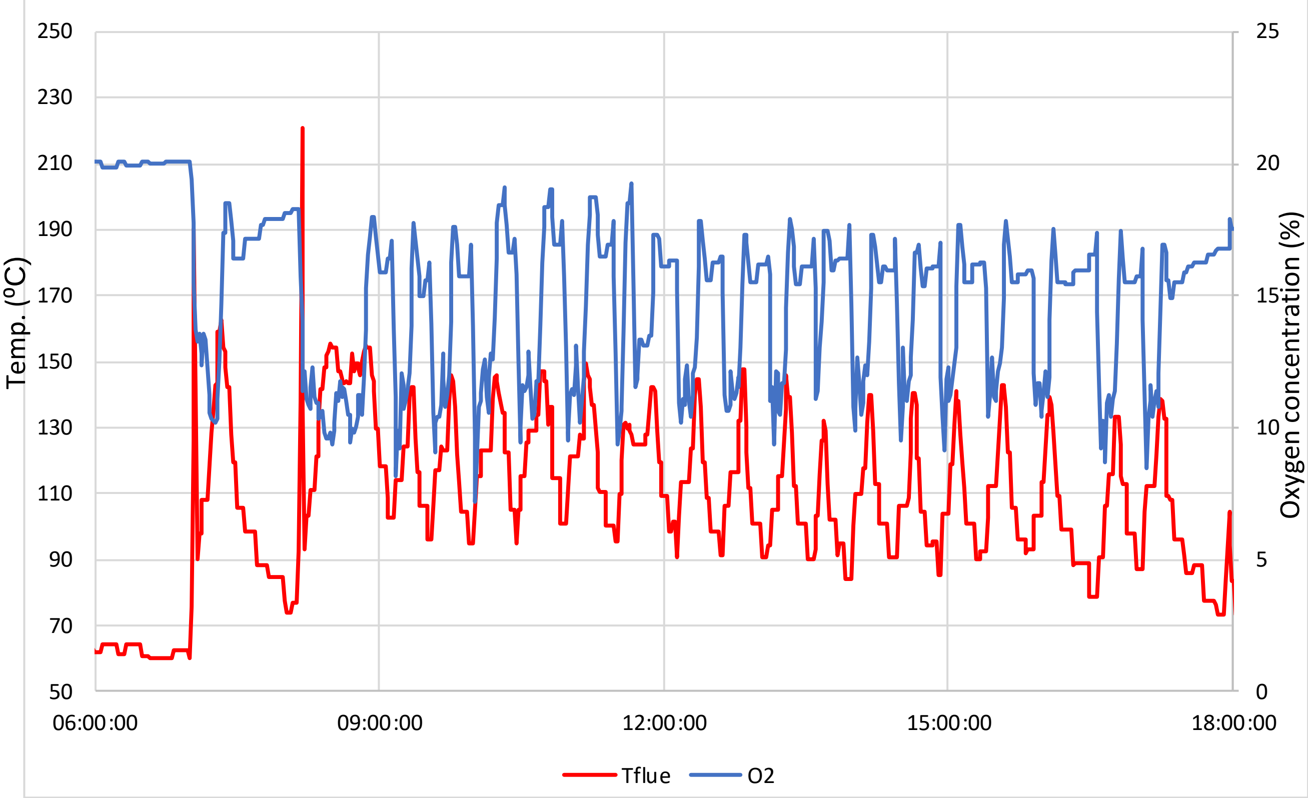


Figure 5: Oxygen and flue gas temperature for B912 on a typical December day

It is possible that the cycling shown in winter was caused by the same control settings which caused the boiler to cycle in the summer. The oxygen level does not return to 21% (ambient level) after the main burn period is finished and it is thought that the boiler was modulating its output, to attempt to run steadily at a partial heat output. This can be seen in Figure 5 as the step seen in the O_2 data after it rises from the minimum oxygen concentration. Further investigation would be needed to understand how the boiler was operating during this period. The instantaneous load factor on the boiler during winter was around 50%. With more precisely aligned control settings, the boiler might be able to modulate its output more effectively, and meet the load while also maximising the cycle lengths.

Laboratory testing has shown that most of pollutant emissions (hydrocarbons, NOx and particulate matter) are produced during boiler start-up and shut-down. Given the short burn time, it is likely that the steady burn period accounts for only 1/3 of each burn duration (i.e. 10mins) and that the start-up and shut-downs account for a significant proportion of the total daily run time. A boiler operating as in Figure 5 will to produce significantly greater pollutant emissions than one which is able to operate continuously or with fewer cycles. When a boiler turns on and off frequently it also places additional wear on internal components such as fans, electrical heaters and pumps. This may mean that internal components which have a design life, for example, of 10 years could potentially fail prematurely after only a few years. It is believed that the behaviour seen in Figure 5 is the cause of the maintenance issues, caused by mechanical failures in the boiler, since it was not designed to operate in this way.

9 Fuel quality

The quality of the fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. Fuel at this site was in enclosed storage and it was not possible to obtain sample. So, Table 5 presents the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 41

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Average in field trial	Wood pellets	17.469	6.8	49.9	5.7	37.0	0.3	0.13
Minimum		16.482	4.4	-	-	-	-	-
Maximum		18.061	9.3	-	-	-	-	-

10 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31 June 2017 and 31 May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring described in the previous sections of this case study.

10.1 Summer use and DHW load

One of the main findings from the first period of monitoring was the use of the boiler during the summer to provide DHW. It was suggested to the site that the boiler should be turned off in the summer as the very small load on the boiler caused it to operate with very short cycles. The summer load factor is just 2% with the average output per burn of 50 kWh. As the boiler is rated at 230 kW it would only need to run for 13 minutes at full output to meet an output of 50kWh. The average daily heat output in the summer was 200 kWh which was split into four cycles per day. This is the DHW requirement from the boiler and to meet this daily load the boiler would have to run for less than 1 hour at full output. The boiler could not cope well with the very small load and operated in the regime seen in Figure 4, as this was the only way that the boiler could meet the demand. Biomass boilers are designed to run for extended periods, in order to operate efficiently and with low emissions. This is due to the amount of time a boiler takes to start up and shut down, during which the boiler performs very poorly compared with when it runs steadily at its full output. For larger boilers the equivalent pollutant emissions for a start-up can be as much as 4 times higher than when running at steady conditions at full output. The load in the summer does not allow the boiler to enter a steady run mode and turns off immediately after starting up. Effectively the boiler only ever starts and then shuts down in the summer.

The site was advised that turning the biomass boiler off in the summer and using the backup LPG boilers instead, would reduce the amount of NOx and particulate matter emissions from the site. The emissions from using the biomass boiler to provide heat in the summer months would be more polluting than the equivalent heat from the LPG boilers due to the increased particulate, NOx, and hydrocarbon emissions emitted during start up and shut down. Laboratory trials and on-site testing have shown that the emissions from boilers during start-ups and shutdowns are much greater than those at steady operation. In many cases, the emissions from biomass boilers during start-up and shutdown will be over the emission limits for biomass. The use of LPG is much more suited to starting up and shutting down quickly typically a few seconds rather than the 20 minutes that it takes for biomass.

The site staff were unwilling to deactivate the biomass boiler during the summer. The site staff did agree that the emissions from the boiler would be greater than using LPG to meet the load in summer. However due to the investment in renewable technologies at the site, and the operating organisation’s effort to reduce CO2 emissions wherever possible, a commitment had been made to use renewables. This meant that the site operators were not prepared to use fossil fuels for their energy supply where there was an alternative renewable supply which could be used. This is an interesting finding about the summer use of biomass, and it is important to note that this site does not receive payments for the energy that it produces and the owner is not incentivised for summer use.

10.2 Winter heat use and cycling

The cycling at the site was found to be a problem during the first winter during which the boiler was monitored. Attempts were made during the second winter of monitoring to reduce the number of daily cycles. Figure 5 shows the boiler O_2 not returning to ambient level after each burn. After investigations at the site this was found to be a type of slumber mode where the boiler keeps the bed hot after it ends a burn, so that it can start very quickly if required, by forcing air through the fuel bed. This was an unusual control method, a partial shut down, which allows for faster start-ups reducing the amount of time the boiler takes to start producing heat. The boiler will spend a fixed amount of time in this slumber mode and if no more heat is required will enter a full shut down. This may have some benefit for boilers which cycle often, however ultimately it is less efficient than continuous operation as there are increased losses which occur during slumber mode.

The highest monthly load factor was 22% in December 2016. The peak daily load factor during the entire monitoring period was 47% in February 2018. This is lower than would be expected from a well sized system and suggests that the boiler is oversized for the load. The cycling of the boiler was believed to be caused by the boiler being oversized, combined with poor control settings which exacerbated the problem. This was confirmed during the intervention visit, during which the control set points of the boiler were investigated, and attempts were made to make changes to the set points. The boiler was activated when the water in the bottom of the accumulator fell below a certain temperature. An attempt to change the set points was made during the visit and the difference between the input and output temperatures was increased to maximise the heat delivered during each burn period, and to reduce cycling. The settings which were changed had no effect on the boiler after the visit and the cycling continued until early January, when the boiler was visited by the maintenance team who used their knowledge of the system to adjust the temperature set points of the boiler. This had an immediate effect on the boiler performance as it cut the number of daily cycles and increased the efficiency of the boiler.

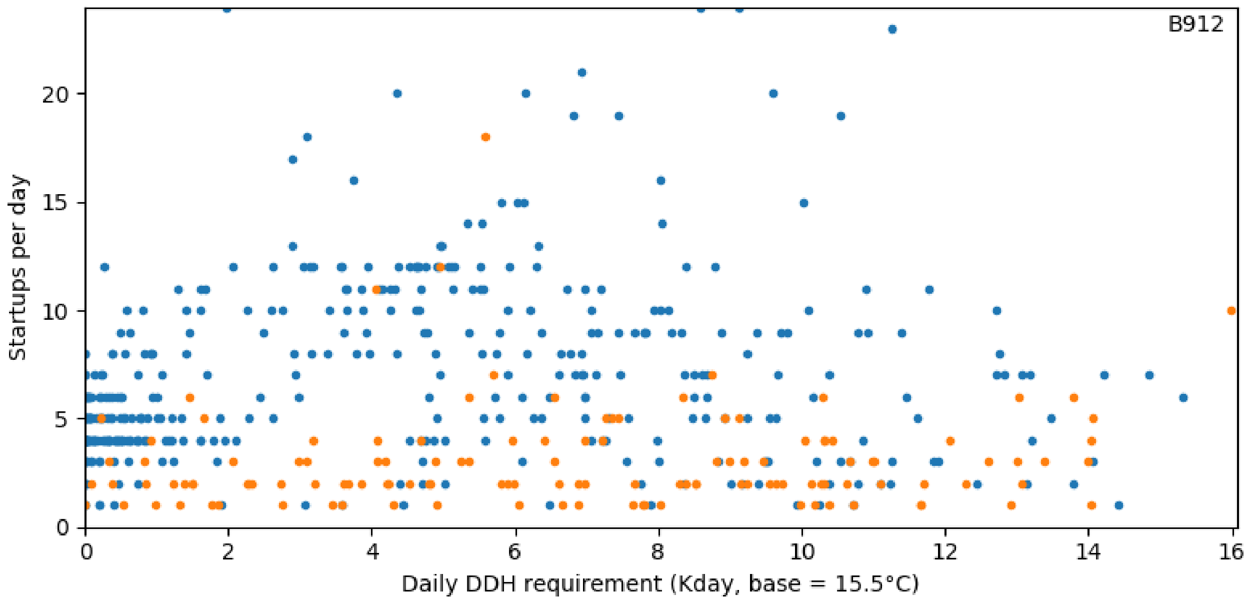


Figure 6: Start-ups per day against daily degree days (blue before intervention, orange after intervention)

Figure 6 shows the number of starts from the boiler before and after the changes were made in January 2018. After the change was made the boiler rarely started more than 5 times per day. Figure 6 also allows comparison of the reduced cycling for similar degree days where the load is comparable which shows that the change is not caused by changes in external temperature.

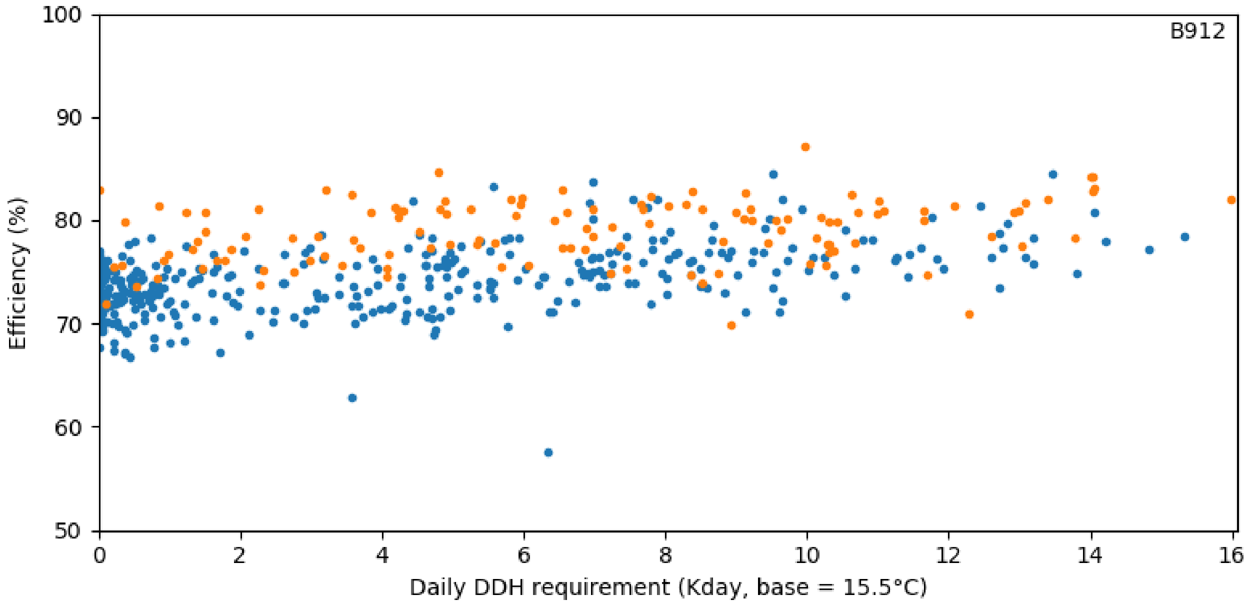


Figure 7: Daily efficiencies against daily degree days (blue before intervention, orange after intervention)

Figure 7 plots the efficiency of the boiler against daily degree days which shows that the boiler is more efficient after the changes were made. The boiler now supplies the same amount of heat but with a reduced number of cycles, increasing the amount of heat delivered per start. Efficiency is increased because the boiler now spends longer running at its most efficient and the time spent in start-ups and shutdowns is reduced.

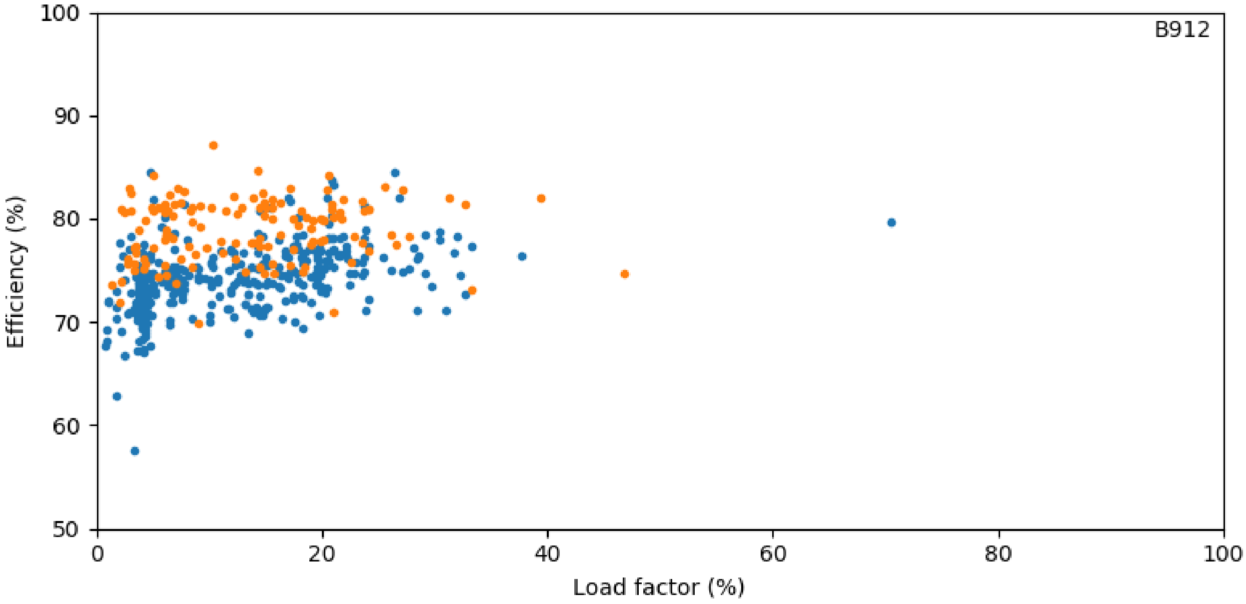


Figure 8: Start-ups per day against daily degree days (blue before intervention, orange after intervention)

Figure 8 shows the boiler's efficiency against load factor and shows that for comparable load factors the boilers efficiency is increased. The boiler had an increased efficiency of around 6% with the average before the change of 74% and 80% after the change.

11 Summary

This case study focusses on two issues which affected boiler operation at B912, and their impact on pollutant emissions and efficiency. Summer usage and boiler cycling are both considered problem issues because of the poor performance of boilers during start-up and shut down. Two separate interventions were attempted at this site in order to address these issues.

Firstly, summer cycling was investigated at the site, which showed that the site experiences lower boiler efficiencies in summer due to very short run times. It appeared to Kiwa that there ought to be a more efficient method of providing DHW heat in summer which would produce less pollutant emission. The site operators were advised to switch to LPG boilers for this heat load in the summer, however their own commitment to using renewable sources of energy meant that they were unwilling to turn off the biomass boiler.

The second issue identified was the cycling behaviour from the boiler. The very short cycles and short time between cycles caused the boiler to perform poorly with regards to pollutant emissions. The short cycles also affected the efficiency of the boiler as it increased the losses from the boiler due to inefficient combustion. Unlike the summer intervention, the intervention to reduce cycling was successful as the site was able to reduce the rate of cycling and increase the duration of each burn by changing the temperature set points in the boiler controls.

Department for
Business, Energy
& Industrial Strategy

Biomass boiler field trial
Case studies – B920

Trust
Quality
Progress

1 Introduction

As part of the Department for Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B920 was monitored from 13 April 2016 to 31 May 2018. This case study contains information on the performance and efficiency of the biomass system and recommendations on how to improve its operation. Information on performance of all systems across the trial is also included.

2 Background

B920 was one of 67 biomass boilers across England, Wales and Scotland which were monitored by Kiwa via logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip or log.

B920 was also part of further year of monitoring where 21 sites were selected for monitoring for a further year. Interventions were made at 15 of these sites to improve the boiler performance in terms of both efficiency and pollutant emissions.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data which was kindly provided by trial participants was used (along with the compositional analysis Kiwa carried out) to give a picture of energy input and combined with heat output and oxygen consumption to provide an indication of the overall boiler efficiency.

3 Description of the boiler and system

The monitoring was completed on a 140kW wood pellet biomass boiler located in a section of barn used for farm equipment. During the field trial there were a few periods where the boiler was down or turned off. However, most faults resulted in the boiler being inoperable for only a few hours. There was a prolonged period of down time during the field trial where the boiler was turned off. This was from 07 June 2016 to 19 October 2016. There was also no heat meter present at the very start of the monitoring period although a site representative installed one, sixteen days later. This meant there was no heat output from 05 April 2017 to 20 April 2017.

The boiler was owned and operated by a third party and the site paid for the heat supplied. This meant that the maintenance and fuelling of the boiler was not the responsibility of the people who were on site although they were responsible for emptying the ash from the boiler. The boiler incorporated an underfeed stoker type burner. Primary combustion air was fed under the fuel bed by rows of air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and the residual ash was thus pushed away as more fuel is fed and subsequently removed from the combustion chamber.

Table 42: About the site

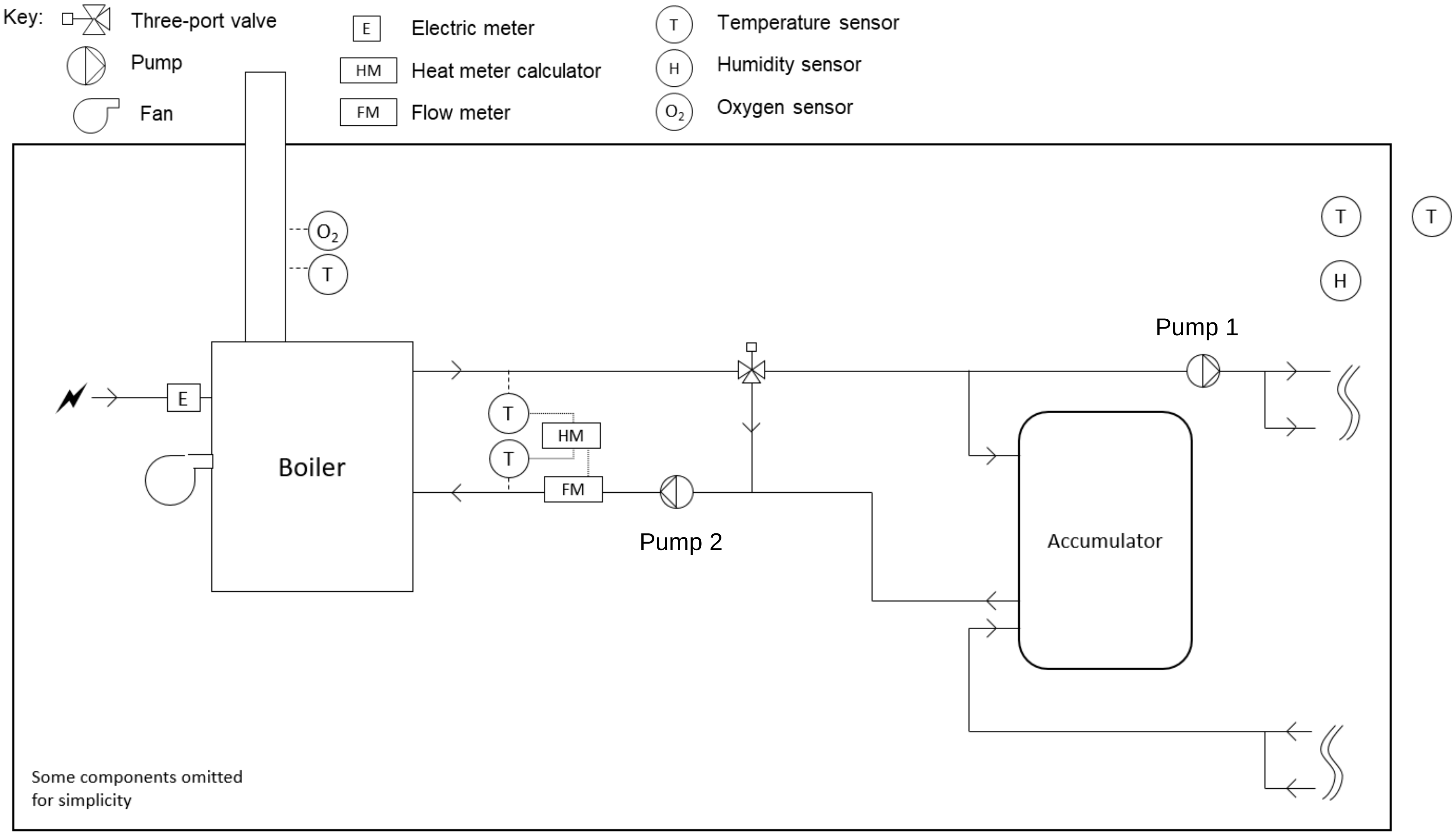
Building description	Large farm house with large oubuildings including stables.
Fuel storage issues	None reported
Heat losses	All pipework is insulated. Small length of underground pipework to the main house.

The primary use of the boiler was to provide space heating to a stables and space heating and domestic hot water to a large farm house. There was a section of underground pipe work between the barn and farm house from which there would be moderate amount of heat loss. There was an accumulation vessel present in the system which was estimated to be 5,000 litres in capacity.

Table 43: About the biomass boiler

Rated output	140 kW
Fuel type	Wood pellets
Thermal store	Yes
Draught diverter	1m into flue
Dilution components	None reported
Fans	Forced draft
Cyclones	None present
Filters	None present
Boiler faults	None reported

4 System schematic



5 The performance and efficiency of the boiler

This section shows how the boiler performed between 13 April 2016 to 30 Jun 2017. In accordance with EN standards, the efficiencies have been calculated on a Net basis using efficiency equations outlined in BS 845-1.

5.1 Performance of the boiler

The following table presents a summary of the main parameters measured during the trial for the boiler.

Table 44: Main parameter monitored

Data collection period was from	13 April 2016 to 30 Jun 2017
Heat output over this period	86,940 kWh
Estimated fuel use over this period	26,000 Kg
Electricity consumption over this period	1,126 kWh
Hours of operation over this period	2,581 hours

5.2 Annual equivalent use

Table 45: Annual equivalent use and summer and winter usage

	Annual equivalent use		**Typical winter month (February)**	
Heat output	69,360	kWh	11,420	kWh
Estimated fuel use	21	tonnes	4	tonnes
Electricity consumption	935	kWh	143	kWh
Efficiency	68	%	68	%
Hours of operation	2,143	hours	312	hours
Load factor	6.1	%	13.0	%
Average starts per day	5.7	starts	7.2	starts

5.3 Overall boiler efficiency

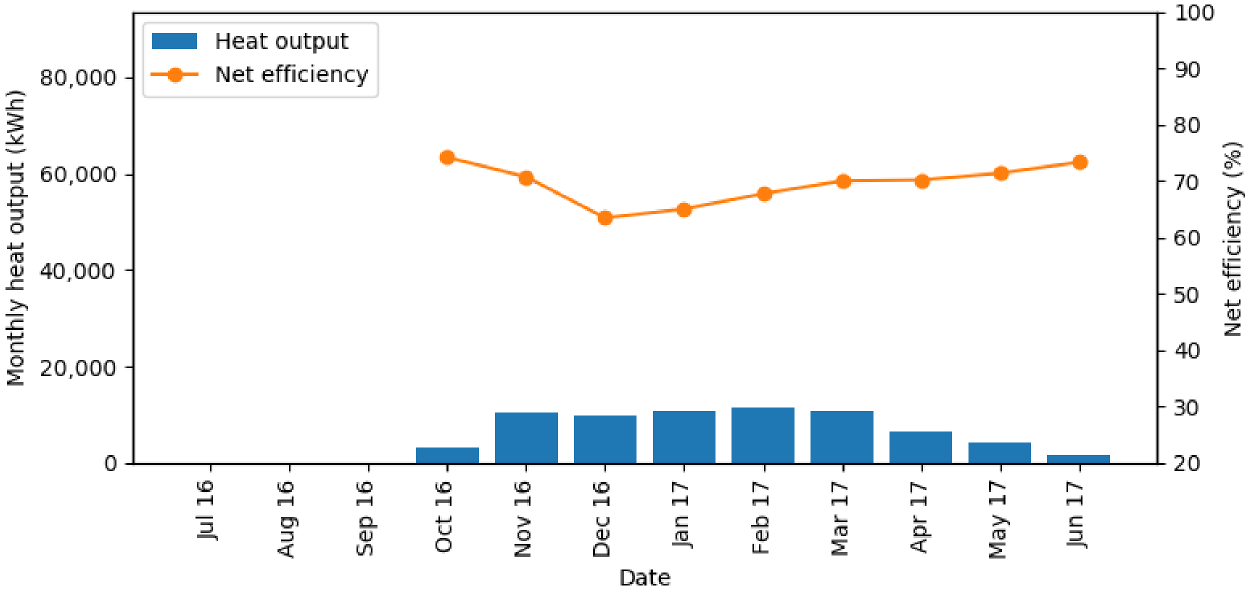


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the trial period. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The net efficiency was calculated for the boiler by specifically looking at how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, have their own heat losses which can decrease the net efficiency of the system as a whole. If the site had large water tanks (such as accumulator tanks) in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency may have been much lower. This is explored further in the published field trial report.

The average measured annual equivalent net efficiency of the boiler was 68.3% (over the period for which there were data). The efficiency varied throughout the year, from a low of 67.7% in December 2016 to a high of 77% in July 2017. The reasons for this are explored later in this case study. It is important to note that the efficiency is for the boiler only and uses the heat meter shown directly after the boiler in the schematic.

In the summer the boiler is used for domestic hot water (DHW) on the farm and although the boiler was off during the summer of 2016, the reduced load when the boiler operated in the summer of 2017 can be seen.

5.4 Heat output vs. degree day heating requirement

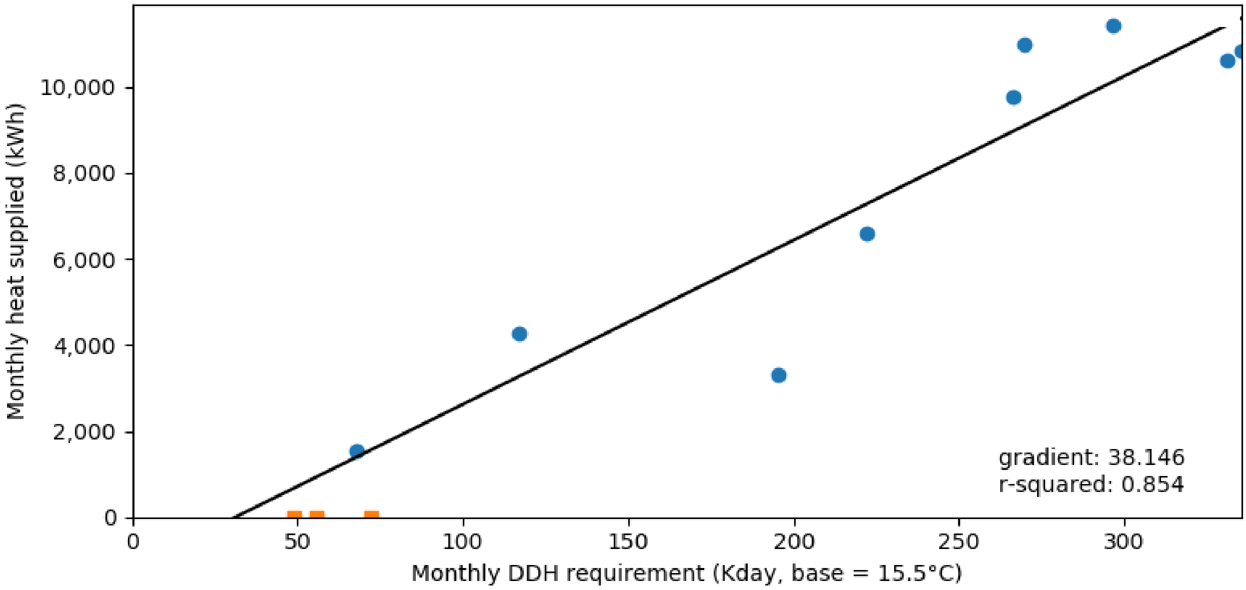


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

For B920 there was good correlation between degree day requirement and heat output of the boiler, reflected by the r^2 value being close to 1. On a DDH plot one would normally expect to be able to determine the DHW demand from the point where the line of best fit crosses the y-axis (this is the point where there is no space heating requirement and the boiler is being used only for DHW). There was insufficient data to make a good estimate of the DHW consumption at B920.

The peak monthly demand was during February 2017 and was approximately equal to 11,500kW. This was equivalent to the 140kW boiler operating at full output for only 3 hours each day. This is a very short daily operating time for a boiler during the month of maximum heat demand .

6 Comparison with other sites

Net efficiency of the boiler in relation to other boilers in the trial

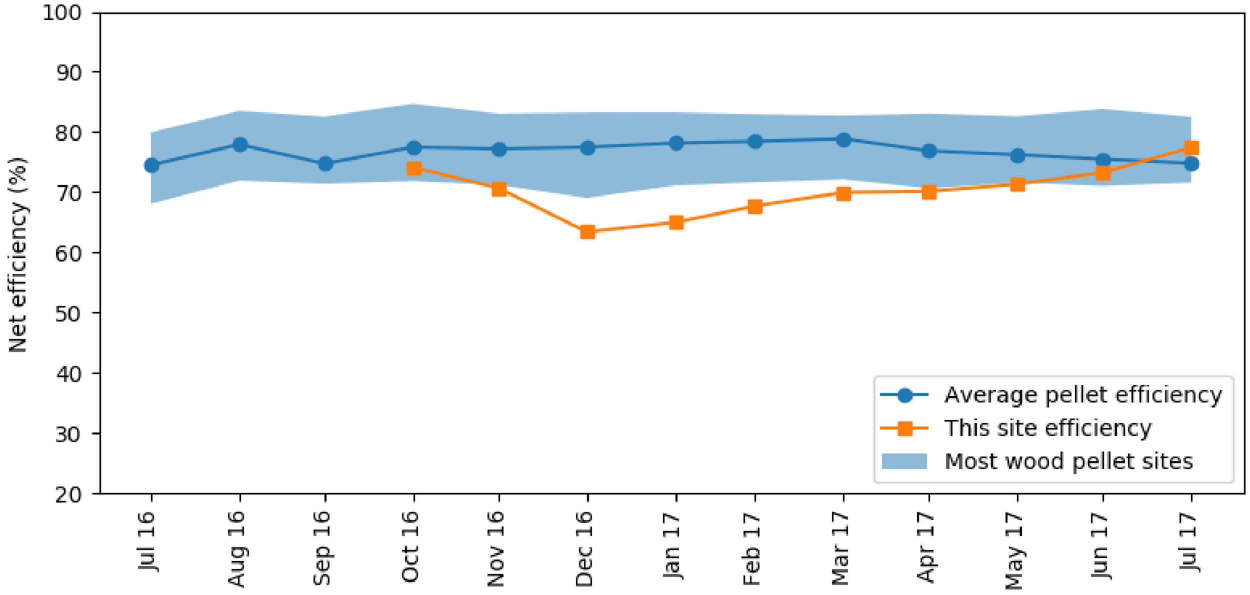


Figure 3: Graph showing net efficiency of boilers in the field trial

The above graph shows the net efficiency of all the boilers in the trial using the same fuel as the boiler at B920. The net efficiency of the boiler (in orange) is shown along with the average boiler efficiency (in blue). The light blue band on the graph shows the efficiency range of most of the boilers in the field trial (the middle 75%).

If the boiler falls above this band, it performed particularly well compared with the other boilers of this type in the field trial. If the boiler falls below this band, it performed particularly badly compared with the others.

B920 operated particularly poorly with regards to efficiency in the winter and recovered its performance in the summer. This is an unusual pattern as boilers tend to operate with lower efficiency in the summer when the load on the boilers is at its lowest. There was a large drop after October where the average efficiency fell by 15% over three months to its lowest point in December.

7 Fuel quality

The quality of fuel used in the boiler has been found to have a considerable impact on its efficiency and performance. As part of the field trial, fuel samples from other trial sites were analysed. The table below gives the results of the analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 46: Fuel quality at the site

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Site sample	Wood pellets	17.157	6.7	52.2	6.4	34.2	0.3	0.11
Average in field trial	Wood pellets	17.469	6.8	49.9	5.7	37.0	0.3	0.13
Minimum		16.482	4.4	-	-	-	-	-
Maximum		18.061	9.3	-	-	-	-	-

8 Summer heat use

During the first summer of the trial period, the boiler was switched off for almost 3 months. It is not clear why this happened but as the initial survey identified a back-up oil boiler present at the site, it is likely that this boiler was still being used to supply DHW.

Towards the end of the trial, the data illustrated that the boiler was operating throughout the summer. Additionally, the site owner confirmed that the heat exchanger from the biomass system had replaced the oil boiler in its entirety, suggesting that the biomass system was then used throughout the year. This is an unusual decision since it is usually regarded to be good practice that a biomass boiler is deactivated during the summer, and an alternative method is used to provide hot water. Nevertheless, this site owner made the decision to remove their oil back up boiler which had previously been used to provide hot water in the summer.

9 Boiler cycling

There were three main types of operation throughout the monitoring period as can be seen in Figure 4: very high cycling which is shown in red; medium cycling in orange; and low cycling in blue. The summer DHW load was when the daily heat output was at its lowest, and also when the boiler had its lowest number of cycles (shown in blue). It is not clear why the boiler entered very high cycling regimes however each time this occurred the boiler would be turned off for a period of a few days before it resumed in the medium cycling fashion. Most of the year the boiler operated with between 5 and 10 starts per day with the fewest cycles occurring in the summer.

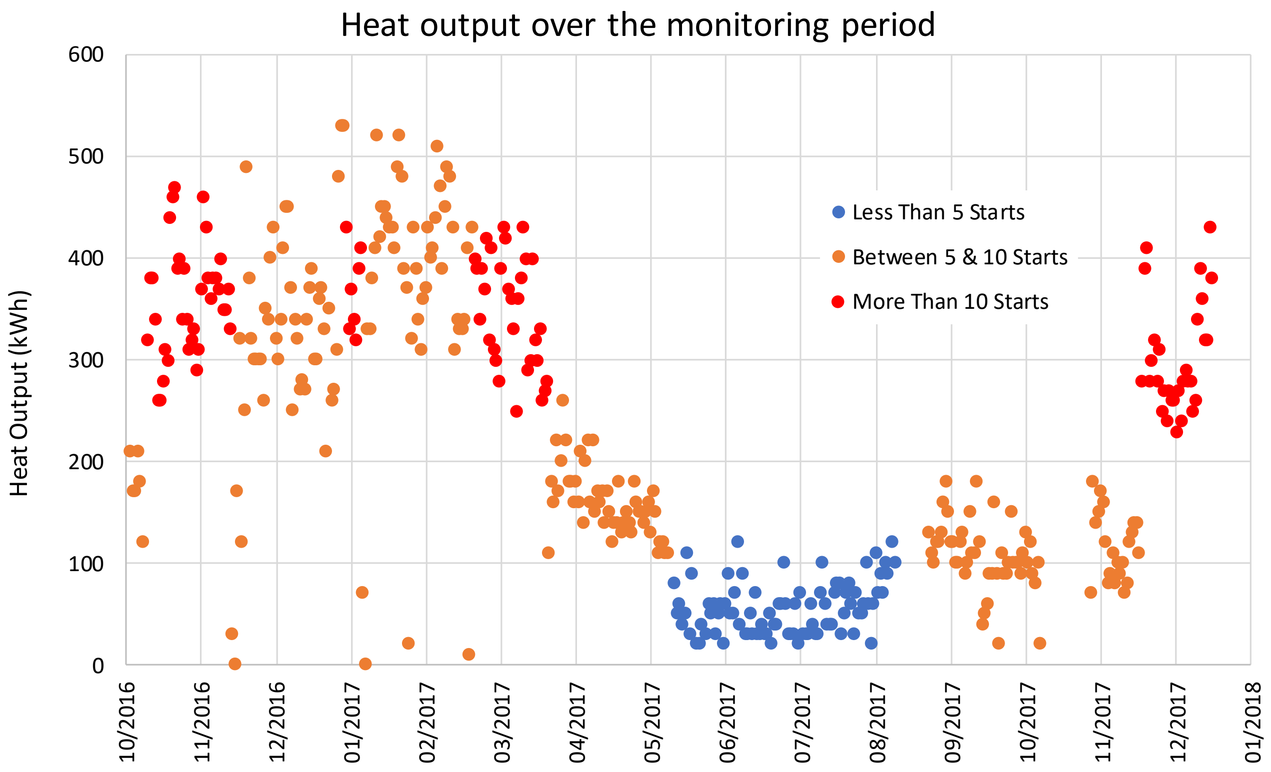


Figure 4: Boiler efficiency and starts during the monitoring period

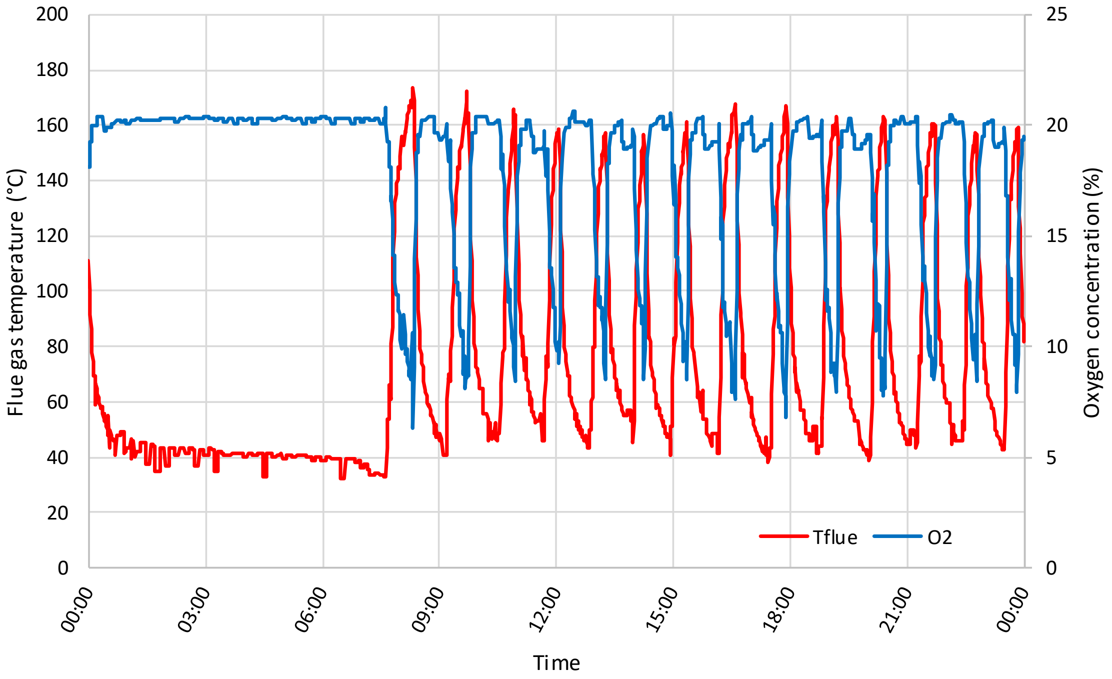


Figure 5: Boiler cycling during a typical day in March

Figure 5 above, shows the operation of the boiler on the 10th March during a period of very high cycling. The boiler displayed a unimodal pattern of operation, being turned on at around 7.30am and operating until midnight. During this period, there were 14 occasions when the boiler cycled on and off, with the burn duration equal to around ½ an hour.

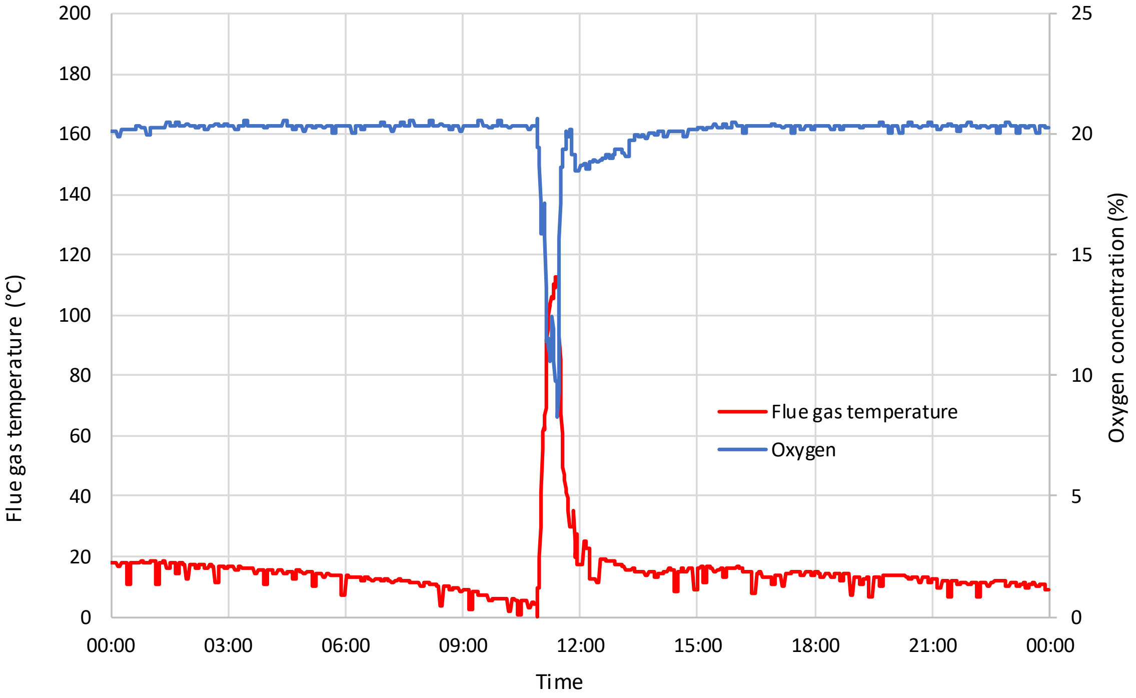


Figure 6: Boiler operation during a typical day in August

A cycle is defined as consisting of a start-up period, a period of steady burn and a cool down period. Laboratory testing has shown that the majority of pollutant emissions (hydrocarbons, NOx and particulate matter) are produced during boiler start-up and shut-down. Given the short burn times, the steady burn periods account for only around a third of them (i.e. 10 minutes). Consequently, the start-up and shut-down periods account for a significant proportion of total daily run time. A boiler operating as in Figure 5 will produce significantly more pollutants than one that is able to operate continuously or with fewer cycles. When a boiler turns on and off frequently it also places excessive wear on internal components such as fans, electrical heaters and pumps. This may mean that internal components which have a design life, for example, of 10 years could potentially fail prematurely after only a few years.

Figure 6 shows how the summer operation of the boiler contrasts with winter where the boiler only cycles once in 24 hours. During this period the boiler has very low load factors of around 2%. There is no requirement for space heating during this period and it is thought that one very short burn from the boiler was enough to satisfy the daily DHW. It is surprising that the boiler can operate in this way but is similar to operation observed in laboratory trials where a biomass boiler at very low loads had reduced cycling rates when it produced much more heat than was demanded from it due to being vastly oversized relative to its load. This overproduction of heat was then able to satisfy the load for long periods.

The high frequency of boiler cycling was mainly attributed to the boiler being oversized (i.e. being of a substantially larger capacity than required to meet the heat demands) and the relatively low heat loads. An appropriately sized boiler should have an annual load factor of around 20%. The annual load factor for this boiler was 6%. Over the monitoring period the highest daily load factor achieved was 17%.

Two ways of addressing the high cycling rates were identified; adjustment to the system configuration and adjustment to temperature set-points. These are described below.

9.1 System configuration

The system incorporates an appropriately sized accumulator. This is connected in a 3-pipe configuration (see system schematic, section 4); one inlet (return from heating system), one outlet (return to the boiler) and one inlet / outlet (either flow from the boiler into the accumulator or flow from the accumulator to the heating system). Compared to a conventional 4-pipe arrangement, this has the advantage that the flow from the boiler to the heating system can bypass the accumulator providing shorter response times. However, the effective operation of 3-pipe configurations depends on the hydraulic balance of the system. So, they can be more difficult to control than 4-pipe configurations. The positioning of the pumps in this system (see system schematic, section 4) allows three operating modes:

- **Charging the accumulator:** When there is no heat demand the biomass boiler can charge the accumulator using only pump 2.
- **Depleting the accumulator:** When there is a demand for heat and the accumulator is charged the system activates pump 1 while pump 2 is off. This ensures that the heat stored in the accumulator is used to satisfies the load.
- **Using the boiler to satisfy the load:** When the accumulator is not charged, pump 2 is activated and the boiler turns on to provide heat. When the load is satisfied pump 1 turns off and the boiler recharges the accumulator.

Problems can occur with this system if the control of the pumps or the balancing of the hydraulics is incorrect. For example, running pump 1 continuously would not allow the accumulator to be used as a store of heat. This may mean that the boiler responds directly to changes in demand resulting in frequent on and off cycles. If the system controls cannot be adjusted to prevent this behaviour, then changing the accumulator to a 4-pipe configuration should be considered.

9.2 Temperature set points

System controls determine when heat is supplied from the boiler to the accumulator. At some temperature heat is demanded by the accumulator at some higher temperature it stops calling for heat. If the difference between these temperatures is small the boiler will be frequently fired to top up the accumulator with a relatively small amount of heat. Widening this temperature band will allow more heat to be supplied from the accumulator before the boiler needs to fire again. This will also mean that the boiler needs to fire for a longer period to recharge the accumulator with heat. In this case, the operator should examine the control system and ensure there is sufficient difference between the hot and cold buffer temperature set points.

10 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31st June 2017 and the 31st May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring described in the previous sections of this case study.

10.1 Summer heat use

One of the main findings from the first period of monitoring was the use of the boiler during the summer to provide Domestic Hot Water. Only a small amount of heat is required during this time and it would usually be suggested that the boiler is switched off during this time and heat provided by other means. Due to recent investment into changes to the system to provide DHW heat by the biomass boiler in the summer it was not possible to persuade the site to agree to turn the boiler off.

10.2 Boiler cycling

The biggest problem this site faced was reducing the number of daily cycles caused by the boiler being oversized for the load. Two suggestions were made to the site in how to reduce the cycling.

Change the boiler system set up:

> During the site intervention visit it was clear the accumulator temperatures were very low which suggested that the accumulator was not being used to store heat. It was advised that the system was not set up correctly so that pump 1, which supplied the heat to the house, was running continuously preventing the boiler from running optimally. It was suggested that either the control of the pump be improved or that the accumulator be connected in a 4-pipe configuration and the controls adjusted accordingly.

Adjust the controls to limit cycling:

> As the boiler is oversized the control could be investigated to ensure that each time the boiler fired the burn period is optimised. Control settings which maximise the temperature difference between set points could be investigated to allow the boiler to run for longer. It was suggested that the operator could examine the control system and ensure there was sufficient difference between the hot and cold buffer temperature set points.
>
> The site was operated by a third party and it proved difficult to persuade them to adjust the controls at the site. They were reluctant to make changes as they believed that the site had been optimised and set up correctly. Monitoring data and schematics were passed to the site

owner who arranged for a site visit by a maintenance company on the 10th of December 2017. The boiler controls were adjusted, and changes made to the control of a pump which delivered heat to the farm house (pump 1). During the visit, the finding from the first intervention visit was confirmed, i.e. that this pump was running continuously.

Although the changes were made to the boiler pump and boiler controls there was no improvement in boiler performance.

11 Summary

Monitoring of the B920 boiler showed that the boiler was oversized for the system and it did not perform well. The average net efficiency of 70.3% is lower than most pellet sites with the winter efficiencies in the lowest 12.5% of sites in the field trial. The low efficiencies were attributed to frequent cycling of the boiler.

Options for reducing cycling frequency were suggested:

- Adjust temperature settings to ensure that the accumulator is used more effectively
- Adjust the configuration or recommission the pumps

The owner arranged for the boiler to be recommissioned, and adjustments were made to the boiler controls. This did not reduce the frequency of boiler cycling. It is believed that the problems caused by the oversizing of the boiler could not be overcome by adjusting the settings and recommissioning the boiler.

Issues with the boiler performance and a costly breakdown in January 2018 led to a decision not to repair the boiler and to decommission it. The boiler and it was sold in March 2018. This was the only site that made the decision to remove their biomass boiler during the field trial.

Department for
Business, Energy
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Biomass boiler field trial
Case studies – B921

Trust
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1 Introduction

As part of the Department of Business, Energy and Industrial Strategy's (BEIS) Biomass Boiler Field Trial, a number of detailed case studies have been generated. The trial resulted in more than a year's worth of monitoring data from 67 boilers across England, Wales and Scotland. The site B921 was monitored from 12 April 2016 to 31 May 2018. This case study contains information on the performance and efficiency of the biomass system and recommendations on how to improve its operation. Information on performance of all systems across the trial is also included.

2 Background

B921 was one of 67 biomass boilers across England, Wales and Scotland which were monitored by Kiwa via logging equipment installed on and around the biomass boiler. A wide range of property types and heat uses were investigated during this trial and the range in nominal outputs of the boilers involved was 10 to 800 kW. Fuels were either wood pellets, chip or log.

B921 was also part of further year of monitoring where 21 sites were selected for monitoring for a further year. Interventions were made at 15 of these sites to improve the boiler performance in terms of both efficiency and pollutant emissions.

The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data which was kindly provided by trial participants, was used (along with the compositional analysis Kiwa carried out) to give a picture of energy input, and combined with heat output and oxygen consumption to provide an indication of the overall boiler efficiency.

3 Description of the boiler and system

The monitoring was completed on a 45 kW wood pellet biomass boiler located in its own section of an outbuilding used for storage. During the field trial there was a period when no oxygen or flue gas temperature measurements were collected, which meant that efficiencies could not be calculated. This period was from the 12 April 2016 to 09 February 2017.

The boiler was owned and operated by a third party, whom the site paid for the heat supplied. This meant that the maintenance and fuelling of the boiler was not the responsibility of the people living at the site although they were responsible for carrying out simple maintenance such as emptying the ash from the boiler. The boiler incorporated an underfeed stoker type burner. Primary combustion air was fed under the fuel bed by rows of air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and the residual ash was thus pushed away as more fuel is fed and subsequently removed from the combustion chamber.

Table 47: About the site

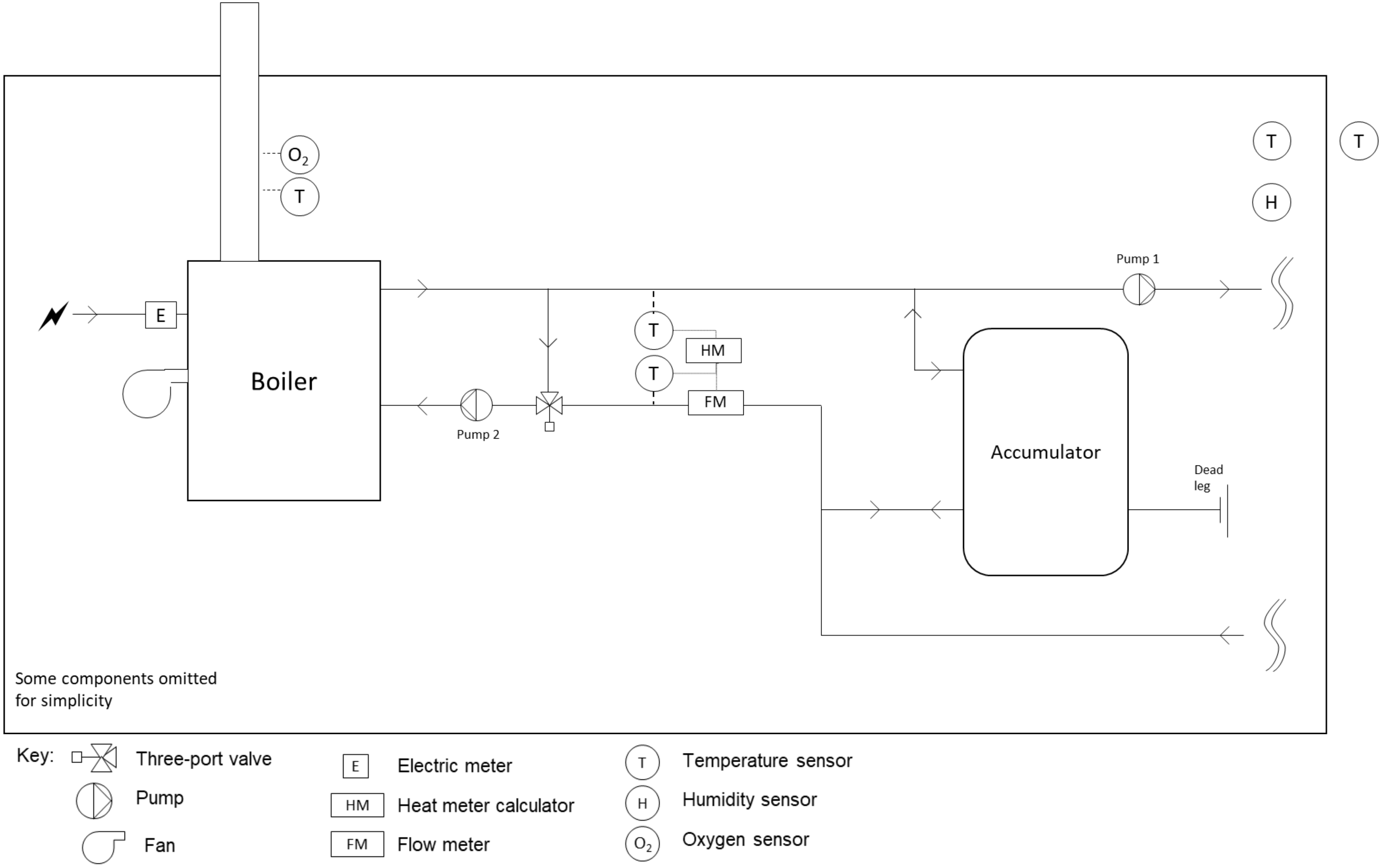
Building description	Large Residential Property
Fuel storage issues	None reported
Heat loss issues	Some uninsulated pipe in the boiler room. Boiler room in separate building from the property and was unheated.

The boiler’s primary use was to provide space heating to a large residential property. There was a section of underground pipe work between the boiler house and the property from which there would be a moderate amount of heat loss. There was also a 2000 litre accumulation vessel present in the system.

Table 48: About the biomass boiler

Issues raised by operator at time of installation	Boiler had not been providing enough heat to the property and had numerous issues with maintanence.
Rated output	45 kW
Fuel type	Wood pellets
Thermal store	Yes
Dilution components	None reported
Fans	Forced draft
Cyclones	None present
Filters	None present
Boiler faults	None reported

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

This section shows how the boiler performed between 13 April 2016 to 30 June 2017. In accordance with EN standards, the efficiencies have been calculated on a net basis using efficiency equations outlined in BS 845-1.

5.1 Total data collected

The following table presents a summary of the main parameters measured during the trial for the boiler. As there were only oxygen sensor readings from February 2017 onwards the previous data has not been included in the following summaries.

Table 49: Main parameters collected

Data collection period	10th of February 2017 to 31 May 2018
Heat output over this period	154,799 kWh
Hours of operation over this period	5,786 hours
Estimated fuel use over this period	38,578 kg

5.2 Annual equivalent use

Table 50: Annual equivalent use and summer and winter usage

Data collection period	**1st of June 2017 to 31 May 2018**		
	Annual equivalent use	Typical winter month (February)	Typical summer month (August)
Heat output	117,580 kWh	17154 kWh	410 kWh
Estimated fuel use	29,960 tonnes	4,328 kg	103 kg
Efficiency	82 %	83 %	83 %
Hours of operation	4431 hours	597 hours	15 hours
Load factor	28 %	57.0 %	1.0 %
Average starts per day	5.9 starts	3.2 starts	0.4 starts

5.3 Overall net boiler efficiency

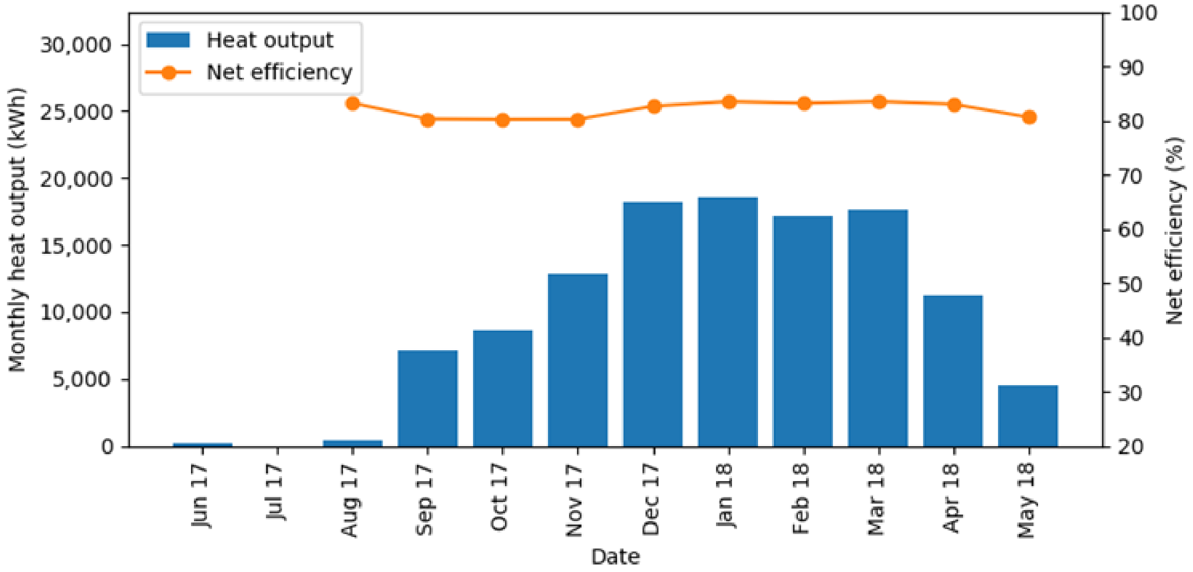


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the second period of monitoring. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The net efficiency was calculated for the boiler by specifically looking at how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, have their own heat losses which can decrease the net efficiency of the system as a whole. If the site had large water tanks (such as accumulator tanks) in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency may have been much lower. This is explored further in the published field trial report.

The measured net efficiency of the boiler was at 82.2%. The boiler had a steady efficiency throughout the year and higher outputs during the winter months. The summer has very low usage in comparison to the winter.

5.4 Heat output vs. degree day heating requirement

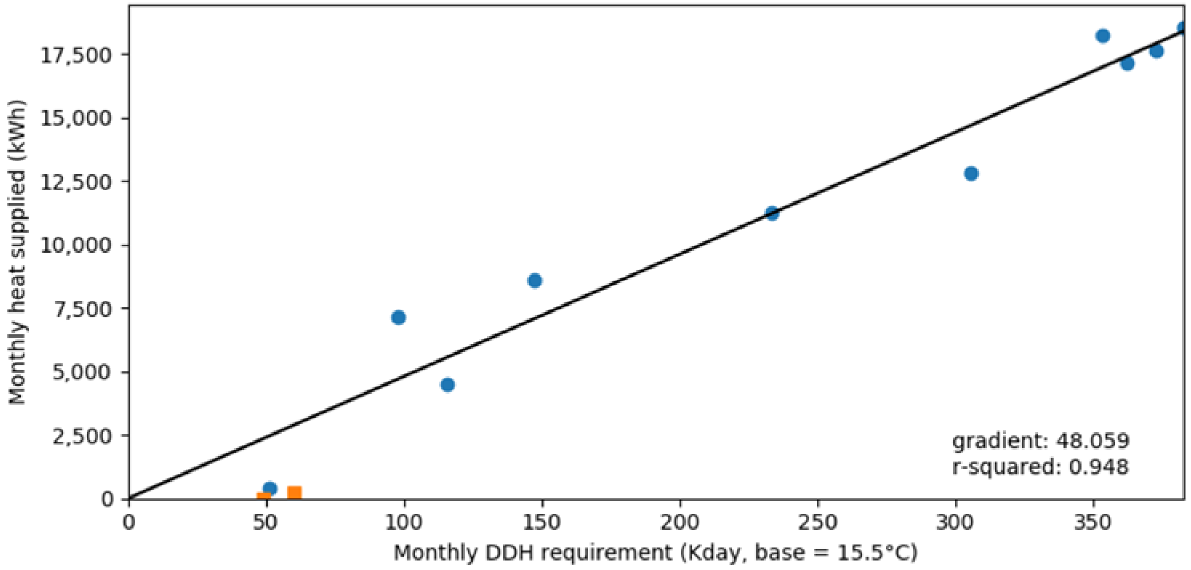


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

The r^2 value calculated for the system is displayed in Figure 2. The value of 0.948 shows good response to temperature. There is no y axis intercept which is indicative that this boiler does not provide Domestic Hot Water (DHW) load in the summer.

6 Fuel quality

The quality of fuel used in biomass boilers has been found to have a considerable impact on its efficiency and performance. As part of the field trial, fuel from every site was analysed. The table below gives the results of the analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 51: Fuel quality

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Your Fuel	Pellet	17.157	6.7	52.2	6.4	34.2	0.3	0.11
Average in field trial	Pellet	17.403	7.0	49.9	5.6	37.1	0.3	0.12
Minimum		16.482	4.4	-	-	-	-	-
Maximum		18.061	9.3	-	-	-	-	-

7 Boiler cycling

This boiler operates with good control and the heat output matches the outside temperature well. The efficiency is also higher than most other sites in the field trial. Maintenance issues were reported as a problem at this site and the occupiers of the property heated by the boiler expressed dissatisfaction with the boiler suggesting that the heat output is not as high as required by the site.

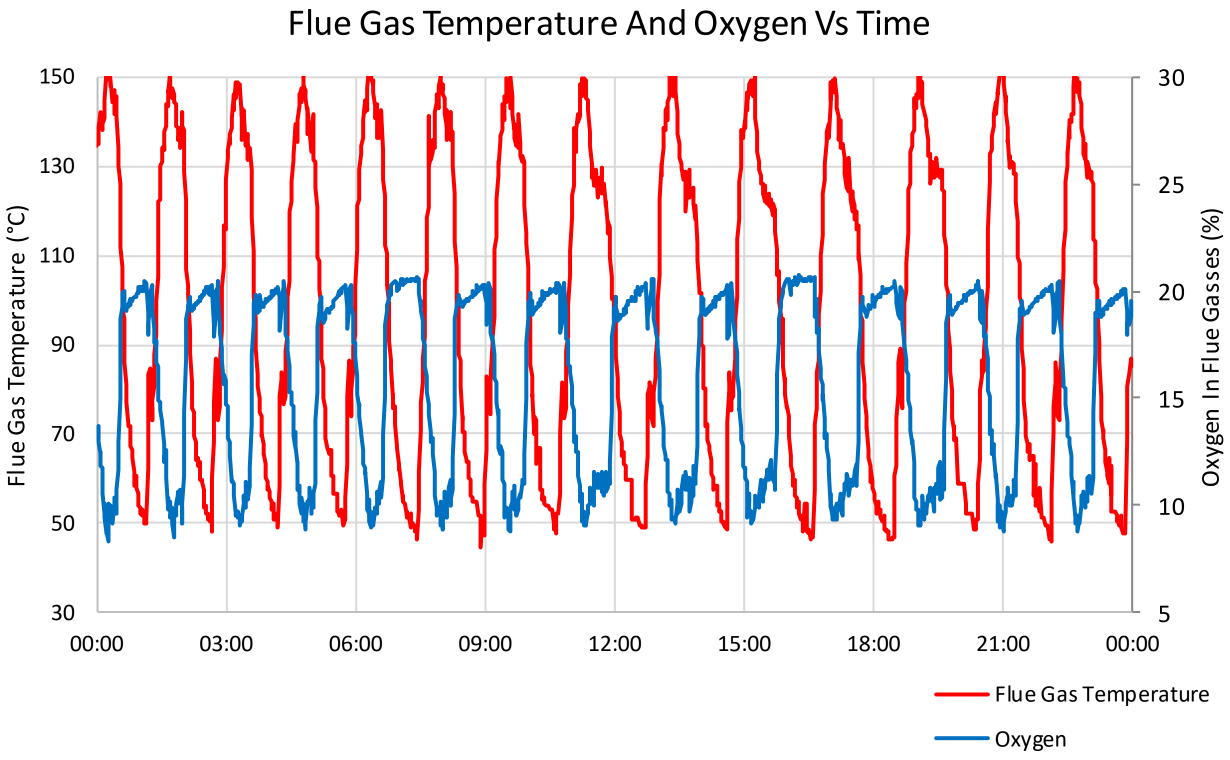


Figure 4: Graph showing flue gas temperature and oxygen vs time

Figure 4 shows a typical day of operation from the boiler on the 14th of November 2017. The boiler cycles 14 times in this period to meet the heating load, with the burn duration equal to around 50 minutes. The boiler operates in a continuous pattern activated 24 hours a day.

A cycle is defined as consisting of a start-up period, a period of steady burn and a burnout/shut down period. Laboratory testing has shown that most of pollutant emissions (hydrocarbons, NOx and particulate matter) are produced during boiler start-up and shut-down. Given the short burn time, it is likely that the steady burn period accounts for only 1/3 of each burn duration (i.e. 10 mins) and that the start-up and shut-downs account for a significant proportion of the total daily run time. A boiler operating as in Figure 5 will produce significantly more pollutants than one that is able to operate continuously or with fewer cycles. When a boiler turns on and off frequently it also places excessive wear on internal components such as fans, electrical heaters and pumps. This may mean that internal components which have a design life, for example, of 10 years could potentially fail prematurely after only a few years.

The main cause of the boiler cycling is usually due to boiler oversizing and therefore very low loads on the boiler. This was not the case for this site as the boiler had high load factors in the winter months with a daily load factor of 40% for the day shown in Figure 5. Over the monitoring period the maximum load factor of the boiler was 68%. The annual load factor of 28% suggests that the boiler is sufficiently sized. It would be expected that an appropriately sized boiler would have an annual load factor of 18%-20%. As the boiler is appropriately sized it was deduced that there are other issues with the system at this site, causing the boiler to cycle frequently.

7.1 System configuration

There is an appropriately sized accumulator present at the site. Its configuration is as can be seen in the system schematic shown in section 4. The accumulator has been installed using two ports one at the top and one at the bottom of the accumulator. This accumulator installation has been adapted from a 3-pipe configuration which can be inferred from the presence of the dead leg which used to connect the return from the system directly into the accumulator. This configuration is designed to allow flow in both directions in both ports into the accumulator depending on whether the accumulator is being charged or discharged. When the accumulator is being charged with heat from the boiler the heat flows into the top of the accumulator and out of the bottom back to the boiler. When the accumulator is supplying the load the opposite is true, heat flows out through the top port and water from the return flows into the bottom of the tank. A system set up in this way has an advantage over a conventional four pipe system as the boiler can supply heat directly bypassing the accumulator altogether, which can speed up response times. The drawback of this setup is that it can be more difficult to control as it depends on the balance of the hydraulics of the system.

- **Charging the accumulator:** When there is no heat demand on the biomass boiler, it can charge the accumulator using only pump 2.
- **Discharging the accumulator:** When there is a demand for heat and the accumulator is charged the system activates pump 1 while pump 2 is off. This ensures that the heat stored in the accumulator is used to satisfies the load.
- **Using the boiler to satisfy the load:** When the accumulator no longer has enough heat stored, pump 2 is activated and the boiler turns on to provide heat. When the load is satisfied pump 1 turns off and the boiler recharges the accumulator.

Problems can occur with this system if the control of the pumps or the balancing of the hydraulics is incorrect. Running pump 1 and pump 2 continuously for example would not use the accumulator correctly as a store of heat. Depending on how the control system has been configured, it may mean that the boiler was responding immediately to changes in the demand by frequent switching on and off. In this situation, the accumulator will not have been operating as intended and will stop the boiler from running for more than short bursts. The operator of the system should consider reconfiguring the system so that there is a single flow and return from boiler to accumulator and additional flow and return pipe runs from the accumulator to the residential property's heating system.

7.2 Temperature set points

Another cause of cycling may be due to temperature set points not being optimised. If a boiler is oversized then increasing the temperature range in which it operates will allow the boiler to increase its burn periods which will limit cycling. If the accumulator only cools by a few degrees before the boiler is required to fire then increasing this temperature difference will increase the amount of heat the accumulator delivers during each burn. The operator should examine the control system and ensure there is sufficient difference between the hot and cold buffer temperature set points.

8 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31 June 2017 and 31 May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring described in the previous sections of this case study.

8.1 Boiler cycling

The issue at this site appeared to be excessive cycling, and the solution was reducing the number of daily cycles caused by the boiler being incorrectly configured and/or controlled. Two suggestions were made to the site in how to reduce the cycling.

Change the boiler system set up:

> From the site intervention visit it was clear the accumulator temperatures were very low which suggested that the accumulator was not being used to store heat. It was advised that the system was not set up correctly and that the pump which supplied the heat to the house was continuously running. This is not how the system was designed to operate and will prevent the boiler from running for more than short periods. It was suggested that the control of the pump might be improved or that it may be advantageous to change the system and replumb the accumulator.

Adjust the controls to limit cycling:

> As the boiler is cycling the control should be investigated to ensure that each time the boiler fires the burn period is optimised. Control settings which maximise the temperature difference between when the boilers set points should be investigated to allow the boiler to run for longer. It was suggested that the operator should examine the control system and ensure there is sufficient difference between the hot and cold buffer temperature set points.

As the site was operated by a third party which supplied the heat it proved difficult to persuade them to adjust the controls at the site. They were reluctant to make changes as they believed that the site had been optimised and set up correctly. After sending monitoring data and schematics to the site owner a site visit by a maintenance company was arranged on the 10th of December to make changes to the boiler and recommission it. The boiler controls were adjusted and changes made to the control of the pumps.

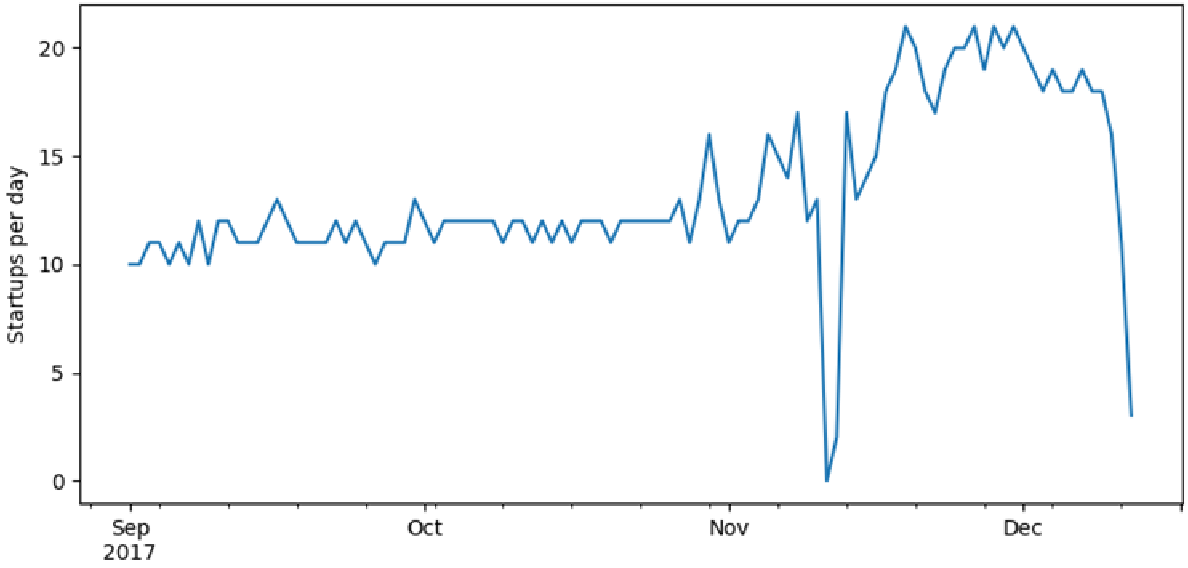


Figure 7: Boiler start-ups against time before changes were made

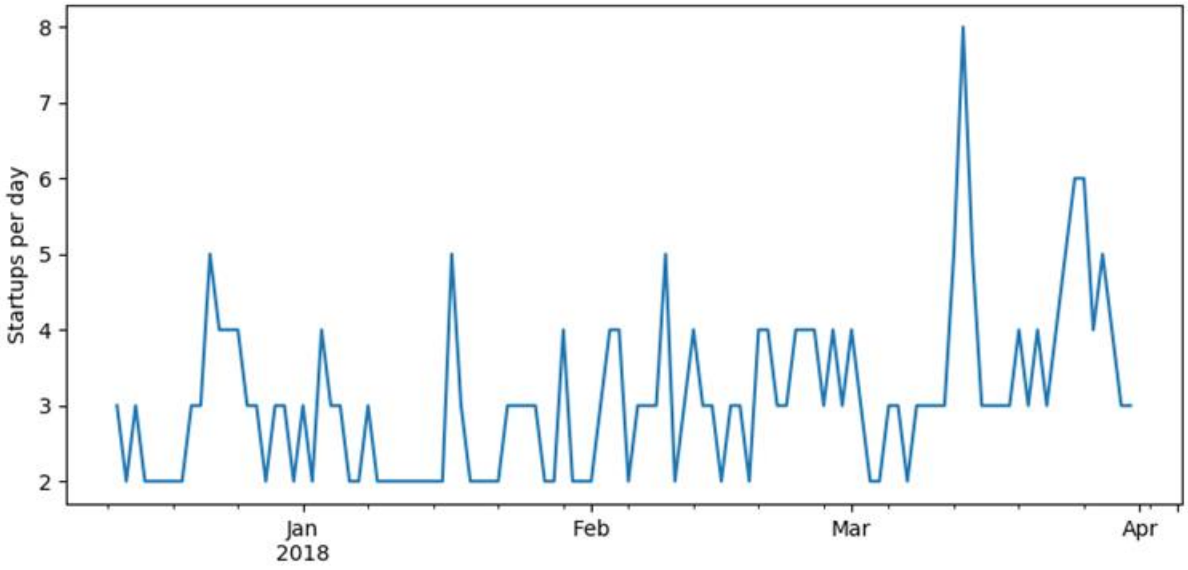


Figure 8: Boiler start-ups against time after changes were made

Figure 7 shows the start-ups per day between the 01 of September and the 10 December 2017 before the changes were made to the boiler. The number of starts-ups is very high with more than 10 cycles per day on average. The changes focused on making changes to the pumps and to the flow and return temperatures. This was an attempt to increase the burn period and reduce cycling. Figure 8 shows the start-ups per day between the 10 of December 2017 and the March 31 2018 after the changes were made to the boiler. One can see the immediate improvement as the boiler entered a period of reduced cycling between 2 and 5 cycles per day.

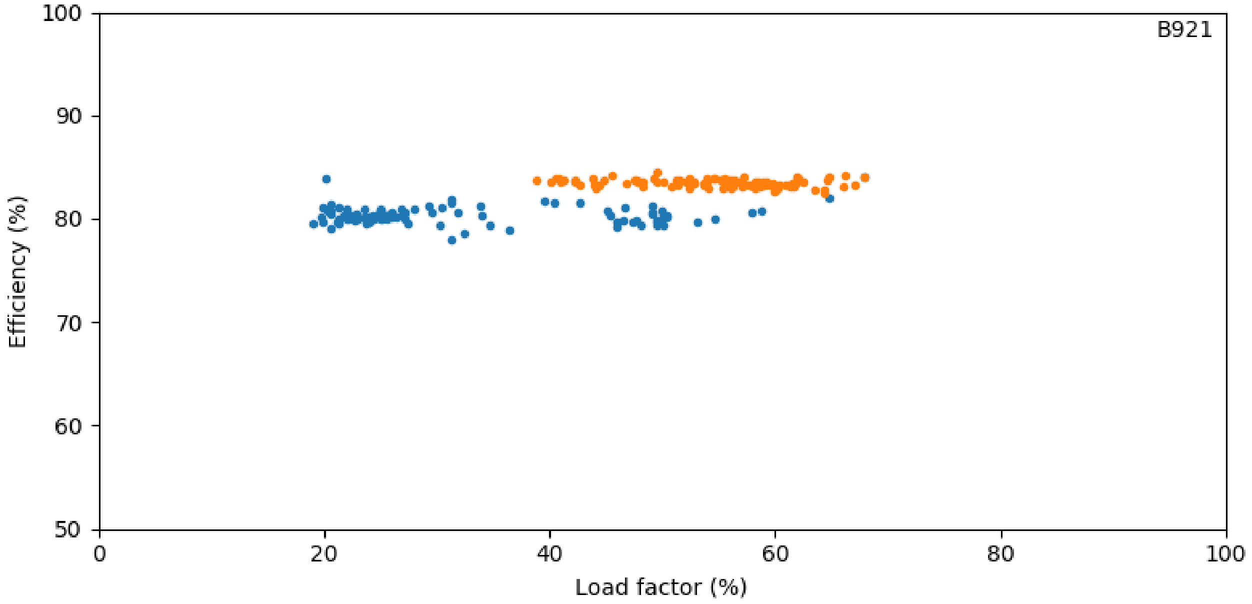


Figure 9: Efficiency against load factor (blue before intervention, orange after intervention)

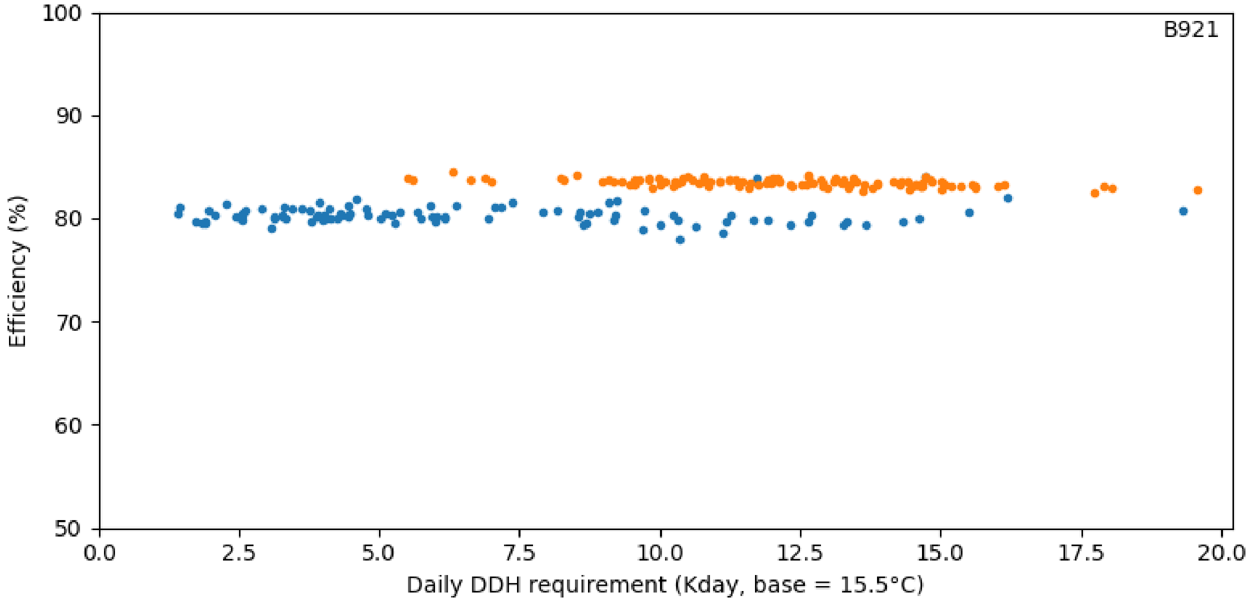


Figure 10: Boiler efficiency against daily degree days (blue before intervention, orange after intervention)

Due to the change being made part way through the heating season the reduced start-ups shown in Figure 8 were investigated further to identify if the weather caused a change in performance. Figure 9 shows the efficiency vs load factor. Two distinct regions can be seen on the graph with the orange points showing the boilers operation after the changes were made. The load factors after the changes were made, were higher due to colder external temperatures. However, for a similar load factor, the boiler was more efficient after the changes were made. Similarly, the increased efficiency can be seen in Figure 10 in the plot against degree days, which again shows that on comparable heating days the boiler was more efficient after the changes were made. Before the change the efficiency was around 82% after this increased to 85%. This increased efficiency is due to the increased burn time where the boiler is able to operate at its most efficient, and due to reduced losses during periods of inefficient combustion during start-ups and shutdowns

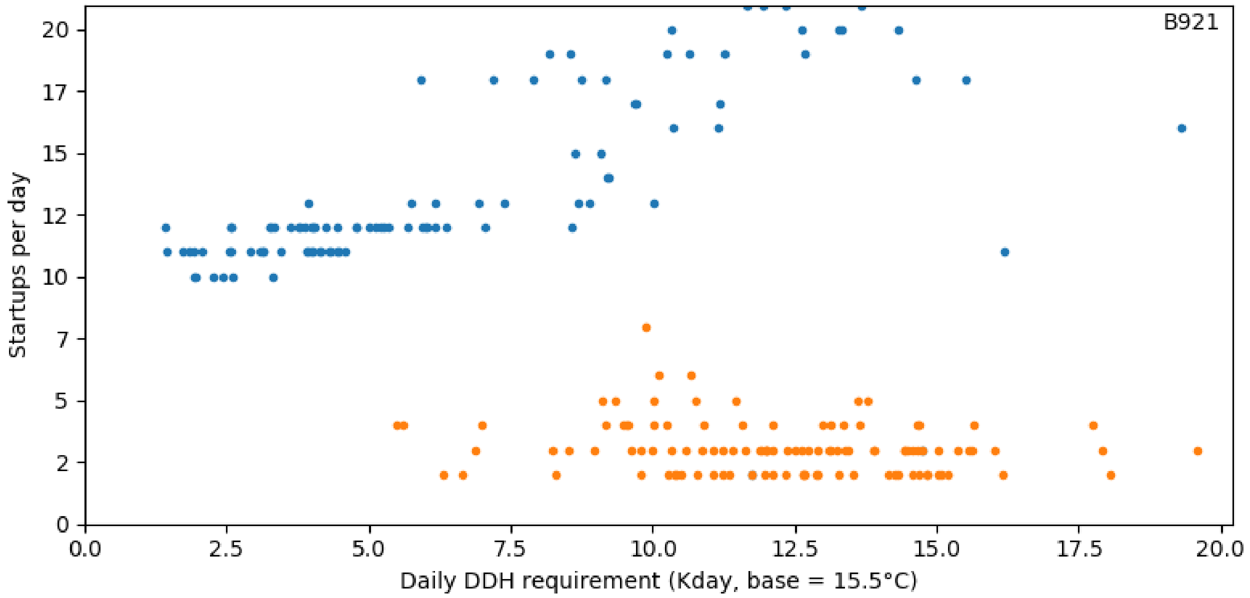


Figure 11: Efficiency against load factor

Figure 11 plots start-ups per day against daily degree days. Orange shows the number of start-ups after the changes were made. The average number of starts before the change was made was 13, after the change the average number was 3. This is a large improvement to the behaviour of how the boiler operates and shows the impact that poor control will have on biomass systems. From Figure 11 one can see that under its previous control settings the number of starts increased during colder weather as the load increased. This is the opposite of what should happen when biomass boilers perform well. When a higher load is placed on them, they should have fewer start-ups and longer burn periods.

9 Summary

Monitoring of the B921 boiler showed that the boiler performed poorly due to frequent cycling. This is the result of the configuration and operation of the system and, in particular, of the accumulators. The efficiencies were comparatively high relative to those at other sites however, the pollutant emissions would also be very high due to the high number of boiler start-ups and shutdowns.

The DDH plot showed good correlation between heat provided and monthly degree days suggesting the boiler was controlled well in response to outside temperature.

The case study looked at the frequent cycling of the boiler and suggested the site re-commission the boiler and adjust the controls to limit cycling. This work was completed to improve the boiler operation and was effective in getting the boiler to reduce its cycling.

The issues causing the boiler to cycle were poor control of accumulator temperatures and control of pumps in the system stopping the biomass boiler from operating correctly. The changes made to the site greatly reduced cycling and increased the efficiency from the boiler.

Department for
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Biomass boiler field trial
Case studies – B921

Trust
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1 Introduction

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The data collected from the site included heat output and electrical consumption of the boiler, oxygen levels and temperatures within the flue, plant room temperature and ambient temperature. The data has been used as a part of the overall analysis of boiler performance by focusing on boiler operation (during start-up, shut down and steady state operation) and on/off cycling behaviour. The fuel consumption data which was kindly provided by trial participants, was used (along with the compositional analysis Kiwa carried out) to give a picture of energy input, and combined with heat output and oxygen consumption to provide an indication of the overall boiler efficiency.

3 Description of the boiler and system

The monitoring was completed on a 45 kW wood pellet biomass boiler located in its own section of an outbuilding used for storage. During the field trial there was a period when no oxygen or flue gas temperature measurements were collected, which meant that efficiencies could not be calculated. This period was from the 12 April 2016 to 09 February 2017.

The boiler was owned and operated by a third party, whom the site paid for the heat supplied. This meant that the maintenance and fuelling of the boiler was not the responsibility of the people living at the site although they were responsible for carrying out simple maintenance such as emptying the ash from the boiler. The boiler incorporated an underfeed stoker type burner. Primary combustion air was fed under the fuel bed by rows of air ports. The fuel was screw-fed into the bottom of the combustion pot. This forced the fuel bed upwards and the residual ash was thus pushed away as more fuel is fed and subsequently removed from the combustion chamber.

Table 52: About the site

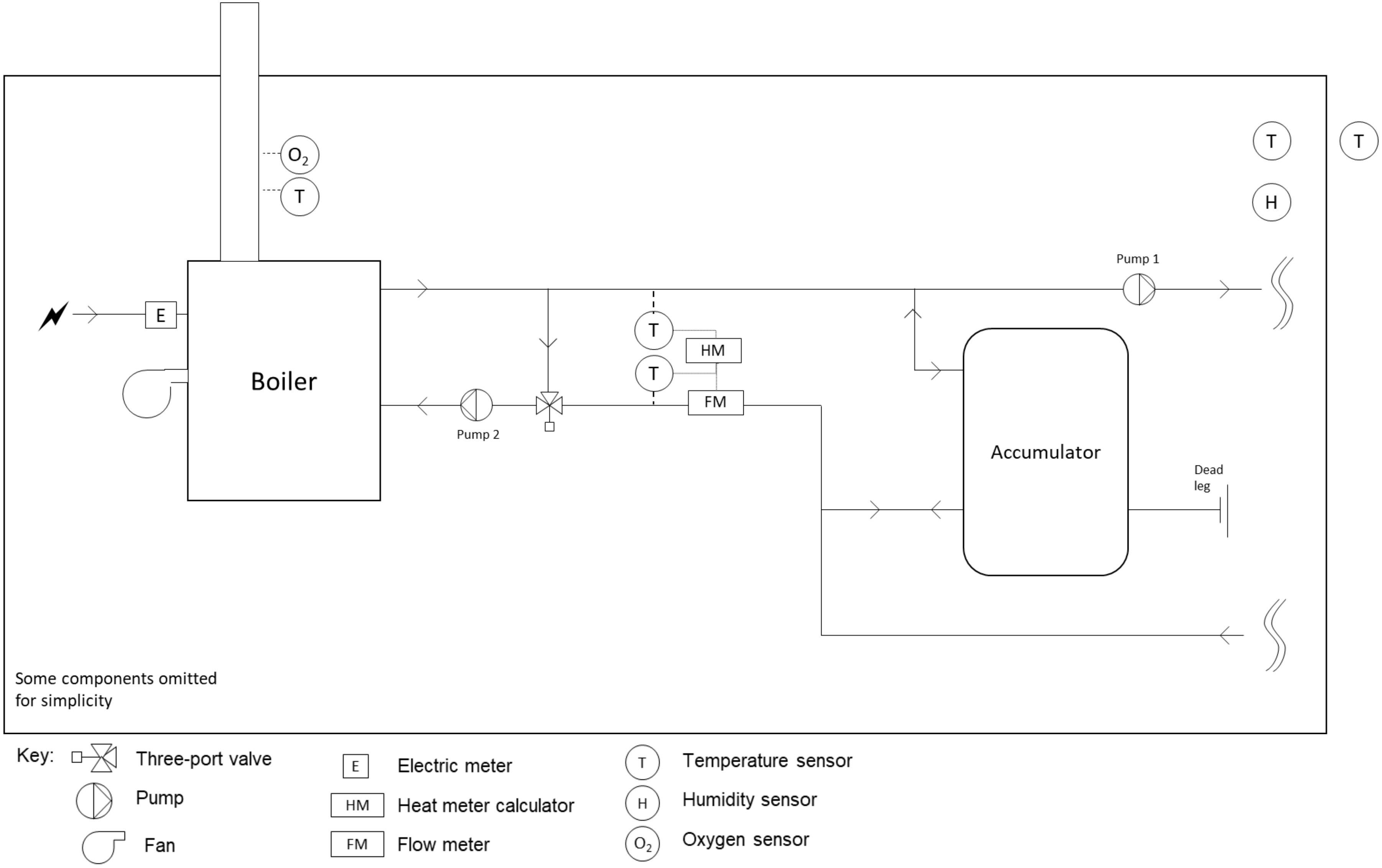
Building description	Large Residential Property
Fuel storage issues	None reported
Heat loss issues	Some uninsulated pipe in the boiler room. Boiler room in separate building from the property and was unheated.

The boiler’s primary use was to provide space heating to a large residential property. There was a section of underground pipe work between the boiler house and the property from which there would be a moderate amount of heat loss. There was also a 2000 litre accumulation vessel present in the system.

Table 53: About the biomass boiler

Issues raised by operator at time of installation	Boiler had not been providing enough heat to the property and had numerous issues with maintanence.
Rated output	45 kW
Fuel type	Wood pellets
Thermal store	Yes
Dilution components	None reported
Fans	Forced draft
Cyclones	None present
Filters	None present
Boiler faults	None reported

4 System schematic



Some components omitted for simplicity

5 The performance and efficiency of the boiler

This section shows how the boiler performed between 13 April 2016 to 30 June 2017. In accordance with EN standards, the efficiencies have been calculated on a net basis using efficiency equations outlined in BS 845-1.

5.1 Total data collected

The following table presents a summary of the main parameters measured during the trial for the boiler. As there were only oxygen sensor readings from February 2017 onwards the previous data has not been included in the following summaries.

Table 54: Main parameters collected

Data collection period	10th of February 2017 to 31 May 2018
Heat output over this period	154,799 kWh
Hours of operation over this period	5,786 hours
Estimated fuel use over this period	38,578 kg

5.2 Annual equivalent use

Table 55: Annual equivalent use and summer and winter usage

Data collection period	**1st of June 2017 to 31 May 2018**					
	Annual equivalent use		Typical winter month (February)		Typical summer month (August)	
Heat output	117,580	kWh	17154	kWh	410	kWh
Estimated fuel use	29,960	tonnes	4,328	kg	103	kg
Efficiency	82	%	83	%	83	%
Hours of operation	4431	hours	597	hours	15	hours
Load factor	28	%	57.0	%	1.0	%
Average starts per day	5.9	starts	3.2	starts	0.4	starts

5.3 Overall net boiler efficiency

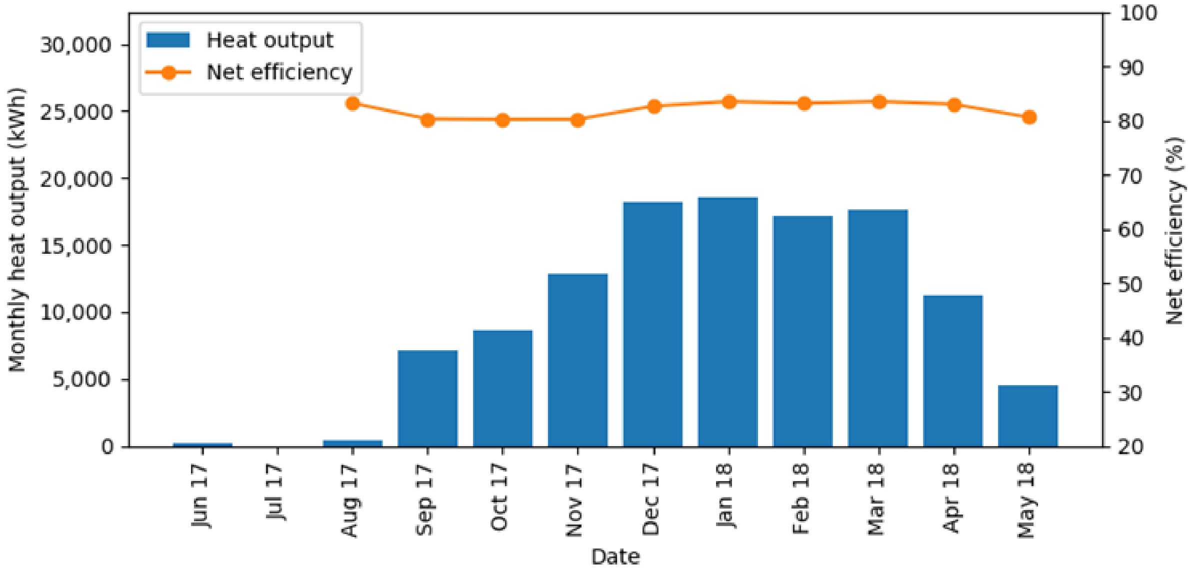


Figure 1: Graph showing the heat output and net efficiency of the boiler by month

Figure 1 shows the net efficiency of the boiler over the second period of monitoring. Efficiency is the ratio of total useful heat output to total energy input (including energy from the fuel and electrical energy). The higher the efficiency, the better the thermal performance of the boiler.

The net efficiency was calculated for the boiler by specifically looking at how well it transferred energy to the water in the heating system. Other components of the heating system, such as water tanks and distribution pipework, have their own heat losses which can decrease the net efficiency of the system as a whole. If the site had large water tanks (such as accumulator tanks) in unheated spaces, or long lengths of underground distribution pipes, then the overall system efficiency may have been much lower. This is explored further in the published field trial report.

The measured net efficiency of the boiler was at 82.2%. The boiler had a steady efficiency throughout the year and higher outputs during the winter months. The summer has very low usage in comparison to the winter.

5.4 Heat output vs. degree day heating requirement

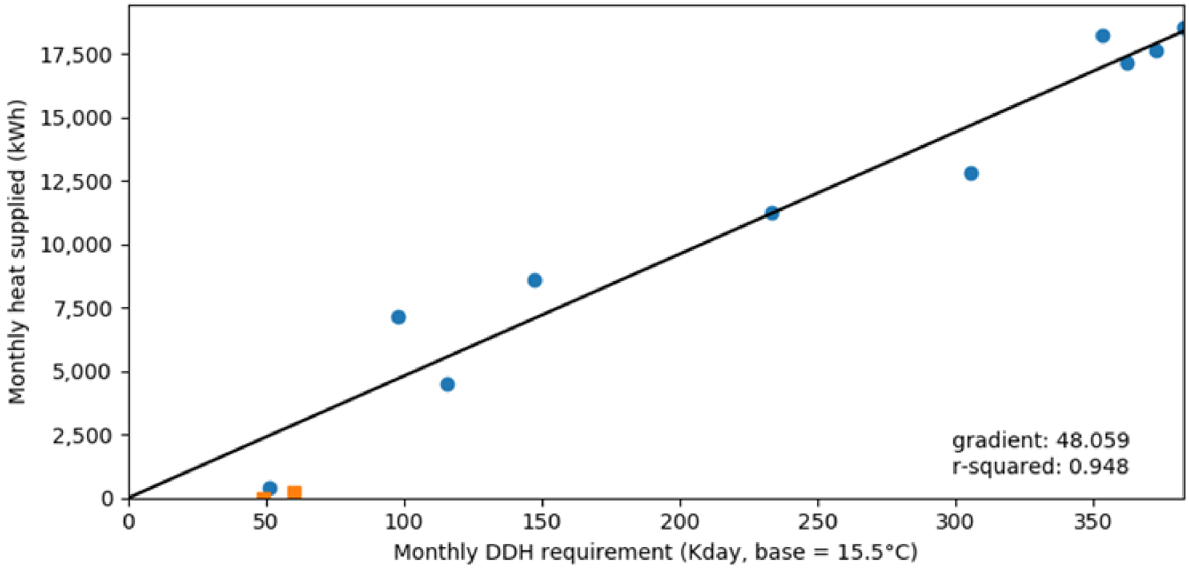


Figure 2: Graph showing heat delivered by the boiler and monthly degree day heating requirement

Figure 2 is a plot of monthly heat output from the boiler against monthly degree day heating requirement. Degree day analysis is a useful way to compare how much heat was delivered by a boiler at different times of the year or between different years, where the prevailing weather conditions may be different - the higher the number of degree days, the colder the outside temperature. It allows a judgement to be made of how well the system responds to temperature.

For systems used for heating buildings, there should be a close correlation between heat output and degree days. This means the points on the graph should cluster around the line. It is standard practice to use a statistical derivative called the correlation coefficient (r^2) to measure this: an r^2 value near to 1 indicates close correlation and good response to temperature, however an r^2 value nearer to 0 indicates less correlation and poorer response to temperature.

For systems with loads which are less dependent on the weather, e.g. poultry farms or hospitals, one would not expect an r^2 value near to 1, and this would not necessarily be indicative of a poorly operating system.

The r^2 value calculated for the system is displayed in Figure 2. The value of 0.948 shows good response to temperature. There is no y axis intercept which is indicative that this boiler does not provide Domestic Hot Water (DHW) load in the summer.

6 Fuel quality

The quality of fuel used in biomass boilers has been found to have a considerable impact on its efficiency and performance. As part of the field trial, fuel from every site was analysed. The table below gives the results of the analysis carried out on the fuel as well as the average values for all fuels of this type from other trial sites. The analysis was done on an as received basis (wet).

Table 56: Fuel quality

	Fuel Type	Net CV (MJ/kg)	Moisture (%)	Carbon (%)	Hydrogen (%)	Oxygen (%)	Ash (%)	Nitrogen (%)
Your Fuel	Pellet	17.157	6.7	52.2	6.4	34.2	0.3	0.11
Average in field trial	Pellet	17.403	7.0	49.9	5.6	37.1	0.3	0.12
Minimum		16.482	4.4	-	-	-	-	-
Maximum		18.061	9.3	-	-	-	-	-

7 Boiler cycling

This boiler operates with good control and the heat output matches the outside temperature well. The efficiency is also higher than most other sites in the field trial. Maintenance issues were reported as a problem at this site and the occupiers of the property heated by the boiler expressed dissatisfaction with the boiler suggesting that the heat output is not as high as required by the site.

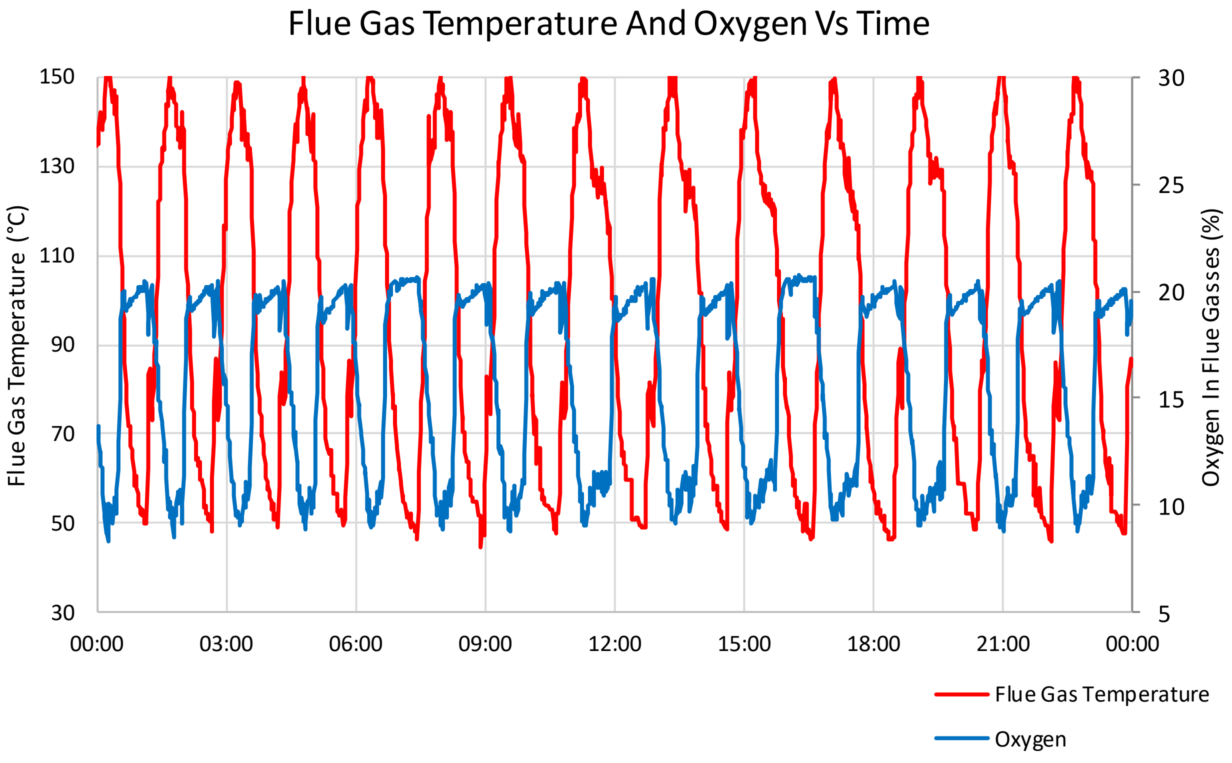


Figure 4: Graph showing flue gas temperature and oxygen vs time

Figure 4 shows a typical day of operation from the boiler on the 14th of November 2017. The boiler cycles 14 times in this period to meet the heating load, with the burn duration equal to around 50 minutes. The boiler operates in a continuous pattern activated 24 hours a day.

A cycle is defined as consisting of a start-up period, a period of steady burn and a burnout/shut down period. Laboratory testing has shown that most of pollutant emissions (hydrocarbons, NOx and particulate matter) are produced during boiler start-up and shut-down. Given the short burn time, it is likely that the steady burn period accounts for only 1/3 of each burn duration (i.e. 10 mins) and that the start-up and shut-downs account for a significant proportion of the total daily run time. A boiler operating as in Figure 5 will produce significantly more pollutants than one that is able to operate continuously or with fewer cycles. When a boiler turns on and off frequently it also places excessive wear on internal components such as fans, electrical heaters and pumps. This may mean that internal components which have a design life, for example, of 10 years could potentially fail prematurely after only a few years.

The main cause of the boiler cycling is usually due to boiler oversizing and therefore very low loads on the boiler. This was not the case for this site as the boiler had high load factors in the winter months with a daily load factor of 40% for the day shown in Figure 5. Over the monitoring period the maximum load factor of the boiler was 68%. The annual load factor of 28% suggests that the boiler is sufficiently sized. It would be expected that an appropriately sized boiler would have an annual load factor of 18%-20%. As the boiler is appropriately sized it was deduced that there are other issues with the system at this site, causing the boiler to cycle frequently.

7.1 System configuration

There is an appropriately sized accumulator present at the site. Its configuration is as can be seen in the system schematic shown in section 4. The accumulator has been installed using two ports one at the top and one at the bottom of the accumulator. This accumulator installation has been adapted from a 3-pipe configuration which can be inferred from the presence of the dead leg which used to connect the return from the system directly into the accumulator. This configuration is designed to allow flow in both directions in both ports into the accumulator depending on whether the accumulator is being charged or discharged. When the accumulator is being charged with heat from the boiler the heat flows into the top of the accumulator and out of the bottom back to the boiler. When the accumulator is supplying the load the opposite is true, heat flows out through the top port and water from the return flows into the bottom of the tank. A system set up in this way has an advantage over a conventional four pipe system as the boiler can supply heat directly bypassing the accumulator altogether, which can speed up response times. The drawback of this setup is that it can be more difficult to control as it depends on the balance of the hydraulics of the system.

- **Charging the accumulator:** When there is no heat demand on the biomass boiler, it can charge the accumulator using only pump 2.
- **Discharging the accumulator:** When there is a demand for heat and the accumulator is charged the system activates pump 1 while pump 2 is off. This ensures that the heat stored in the accumulator is used to satisfies the load.
- **Using the boiler to satisfy the load:** When the accumulator no longer has enough heat stored, pump 2 is activated and the boiler turns on to provide heat. When the load is satisfied pump 1 turns off and the boiler recharges the accumulator.

Problems can occur with this system if the control of the pumps or the balancing of the hydraulics is incorrect. Running pump 1 and pump 2 continuously for example would not use the accumulator correctly as a store of heat. Depending on how the control system has been configured, it may mean that the boiler was responding immediately to changes in the demand by frequent switching on and off. In this situation, the accumulator will not have been operating as intended and will stop the boiler from running for more than short bursts. The operator of the system should consider reconfiguring the system so that there is a single flow and return from boiler to accumulator and additional flow and return pipe runs from the accumulator to the residential property’s heating system.

7.2 Temperature set points

Another cause of cycling may be due to temperature set points not being optimised. If a boiler is oversized then increasing the temperature range in which it operates will allow the boiler to increase its burn periods which will limit cycling. If the accumulator only cools by a few degrees before the boiler is required to fire then increasing this temperature difference will increase the amount of heat the accumulator delivers during each burn. The operator should examine the control system and ensure there is sufficient difference between the hot and cold buffer temperature set points.

8 Site intervention

This site was one of 15 chosen to implement an intervention visit. The site was monitored for a further year between 31 June 2017 and 31 May 2018. Interventions were made to improve performance at the site by raising efficiencies and lowering pollutant emissions from the boiler. The interventions carried out at this site followed the findings from the first year of monitoring described in the previous sections of this case study.

8.1 Boiler cycling

The issue at this site appeared to be excessive cycling, and the solution was reducing the number of daily cycles caused by the boiler being incorrectly configured and/or controlled. Two suggestions were made to the site in how to reduce the cycling.

Change the boiler system set up:

> From the site intervention visit it was clear the accumulator temperatures were very low which suggested that the accumulator was not being used to store heat. It was advised that the system was not set up correctly and that the pump which supplied the heat to the house was continuously running. This is not how the system was designed to operate and will prevent the boiler from running for more than short periods. It was suggested that the control of the pump might be improved or that it may be advantageous to change the system and replumb the accumulator.

Adjust the controls to limit cycling:

> As the boiler is cycling the control should be investigated to ensure that each time the boiler fires the burn period is optimised. Control settings which maximise the temperature difference between when the boilers set points should be investigated to allow the boiler to run for longer. It was suggested that the operator should examine the control system and ensure there is sufficient difference between the hot and cold buffer temperature set points.

As the site was operated by a third party which supplied the heat it proved difficult to persuade them to adjust the controls at the site. They were reluctant to make changes as they believed that the site had been optimised and set up correctly. After sending monitoring data and schematics to the site owner a site visit by a maintenance company was arranged on the 10th of December to make changes to the boiler and recommission it. The boiler controls were adjusted and changes made to the control of the pumps.

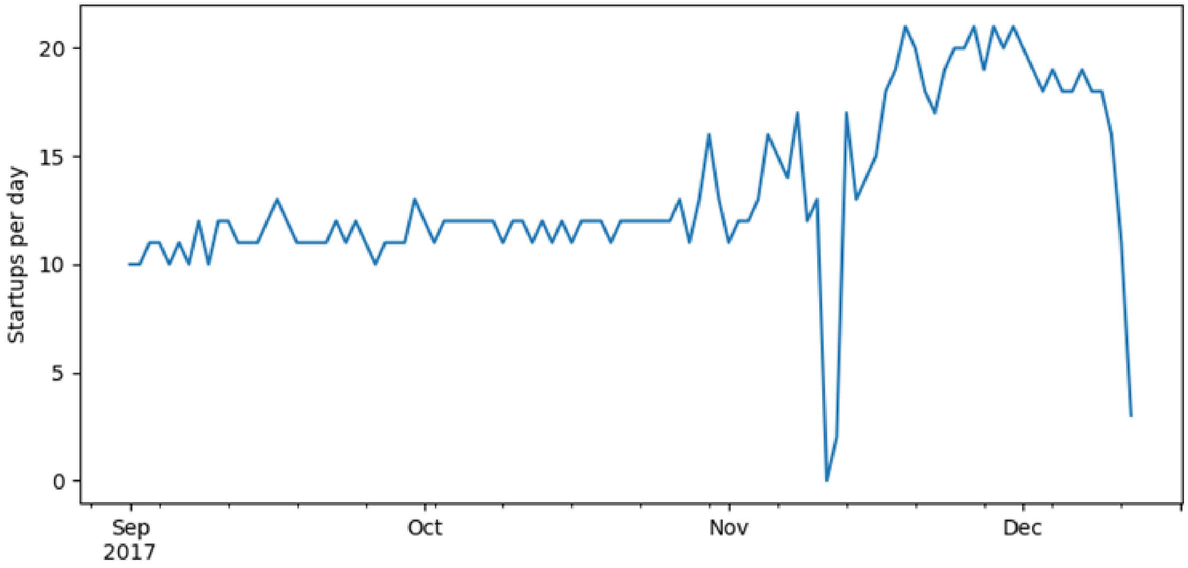


Figure 7: Boiler start-ups against time before changes were made

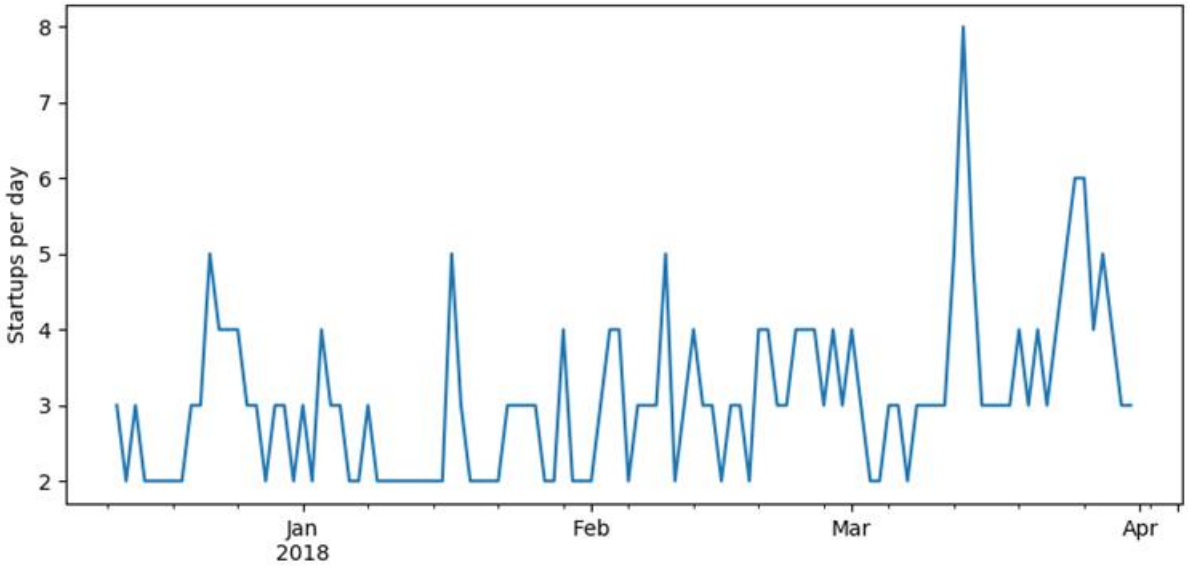


Figure 8: Boiler start-ups against time after changes were made

Figure 7 shows the start-ups per day between the 01 of September and the 10 December 2017 before the changes were made to the boiler. The number of starts-ups is very high with more than 10 cycles per day on average. The changes focused on making changes to the pumps and to the flow and return temperatures. This was an attempt to increase the burn period and reduce cycling. Figure 8 shows the start-ups per day between the 10 of December 2017 and the March 31 2018 after the changes were made to the boiler. One can see the immediate improvement as the boiler entered a period of reduced cycling between 2 and 5 cycles per day.

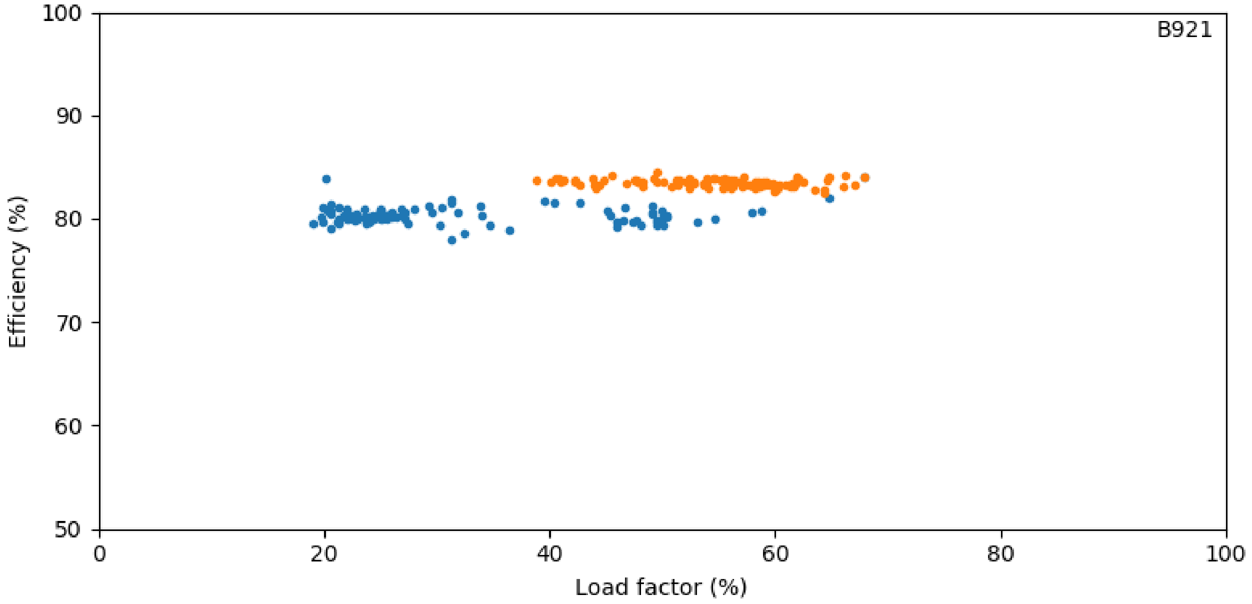


Figure 9: Efficiency against load factor (blue before intervention, orange after intervention)

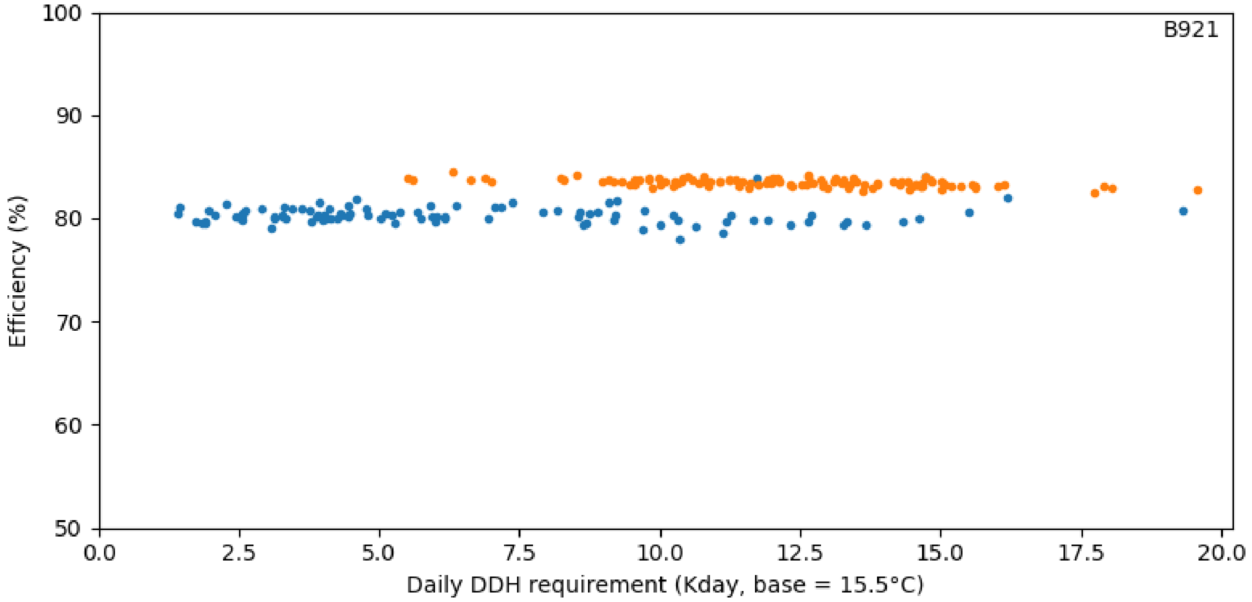


Figure 10: Boiler efficiency against daily degree days (blue before intervention, orange after intervention)

Due to the change being made part way through the heating season the reduced start-ups shown in Figure 8 were investigated further to identify if the weather caused a change in performance. Figure 9 shows the efficiency vs load factor. Two distinct regions can be seen on the graph with the orange points showing the boilers operation after the changes were made. The load factors after the changes were made, were higher due to colder external temperatures. However, for a similar load factor, the boiler was more efficient after the changes were made. Similarly, the increased efficiency can be seen in Figure 10 in the plot against degree days, which again shows that on comparable heating days the boiler was more efficient after the changes were made. Before the change the efficiency was around 82% after this increased to 85%. This increased efficiency is due to the increased burn time where the boiler is able to operate at its most efficient, and due to reduced losses during periods of inefficient combustion during start-ups and shutdowns

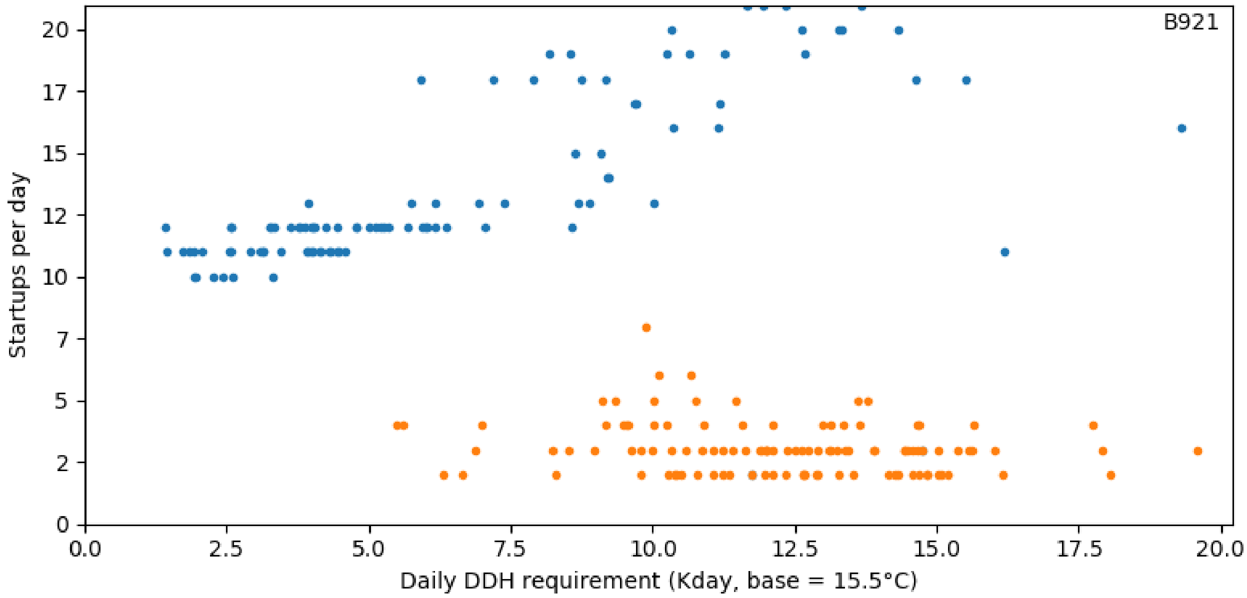


Figure 11: Startups per day vs daily degree day

Figure 11 plots start-ups per day against daily degree days. Orange shows the number of start-ups after the changes were made. The average number of starts before the change was made was 13, after the change the average number was 3. This is a large improvement to the behaviour of how the boiler operates and shows the impact that poor control will have on biomass systems. From Figure 11 one can see that under its previous control settings the number of starts increased during colder weather as the load increased. This is the opposite of what should happen when biomass boilers perform well. When a higher load is placed on them, they should have fewer start-ups and longer burn periods.

9 Summary

Monitoring of the B921 boiler showed that the boiler performed poorly due to frequent cycling. This is the result of the configuration and operation of the system and, in particular, of the accumulators. The efficiencies were comparatively high relative to those at other sites however, the pollutant emissions would also be very high due to the high number of boiler start-ups and shutdowns.

The DDH plot showed good correlation between heat provided and monthly degree days suggesting the boiler was controlled well in response to outside temperature.

The case study looked at the frequent cycling of the boiler and suggested the site re-commission the boiler and adjust the controls to limit cycling. This work was completed to improve the boiler operation and was effective in getting the boiler to reduce its cycling.

The issues causing the boiler to cycle were poor control of accumulator temperatures and control of pumps in the system stopping the biomass boiler from operating correctly. The changes made to the site greatly reduced cycling and increased the efficiency from the boiler.