Programme Area: Bioenergy

Project: TEA Biomass Pre-processing

Title: Small Scale Technologies for Dedicated Biomass Conversion to Heat and CHP

Abstract:

This Deliverable 1a report exists as a standalone document, which can be read alongside the “Deliverable 1 - Review and benchmarking report” within the ETI’s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) study. The original report 'D1' excluded technologies below 200kWth input; hence this report 'D1a' is focused on the state-of-the-art, techno-economics and real-world issues faced by these small-scale combustion technologies.

In this report, the technologies typically used for combustion of biomass have been separated into three types (although some plant designs exist that incorporate multiple technologies). Based on the fuel feeding methods and the operation of the fuel bed, the main technologies are as follows: a manually-fed boiler, an automatically-fed boiler with a fixed combustion bed, and an automatically-fed boiler with a moving combustion bed. The report also covers Organic Rankine Cycle technologies (as a Stirling engines are covered in Section 6.3.4.1 of D1 Report), detailing their development status, integration with biomass-fired systems, their strengths, weaknesses and main suppliers.

Details of the European biomass fuel standards that have been developed are also covered within the report, together with fuel quality assurance schemes that enable biomass feedstocks to meet boiler specifications and avoid issues when burnt in biomass boilers.

Context:

The techno-economic project will provide a greater understanding of the options available to modify or improve the physical and chemical characteristics of different types of UK-derived 2nd generation energy biomass feedstocks, that may otherwise reduce the cost-effective performance of conversion technologies.

BI2011

Techno-Economic Assessment of Biomass Pre-Processing (TEABPP)

Deliverable 1a (VAR002)

Small scale technologies for dedicated biomass conversion to heat and CHP

Version 2.0

The TEABPP Consortium

For the Energy Technologies Institute

4th July 2016

Title	Deliverable 1a: Small scale technologies for dedicated biomass conversion to heat and CHP
Client	Energy Technologies Institute
Date	4th July 2016
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Reviewers/Approved by	The TEABPP Consortium
Version	V1.0 Conditional acceptance by the ETI V2.0 Revised and submitted to the ETI
Distribution	ETI Program Management team TEABPP Consortium

Version no.	Prepared	Checked	Reviewed	Approved	Issue date	Issue status
1.0	T. Milne, A. Webb, L. Martinez	A. Webb	M. Eastwood	A. Baldock	13th May 2016	Draft
1.1	T. Milne, A. Webb, L. Martinez	T. Milne	M. Eastwood	A. Baldock	26th May 2016	Draft
2.0	T. Milne, L. Martinez	M. Eastwood	M. Eastwood	A. Baldock	30th June 2016	Final

Contents

1 Exec summary

This Deliverable 1a report exists as a standalone document, which can be read alongside the "Deliverable 1 - Review and benchmarking report" within the ETI's Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) study. The original Deliverable 1 report excluded technologies below 200kW$_{th}$ input; hence this Deliverable 1a report is focused on the state-of-the-art, techno-economics and real-world issues faced by these small-scale combustion technologies.

In this report, the varying technologies most typically used for combustion of biomass have been separated into three distinct types (although some plant designs are also available that incorporate functions of more than one technology type). Based on the fuel feeding methods and the operation of the fuel bed, the main technologies are determined as follows:

1. A manually-fed boiler, typically with a fixed combustion bed, operates on a batch-firing principle and is usually fired using logs or larger size feedstock that may cause problems in automatic handling systems. Systems are generally more basic than other technology types and are therefore typically lower-priced. The batch-fired operation may produce prolonged periods of sub-optimal combustion conditions, resulting in lower boiler efficiencies, higher emissions and greater maintenance requirements.
2. An automatically-fed boiler with a fixed combustion bed can receive fuel in a number of ways (under-fed, side-fed, top-fed); however, the lack of movement on the grate requires a homogenous feedstock with lower moisture content to encourage complete burnout. Although fuel specifications are typically stricter with this technology, with the correct feedstock this boiler technology offers a responsive and efficient thermal output at a lower installed cost than moving bed alternatives.
3. An automatically-fed boiler with a moving combustion bed is typically the most expensive installed cost option; however, it pairs the benefit of improved consistency in optimal combustion conditions with an increased ability to burn more challenging feedstocks (higher moisture, reduced homogeneity etc.). The tilting grates are more common at lower output boiler sizes, whereas reciprocating grates are more common as units approach 200kW$_{th}$ and larger.

Combined heat and power (CHP) can be an attractive solution for sites that have appropriate heat and electrical demands. Within the lower electrical output ranges in scope, the principal technology is an Organic Rankine Cycle (ORC), in this case utilising the low/medium temperature thermal outputs of small-scale biomass combustion technologies. Advantages of this technology are comparatively low capital costs and maintenance requirements (compared to steam turbine systems that are not considered viable at this size range) and high availability. However, the electrical efficiency is typically very low and satisfactory commercial payback can be difficult to obtain. For this reason, small-scale ORC systems are generally more commonly installed in waste heat processes than integrated with systems combusting biomass for the purpose of electricity and heat production.

Each technology is reviewed through a summary of the general operation, the development status and history, and options for improvement. In addition, feedstock considerations and the impact on operation and cost are reviewed, including sensitivity analysis of key scale and feedstock criteria.

Due to the substantial number of systems that have been deployed, all boiler technologies described above are considered at TRL9, whilst the biomass-driven ORC technology is at a current TRL of 8-9, with TRL 8 being more applicable to the sub $50kW_e$ market.

The present UK market for small-scale biomass boilers has focused on a relatively small number of bed designs, mostly manufactured in mainland Europe. A review of the major UK equipment suppliers shows that most automatically-fed boilers of fixed bed technology are sized at less than $100kW_{th}$ output with moving bed technologies more common in the 100 – $200kW_{th}$ range. Batch-fired boilers are typically installed up to $150kW_{th}$ but larger industrial-type units are available. As per all boilers in this range, the relatively small and 'off-the-shelf' nature of this technology means that system install times can be very short and the offering of 'containerised' solutions can simplify integration with existing heating systems further.

In all the boiler technologies considered, a biomass feedstock with higher moisture content may struggle to effectively dry and completely combust in a smaller grate area and this will result in lower efficiencies and higher emissions. These factors increase the likelihood of corrosive condensation within the heat exchanger tubes and ultimately either increase the maintenance requirements or reduce the boiler life. Fuels with higher ash content may cause blockages on the grate and could, in high temperature conditions, form deposits that will require manual intervention to remove – alkali metals will also contribute to fouling and slagging, increasing maintenance costs. In addition, combustion of particularly dry (<10%) or irregularly sized fuels may lead to the creation of hot-spots on the grate, creating thermal damage within the furnace. In all cases, a virgin-biomass fuel specification focused on a dry, low ash, and homogeneous supply will result in improved combustion efficiency. However, boiler technologies that can improve the mixing of fuels on the grate, and/or vary the residence time within the furnace will improve fuel burnout rate.

Due to the 'bolt-on' nature of ORC CHP integration with a heat source (biomass-fired or otherwise), small-scale ORC CHP is considered technology and feedstock agnostic with the main contributing factors in cost and output efficiencies being the unit size.

Studies in the UK have found that the average realised efficiency of boiler systems is c. 67%, which is c. 10%-points lower than the average performance standard claimed by European boiler systems of c. 77%. The UK has typically relatively mild and short winters compared to those on mainland Europe and, as a result, it is more likely that a boiler is oversized and operating inefficiently at part load for a larger proportion of time. The banding structure of the Renewable Heat Incentive (RHI) has also contributed to boiler oversizing, leading to poor efficiencies and to higher emissions, plus reliability issues.

Emissions from biomass boilers that are expected to cause the most significant impact to air quality and human health are particulate matter (PM) and nitrous oxides (NO_x). The UK Renewable Heat Incentive (RHI) emission limits dictate that installations need to meet specific emissions limits for PM and NO_x of 30 and 150g/GJ net thermal heat input respectively. Evidence from the boiler manufacturers shows that most modern biomass boilers will not exceed the stated levels when tested in laboratory conditions, but research in Europe shows that emissions rise with inefficient schemes. However, modern boiler designs usually incorporate primary and/or secondary abatement technologies in order to limit the formation of NO_x, and maintain PM emissions under the threshold. PM abatement technology options include multi-cyclones (the most commonly used option), electrostatic precipitators (ESP) and filtration. NO_x primary abatement technologies focus on reducing grate temperatures through the boiler design, and include staged combustion, automated process control systems and fuel gas recirculation. Selective catalytic reactors (SCR) are currently the only secondary NO_x abatement technology available at small scale, but expensive.

There is a wide range of biomass feedstocks available that can be burnt in biomass boilers. To facilitate selection and equipment compliance, European biomass fuel standards have been developed, and fuel quality assurance schemes have been set up to ensure compliance with these standards by suppliers accredited under these schemes. For instance, the ENplus certification scheme was developed to define and ensure consistent quality of wood pellets. Whilst most pellet boiler manufacturers require use of A1 quality pellets to meet the boiler emissions certificate, there is anecdotal evidence that a percentage of pellets used in the commercial and domestic market are not A1 quality. Feedstock must be close to the specification required by the boiler, otherwise it may cause blockages, inefficient operation, condensation in the flue, automatic shutdown of the equipment and emissions problems.

2 Manual Feed – Batch Fired/Fixed Bed

2.1 Technology description

Typically suitable for small commercial or domestic applications, manually fed devices are simple to operate but require a managed wood store and consistent availability of labour. Biomass fuel, which may comprise logs and larger pieces of wood, is manually loaded onto a fixed grate within the appliance. This is typically orientated in an organised, stacked way to maximise the furnace volume available and allow sufficient flow of combustion gases through the fuel bed.

The amount of wood fuel that can be fed into the boiler at one time and the stoking frequency of the boiler are dictated by the size of combustion chamber. Consideration needs to be given to the potential of lower labour availability to feed the wood fuel into the boiler during night or weekend periods to ensure a sufficient thermal energy supply[1]. Where the boiler heat output may be greater than the system load present, it is considered good practice to install a large water storage cylinder (thermal store, accumulator or buffer tank) to capture the heat produced from a manually fed boiler. For instance, when the water temperature rises to above 90°C it will automatically limit combustion air and ensure the heat exchanger pumps are kept turned on to distribute heat elsewhere in the system.

In the event of a critical system failure (for example power failure), there is the potential for a large amount of wood to remain in the furnace and failure of the heating medium pumps. In this event, an emergency heat exchanger coil is usually present within the boiler to rapidly remove heat. This is often connected to mains water supply and released directly to drain.

The biomass grate is located near the base of the furnace and is normally fixed. Once a batch of fuel is loaded onto the grate, ignition is usually carried out manually by the boiler operator using kindling or standard fire lighting procedures. These boilers are often designed to be manually fired over the course of a single day and when the existing fuel batch burns down the next batch is added to the furnace. This activity is repeated as required depending on the appliance output and the required amount of heat[2].

Following each firing, most batch boilers available require a proportion of the solid products of combustion remaining within the furnace to be removed before a new batch is added. Batch fired boilers are usually most competitive on a unit cost basis and, to maintain this simplicity of design, boilers are typically manually fed and de-ashed at the same time. It is usually necessary to leave some ash on the combustion grate to provide a smouldering bed for new fuel. Any visible ash that has deposited in front of air openings within the combustion chamber should also be removed to avoid limiting air supply. A more thorough clean is typically recommended on a monthly basis and this may require a full unit cool-down and may necessitate the removal of accessible combustion chamber parts.

The current state-of-the-art within batch fired boilers is a downdraft boiler. During the ignition process in a downdraft boiler, primary air is added beneath the grate (typically via a manually opened lower door) and a flue bypass flap is opened which enables flue gases from ignition to bypass the heat exchanger section of the boiler. Air is naturally drawn up through the wood towards the flue outlet with primary air manually adjusted to aid progression to a steady combustion state.

Once combustion is underway, an induced draft fan is started and the flue bypass flap is closed. An additional primary air inlet is opened near the top of the fuel pile and the flow of combustion gases is directed down through the furnace. A limited supply of secondary air at the base of the wood pile provides a controlled reduced oxygen combustion process environment, reducing the stack of wood fuel to volatile gases from the bottom of the pile up. These volatile gases are drawn down through the bed and below the furnace grate where full secondary air requirements are added to ensure complete combustion of the volatiles within the gas. Flue gases are then drawn up via a vertical-tube heat exchanger and out of the flue, as shown in Figure 1.

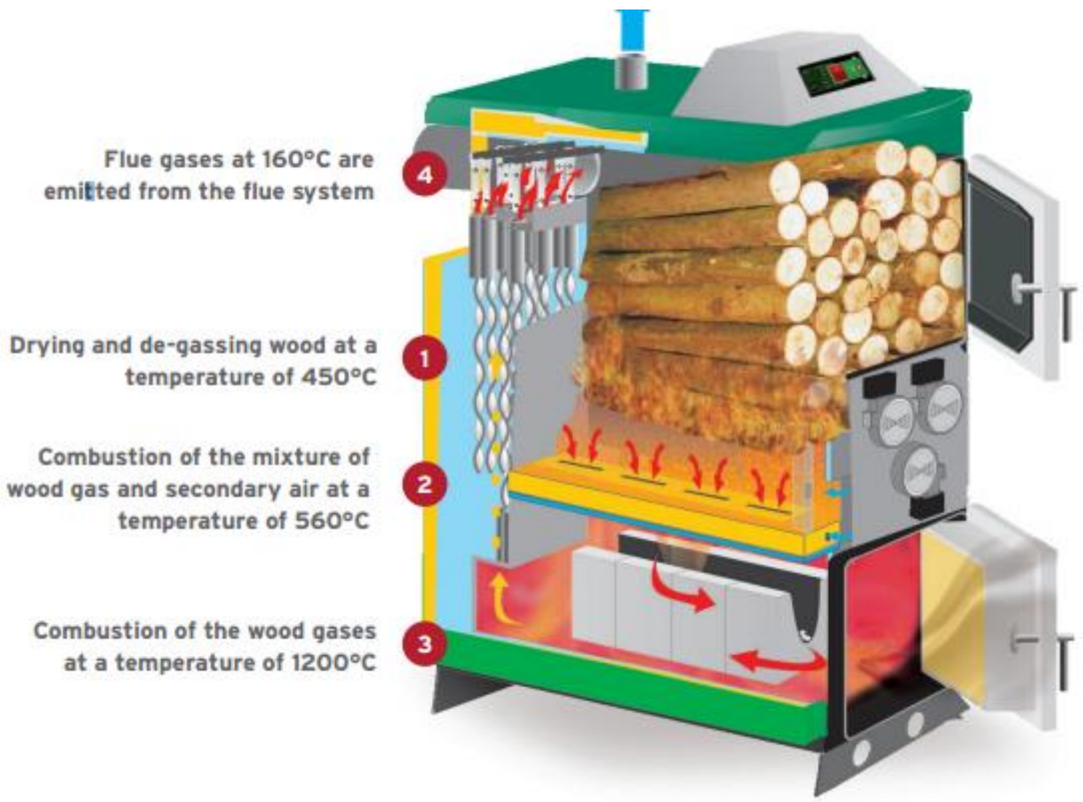

Figure 1: Downdraft log boiler – Eco Angus[3]

For manually-fed plant, a large amount of feedstock is added to the furnace in one load to avoid constant manual re-fuelling duties. This downdraft method leads to a more controlled gasification (reduced oxygen) type process and is now preferred to regulate the consumption of feedstock and normalise the volatile gases produced and combusted, instead of updraft methods where there is less control of burn rate as combustion spreads through the feedstock load.

Up-draft boiler designs were previously more common, and still in use in more traditional log stoves and room heaters. This method of adding combustion air beneath the grate, drawing gases up through the feedstock and completing combustion above in the freeboard section of furnace, is still utilised in many automatically-fed wood boilers where the amount of fuel on the grate is typically much less, more consistent throughout the burn, and certainly less deep at the point of ignition.

The up-draft boilers tend to be more industrial in quality and are designed to handle more substantial heat load demands and these require significantly larger furnace areas, see Figure 2.

These industrial-design boilers pass flue gases through a number of horizontal heat exchanger tubes, often with multiple-passes to improve heat transfer rates. These boilers are typically selected for their cost effectiveness and therefore are less likely to include significant combustion control.

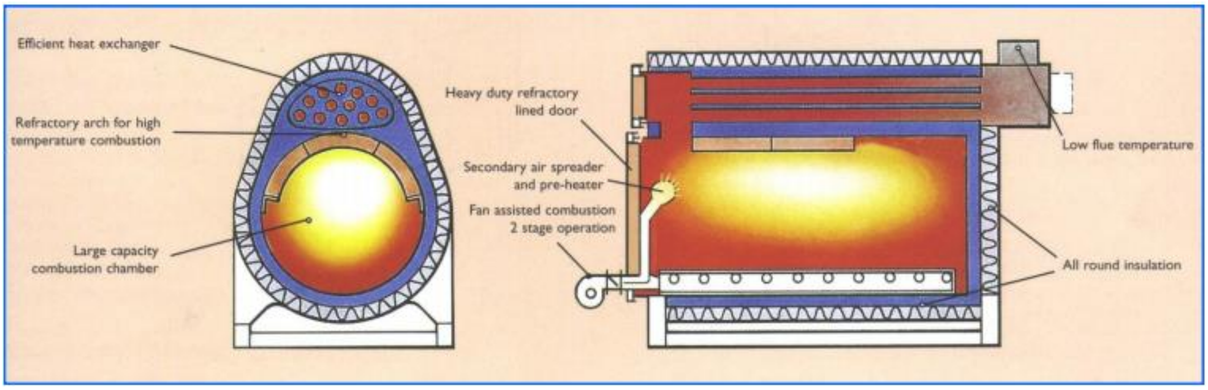

Figure 2: Updraft boiler example – Farm2000[4]

The combustion controls on downdraft log boilers can be as sophisticated as those on fully automatic boilers. Separate control of primary and secondary air can be based on oxygen levels detected within the flue gases and gas exit temperatures, together with a control package to allow control of heating and hot water circuits[1]. However, compared to an automatically fed boiler in which combustion and therefore the heat release rate can be largely controlled by altering the fuel feed rate, manually fed boilers refuelled in batches are not so responsive and rely more on control of air supply as it is not possible to accurately control the fuel feed rate onto the grate[5].

In either style of furnace, refractory is usually focused at the hottest area of the furnace. In the downdraft design this is situated below the grate as this is the predominant combustion zone whereas updraft boilers tend to have refractory above the grate.

Combustion furnaces and heat exchangers are available in different designs and this depends on their end-use energy requirement, biomass properties and characteristics. In general, the biomass combustion process occurs in the furnace where hot flue gas is generated which in turn is directed around a heat exchanger system to transfer thermal energy to the heating medium. In the majority of plant at this scale, the predominant heat output is Low Temperature Hot Water (LTHW) (up to 90°C flow output) to meet space heating and hot water requirements. Heat exchanger tube cleaning is rarely automatic in manually fed boilers; for vertically oriented tubes, an external lever is pulled by the operator which causes a spring type agitator within the tubes to mechanically dislodge any ash deposits on heat exchange surfaces. This process is usually completed as part of the regular batch removal of ash and reloading of fuel. Manufacturers recommend this manual agitation is carried out for each batch process. However, a less frequent complete shutdown will typically also be required and necessitate the boiler to be cooled down completely, after which manual "rodding" of the boiler tubes can be carried out. This is usually via a dedicated inspection port to facilitate access. Adequate space must be allocated around the boiler during design to allow for later in situ maintenance. The industrial-design boilers with horizontal heat exchanger tubes do not typically benefit from agitation between batch firing but do require regular shutdowns and manual rodding procedures to be completed.

Certain manufacturers suggest installing a manually fed boiler with a higher maximum thermal output than the envisaged maximum site demand with the intention of purposefully generating additional heat to charge a thermal store. If the excess heat output and heat accumulator volume is designed correctly then there would be enough thermal energy stored to supply the load demand when the boiler is no longer firing. As boilers operate more efficiently and cleanly when at full output (due to complete combustion being achieved), this strategy needs careful design and consistent loading patterns to maintain efficient operation. This strategy tends not to be followed for suppliers of automatically fed boilers because their technology can restrict the fuel feed entering the combustion chamber.

Due to the thermal storage requirements, manual loading, de-ashing and maintenance requirements, batch boilers are usually installed in a stand-alone boiler house, separate from the building(s) to which heat is being supplied.

2.2 Development status and timescales

Methods of burning biomass feedstocks in manually fed batches for heating purposes have changed over time. The addition of metallic parts such as heat exchanger tubes to continually produce hot water was developed around the industrial revolution, c. 250 years ago. Although certainly considered to be at TRL 9, such an established process still benefits from improvements in design and process conditions, and as such modern log wood boilers can reportedly achieve net combustion efficiencies of circa 90%, compared to approximately 55% in the early 1980´s[6].

Due to the often significant manual labour requirements involved in maintaining and operating batch boilers, common installed sizes are limited to c. 150kW$_{th}$ and most common downdraft units are now available in the range 15 – 70kW$_{th}$ for small commercial applications[6]. Larger industrial units (up to 300kW$_{th}$) are available using updraft technology and can usually be found on farms or basic industrial sites where the required equipment and labour skillset to load fuel and unload ash are present and supplies of suitable feedstocks are available.

Due to the structuring of Renewable Heat Incentive (RHI) tariff bands, heat producing biomass boilers below the 200kW$_{th}$ threshold have been by far the most popular size installed in the UK over the last five years. With the RHI payments come regulations for emissions limits, sustainability of fuel, and the eligibility of the heat demands that are supplied. Historically, commercially-operating farms have benefited from this batch fired technology as it matched well with the specialist labour and handling machinery on site, the potential for batch-style heat demands (e.g. water heating for once-daily clean down processes), and the presence of a multitude of feedstocks. These sites typically benefit from a simple and robust boiler design that is more focused on cost-effectiveness rather than automation or indeed higher efficiencies. It was not uncommon for farmers to be adding clean waste wood, agricultural residues and other biomass wastes into the furnace as a way of both disposal and providing heat. However, this process has officially all but ceased for operators looking to benefit from RHI returns, where all consignments burnt must now be logged and clearly identified as legal and sustainable fuel consignments. The inclusion of emission limits has also meant that these simpler furnace designs either required significant redesign to ensure a more complete combustion and/or, more commonly, the inclusion of flue gas clean up equipment – most commonly an inline cyclone. Specific clean up equipment for nitrogen oxides (NO_x) reduction, via selective catalytic reduction (SCR) or similar, is not commonly included.

Although the domestic / small commercial downdraft type boilers were initially the smaller segment of this technology market, these types were significantly less affected by the changes brought in by the RHI as the plant design was already more focused on efficiency and cleaner combustion in line with the 'green life choice' improvements it offered potential operators.

The main suppliers of biomass boiler technology are from European nations, notably Austria and Germany, where a highly established biomass heating market has existed for decades.

Looking toward the future, recent government announcements for the funding of the RHI are favouring larger (>1MW_{th}) systems. The government appears to be refocusing available incentive funding towards fewer systems and to those with larger heating consumption profiles to meet carbon targets. This has had the effect of putting the future of the smaller scale biomass industry in doubt as in general the potential smaller scale biomass projects will not make the financial returns that they had done pre-RHI (2009), as wood fuel is not as competitive as it was in 2009 due to a significant reduction in fossil fuel market prices since 2014, which will likely slow the sector development to all but the most financially attractive of projects (e.g. self-supplied biomass fuel replacing expensive fossil fuel systems). The batch operation of this technology means it is likely that there will be a lower capacity factor across the year, which would further limit opportunity to make savings on fossil fuels. UK annual sales of batch fired boilers in small commercial environments are projected to reduce significantly under the reformed RHI regime[7].

Due to the 'off-the-shelf' nature of this size range and technology, the timescale for installation of these boilers is typically short. In particular, the absence for the requirement to install a specialist feedstock fuel store and handling equipment makes batch fired boilers arguably the quickest biomass boiler technology to install (typically 1 to 2 months). However, special consideration must be given to the system in which the boiler is to be integrated - in particular the inability to accurately control the boiler output to match specific demands - this drawback may require a thermal store to match the heat demand. Even though a boiler may be shut down, the energy from the fuel load in the furnace needs to be dissipated, and a means to prevent over pressurisation of heating the system is required.

2.3 Impact of different feedstock parameters on operation and cost

General feedstock considerations - size, moisture, ash limits

Handled correctly, batch fired technologies are appropriate for biomass fuels with a high moisture content, of different sizes, and high ash content[8,9]. Upper limits tend to be c. 50% moisture, 2m long fuel (typically baled) and 10% ash for updraft boilers; however, a significant increase in maintenance activity/decrease in combustion efficiency is assumed in these conditions. Downdraft boilers are more focused towards the non-industrial market in which combustion efficiency, low emissions and reduced maintenance requirements are more valued. As such, many downdraft boiler suppliers provide efficiency and emission test results at lower (c. 20%) moisture content and the reduced boiler footprint means upper fuel size limits of c. 0.6m are more common.

The manually fed design has the inherent benefit that there is a much wider scope for fuel feed inputs: if it can be handled and passed into the furnace, then it could theoretically be combusted in the furnace. This could include chips, split logs, whole logs and even bales of brash/energy crops. However, the spacing of the feedstock bed will certainly affect combustion conditions and also likely the length of burn time. For example, a dense bed of tightly packed feedstock may inhibit combustion air flow and either result in pockets of non-combusted fuel or poor combustion conditions in the freeboard, leading to incomplete combustion. Large amounts of small particle size fuel may burn quicker than the same mass of log wood resulting in a more intense, but less prolonged, burn out and require more frequent refuels. For this reason, operators of batch fired plant tend to either stick exclusively to what the manufacturers recommend (this is particularly true in cases where supplier warranty or RHI payments will be affected), or develop a strong understanding of their equipment and the varied results from unique feedstocks and preparation – typically requiring significant labour attention and understanding.

Emission limits

Compared to the larger technologies, these smaller technologies have limited clean-up technology in place. A significant reason for this is to retain cost effectiveness: significant flue-gas clean up equipment will typically not be cost effective for smaller plants. As described in the previous section, RHI emission limits have required suppliers of the more basic technology types to bring their products into line (see Section 6.3 for figures). From a feedstock perspective, this also means that fuel specifications need to be significantly stricter; typically limiting feedstocks to virgin wood with low ash and low moisture content to improve combustion conditions.

The incomplete combustion of wood results in the release of carbon monoxide (CO), volatile organic gases, benzene and other undesirable substances. Studies have shown CO emissions up to 50 times higher in simple batch fired equipment compared to automatic fed systems, with this figure reducing with the introduction of air staging or other combustion controls. However, even in automated combustion appliances, when the combustion conditions are not optimal, the CO emissions may increase. This finding was observed with low loads, where the CO emissions are more likely to exceed the limits imposed by RHI regulations and may require improved design for handling partial loads[1].

High combustion temperatures (>1,300°C) promote NO_x, so in small-scale biomass boilers capable of temperature control within the furnace (via flue gas recirculation or otherwise), combustion temperatures are typically controlled to <1,200°C, thereby reducing NO_x formation. Therefore the principle NO_x emissions from appliances of this scale are reported to be fuel dependant[10], providing the combustion technology is sufficient to regulate combustion temperatures. As discussed in Section 6.3, there are secondary abatement technological options available to decrease NO_X emissions (such as SCR); however, these options are not yet common in small-scale appliances. Moreover, the emissions are more likely to remain below the emission limit when commercial wood pellets and other pellets that are primarily composed of virgin wood are used. When the fuel contains more bark (containing N), such as in logging residues, it is more likely that NO_X limits are exceeded.

Particulate organic matter (POM) and soot are products of incomplete combustion; their contributions to the total particulate matter (PM) emissions can vary significantly depending on the combustion conditions. Inorganic fine fly ash particles are not products of incomplete combustion: their reduction is not possible by improving combustion efficiency; however, it should be noted that improved efficiency generally results in lower fuel input requirements and therefore lower ash input. Equipment suppliers who want their new boiler sales to be eligible for RHI payments have added cyclones (or ceramic filters) to reduce particulate emissions to within limits[2].

Sensitivity Analysis

The cost curve in Figure 3 corresponds to the total investment cost per unit of output thermal capacity for a manually fed biomass boiler (both updraft and downdraft furnace designs inclusive). It has been derived from quotes provided by suppliers (2016) for all-in overnight Engineering, Procurement, Construction (EPC) costs.

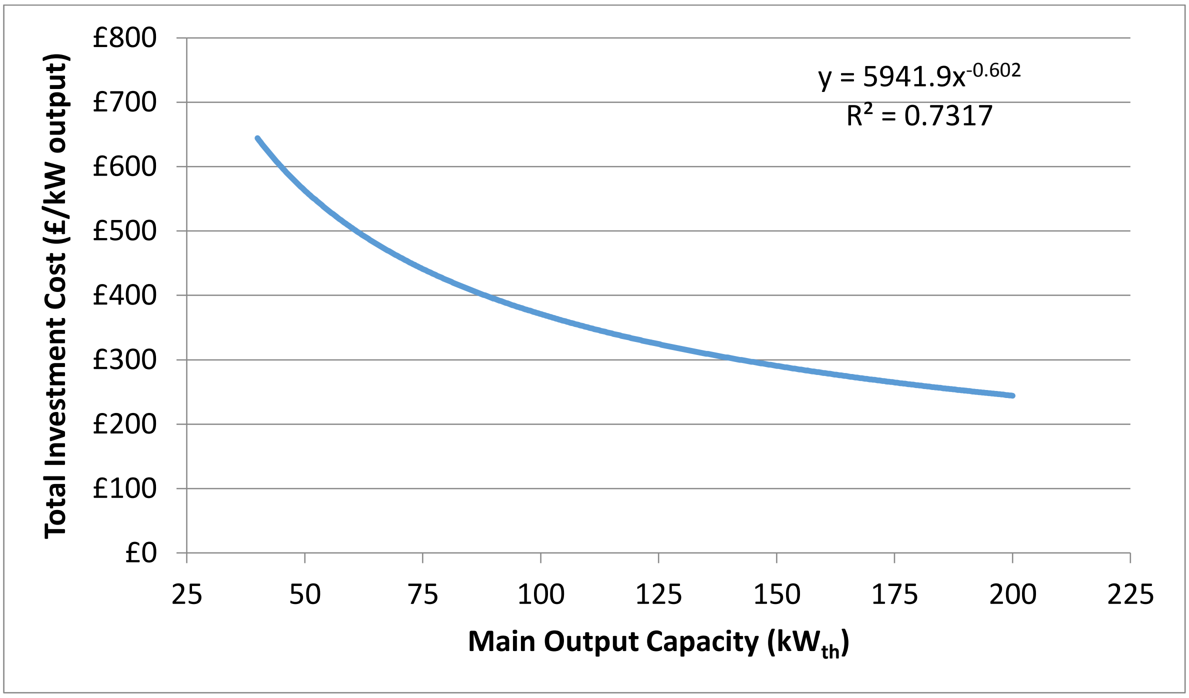

Figure 3: Manually fed (biomass heat) total investment cost vs. heat output capacity (derived from 23 supplier quotes (2016) and B&V data for all-in overnight EPC costs)

Total operational costs for manually fed heat technologies include fixed costs (insurance, maintenance parts and labour) and variable costs (operations labour, ash disposal). For Low Temperature Hot Water (LTHW)/ Medium Temperature Hot Water (MTHW) boilers, water use is negligible and that the operating thermal output range does not require the addition of reagents. Figure 4 shows the relationship between annual total operational cost for a manually fed boiler per unit of energy output and the output capacity.

Except where the parameter of interest is shown on the x-axis, the curves in Figure 4 to Figure 8 are all created using the following base values: Main output capacity = 50kW$_{th}$; boiler capacity factor of 20%; feedstock moisture content (WB) = 30% and a feedstock ash content (DB) = 1.5%.

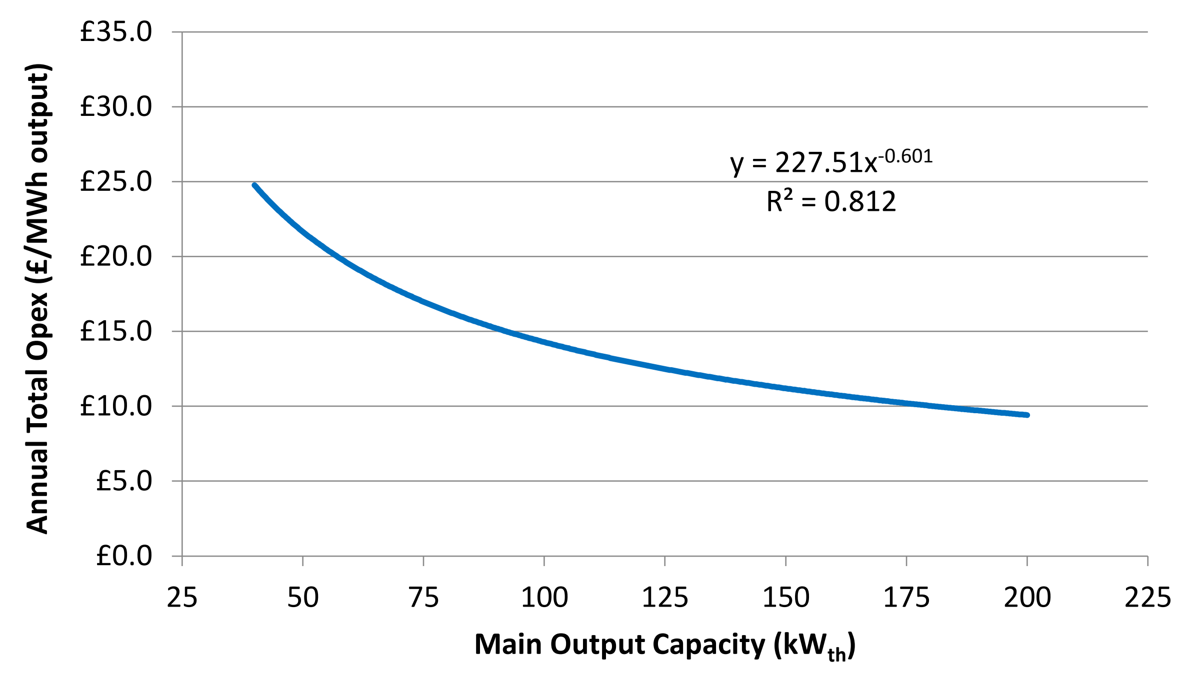

Figure 4: Manually fed (biomass heat) annual operating cost per unit of energy output vs. heat output capacity (derived from B&V industry data)

Figure 5 below highlights the change in overall manually fed boiler (Low Heating Value (LHV)) efficiency over varying feedstock moisture content. The efficiency is calculated as heat energy output over fuel energy input. The curve is considered to be a representative average across the potential rated output range.

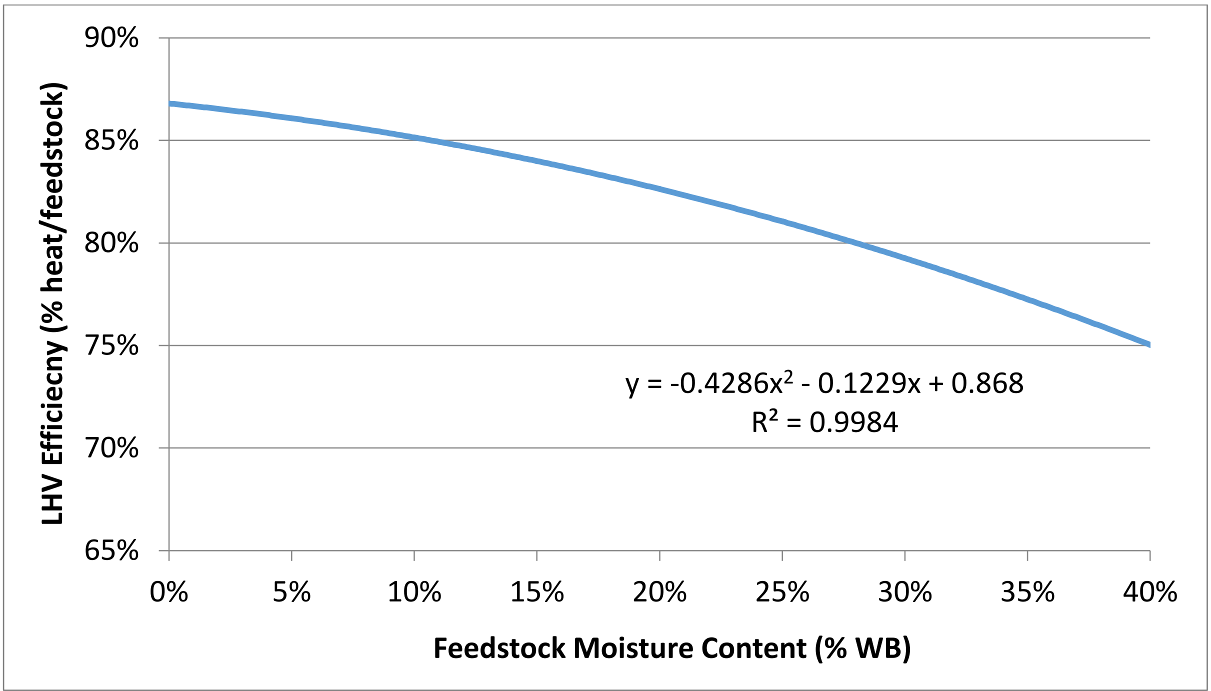

Figure 5: Manually fed (biomass heat) efficiency vs. feedstock moisture content (derived from Original Equipment Manufacturer (OEM) data and B&V data, considering a representative average across the rated output range)

The total operational costs for manually fed heat technologies are related to feedstock moisture content as shown in Figure 6 below. Annual operational costs also vary with the percentage of ash present[11] within the feedstock, as shown in Figure 7 below.

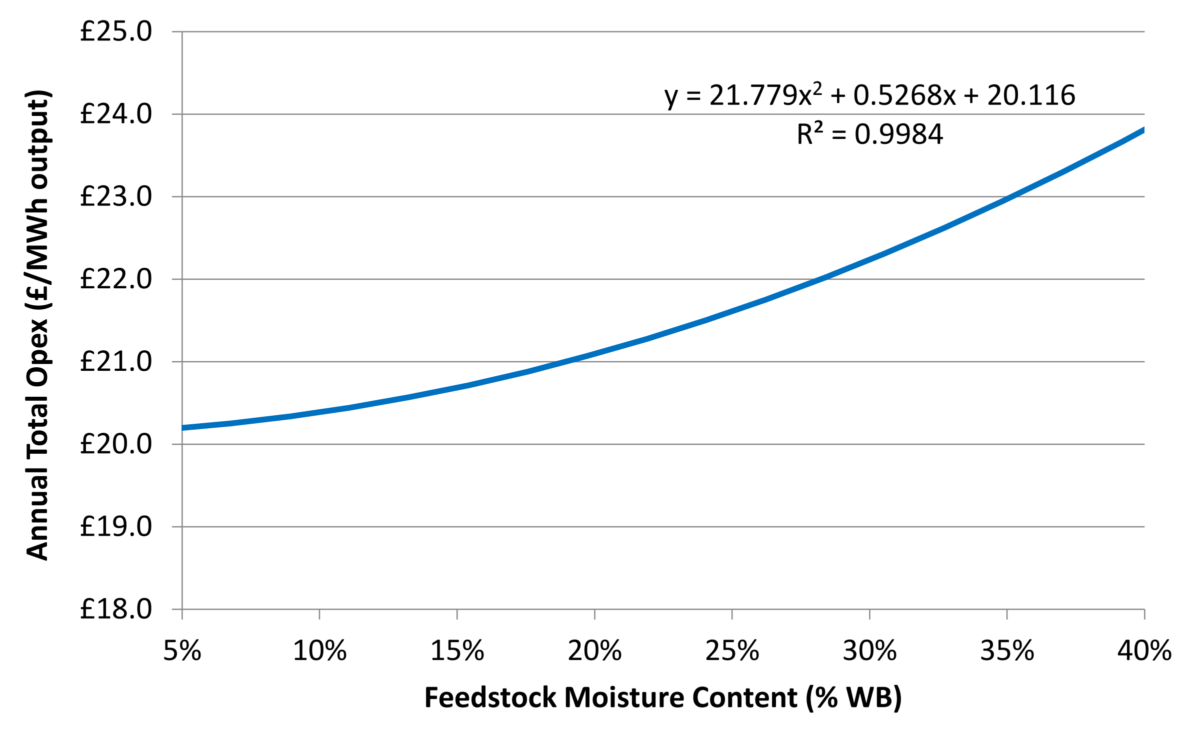

Figure 6: Manually fed (biomass heat) annual operating cost per unit of energy output vs. feedstock moisture content (derived from B&V industrial data)

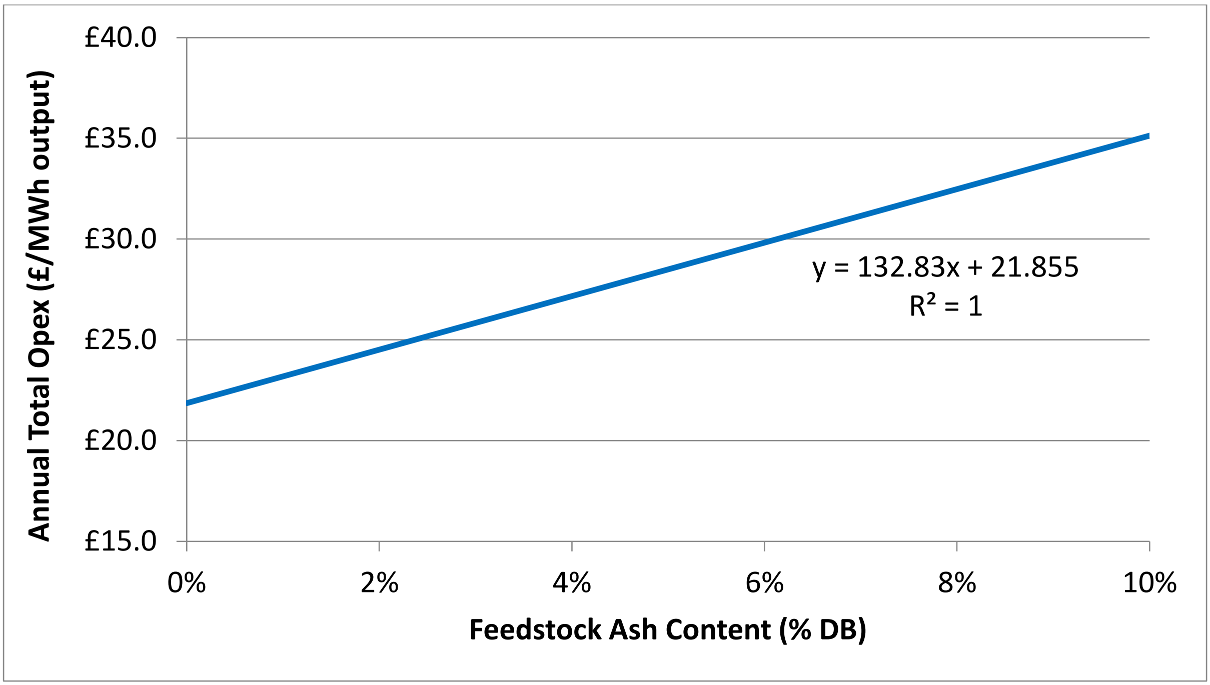

Figure 7: Manual fed (biomass heat) annual operating cost per unit of energy output vs. feedstock ash content (derived from B&V industrial data)

As described above, reagent use is typically negligible across the output range available for heat only boilers, although high alkali metals will lead to increased maintenance. Figure 8 below displays the relationship between the alkali index (kg potassium oxide (K_2O) and sodium oxide (Na_2O) per GJ input energy) and the annual total operational cost for a manually fed plant per unit of energy output.

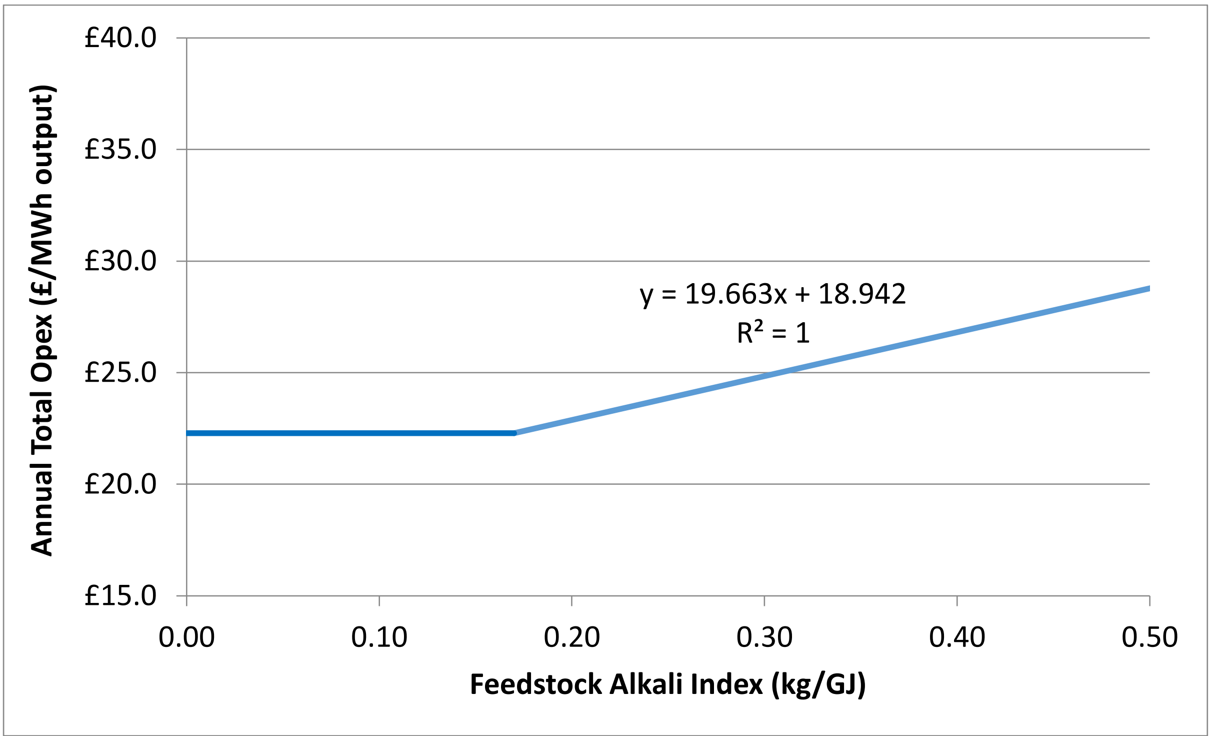

Figure 8: Manually fed (heat) annual operating cost per unit of energy output vs. feedstock alkali index (derived from formula based on [12] and Section 2.4.2.5 of D1).

2.4 Available options for improvement

Some of the more significant improvements in manual feed boiler design are listed in Table 1 and summarised below.

Table 1: Improvements Analysis of Manual Feed Furnaces

Issue arising due to biomass characteristic	Options to ameliorate	Evaluation of effect	Long Term Improvements
Poor combustion conditions due to high feedstock moisture content.	Dry the fuel before use; Limit the wet fuel used; Use of down-draft method may increase drying time within furnace before controlled combustion.	If fuel specification is fixed for wet fuel, use of a down-draft method may increase the fuel drying time within furnace before controlled combustion takes place.	Reduction in PM emissions due to incomplete combustion; Improved boiler efficiency and availability.

Fouling of heat exchanger tubes from biomass ash and volatiles content	More thorough maintenance routine; Automatic heat exchanger tube cleaning; Vertical heat exchanger tubes; Increase combustion gas residence time within furnace.	Boiler suppliers will give recommendations on the maintenance requirements. However this may need to be increased in frequency / depth of clean depending on fouling present after each burn[1].	Increased cleaning frequency improves heat transfer and boiler efficiency; Preventative maintenance reduces unplanned boiler downtime.
High fouling of unburnt organics due to poor combustion (typically high moisture content fuel)	Design furnace for full combustion - e.g. air staging to burn off all flue gases.	When combustion air is fed in two stages, the primary combustion air flow can be reduced. This slows the gasification of the fuel and creates both a separate zone for the gasification of the fuel and a secondary combustion zone in which combustion gases are efficiently burned out[1314].	Reduced emissions and environmental impact; Combustion conditions easier to control; More stable combustion.
Increased emissions due to poor combustion conditions (typically from high moisture content fuel)	Install flue gas clean up equipment; Increase combustion gas residence time within furnace; Use of down-draft method may increase extent of combustion of volatile gases created.	If methods to improve boiler combustion efficiency are not successful (under-fed design, two-stage combustion air addition etc.) then the use of a cyclone or similar will remove a proportion of particulate from the flue gas and should be designed to ensure emissions are within required limits.	Reduced emissions and environmental impact.
High ash fuel blocking combustion air inlets	More thorough maintenance routine;	Due to repeated manual loading requirements of this technology, most suppliers advise that grate and furnace walls are de-ashed between each refuel or similar; Automated ash removal is uncommon from the grate.	Improved heat transfer; Lower differential pressure and fan power.
Inconsistent combustion conditions due to non-homogenous fuel within furnace	Combustion air control – staged and auto varying depending on flue gas conditions.	Allows adjustment of combustion air flows to be sufficient for conditions present within the furnace.	Increased combustion efficiency; Reduced emissions and environmental impact.

Manual feed boilers often have relatively low capital costs compared to competing technologies within the size range. As discussed in the previous sections, this is often reflected in their fuel and ash handling abilities. Therefore, any design additions or modifications to improve operational improvement must consider the increases in equipment costs to retain competitiveness.

This type of boiler is not usually provided with automatic ignition, but a significant technology modification is to manufacture batch-fired boilers that incorporate automatic feed pellet burners. These boilers combine the best features of a batch fed log burner and an automatic ignition function, giving the user considerable flexibility over the way in which the boiler is operated. The logs (or other manually fed biomass fuel) can be automatically lit at any time using the pellet burner and once the logs have completely combusted, the system automatically switches to pellet operation. Such boilers may have an automatic feed auger entering a pellet burning chamber, with a separate, adjacent, combustion chamber for logs. They may also feature automatic de-ashing, control of combustion air supply fans by a lambda sensor in the flue, and automatic ignition[1,15]. A pellet fuel store or silo is required for use with this type of boiler, but the advantage is this technique reduces the variations in the batch combustion process, maintains combustion, and avoids start up and shut down issues[1].

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[1] Palmer, D., Tubby, I., Hogan, G. and Rolls, W. (2011). Biomass heating: a guide to small log and wood pellet systems. Biomass Energy Centre, Forest Research, Farnham.

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[9] Vos, J., 2005. Biomass energy for heating and hot water supply in Belarus. Enschede: University of Twente.

[10] Rabacal, et al, 2014. Fuel, Volume 199, pages 141-152.

[11] The ash disposal chart does include a £120/tonne cost for ash disposal, in addition to the other fixed and variable costs. Although it is true that many sites will just be binning their ash along with other waste streams from the buildings, B&V have stated that commercial (non-domestic) best practice would not be to dispose of ash in this way, and hence keeping the same ash disposal cost assumption as for larger plants is appropriate

[12] Fahmi R., Bridgwater A. V., Darvell L. I., Jones J. M., Yates N., Thain S., et al. (2007). The effect of alkali metals on combustion and pyrolysis of Lolium and Festuca grasses, switchgrass and willow. Fuel 86, 1560–1569 10.1016/j.fuel.2006.11.030.

[13] Tissari, J. 2008. Fine Particle Emissions from Residential Wood Combustion.Ph.D. Thesis. Kuopio University Publications C. Natural and Environmental Sciences 237. 63 p.

[14] Van Loo, S. & Koppejan, J., 2003. The handbook of biomass combustion and co-firing. s.l.: International Energy Agency.

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3 Automatic Feed – Fixed Bed

3.1 Technology description

At output scales less than 200kW$_{th}$, automatic fed boilers with fixed beds are commonly used for simple, less labour intensive heat generation to combust pelletised biomass feedstocks produced to strict fuel specifications. What this technology may lack in fuel flexibility when compared to batch fed devices, it makes up for in increased control of thermal output and resulting efficiency and emission improvements.

Small scale fixed bed boiler design will typically introduce fuel to the grate in one of three ways, named in this report as: under-fed (1), side-fed (2) or top-fed (3), as shown below in Figure 9.

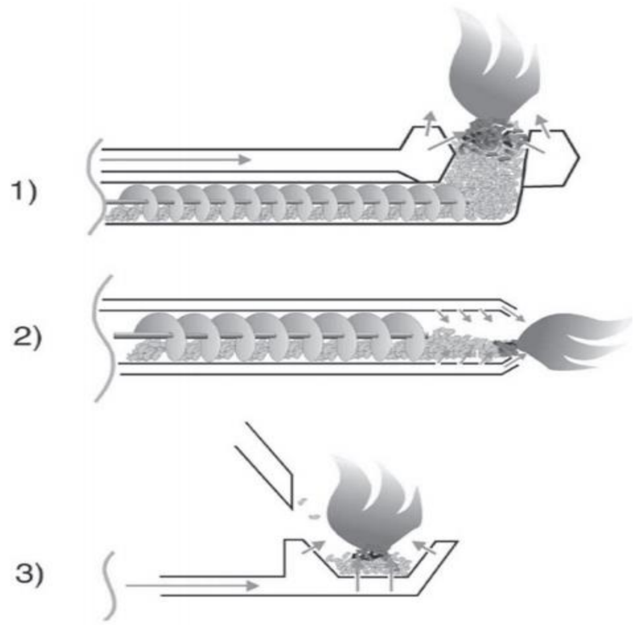

Figure 9: Representation of under-fed (1), side-fed (2) or top-fed (3) fixed bed grates, derived from [16]

From a technological perspective, the operation and combustion processes of under-fed furnace types are very similar to that which are present in the larger units described in Section 3.1 of D1. The combustion grate located inside the boiler is supplied with biomass using an augur feeding system that is located beneath the combustion area. The auger feeds a chamber, commonly known as a 'retort', and the pressure from the feeding system pushes the biomass fuel upwards from below into the retort. Fuel coming into the retort then provides a controlled flow of biomass for combustion and also prevents movement of air between the combustion chamber and fuel store, with fuel exiting the retort onto the grate being at the combustion front.

In smaller systems, the retort is located in the centre of the combustion chamber and as more fuel enters, it spills over and spreads across a surrounding grate or plate, where it is subject to primary air and radiant heat[17]. Typically, the grate system is designed for combusted ash to be pushed until reaching the edge of the grate where it drops into an ash collection area. However, at the smaller scale, as the load increases, manual intervention for ash removal may be required due to combustion occurring at less than optimum conditions.

With side-fed burners, the fuel is introduced horizontally into the combustion chamber that is fitted with a grate in a similar fashion to underfed designs. Forcing sufficient fuel through the auger tube creates a “fuel plug” preventing the passage of air between furnace and fuel store. Fuel is shunted along the fixed grate by new feedstock from the stoker auger. The fuel feed rate is regulated to ensure sufficient time to achieve maximum burnout on the grate and this varies with moisture content. Well-designed systems ensure fully combusted fuel is pushed off the end of the grate or falls through into a collection area. The grate is often slightly sloped to encourage movement across the grate.

The design of both underfed and side-fed systems makes the potential for burn-back along the stoker auger high, typically requiring it to be emptied on boiler shut down to prevent back combustion of the fuel in the feeding mechanism. In the event of over-temperature in the stoker auger, water dousing is provided and controlled via a bimetallic strip or basic wax seal. The smaller fuel quantities involved in these systems may be able to benefit from pneumatic delivery systems. Smaller systems are less likely to have purpose-built boiler houses due to additional costs (to remain competitive with fossil fuel alternatives) and pneumatic delivery gives greater flexibility in locating the fuel storage as typically plant room space is more restricted. Pellets are normally blown into a day hopper which would be used to feed the stoker auger. However, this pneumatic approach is uncommon in plant with output greater than $100kW_{th}$.

Top-fed systems are developed for pellet combustion in small scale units such as pellet stoves. Fuel feeding from above the grate via a downward sloping chute: the pellets then fall via gravity through a shaft onto a fire bed below within a retort or grate. This provides an inherent advantage of an air gap between the combusting fuel and the fuel feed auger and so prevents burn back. The newly added biomass fuel will be continually burnt on the grate. This design is considered to be less common when configured with a fixed bed, since ash removal is limited to burned fuel falling through gaps in the grate which itself limits the flow of primary combustion air. There is therefore an increased requirement for manual de-ashing intervention with top-fed systems.

Whether bottom ash is pushed off the sides from the grate or falls through the grate, it is typically collected in a dedicated area which can either be manually removed from the furnace or, more commonly, transported via another auger into an ash storage vessel to aid simple waste disposal for the operator. Smaller ash particles are held in suspension in the flue stream. Depending on the emission controls present on the boiler, flue gas particles may be collected within a multi-cyclone unit or discharged direct to atmosphere. Any ash deposits that form inside the boiler (in particular, on the heat exchanger tubes) will also need removing as part of a regular maintenance routine.

With all of the fuel feed options, once fuel is present on the grate, the boiler controls run through an auto ignition procedure: ignition is generally by an electrically-heated hot air gun. Due to the continuous nature of the process, which is ensured with automatic fuel and air feeds, both heat release and gaseous emission are more stable than in batch combustion[16]. To ensure correct combustion conditions, measurement of oxygen levels in the flue gas can be used for controlling the combustion conditions and adjusting the air to fuel ratio.

High residual heat held in the furnace will heat and dry the feedstock on entering the combustion chamber. Primary air is supplied from under the grate for the combustion of the biomass. Secondary air is supplied in the combustion chamber freeboard for the combustion of the volatile gases. All newly added biomass fuel will be continually burnt by heat from the char combustion and the smaller scale process has an advantage of being easier to control in partial-load behaviour than other technologies, since load changes can be achieved quickly and easily by fuel feed supply[16,18].

Smaller units may utilise a single fan to supply both primary and secondary air supply with modulating butterfly type valves to direct air around the furnace as required. Certain boiler suppliers also combine the induced draft fan operation into one single fan unit, maintaining the furnace under a set negative pressure whilst drawing in fresh air at determined primary and secondary points. This has advantages for both parasitic and maintenance purposes.

The combustion chamber is typically lined with temperature resistant tiles/bricks/castable refractory. As is common in most boilers, the refractory is in sections to allow thermal expansion and replacement as required. Certain boiler models direct the combustion air in channels through the refractory material to provide both wall cooling and to prevent thermal damage and a degree of pre-heating of the combustion air to improve combustion efficiency[19]. Water cooling of the grate or refractory walls is uncommon at this size scale (less than $200kW_{th}$).

In the majority of plant at this scale, heat output is predominantly via LTHW (up to 90°C flow output) to meet space heating and hot water requirements. Heat exchanger tube cleaning is typically automatic, as the fuel feed may require continual operation, so would not benefit from frequent manual operation like a batch-fired boiler. At this scale, physical agitation of tubes (via hollow core auger or similar) is more common than compressed air (via separate compressor unit) to minimise additional equipment requirements. The method of physical (as opposed to pneumatic) tube cleaning has a potential benefit of acting in such a way as to increase turbulence and heat transfer rates of flue gases within the tubes. However, care must be taken to avoid fouling on the agitator itself. Most heat exchangers are supplied with suitable tools for rodding and manufacturers will recommend this is carried out at least at 6 monthly intervals. Horizontally mounted heat exchangers are more prone to fouling as ash can build up more easily in the horizontal tubes.

The volume of water in the boiler is typically low in order to produce a fast response to heating load demands and control of fuel feed rate allows for significant modulation of thermal output. Many suppliers advise that their boiler products offer modulation and response abilities to directly replace fossil fuel systems without the inclusion of a thermal store. However, it is considered best design practice that a thermal store is provided when using biomass boilers to increase the amount of heat provided by biomass. This is to encourage the boiler to operate at a thermal output near design rather than modulate down to a lower site demand. Higher output near or at design condition improves combustion and reduces the production of pollutants when compared to part load operation[18].

3.2 Development status and timescales

Following its early use in small-scale coal burning units, automatic feeding of fuel onto a fixed bed, either from above or below the grate, has been developing for more than 100 years. Within the smaller (<$200kW_{th}$) scale units, this technology has been adapted to suit specific biomass feedstocks and over the last 30 years has become a safe and relatively cheap technology. The current status is therefore technology readiness level (TRL) 9.

The RHI has significantly strengthened the UK market for biomass boilers smaller than $200kW_{th}$, with over 11,200 non-domestic installations registered since 2011. Of these, the majority of non-domestic installations were in the capacity ranges of 45-100kW$_{th}$ and 150-199kW$_{th}$. These trends can be in part explained by the banding and tiers in the RHI. Therefore, it can reasonably be assumed that trends in future are likely to be influenced by policy as long as biomass boilers require subsidies to make them economic to install[20]. Without subsidies, business cases will typically be determined by fossil fuel prices and the availability and price of the biomass resource. As the smaller fixed bed units are typically limited to pellet fuels only (commonly much more expensive fuel than wood chip), then non-subsidised business cases for these boilers may be limited to sites not connected to the national gas grid or using expensive fossil fuels.

Mostly supplied by European boiler models, the present UK market for fixed bed auto-fed boilers has focused on a relatively small number of fixed bed designs. A review of the major UK equipment suppliers shows that most boilers of this technology are sized at less than 100kW$_{th}$ output with moving bed technologies more common in the 100 – 200kW$_{th}$ range. Should a site owner wish to utilise fixed bed technology at a size closer to 200kW$_{th}$ (or larger), then most suppliers offer the capability to install boilers in cascade, sharing central control processes to operate and modulate individually as required to meet a total heat demand. Suppliers typically highlight the enhanced response and modulation abilities of this approach. For example, a 400kW$_{th}$ system comprising 4 x 100kW$_{th}$ boilers may be capable of operating anywhere in the range of 20kW$_{th}$ (by firing a single boiler at lowest output) to 400kW$_{th}$ (all four boilers at 100% output). This is an output range of 5 – 100% and is typically not possible for a single biomass boiler to achieve. Cascaded systems also offer improved redundancy should a boiler breakdown. However, these advantages always must compete with the available footprint area and the capital to purchase, maintain and operate multiple biomass boilers.

The relatively small and 'off-the-shelf' nature of this technology means that system install times can be very short. The boiler install itself can often be done in under a week as it is essentially delivered complete in modules, requiring modular assembly, flue(s) installation and integration into the heat demand. Typical project installation of the biomass boiler and integration may take in the order of 2-3 months depending on the actual site requirement.

3.3 Impact of different feedstock parameters on operation and cost

General feedstock considerations

Within a thermal output range below 200kW$_{th}$, the physical size of the boilers are a limiting factor on the fuel types that can be combusted. As stated previously, fixed bed boilers are more common within the <100kW$_{th}$ output range and, as a result, typically have a small boiler footprint. This smaller footprint means less combustion chamber volume and fuel grate surface area are available for the complete burnout of fuel.

An inherent design advantage of this type of boiler is the ability to control fuel feed rate and this will assist in improving responsiveness. For under- and side-fed boilers, the requirement to continually feed fuel onto and across a grate means a design preference for homogeneous, more free-flowing fuel types which is most common in pelletised fuel. More irregular size or specification fuels may increase the tendency for bridging, fuel blockages or inconsistent supply of fuel across the grate. In the event of sudden fuel shortage on the grate, the boiler output may fall and/or potentially the grate will be exposed to high radiant temperatures from localised refractory. If repeatedly occurring, this may cause heat damage to the grate and lead to increased maintenance costs.

For top-fed boilers, a non-homogeneous fuel may undergo combustion reactions at different rates and cause temperature imbalances within the combustor retort. This may result in incomplete combustion of fuel, the products of which would fall through the grate, blocking the primary combustion air outlets and generally reducing combustion efficiency. Inversely, certain fuels may combust faster and create localised high temperature areas which may cause damage to the surrounding grate and refractory.

For the fixed bed design in general, there is little in the way of fuel mixing to provide even combustion conditions. Fuel with higher moisture content such as wood chip may struggle to effectively dry and completely combust in a smaller grate area and this will result in lower efficiencies and higher emissions. These factors increase the likelihood of corrosive condensation within the heat exchanger tubes and ultimately either increase the maintenance requirements or reduce boiler life. Fuels with higher ash content may cause blockages on the grate and could, in high temperature conditions, form clinkers (vitrified residue) that will require manual intervention to remove. Ash-rich biomass fuels, such as Miscanthus, require increasingly efficient ash removal systems. For this reason, suppliers will often specify a dry homogeneous pellet fuel only to be used.

Emissions

The PM_{10} and NO_x emission limits imposed as part of RHI acceptance criteria mean that the majority of boiler suppliers have specified that only 'ENplus (A1 or A2)' certified wood pellets should be used in their boilers, otherwise the warranty could be at risk. This means that very few boilers of this technology and scale in the UK advise they can handle anything other than pellets. By permitting only a dry, consistent fuel, combustion conditions can be better regulated and the combustion is more fully completed. The addition of secondary air to complete burn-out of volatile materials in suspension will help reduce particulate emissions.

Commercially operating plants often incorporate an integrated multi-cyclone unit to remove fly ash and particulates from the flue gases and it is unusual for any additional flue gas treatment to be included such as filters. The strict fuel specifications and lower output capacities typically negate the requirement for additional emission control equipment (including chemical additions) for all but the lowest permitted cases. Due to the lack of advanced flue gas treatment equipment (SCR etc.) on these simple boiler units, fuels with 'non-standard' chemical composition are not permitted to be burnt if the operator is to stay within warranty.

In addition to the more common form of pelletised or granular fuels being capable of combustion (such as wood pellets, energy grain, rape pellets and straw pellets etc.), bespoke units may also burn wood chips up to a maximum size of 60 mm in length and 20 mm diameter, with moisture contents of 15% - 40%.

Sensitivity Analysis

The cost curve in Figure 10 corresponds to the total investment cost per unit of output thermal capacity for an automatic feed, fixed bed biomass heat boiler. It has been derived from quotes provided by suppliers (2016) for all-in overnight EPC costs.

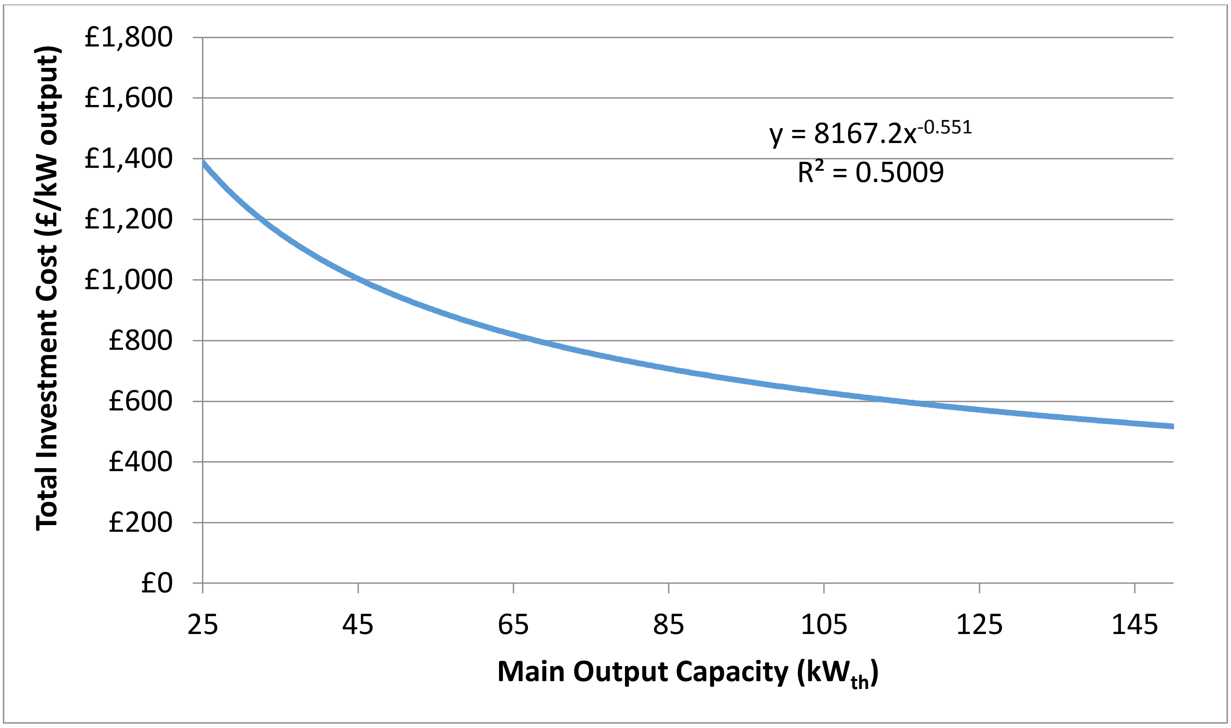

Figure 10: Automatic feed, fixed bed (biomass heat) total investment cost vs. heat output capacity (derived from 20 supplier quotes (2009-2016) and B&V data for all-in overnight EPC costs)

Total operational costs for automatic feed, fixed bed heat technologies include fixed costs (insurance, maintenance parts and labour) and variable costs (operations labour, electrical operating load, ash disposal). For LTHW/MTHW boilers, water use is negligible and that the operating thermal output range does not require the addition of reagents. Figure 11 shows the relationship between annual total operational cost for an automatic feed, fixed bed fed boiler per unit of energy output and the main output capacity rating.

Except where the parameter of interest is shown on the x-axis, the curves in Figure 11 to Figure 15 are all created using the following base values: Main output capacity = 90kW_{th}; boiler capacity factor of 40%; feedstock moisture content (WB) = 30% and a feedstock ash content (DB) = 1.2%.

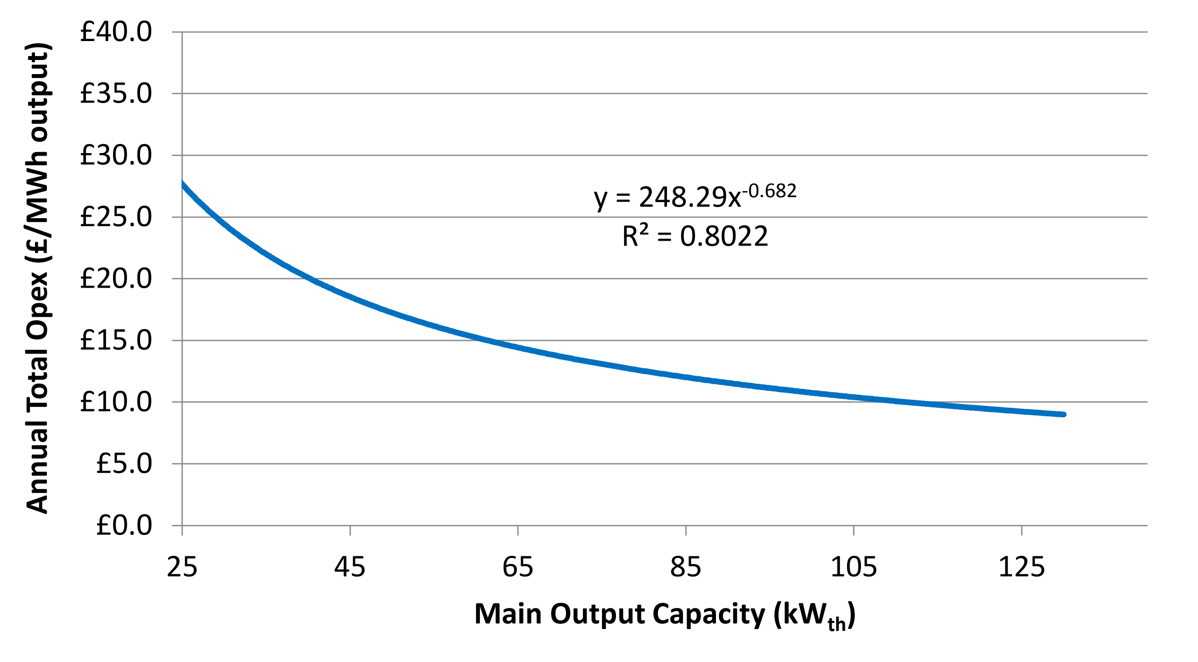

Figure 11: Automatic feed, fixed bed (biomass heat) annual operating cost per unit of energy output vs. heat output capacity (derived from B&V industry data)

Figure 12 below highlights the change in overall automatic feed, fixed bed boiler (LHV) efficiency over varying feedstock moisture content. The efficiency is calculated as heat energy output over fuel energy input. The curve is a representative average across the automatic feed, fixed bed potential rated output range.

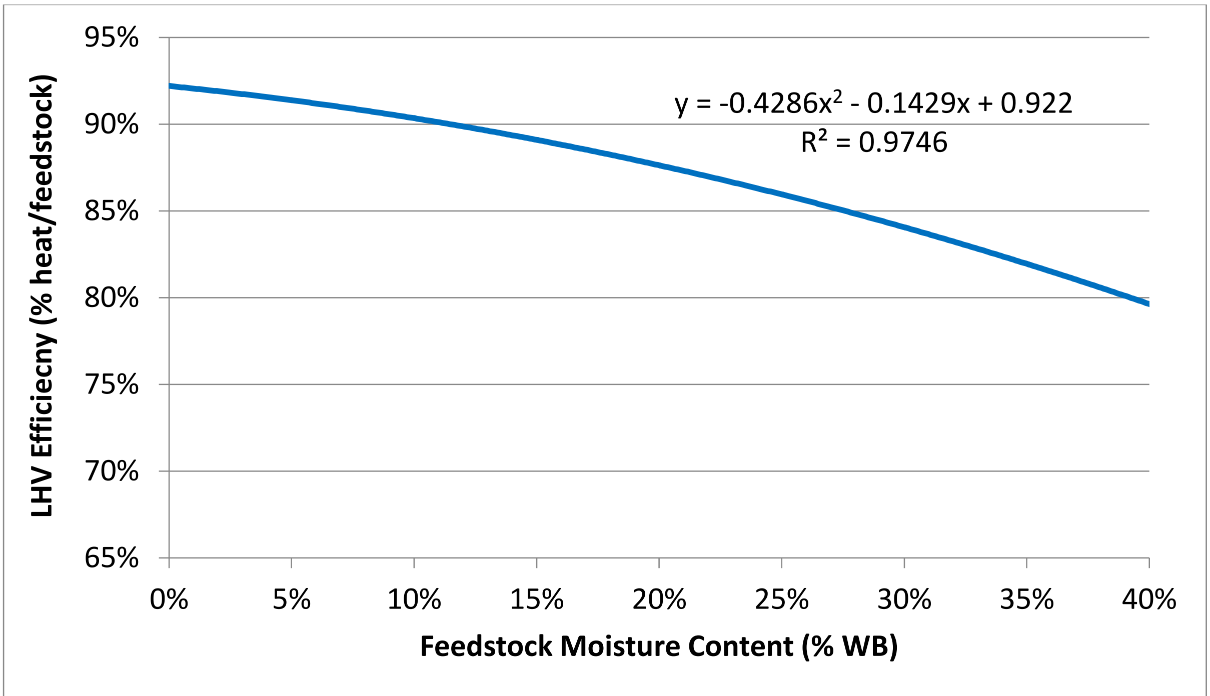

Figure 12: Automatic feed, fixed bed (biomass heat) efficiency vs. feedstock moisture content (derived from OEM data provided by B&V, considering a representative average across the rated output range)

The total operational costs for automatic feed, fixed bed heat technologies are related to feedstock moisture content as shown in Figure 13 below. Annual operational costs also vary with the percentage of ash present within the feedstock, as shown in Figure 14 below.

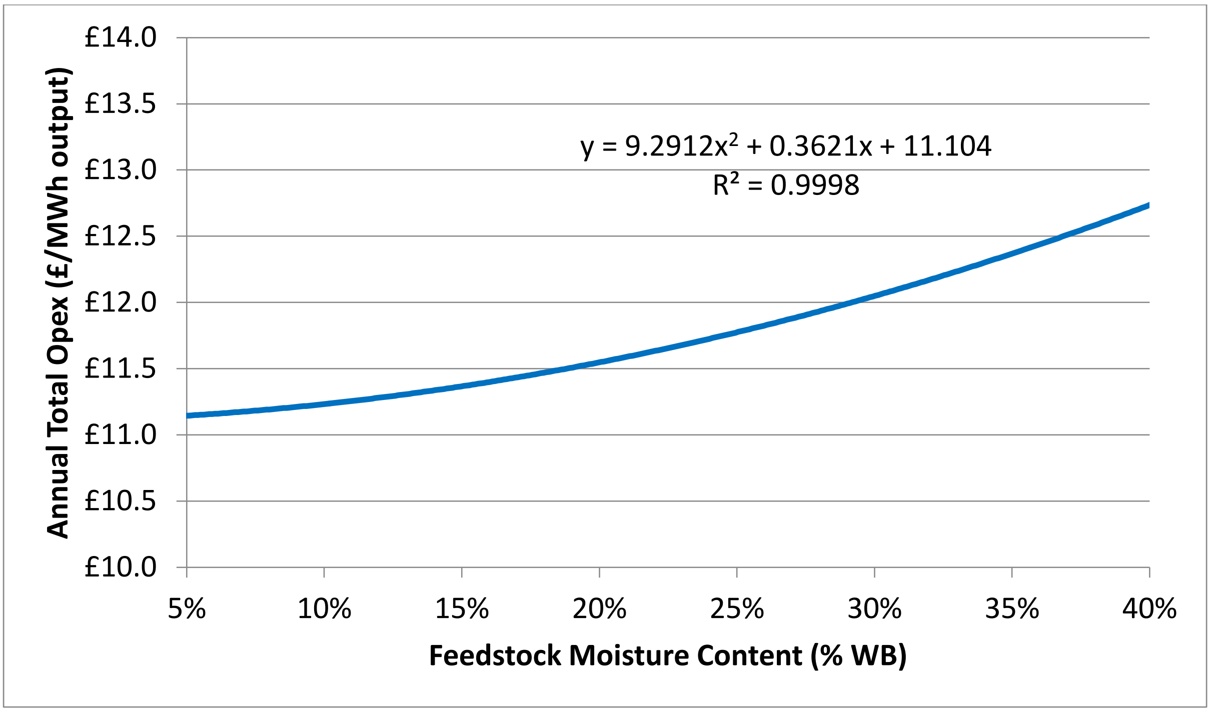

Figure 13: Automatic feed, fixed bed (biomass heat) annual operating cost per unit of energy output vs. feedstock moisture content (derived from B&V industrial data)

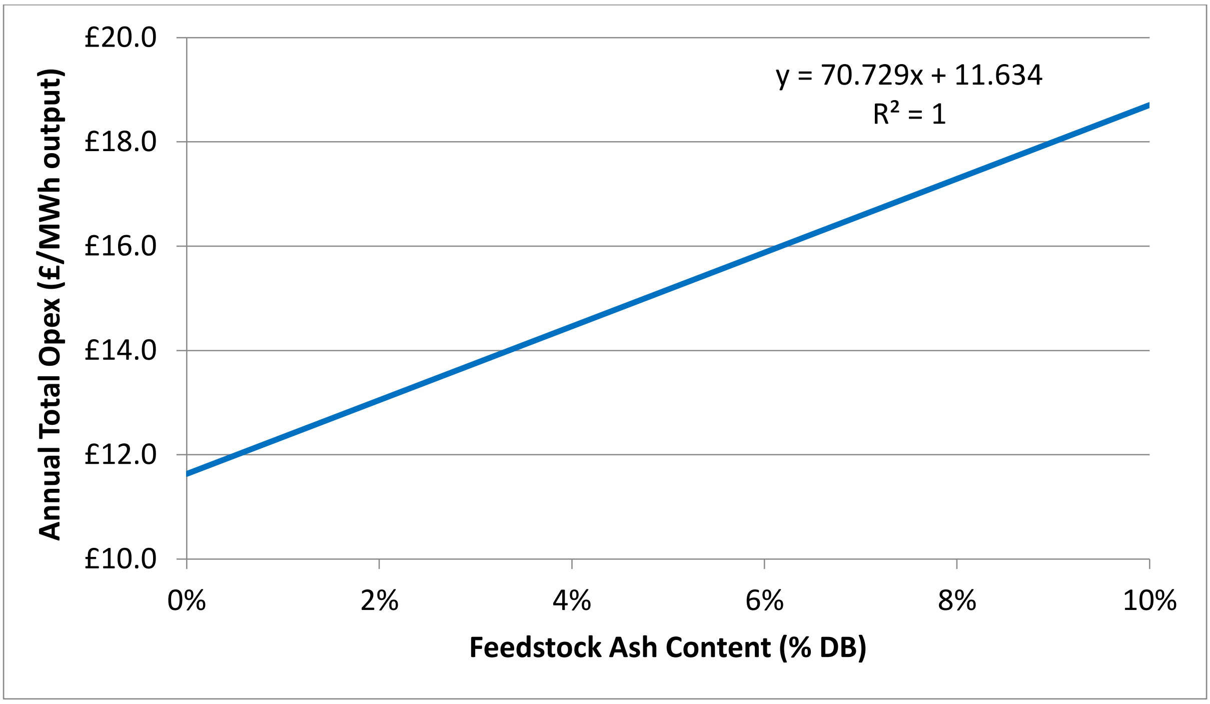

Figure 14: Automatic feed, fixed bed (biomass heat) annual operating cost per unit of energy output vs. feedstock ash content (derived from B&V industrial data)

As described above, reagent use is typically negligible across the output range available for heat only boilers, although high alkali metals will lead to increased maintenance. Figure 15 below displays the relationship between the alkali index (kg K_2O and Na_2O per GJ input energy) and the annual total operational cost for an automatic feed, fixed bed plant per unit of energy output.

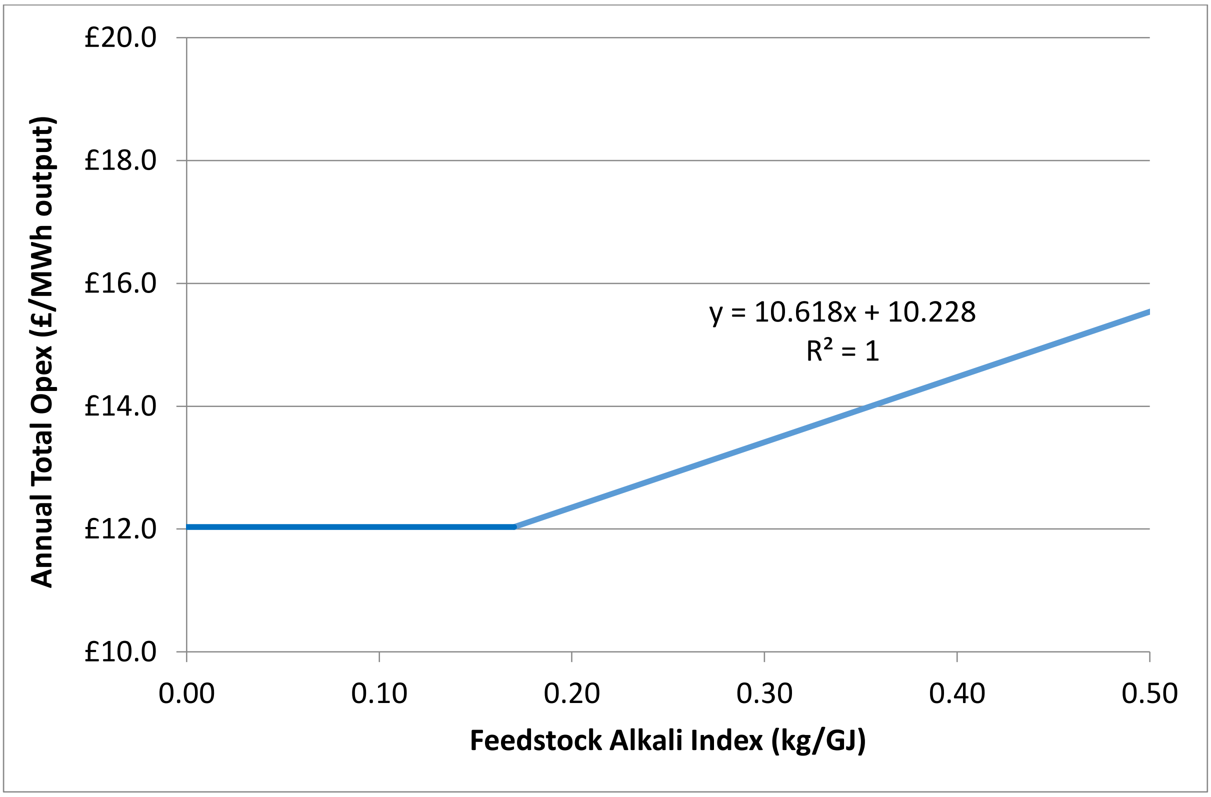

Figure 15: Automatic feed, fixed bed (heat) annual operating cost per unit of energy output vs. feedstock alkali index (derived from formula based on [21] and Section 2.4.2.5 of D1).

3.4 Available options for improvement

Fixed bed boilers tend to occupy the middle ground price-wise between manually batch fed boilers and auto-fed moving bed technologies. As such, significant additions to the technology may result in lower financial returns. Some of the more significant improvements in manual feed boiler design are listed in Table 2 and summarised below.

Table 2: Improvements Analysis of Manual Feed Furnaces

Issue arising due to biomass characteristic	Options to ameliorate	Evaluation of effect	Long Term Improvements
Poor combustion conditions due to high feedstock moisture content	Preheating the primary combustion air; Larger grate area; Improved fuel preparation; Variable fuel feed rates.	Upper limits of moisture content can be increased when air is preheated before entering the furnace. However, boiler design must account for the reduction of cooling effect to the grate.	Increased tolerance of fuel specs; Improved efficiency.

Fouling of heat exchanger tubes from biomass ash and volatiles content	Automated soot blowing; Plate cleaning; Turbulator coils within the tubes.	Soot blowing cost prohibitive for smaller boilers; Movable turbulator coils improve residence time (heat transfer) and physically agitate deposits to prevent deposits (vertical HX).	Reduced maintenance Opex; Improved availability; Improved efficiency.
Increased emissions due to poor combustion conditions (typically from high moisture content fuel)	Install flue gas clean up equipment; Increase combustion gas residence time within furnace; Use of secondary air control may increase extent of combustion of volatile gases created.	If methods to improve boiler combustion efficiency are not successful (under-fed design, two-stage combustion air addition etc.) then the use of a cyclone or similar will remove a proportion of particulate from the flue gas and should be designed to ensure emissions are within required limits.	Reduced emissions and environmental impact.
Inconsistent combustion conditions due to non-homogenous fuel within furnace	More robust auger / fuel feed system; Larger grate area; Improved fuel preparation; Variable fuel feed rates.	Increased control over residence time will improve burnout of fuel and allow drying of higher moisture fuels; Consistent bed depth will reduce hot / cool spots on the grate.	Reduced grate wear; Increased tolerance of fuel specs; Reduced emissions and environmental impact.
Slagging in furnace from biomass ash and chemical composition	Increased maintenance requirements to ensure grate is clear of clinker; Controlled modulation of air flows; Furnace turbulators (vortex fans and or baffles); Control of airflow to regulate furnace temperature and ensure flow consistency.	Recirculation of inert flue gases (if primary air is preheated); Optimum oxygen supply to handle changing combustion conditions; Improved mixing and residence time to burn off volatiles.	Preventative maintenance reduces unplanned downtime; Improved efficiency; Improved availability; Reduced maintenance Opex.
Furnace thermal damage from dry fuels	Recirculation of inert flue gases (if primary air is preheated); Direction of primary air around grate to provide degree of cooling; Ensure consistent cover of fuel across grate surface.	The addition of flue gas recirculation within the flow of secondary combustion air can help to control the refractory temperatures but does less to protect the grate.	Reduced maintenance Opex; Improved availability.

Note that automatically-fed fixed bed boiler manufacturers have not developed new combination designs beyond those discussed in Section 2.4 (log boiler combined with automatically fed pellets), hence there is no further information available for presentation in this section.

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[16] Van Loo, S. & Koppejan, J., 2003. The handbook of biomass combustion and co-firing. s.l.: International Energy Agency.

[17] Solid Fuel/Biomass Energy Systems Component & System Guide, volume 45; Hurst Boiler And Welding Co., INC.,http://www.hurstboiler.com/documents/component-system-guide.pdf

[18] Verojporn, S.; 2011; Technical and Economic Feasibility of Using Waste Wood as Biomass Fuel for Small Scale Boiler and CHP in Solway Precast, Scotland; University of Strathclyde.

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[20] Kiwa et al., 2015. A methodology for evaluating the in-situ performance of solid fuel biomass boilers. Report for DECC, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/458581/Evaluation_of_the_In-Situ_Performance_of_Biomass_Boilers_Final_Report_after_final_boiler_anonymisation.pdf

[21] Fahmi R., Bridgwater A. V., Darvell L. I., Jones J. M., Yates N., Thain S., et al. (2007). The effect of alkali metals on combustion and pyrolysis of Lolium and Festuca grasses, switchgrass and willow. Fuel 86, 1560–1569 10.1016/j.fuel.2006.11.030.

4 Auto Feed – Moving/Tilting Bed

4.1 Technology description

Automatic fed boilers with moving beds are the most commonly installed design in the UK small scale 'non-domestic' biomass boiler market – more common that the fixed bed designs discussed in Sections 2 and 3. The moving bed design combines the simple operational requirements of an automatic fixed bed with an increased ability to burn a wider variety of fuel specifications. Two main grate designs have proven to be dominant; these are tilting and reciprocating/step grates.

Tilting grates are best described as an extension of a fixed bed design with an automated batch-fed operation. Fuel is usually delivered onto a horizontal grate in a top-fed or side-fed stoker arrangement with localised refractory forming an enclosed combustion chamber. Primary air is delivered below the grate and secondary air above the bed of fuel in measured amounts based on recycled flue gas to control combustion conditions and encourage complete burn-out of the fuel. Material is continually added to maintain the required boiler thermal output until a point where no further fuel is added and the feedstock is left to fully combust. Once the biomass is deemed to be fully burnt out the remaining bottom ash product and any inert foreign bodies are removed from the combustion chamber by automatically tilting the grate from the horizontal plane to over 90° downwards. The grate is thoroughly cleaned and all material drops into a collection area. Both the point at which fuel is no longer fed onto the grate and the point at which the fuel is deemed to be fully combusted is determined automatically by the boiler control unit, typically using a combination of boiler thermal output, oxygen content in the flue gas (via lambda sensor) and pre-set time limits.

Figure 16: Tilting bed boiler - ETA[22]

The pre-set time limits also have the added purpose of acting as a form of safety precaution that prevent the grate becoming overfilled, particularly in the instance where combustion conditions are not optimal such as with wet or low calorific value (CV) fuel. The required timings are usually calculated at boiler commissioning based on the expected biomass feedstock specifications. Should the boiler be able to burn a number of different feedstocks, a 'feedstock selection menu' may be included on the boiler control panel and it is important that the boiler operator selects the most appropriate description for the fuel burnt.

Once the grate has been emptied and if there is still a heat demand, the fuel feed operation begins again and biomass is augered onto the grate. By minimising the time between emptying and refuelling, the initial fuel may be able to ignite based on the residual heat within the combustion chamber refractory and any embers that remain on the grate. An electrically-heated hot air probe is present to encourage ignition as required with operation limited by monitoring the flue gas temperature and oxygen content.

Smaller scale boilers (<200kW$_{th}$) utilising reciprocating or step-type grates are in certain ways similar to the moving bed technology present in larger units discussed in Chapter 3.2 of D1. The design basis is a side-feed stoker auger delivering fuel to one end of the combustion chamber. Fuel is transported across the length of the chamber by a moving grate, typically consisting of independent reciprocating plates moving in sequence. The grate can either be downward sloping or horizontal with the action of the bed designed to turn-over and mix feedstock to improve homogeneity of the bed. Upon entering the combustion chamber, the feedstock is heated by radiant heat and moisture is first driven off. As the fuel travels the length of the grate, primary air (often pre-heated) is delivered from underneath the bed and the feedstock undergoes a full combustion process. Fully burnt material either falls through the grate as it is travelling or is dispatched off the end into a collection area.

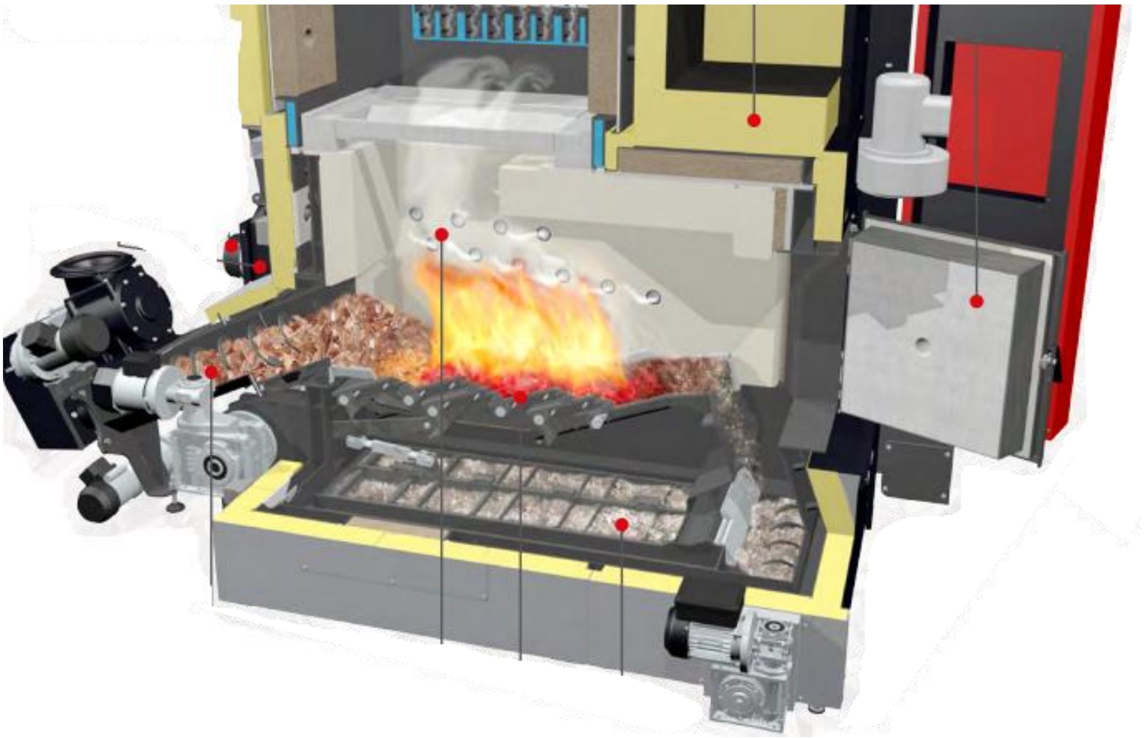

Figure 17: Moving grate boiler - Froling[23]

Secondary combustion air is added in the freeboard above the bed to ensure complete conversion of the combustion gases produced and the flow is drawn up through heat exchangers. Flow directions of the fuel and the flue gas can be counter-current flow, co-current flow, and cross-flow. In counter-current flow, the flame is drawn towards the point of fuel feed and potentially increases the drying effect; whereas in co-current combustion, the flame is in the same direction as fuel travel and is more suited to drier fuels. In a cross-flow design, the flame is removed above the centre of the bed to provide a more flexible result[24].

These boilers commonly incorporate automatic ignition systems; this is usually with an electrically-heated hot air probe as per other technologies at these smaller scales. The use of a fossil fuel burner in this range would be considered uncommon. Systems without automatic ignition cannot simply stop combustion in periods of low load to reignite as required later, therefore these units will often enter a 'slumber mode' in which a consistent low feedrate and burn of fuel is maintained to enable output to ramp back up later as loads increase. This can involve quite high fuel use just to keep the boiler warm[25].

Depending on the feedstock required to be combusted, the reciprocating grate type boiler can be selected to handle the fuel specification with more robust fuel handling and grate mechanisms. Increased refractory lining is also available for more complex biomass fuels. Due to alternative technology options available, it is generally less common at this scale for reciprocating grate boilers to burn wood pellets due to cost effectiveness, unless a larger grate capacity, and therefore thermal output, is required.

Independent of the grate design (i.e. both moving and tilting type operation), feed rate and residence time of the fuel in the combustion chamber are typically set during commissioning and are dependent on the feedstock selected. As with other technologies in this sector, primary and secondary air supply is controlled to maximise the level of combustion before gases exit via the flue. Grate-cooling is typically accommodated through flow of the primary combustion air supply and allows the transfer of heat to provide a degree of air pre-heating. It is uncommon at this output scale for units to incorporate water cooled grates. In addition, in very high temperature combustion conditions (typically present with very dry fuels), flue gases can be recirculated back into the combustion chamber once they have transferred heat to the working boiler fluid. The presence of inert product gases reduces the oxygen content in the combustion air and helps to control the thermochemical reactions. Another method of protecting the grate material against high localised temperatures in the freeboard above the grate is to maintain a constant bed of wood fuel. However, due to the nature of the tilting beds, the combustion grate will be left exposed between de-ashing and refuelling and so special consideration must be made when selecting a suitable grate material.

Flue gases leaving the combustion chamber move through the heat exchanger tubes (as with other boiler technologies), with higher specification units typically allowing for multiple passes to both increase heat transfer and remove fly ash and particulate matter from the gas flow. Most boilers in this size range include automatic de-ashing capability within the tubes with a mechanical agitator often doubling as a means to turbulate gases within the tubes and increase residence time.

All ash collected in the majority of automatic feed boilers, either from bottom ash within the furnace or fly ash within the heat exchanger tubes, is transported via auger into one or more dedicated containers that allows the operator to easily remove the accumulated products of combustion.

4.2 Development status and timescales

As discussed in Chapter 3.2 of D1, moving bed boilers have been operating for over 150 years and the technology is well established with coal. Small scale reciprocating grate furnaces burning biomass may also be traced back this far but it is only in the last 50 years that a considerable commercial offering has developed. The tilting grate boilers are a more recent development of the market, with commercial maturity on a large scale appearing in the last 10 years. As with all biomass boilers they are considered to be at TRL 9 with the majority of boiler suppliers reporting combustion efficiencies of over 85% when combusting dry fuel.

The tilting grate design boilers are typically available with thermal outputs below 150kW_{th} although models are available with outputs up to 250kW_{th}. Reciprocating grate boilers are more common at sizes greater than 150kW_{th} and, as discussed in Chapter 3.2 of D1, the technology can scale up to c. 50MW_{th} or greater.

All of the previously discussed points regarding how the RHI has skewed output deployment in the UK market are also applicable for the moving bed technologies, with the majority of the main European suppliers offering furnace and boiler combinations across a number of the small heat technology types. Due to the ability for moving bed furnaces to handle lower specification fuels they are more likely to be installed in small industrial, rural or other 'self-supply' type sites. However, as the technology is also designed for pellet combustion, they are common at many of the commercial sites where labour is less available. Auto-fed moving bed boilers have become the most commonly installed technology type in the <200kW_{th} size range over the last 10 years. Historically found to be more expensive than fixed bed type boilers, a combination of falling technology prices and operator desire for more robust fuel handling is thought to have led to this increase. In addition, the previous UK market desire to potentially oversize plant output to 199kW_{th} (to maximise RHI payments) may have caused moving bed boilers to become the more common technology as they are better suited to handle the larger volumes of fuel and ash required.

As per all boilers in this range, the relatively small and 'off-the-shelf' nature of this technology means that system install times can be very short. The installation time of the boiler itself may often be achieved in a couple of days as the boiler is almost complete at delivery and needs simple bolting together of modules. Typical project completion may take anywhere upwards of 2-3 months depending on the lead times and additional site works (including integration with the existing heating system). The majority of UK suppliers offer containerised solutions in which the boiler, fuel store and all ancillary equipment are pre-installed in a shipping container. This approach allows minimal civil engineering and building work and site preparation with system integration often limited to connecting the existing and new systems via a plate heat exchanger at many sites. Whilst this may not always be the optimal bespoke hydraulic design from a system efficiency perspective, the benefits of such a simple installation process have proven very attractive to the UK market.

4.3 Impact of different feedstock parameters on operation and cost

General feedstock considerations

The automatic fed, moving bed boilers at scales below 200kW$_{th}$ retain an advantage of good partial-load behaviour and simple load control. Boiler reaction to changes in load is faster than for larger output plants due to a lower volume of heating medium (e.g. water) within the heat exchanger and reduced fuel mass on the grate. For reciprocating grate boilers, the larger grate size may increase thermal inertia and therefore they may be slower to react than tilting or fixed bed type boilers. However, the ability to effectively combust less clean and/or homogeneous feedstocks is a strong advantage.

A tilting grate boiler is more typically suited to dry and homogenous fuel such as virgin wood pellets. This is similar to fixed bed boilers due to a reduced ability to effectively homogenise the fuel on the grate or provide sufficient grate surface area to thoroughly dry fuels with higher moisture content before entering a combustion zone. However, the batch-fired nature of operation does allow for a more controlled combustion process than simply continually adding wet fuel on top of material already burning on the grate. Wetter or irregular sized particles can be added at a rate that allows sufficient drying and/or a consistent combustion condition to develop throughout the feedstock present. Once the fuel has completely burnt, the automatic removal of ash and inert materials from the combustion zone via the tilting mechanism allows for fuels with higher ash content to be burnt. A key design point is ensuring that the surrounding combustion chamber refractory can hold sufficient heat to retain a constant thermal output from the boiler.

A reciprocating type grate has the capability to mix and dry the fuel effectively before combustion and can therefore handle wetter and less homogenous feedstocks efficiently. By ensuring the commissioning procedure has adequately calculated the appropriate fuel feed rate and grate travel speed for the specification of fuel required, the residence time of the bed material should encourage conditions for a complete combustion of biomass. Certain elements will also be controlled via feedback from flue gas oxygen content and temperature but typically the fuel type combusted must be entered into the boiler control panel prior to ignition to ensure suitable conditions. It is because of this reason that most boiler suppliers do not recommend that different specifications of feedstock are combusted simultaneously. Higher ash quantities are not considered a problem with reciprocating type grates, as ultimately all material is transferred off the end of the moving bed into an ash collection chamber. It is, however, still important to ensure feedstock is sufficiently combusted by this point to retain good combustion conversion efficiency.

As per the other technologies discussed in the output range below 200kW$_{th}$, it is very uncommon for boilers to require more than a multi-cyclone unit to meet emission limits set by the RHI (such as filters, SCR etc.). There are a limited number of units that manufacturers state can burn wider varieties of feedstocks. However, the majority in this size range specify that only virgin wood can be burnt to retain the boiler warranty. The smaller and more intricate size of components within the furnace and heat exchangers make the boiler more susceptible to fouling should the fuels contain excessive alkali metals and other elements that encourage fouling. This will reduce heat transfer efficiency and ultimately increase maintenance requirements on the boiler. If left unchecked it is likely that fouling will cause damage to components and require boiler repair.

Sensitivity Analysis

The cost curve in Figure 18 corresponds to the total investment cost per unit of output capacity for an automatic feed, moving bed heat boiler. It has been derived from quotes provided by suppliers (2016) for all-in overnight EPC costs.

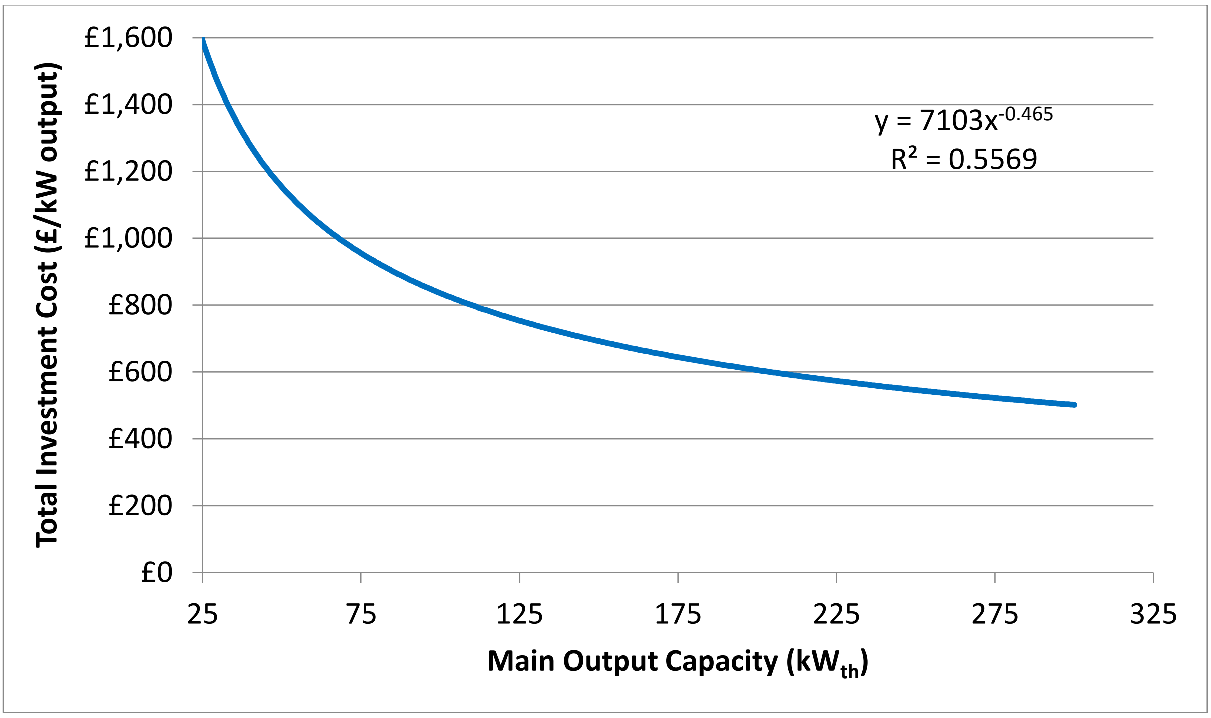

Figure 18: Automatic feed, moving bed (biomass heat) total investment cost vs. heat output capacity (derived from 40 supplier quotes (2009-2016) and B&V data for all-in overnight EPC costs)

Total operational costs for automatic feed, moving bed heat technologies include fixed costs (insurance, maintenance parts and labour) and variable costs (operations labour, ash removal, electrical operational load). For LTHW/MTHW boilers, water use is negligible and the operating thermal output range does not require the addition of reagents. Figure 19 shows the relationship between annual total operational cost for an automatic feed, moving bed fed boiler per unit of energy output and the main output capacity rating.

Except where the parameter of interest is shown on the x-axis, the curves in Figure 19 to Figure 23 are all created using the following base values: Main output capacity = 199kW$_{th}$; station capacity factor of 40%; feedstock moisture content (WB) = 30% and a feedstock ash content (DB) = 1.2%.

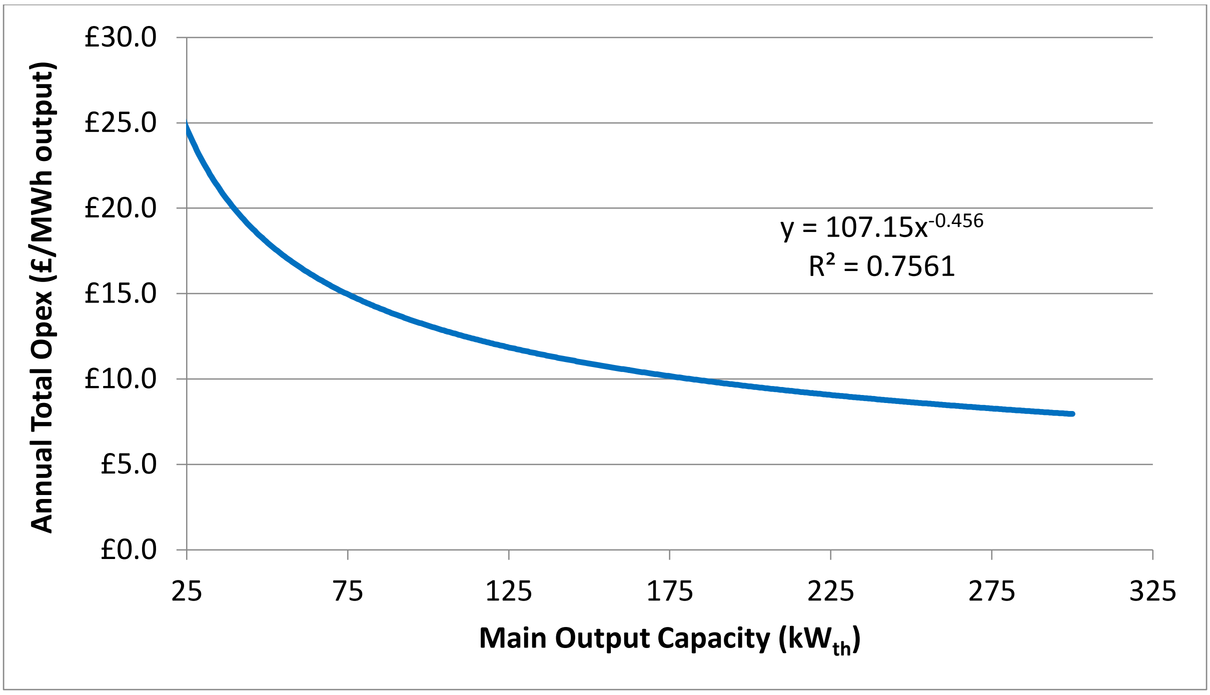

Figure 19: Automatic feed, moving bed (biomass heat) annual operating cost per unit of energy output vs. heat output capacity (derived from B&V industry data)

Figure 20 below highlights the change in overall automatic feed, moving bed boiler (LHV) efficiency over varying feedstock moisture content. The efficiency is calculated as heat energy output over fuel energy input. The curve is a representative average across the automatic feed, moving bed potential rated output range.

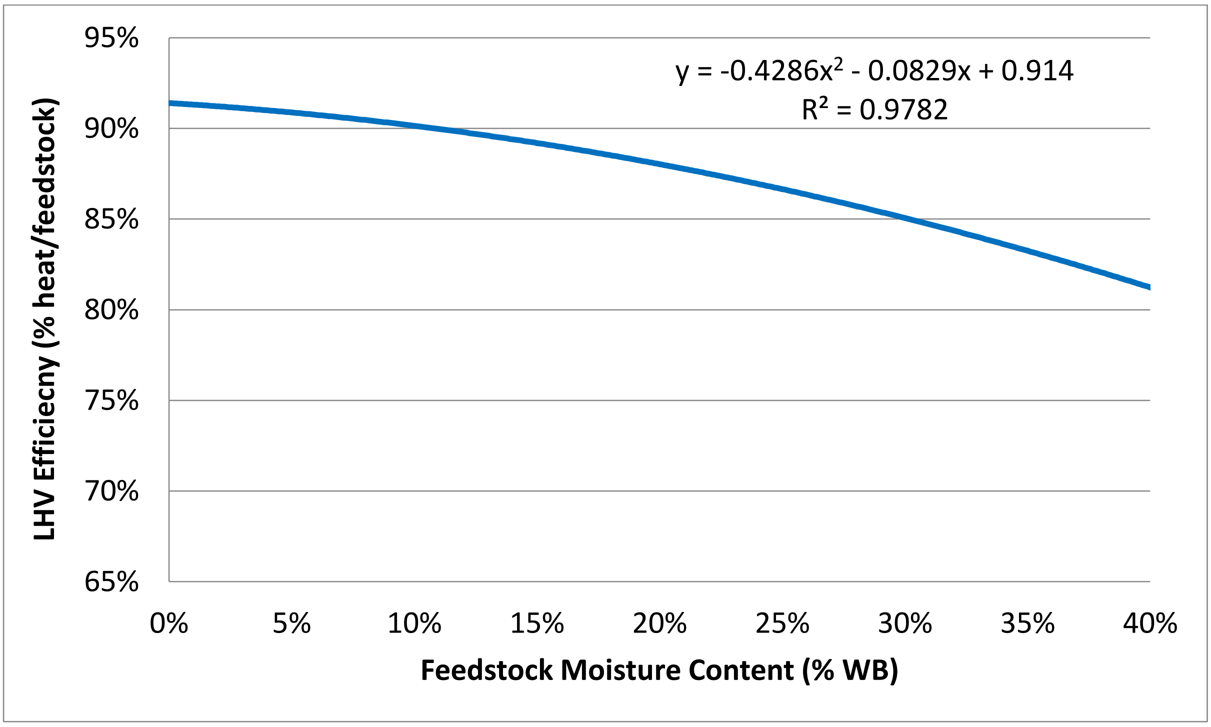

Figure 20: Automatic feed, moving bed (biomass heat) efficiency vs. feedstock moisture content (derived from OEM data provided by B&V, considering a representative average across the rated output range)

The total operational costs for automatic feed, moving bed heat technologies are related to feedstock moisture content as shown in Figure 21 below. Annual operational costs also vary with the percentage of ash present within the feedstock, as shown in Figure 22 below.

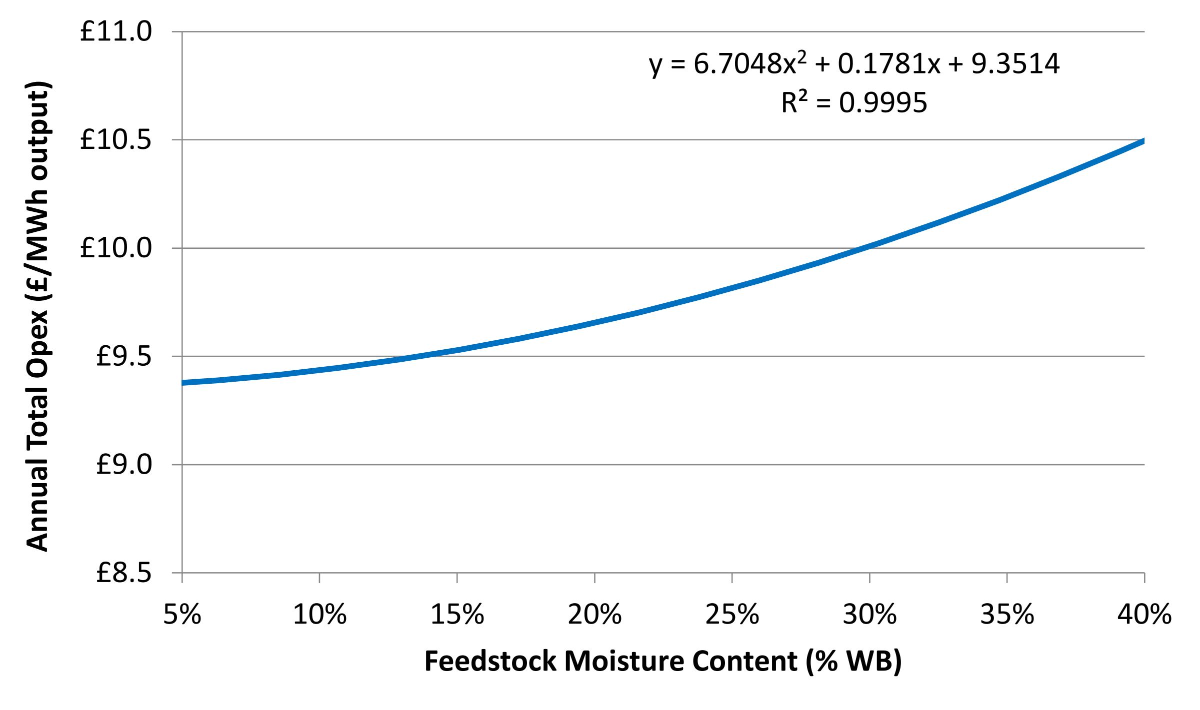

Figure 21: Automatic feed, moving bed (biomass heat) annual operating cost per unit of energy output vs. feedstock moisture content (derived from B&V industrial data)

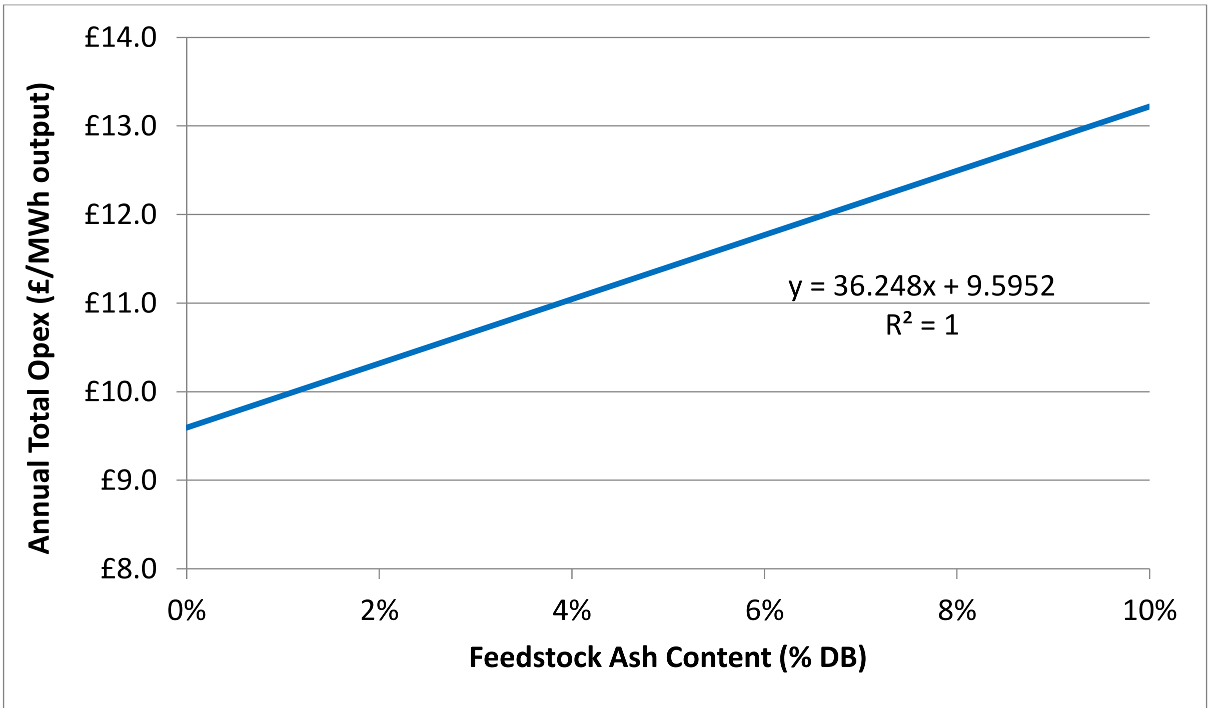

Figure 22: Automatic feed, moving bed (heat) annual operating cost per unit of energy output vs. feedstock ash content (derived from B&V industrial data)

As described above, reagent use is typically negligible across the output range available for heat only boilers, although high alkali metals will lead to increased maintenance. Figure 23 below displays the relationship between the alkali index (kg K_2O and Na_2O per GJ input energy) and the annual total operational cost for an automatic feed, moving bed plant per unit of energy output.

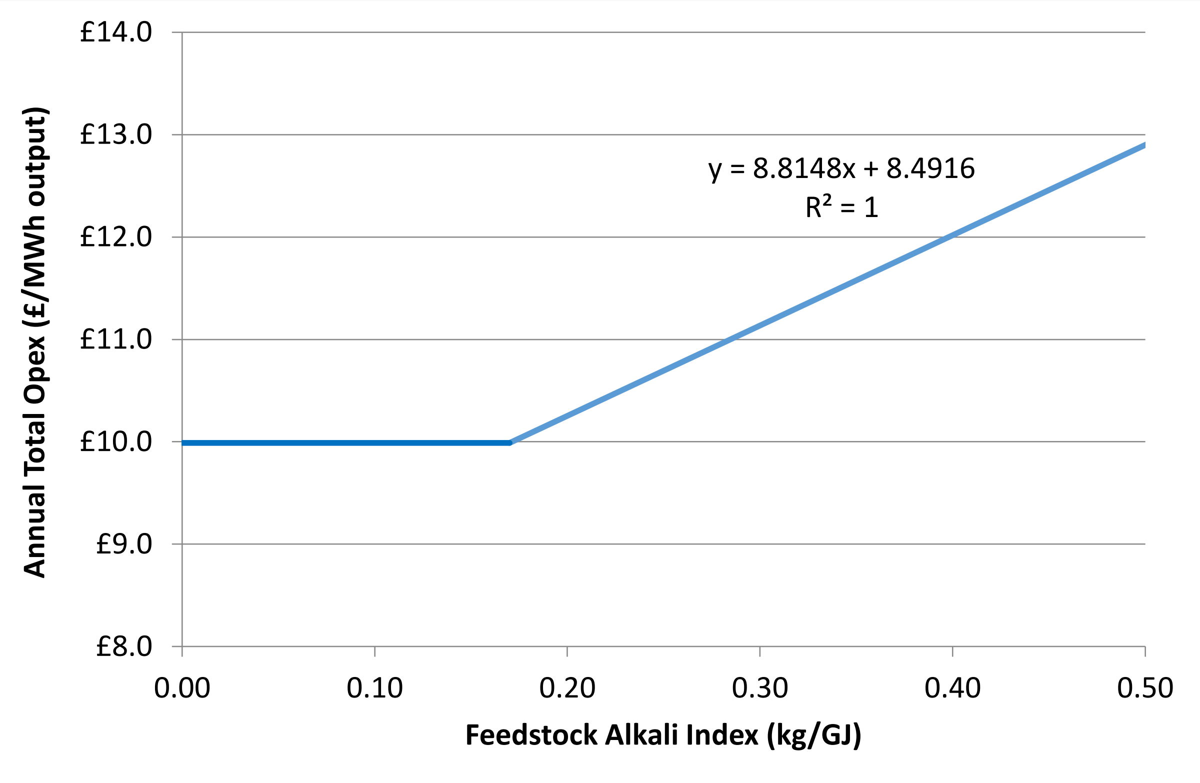

Figure 23: Automatic feed, moving bed (heat) annual operating cost per unit of energy output vs. feedstock alkali index (derived from formula based on [26] and Section 2.4.2.5 of D1).

4.4 Available options for improvement

Some of the more significant improvements in moving bed boiler design are listed in Table 3 and summarised below.

Table 3: Improvements Analysis of Moving Bed Boilers

Issue arising due to biomass characteristic	Options to ameliorate	Evaluation of effect	Long Term Improvements
Poor combustion conditions from high moisture content feedstock	Draw combustion gases counter-flow to increase heat contact with new wet fuel; Longer grate area; Controllable bed speed; Variable fuel feed rates; Pre-heat primary combustion air.	Ensure design includes sufficient control over residence time within the furnace to increase drying ability and mixing of feedstock.	Increased boiler combustion efficiency; Reduced CO emissions; Reduced emissions and environmental impact.
Fouling of heat exchanger tubes from biomass ash and volatile content	Plate cleaning; Turbulator coils within the tubes.	Soot blowing cost prohibitive for smaller boilers; Movable turbulator coils improve residence time (heat transfer) and physically agitate deposits to prevent deposits.	Reduced maintenance Opex; Improved availability; Improved efficiency.
Furnace thermal damage from dry fuels	Consistent covering of fuel on the grate; Zoning of primary air across grate; Recirculation of inert flue gases (if primary air is preheated); Water cooled grate.	At smaller output scales, water cooling and zoning of primary air is considered uncommon; Recirculation of inert gases into secondary air will improve conditions in freeboard but will not cool grate; Fuel can provide a physical barrier from heat in freeboard – therefore not recommended for tilting grate.	Reduced NO_x emissions; Reduced maintenance Opex; Improved availability.
Poor bed conditions from non-homogeneous feedstock	Consider multiple feed augers; Step grate to ensure mixed with other fuel on the bed.	Recommended to improve fuel screening beforehand to avoid this situation occurring; Reduction of moving parts aids movement of oversize – increasing residence time of grate to ensure full burnout.	Increased tolerance of fuel specs; Reduced emissions and environmental impact.
Slagging in furnace from biomass ash and chemical composition	Cooled grate to prevent sintering; Good movement across grate to ensure fuel doesn't stick; Tilt away once combusted; Regular maintenance to clear air supply ports; Install of flue gas abatement equipment.	Key to avoid entrainment of fines as danger of fires in downstream; Typically multi-cyclones are included at this size range.	Improved availability; Better fuel air mixing giving better combustion; Improved efficiency.

A third type of design is available in this technology type in which the moving and tilting grate elements are combined. Fuel is added to a stepped grate where it is dried and mixed before travelling down to a horizontal grate where the fuel is combusted. This latter grate intermittently tilts through 90° to remove ash produced. In this design, the stepped grate region is typically shortened so that combustion only occurs on the tilting grate. This has the advantage of reducing the material in contact with the highest combustion temperatures to the tilting grate but provides a better quality feedstock for combustion than if it had been directly stokered on. However, close control of combustion conditions is required to prevent fire spreading up the step grate (reducing residence time, primary air supply etc.).

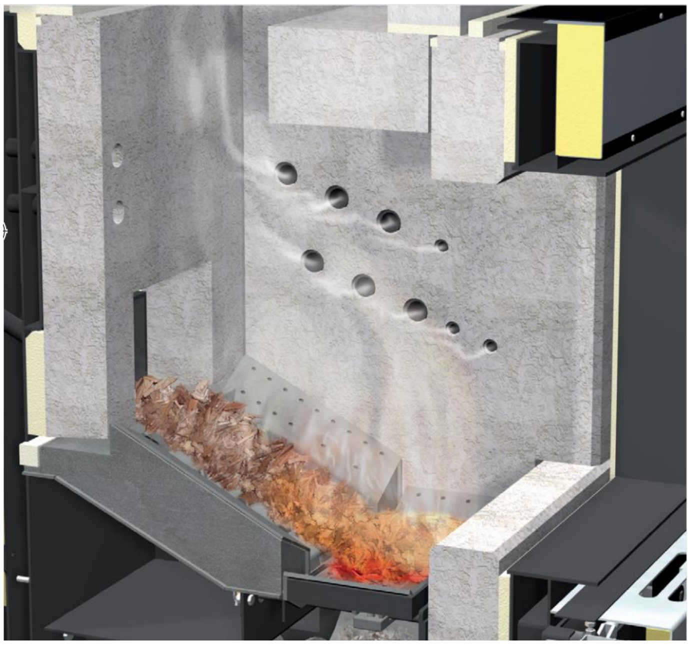

Figure 24: Moving and tilting bed boiler - Froling[27]

The combination of tilting and reciprocating grates is less commonly available and is limited in size range based on the parent technologies; i.e. 150kW$_{th}$ minimum size for the stepped grate and 250kW$_{th}$ maximum size for the tilting grate.

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[22] https://www.eta.co.at/index.php?id=95&download=f11eb1a928e45080dcd300341c886e08
[23] http://www.froeling.com/fileadmin/content/produkte/downloads/EN/EN_Prospekt_Turbomat.pdf
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[26] Fahmi R., Bridgwater A. V., Darvell L. I., Jones J. M., Yates N., Thain S., et al. (2007). The effect of alkali metals on combustion and pyrolysis of Lolium and Festuca grasses, switchgrass and willow. Fuel 86, 1560–1569 10.1016/j.fuel.2006.11.030.
[27] Froling (2014) "Wood chip and pellet boilers", Available at: http://www.froeling.com/fileadmin/content/produkte/downloads/EN/EN_Prospekt_TX_150.pdf

5 CHP Applications using Small Scale Biomass Combustion Technologies

Combined heat and power (CHP) can be an attractive solution for sites that have appropriate heat and electrical demands. For the best return on investment, CHP electrical generation should be achieved at the most efficient conditions and the heat usage maximised. Therefore, CHP is suited to sites that have a reasonably constant heat demand, or for providing base load heat demand (this also prevents a CHP plant from short-cycling on and off). Different CHP systems yield varying amounts of heat and power depending on the prime mover (e.g. steam turbine, organic Rankine systems, gas engine).

For CHP applications using small scale biomass combustion technologies, the following technologies are available:

- Rankine cycle using an Organic Rankine Cycle (ORC);
- Stirling engines.

Stirling engines are covered in Section 6.3.4.1 of D1 as this technology is still under development and there is insufficient commercial practice or information publically available. ORC systems are well developed and have been implemented on a commercial basis and hence this CHP technology is reviewed in the following section.

5.1 Technology description

ORC systems generally utilise waste heat from various processes to generate electricity through a turbine system with an organic fluid as the working medium. The ORC system is very similar to the water and steam Rankine cycle first originated by William Rankine in the 19th Century, but it has been altered to handle much lower temperatures with fluids other than water.

Typical heat sources for an ORC would be from the combustion of biomass and biogas, or waste heat from industrial processes and geothermal wells.

ORC systems operate using an organic working fluid, specifically chosen to best suit the application. This fluid should be the most suitable fluid with critical temperatures suitable for the generation process and integrated with the external process conditions providing the heat source. The commonly employed intermediate fluids between the heat source and ORC working fluid are thermal oil, pressurised water or steam. Of these, the most common to date is thermal oil due to the type of ORC units first commercially proven and the nature of the projects first developed.

Whilst the potential for fire exists with a thermal oil biomass boiler, strong preventive maintenance programs and robust plant design will reduce the risk of fire. There are hundreds of different working fluids[28] which can be used in an Organic Rankine Cycle. The fluid can be non-flammable but this will be dependent upon the specific supplier’s design and the system integration requirements.

The ORC working fluid is evaporated by the heat input and is then allowed to expand through an integrated turbine to produce electricity at the alternator. The working fluid is usually then passed through a recuperator, into a condenser and then pressurised up to evaporator pressure to start the cycle again. An overall schematic of the system is given in Figure 25, with a biomass boiler shown to be the heat source.

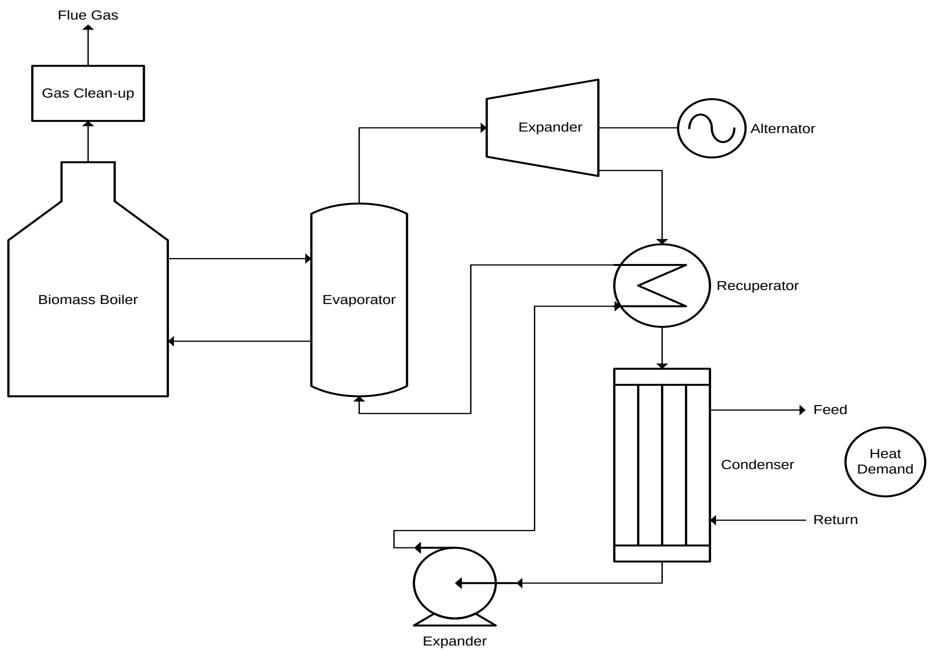

Figure 25: ORC system with recuperator[29]

An indicative energy balance for the production of electricity and heat is depicted in Figure 26, with the input feedstock equating to 100 units of energy (e.g. MW_{th} input) on a LHV basis.

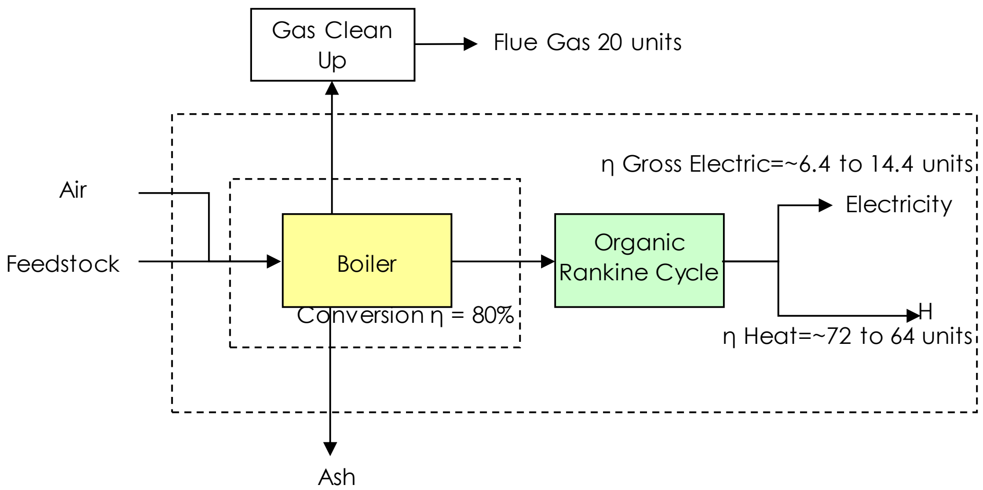

Figure 26: Schematic of a typical ORC system[30]

ORC systems have the following strengths:

- Compared to a heat source for a steam turbine, the mechanical design will be less expensive as the heat source required would be at a lower pressure and temperature. ORC systems operate at low pressure, c. 10barg or less, as opposed to high pressure steam turbine cycles at c. 45barg;
- Reduced installation cost to that of a steam turbine because, as the ORC is a sealed process, the unit is nearly always factory manufactured, wherein it largely can be assembled and

tested for performance before dispatch to site. Units below circa 300kW$_e$ can be containerised but this is partly dependent upon the supplier's ORC design concept;

- Minimal erosion on turbine and casing wear due to absence of moisture;
- Relatively low turbine speed on some designs, circa 1,500rpm, which allows direct coupling to the alternator. Small to medium sized steam turbines require a gearbox due to their higher operating speeds (circa 7,000 to 11,000rpm);
- No liquid or gaseous emissions from ORC as it is a sealed system;
- With the exception of the biomass boiler system, the ORC daily operational attendance time would be minimal as the system is an independent thermal system with limited moving parts;
- High levels of availability, 90 to 95%.

ORC systems have the following weaknesses:

- Low electrical efficiency in terms of electrical power compared to direct energy input to the ORC. For instance, for an electrical power output of 200kW$_e$, the gross efficiency would be in the order of 8% of direct energy input, whereas at c. 500kW$_e$ the electrical efficiency would be in the order of 18%. The reason for this is that units below c. 200kW$_e$ have been developed to take advantage of the anticipated commercial market for heat recovery from low temperature waste gas streams, although some suppliers' designs can use heat from low temperature dedicated boiler systems;
- The system rejects a high percentage of the energy input as low grade heat (e.g. at <50-60°C) which is not normally usable unless used for heating of processes such as anaerobic digestion.

For the application covered by this technology review, a biomass boiler would provide the heat input to the ORC system. At ORC outputs less than typically c. 250kW$_e$, hot water or steam is generally used as the working fluid if working in conjunction with a boiler. At c. 300kW$_e$ and above, the ORC units usually use thermal oil as the intermediate fluid between the heat source and ORC working fluid. The grade of heat required is a function of the ORC fluid which is optimised to the power range being offered by the supplier.

At the size range being considered (with electrical outputs less than 1,000kW$_e$) working in conjunction with a dedicated biomass boiler, the biomass input required would prohibit the use of a manual fed boiler or an automatic underfed type boiler due the large quantities of biomass required. For instance, with a gross electrical output of 1,000kW$_e$ or 300kW$_e$ the biomass input would be 6.4MW$_{th}$ or 2.3MW$_{th}$ respectively, and due to this scale other conversion technologies may be more appropriate. The underfed fuel feeding system would not be able to accommodate the flows required and there would be significant safety issues in manually feeding boilers large volumes of biomass. Consequently, the only biomass boiler suited to this scale would be the automatic moving bed type (see Section 3.2 of D1), as tilting bed designs are also too small. Boilers of this type would operate with availabilities in the order of 85% and this is the limiting factor in achieving higher levels of overall system availability.

At the electrical outputs identified above, electrical generation would be at 400V and the systems lend themselves for integration in existing electrical distribution systems on industrial sites.

5.2 Development Status and Timescales

Since demonstrating their first unit in 1980, Turboden has installed over 300 ORC systems globally. In the past, their focus has been on Italy, Germany and Austria and associated with biomass fired district heating and integration into wood processing facilities. The development of ORC systems is now seeing them being integrated into more diverse applications such as the steel industry and in conjunction with anaerobic digestion. The commercial standard CHP units range typically from 300kW$_e$ to 3MW$_e$ and main feedstocks used are wood biomass (sawdust, chips, bark or treated wood). This scale necessitates the input of c. 2-20 MW$_{th}$ of biomass.

ORC systems have historically used heat sources in the order of 300°C (Turboden). In the past few years, other companies have entered the market, such as Dürr Cyplan, E-Rational, and Electrotherm with ORC units less than 300kW$_e$ using low temperature heat sources, in particular process waste heat, at less than 150°C.

ORC applications at outputs below 50kW$_e$ are more suited for installation in waste heat streams arising from process plants, due to the low overall system efficiency and the lack of commercial viability were a dedicated biomass boiler to be used as the heat source. At this scale, small dedicated biomass boilers are not used with ORC systems, because for instance 50kW$_e$ gross output would require circa 1,000kW$_{th}$ biomass input – both a significant capital outlay, and beyond the scale of most technologies considered within this small-scale heat chapter. Although the combination of small-scale biomass boilers and ORC systems <50kW$_e$ might become an emerging area as ORC efficiencies improve in the future, this combination of technologies is not yet near commercial maturity, nor being actively developed, so is not considered in this report.

The introduction of the Feed in Tariff (FIT) in 2010 and the non-domestic Renewable Heat Incentive (RHI) in 2011 incentivised electrical generation from renewable sources and recovered heat from biomass fuels, respectively. The FIT scheme has particularly incentivised the use of electrical generation less than 500kW$_e$ due to the higher available tariff rate, which when combined with RHI tariff increases the income from an ORC plant. Both schemes are currently advised by Ofgem to continue until 2021.

The overall construction period for a complete biomass fuelled ORC system less than 200kW$_e$ to full operation would be in the order of 7 to 12 months, as the units tend be packaged. However, for larger systems over 300kW$_e$, the period would be of the order of 18 months, as larger ORC units are typically only available for delivery 8 to 10 months after ordering.

Due to the substantial number of biomass-driven ORC systems that have been deployed, the technology is at a current **TRL of 8-9**, with **TRL 8** being more applicable to the sub 50kW$_e$ market.

5.3 Impact of different feedstock parameters on operation and cost

It is unlikely that different feedstock parameters would have an impact on the integration of ORC technology with a biomass boiler, other than the feedstocks impacts on the boiler type as already discussed in other sections of this report.

The relationship for the Total Investment Cost per unit of output capacity for an ORC system complete with biomass boiler, for systems with an electrical output of less than 1,000kW$_e$, is given in Figure 27. It has been derived from quotes provided by suppliers (2016) for all-in overnight EPC costs. The electrical main output is net of all ORC and boiler electrical parasitic loads.

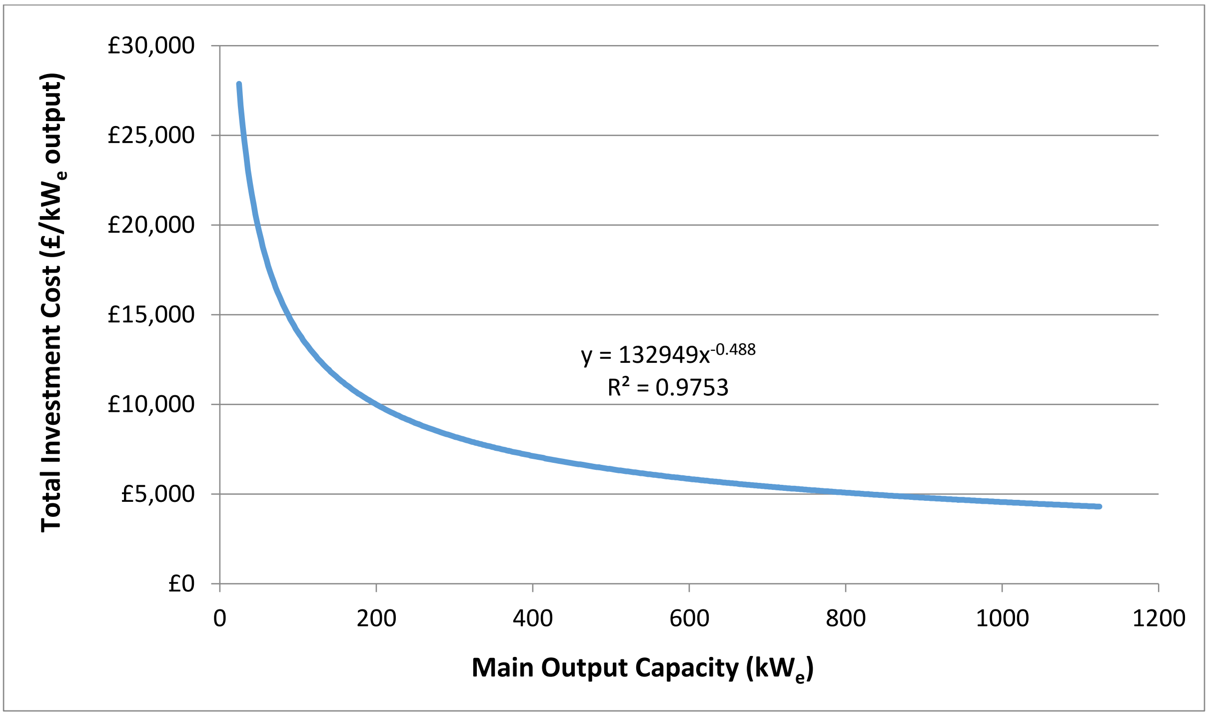

Figure 27: ORC Total Investment Cost vs. electrical output capacity derived from 4 suppliers applied to a range of 15 data points - (2016) and B&V data for all-in overnight EPC costs)

The relationship in the total annual operating cost per unit of electrical output for an ORC system complete with biomass boilers and the main electrical output is given in Figure 28. The operating costs cover both the boiler and ORC maintenance spares, ORC fluid replacement and associated labour costs for both routine operation and maintenance. The overall availability of the system is 85% so as to match the biomass boiler system and the main output is net of all ORC and boiler electrical parasitic loads. The electrical supply for the total system is provided by the ORC.

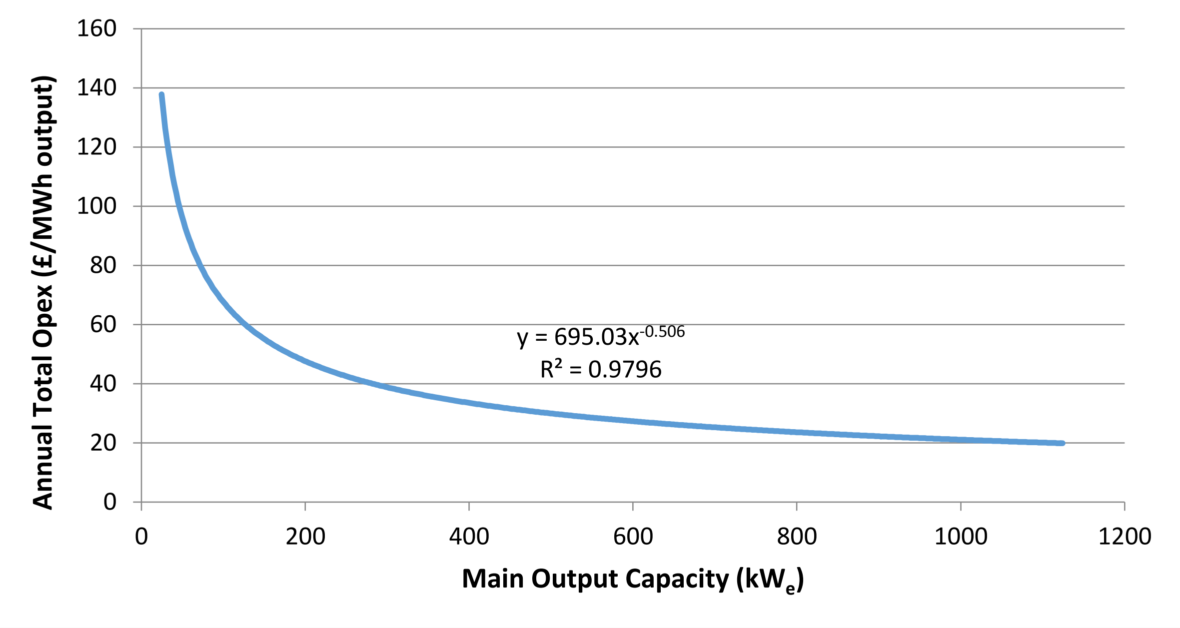

Figure 28: ORC fixed and variable costs vs. main electrical output (derived from 4 suppliers (2016) applied to a range of 15 data points)

As mentioned above, the electrical power output is affected by the temperature of the heat source. High temperature ORC systems use a heat source in the order of 300°C and low temperature a heat sources at less than 150°C. At less than circa 200kW$_e$, ORC units have mainly been developed to take advantage of the anticipated commercial market for heat recovery from low temperature waste gas streams, although some suppliers can use heat from low temperature dedicated biomass boiler systems. Figure 29 illustrates the sensitivity of electrical efficiency with respect to the main electrical output net of all ORC and boiler electrical parasitic loads.

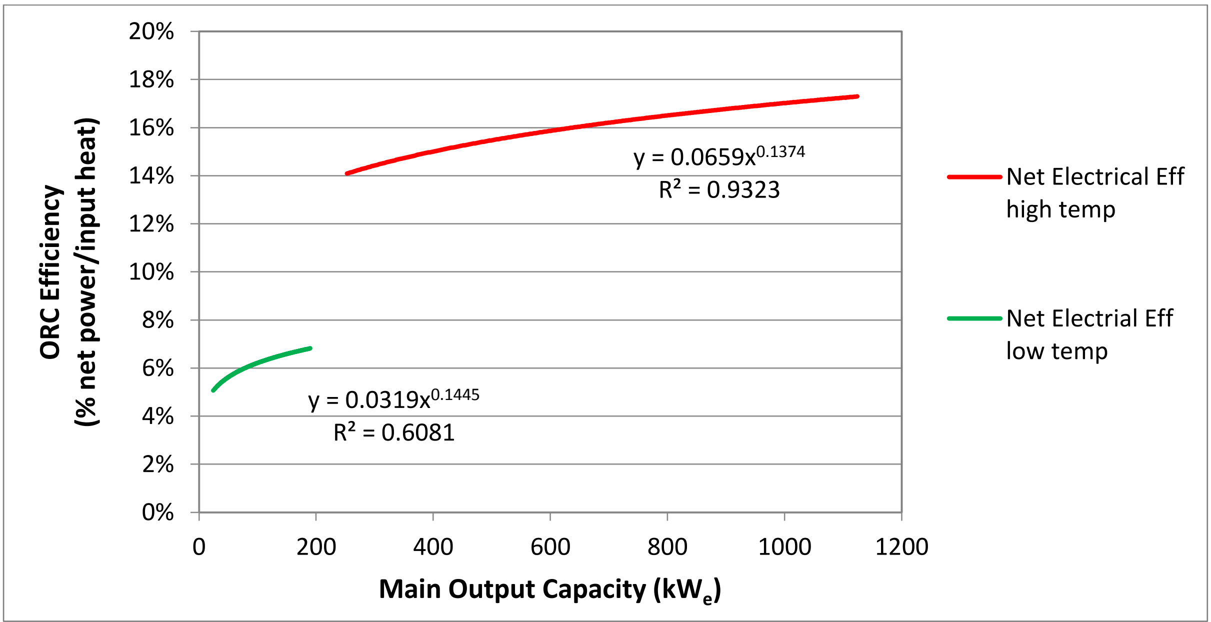

Figure 29: ORC electrical conversion efficiency vs. main electrical output (derived from B&V industry data considering a representative average across the technology potential rated output range)

Note that this efficiency is the net electrical output divided by the heat energy input to the ORC system – not the net electrical output divided by the input biomass energy to the boiler. Calculating the latter measure of efficiency would lower the efficiencies shown in Figure 29 by around another quarter to account for the thermal losses in conversion of input biomass into useful intermediate heat.

5.4 Available options for improvement

The ORC CHP system is a well-developed technology at scale ranges from 300kW$_e$ to 3MW$_e$ and has evolved over the last 30 years - the basic design and operation is well understood, robust and reliable. Improvement to the availability of the biomass boiler operating with an ORC system would allow higher system availabilities to be achieved.

As the ORC design is well understood above 300kW$_e$, the capex for such plant is well defined and has been optimised. For smaller plants, the cost has yet to be optimised as the full potential for small units using lower grade heat has not been developed, and so the resulting commercial savings from increased production volumes are also yet to be realised. At the larger scale of plant above 300kW$_e$, Turboden are leaders in design improvements; over the years they have extended the lower operational rating of their thermal oil fired designs down to 300kW$_e$. At the sub 300kW$_e$ level, smaller scale companies such as E-Rational, Dürr Cyplan and Electratherm are establishing themselves.

At present, the electrical conversion efficiency of ORC systems is low. For the next generation of ORC, research and development is considering alternative fluids and improved ORC cycle design. This is being investigated to allow higher electrical conversion efficiencies similar to that of a steam turbine (25 to 30% for an industrial-sized steam turbine in the range c. 5 - 20MW$_e$) from the current maximum of c. 20% that would be achieved only for large scale high-temperature ORC units over 1MW$_e$.

[28] Nouman, J, 2012. Comparative studies and analyses of working fluids for Organic Rankine Cycles – ORC. Available at: https://www.diva-portal.org/smash/get/diva2:555314/FULLTEXT01.pdf
[29] B&V in-house diagram.
[30] B&V in-house diagram.

6 Real-world experience and considerations for small scale biomass boilers

This section summarises the real world experience of choosing and operating small scale biomass combustion boilers in the UK, looking at the critical issues of real-world efficiencies, boiler suppliers, air quality limitations and feedstock certification.

Unlike northern and central Europe, the UK climate is essentially maritime with only relatively mild and short winters compared to those on the continent. These lower system capacity factors mean more part-loading and poorer efficiencies, as seen in a significant gap between manufacturer quotes and real-world operational efficiencies achieved in the UK across the year, as discussed in Section 6.1. Oversizing boilers due to the structure of the RHI incentives has also contributed to poor efficiencies and reliability.

The use of wood combustion for small heating applications has been relatively slow to take off in the UK, due to a number of reasons. The capital cost has been high relative to fossil fuel boilers, and the paybacks have been too long to incentivise the market until recently with the advent of the RHI (although this is now under reform). As a result of this, most system suppliers (boilers and CHP) have tended to rely on boiler suppliers from mainland Europe with only a few UK boiler manufacturers trying to penetrate the market, as discussed in Section 6.2.

Over the same period that the early growth in the UK market has taken place, air quality emission limits have been tightened, as discussed in Section 6.3 – this has led to increased expenditure on emissions control thereby exacerbating the payback issue. Woodchip and pellet supplies have also been slow to respond and it has taken a while for the fuels available to meet the specifications required by the boilers, as discussed in Section 6.4 below.

6.1 Installed Efficiency in the UK and comparison to EU

The difference between installed efficiency and quoted efficiency is a big issue particularly because owners wish to see the maximum benefit from their asset. The UK typically has milder winters than on the continent and so it is more likely that a boiler is oversized and operating inefficiently at part load for a larger proportion of time.

If the boiler/heating system is operating well below its design efficiency, this represents significant additional costs due to burning more fuel than necessary. Not only is the capital cost of a biomass fired boiler so much greater than for a gas fired appliance, but it is more difficult to follow the heat demand with a biomass boiler than for gas fired boiler. In the event that the operator is claiming non-domestic RHI, they may be gaining additional income for the larger appliance but they may be burning significantly more wood as they will be operating at part load and therefore reduced efficiency.

There are a number of reasons why non-domestic biomass boiler heating efficiencies in the UK are different from efficiencies experienced in the main developed biomass markets of mainland Europe. The key differences between experience in the UK and in the EU are as follows:

- Boiler efficiency;
- Quality standards;

- Seasonal efficiency and load factors;
- Supply and return temperatures of district heating;
- Fuel mix;
- Reliability.

Boiler efficiency

Biomass boilers are manufactured to use a specific range of fuels. For example, small automatically fed fixed grate boilers typically use dry wood pellets (10% moisture content) and large moving grate boilers use wood chips (45% to 50% moisture content). European manufacturers often state the combustion efficiency of their boilers for these different fuels, which can range from c. 94% (for pellets), down to c. 80% (for wet chips)[31]. However, this is only considering the boiler related losses, before any plant room losses and heat delivery losses are considered.

Gastec at CRE Ltd. ran a monitoring field trial on 18 biomass sites over 19 months during 2008-2009 for the Biomass Heat Accelerator Programme for the Carbon Trust. During the exercise, it was concluded that the total efficiencies of non-domestic wood chip and pellet boilers were within the range 73% to 85% when using the indirect method (measuring stack losses and case losses as prescribed in British Standard BS845-1) and 31% to 79% when using the more traditional, but less robust direct method (heat output divided by the fuel input reported by the site)[32]. The equipment monitored included boilers ranging from 120kW$_{th}$ to 3MW$_{th}$ and the majority were from European boiler manufacturers.

Similarly, a desktop report commissioned by DECC (Steven Luker Associates, 2014) which reviewed the performance of 106 RHI installations in the UK found out that biomass boilers in the non-domestic sector were c. 7-14 %-points less efficient than the specified boiler manufacturers' efficiency[31]. The average realised performance of boiler systems in the UK was 66.5%, which is c. 10 %-points lower than the average performance standard claimed by European boiler systems of 76.8%. However, Kiwa (2015) noted that this data was not sufficiently robust to draw clear conclusions[32], and recommended further work – but only went as far as developing a methodology and conducting a pilot *test*. Note that in contrast to the figures in the paragraphs above, the values in this paragraph are full system efficiencies including the plant room and delivery losses. Suppliers, installers and advisors have been prone to focusing only on boiler combustion efficiencies when asked about performance standards by their customers, instead of adequately acknowledging overall system performance, which is part of the reason for the mismatch in expected and actual performance[31].

Quality Standards

In comparison to the well-established biomass boiler market in Northern Europe, the UK market remains in its infancy and many of the efficiency issues that are currently being experienced in the UK were either avoided or mitigated in Europe by following a long term strategy which included: quality standards, training programmes, and clear information on installation and operation practices. Currently in the UK, there are no quality standards for boiler systems above 45kW$_{th}$. In addition, there are some publications on the subject of biomass heating system design, which are now out of date – as discussed below. These are all contributing factors to poor quality installations[31] occurring in the UK.

There are some publications on the subject of heating system design, some of which are relevant to biomass. Steve Luker Associates (2014) identified the publications that were available and these merely confirmed that such data on high quality installation procedures was not generally available, and that the data that did exist was either patchy or out of date[31]:

- Biomass Heating - CIBSE Knowledge Series: KS10 (for peak heating demand 50kW to 5000kW); Chartered;
- Institution of Building Services Engineers London, 2007;
- Domestic Heating Systems Ranked by Carbon Emissions; BRE; 2007;
- Energy Efficiency Best Practice Guide in Housing - Domestic heating: solid fuel systems; Energy Saving;
- Trust CE47 (EST; 2005);
- Heating CIBSE Guide B1, Chartered Institution of Building Services Engineers London, 2002;
- The Whole House Boiler Sizing method; BRECSU Energy Efficiency Best Practice Programme; 2000;
- Guide A: Environmental design; CIBSE; 2006.

Seasonal Efficiency and Load Factors

Seasonal heat load variation is well-known. It mainly depends on large differences in outdoor temperatures between winter and summer, combined with the demand to have a more or less constant temperature inside the building envelopes[33]. The heating season in both the domestic and the non-domestic sectors in the UK is typically the winter period from October to March when heating is required[34]; however, some sites have different heating patterns.

The standard means of measuring utilisation is via the 'load factor', also known as 'run hours' or 'capacity factor'. This measures heat output over a set time, usually a 12 month period. The DECC RHI impact Assessment based its calculations on medium boilers (200kW to 1,000kW) on a 20% load factor[31]. The Kiwa (2015) study found that the annual average capacity factor for non-domestic biomass boilers in the UK was c. 14%, with most systems (10th to 90th percentiles) falling within the c. 5% - 30% capacity factor range. However, a typical seasonal heat load pattern for a Swedish district heating network shows a load factor of c. 44%[33], which is more than twice that assumed by DECC for the UK's RHI.

Load factors may be low simply because the boiler has been oversized, which can lead to higher emissions and reliability issues when running mostly at part load. Kiwa (2015) shows how low utilisation factors lead to lower boiler efficiencies as shown in Figure 30. The trend line has been added but it is not truly representative at maximum and minimum utilisation factors, as it should level out as the load approaches 100% and approach zero at zero load. A continuous utilisation factor of 5% has shown boiler efficiencies in the low 30% range and a 9% continuous utilisation factor has shown an efficiency of approximately 60%, numbers which Kiwa state fit well with anecdotal evidence reported in the field.

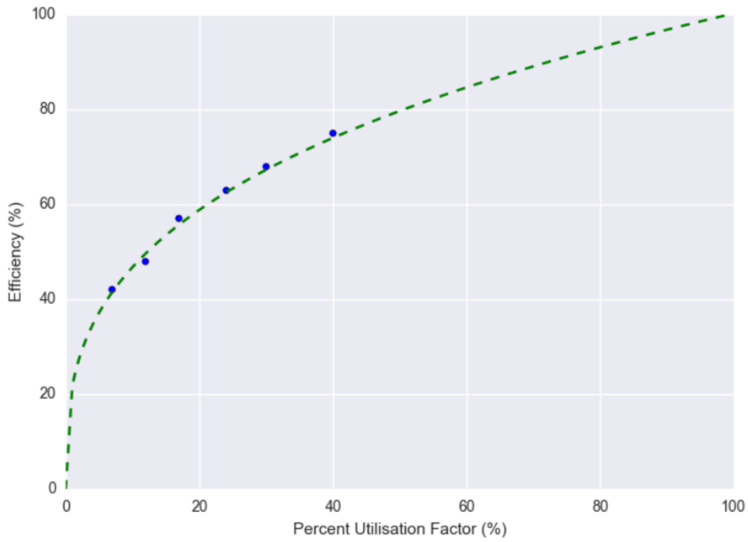

Figure 30: Variation of boiler efficiency with percentage utilisation factor for a 200kW boiler cycling three times per day during normal demand driven operation[32]

Supply and return temperature

Boiler supply and return temperatures have a direct effect on boiler efficiencies. This is particularly applicable for district heating but applies to all boilers. If the return temperature is high, the flue gas temperature is high and the losses are high, and therefore the boiler efficiency is lowered.

High supply and low return temperatures in the distribution networks are important operational factors for obtaining an efficient district heating system. There is a significant difference in the flow and return temperatures between UK and EU installations[33]. In the UK, the supply and return temperatures are generally 82°C and 71°C respectively, whereas the national average supply temperature in Sweden is 86°C and the corresponding return temperature is 47.2°C.

Fuel mix

The Gastec report (2009) concluded that fuel quality was the third most important function affecting plant performance after boiler sizing and the ability of the operative to deal with minor faults[34]. Their monitoring exercise found that many of the sites had difficulty keeping track of fuel used and that this could be, on the best sites' estimates, 10 to 20% different to the calculations from the heat meter data.

Fuel quality issues are further discussed in Section 6.4. In particular, one of the main reasons for boiler under performance is the quality of the fuel being different from that specified by the manufacturer.

Reliability

The majority of biomass boilers monitored under the Gastec[34] exercise appeared to be considerably oversized. There was a considerable incentive to round up boiler sizes to 199kW$_{th}$ and 999kW$_{th}$ in order to maximize RHI claims. As a result, many boilers were operating at part load and therefore inefficiently leading to smoke and reliability issues. A smaller boiler installed in tandem with an oil or gas unit would lead to much greater reliability of the heating system and, if correctly designed, only a marginal increase in annual site carbon emissions: capital cost is also likely to be substantially reduced. However, this apparent oversizing could also be a result of the boilers not being able to reach their maximum continuous rating, which could be caused by fuel supply or boiler design problems. In addition, the vast majority of the biomass sites under the monitoring exercise suffered "faults". Where the operatives did not deal with these minor faults it resulted in more downtime. This highlighted the need for better training.

CHP and ORC efficiencies are discussed in Section 5.4 although there is no UK experience to compare with EU experience.

6.2 Main biomass boiler and ORC suppliers

Table 4 lists biomass boiler installers identified in the UK, and it shows that the majority of the boilers supplied to the UK market are manufactured in Europe. UK boiler manufacturers include Green Tec, Byworth, Dragon and Talbots. According to the study by Kiwa[32], under the RHI, 91% of non-domestic installations are below 200kW_{th} and they are used to provide mainly space and water heating. 44% of these boilers operate on wood pellets and 35% on wood chips. Only 16% of these boilers operate with wood logs and 5% of the installations use either waste and recycled wood, agricultural residues, energy crops or other fuels. For the domestic RHI, the same Kiwa study found that 88.2% of domestic systems used wood pellets, 0.2% use chips, and 10.5% use logs.

Table 4: UK Boiler Installers for Domestic, Industrial and Commercial Sectors[35]

Company Name	Biomass Boiler Size Range (Thermal Output)	Boiler Manufacturer	Feedstock
Asgard Biomass	20kW-500kW	ETA	Wood chips and pellets
Ashwell Engineering Services Ltd.	10kW - 10MW	D'Alessandro, Komfort, KWB, The Green Tec	Wood chips and pellets
Cochran UK (Scot Heating)	49 kW - 2MW	Kohlbach Kara	Wood chips and pellets
Bioenergy Technology Ltd.	3kW - 10MW	ETA, Fröling	Wood chips and pellets
Biomass Boiler Services	500kW to 6MW	Kob, Viessman	Wood chips, pellets, waste wood
Byworth Boilers	500 – 2.5MW	Byworth	Pellets
Dragon Biomass	30kW - 450kW	Dragon	Wood chips, pellets, saw dust, Miscanthus
Eco Link Resources Ltd.	100kW – 15MW	Uniconfort	Wood chip, pellets, logs
Eco Living Scotland	10-k00W	Hargassner	Wood chips, pellets, logs
British Gas (Econergy Ltd.)	5kW - 200kW	Fröling	Wood chips and pellets
Energy Innovations (UK) Ltd.	Gilles up to 500kW Weiss over 600kW	Gilles, Weiss	Wood chips, pellets
Eratic S.A.	116kW – 14MW	Eratic	Waste wood, agricultural residues
FARM 2000	54kW - 195MW	Teisen	Straw, wood logs
Glendevon Energy Ltd.	10kW – 350kW	ETA	Wood chips and pellets
Hoval Ltd.	15kW-1MW	STU, BioLyt	Pellets

Company Name	Biomass Boiler Size Range (Thermal Output)	Boiler Manufacturer	Feedstock
HWE Ltd.	90kW - 1MW	Fröling, Giles	Wood chips, pellets, waste wood, saw dust
ICI Caldaie	125kW – 5.8MW	ICI Caldaie	Woodchips, pellets, saw dust
Imperative Energy Ltd.	100kW – 5.5MW	Schmid	Wood chips, pellets
Justsen Energiteknik A/S	300kW – 15MW	Justsen	Woodchips, pellet, briquettes, waste wood, bark, husks
KIV (UK) – Energia Ltd.	30kW - 3MW	KIV	Wood chips, pellets
Manco Energy Ltd.	150kW – 1.5MW	Lin-Ka	Pellets
Mawera UK Limited.	850kW - 13MW	Viessman	Woodchips, pellets, residual lumber, bark
Mercia Energy Ltd.	15kW - 850kW	Heizomat	Woodchips, pellets
Perthshire Biofuels Ltd.	8kW – 224kW	Ökofen	Woodchips, pellets
De la Haye Engineering Ltd.	30kW – 900kW	Veto	Woodchips, pellets & grains
Ranheat Engineering Ltd.	150kW- 980kW	Ranheat	Woodchips, pellets, waste wood
Rural Energy	10kW – 10MW	Herz - Binder	Woodchips, off cuts, pellets
Schuberts Biomass	92.8kW to 5.8MW	Uniconfort	Wood pellets, woodchip, straw, waste wood and agricultural residues
Talbotts Biomass Energy Ltd.	50kW – 2MW	Talbotts	Woodchips, pellets
TRECO	10kW – 1MW	Guntamatic	Woodchips, pellets
Wood Energy Ltd.	49 kW - 2MW	Hargassner Binder	Woodchips, pellets, logs

The main ORC - CHP suppliers under $1MW_e$ output are listed in Table 5 below.

Table 5: Main ORC suppliers

Company Name	ORC CHP Range (kW_e output)
Adoratec	300 to 2,400
Dürr – Cyplan	50 to 500
ElectraTherm	35 to 110
Enogia	10 to 100
Eneftech	10 to 30
E-Rational	50 to 500
Turboden	200 to 3,000 as CHP configuration
Orcan Energy	25

6.3 Air Quality regulations impacting the sector

The main emissions from a biomass boiler are particulate matter (including soot, black carbon, organic and inorganic material) and gaseous emissions including carbon monoxide (CO), carbon dioxide (CO_2), water vapour, nitrous oxides (NO_x), sulphur oxides (SO_x) and poly-aromatic hydrocarbons (PAHs). The emissions that are expected to cause the most significant impact to the air quality and human health are particulate matter (PM) and NO_x.

Depending on the type of fuel used, different pollution regulations are applicable. For schemes with a fuel input below $20MW_{th}$ using virgin wood, Local Authorities have powers under the Clean Air Act to regulate dust emissions from a biomass boiler exhaust stack, and also to require the installation of abatement equipment to control emissions. For other fuel types and plant sizes refer to Table 6.

Table 6: Permitting Regime[36, 37, 38, 39]

Fuel Scenario	Plant Size (rated thermal input)	Pollution regulation applicable	Regulator
Burning any fuel	>50MW	EPR – Part A(1a); PPC in Scotland and Northern Ireland.	Environment Agency, NRW, SEPA, and NIEA.
Waste oil, recovered oil, fuel manufactured from, or comprising, any other waste.	3 – 50MW *	EPR – Part A(1b); PPC in Scotland and Northern Ireland.	Environment Agency, NRW, SEPA, and NIEA.
Burning any fuel (other than a fuel mentioned in Part A(1b)	20 – 50MW	EPR – Part B(a); PPC in Scotland and Northern Ireland.	Local Authority, NRW, SEPA, and NIEA.
Burning any waste oil, recovered oil, solid fuel which has been manufactured from waste by an activity involving application of heat	<3MW	EPR – Part B(b); PPC in Scotland and Northern Ireland.	Local Authority, NRW, SEPA, and NIEA.
Burning fuel manufactured from or including waste (other than a fuel mentioned in Part B(b)	0.4 – 3MW	EPR – Part B(c); PPC in Scotland and Northern Ireland.	Local Authority, NRW, SEPA, and NIEA.
Burning fuel manufactured from or including waste (other than a fuel mentioned Part B(c)	0.4 – 3MW	EPR – Part B(d); PPC in Scotland and Northern Ireland.	Local Authority, NRW, SEPA, and NIEA.

Notes:
* where 2 or more appliances with an aggregate rated thermal input of 50 megawatts or more are operated on the same site by the same operator those appliances must be treated as a single appliance with a rated thermal input of 50 megawatts or more.

EPR = Environmental Permitting Regulations
NIEA = Northern Ireland Environment Agency
NRW = Natural Resources Wales
SEPA = Scottish Environmental Protection Agency

In addition, from 2013 the Renewable Heat Incentive (RHI) Regulations dictate that generating stations, which includes biomass boilers, below $20MW_{th}$ will need to meet specific emissions limits for PM and NO_x. These limits came in to force on 24th September 2013, with 30 and 150g/GJ net thermal heat input respectively. In order to be eligible for the incentives under the RHI scheme, an installation needs to present either an emissions certificate or an environmental permit, and has to burn the fuel as stated on the emissions certificate. In addition, under the RHI lifecycle greenhouse gas emissions are limited to $34.8gCO_2e$ per MJ of heat generated[40].

HETAS administers a dedicated website that helps to locate RHI emission certificates for biomass boilers: http://rhieclist.org.uk/. Evidence from this website shows that emission limits for PM and NO_x are not exceeded when boilers are tested under laboratory conditions. Given the issues mentioned in Section 6.1, in practice some boilers might exceed the limits. This will have an impact on emissions as biomass boiler emissions can increase significantly as the efficiency of the boiler decreases. Emission levels also depend on the boiler design and the fuel characteristics. A report on measurement and modelling of PM emissions from biomass boilers in Scotland[41] found that three out of the six biomass boilers under the study exceeded the PM_{10} limit as set by the RHI. However, in 2015 Kiwa reported that in all non-domestic installations assessed, the reported NO_x and PM emissions were below the limits specified in the RHI eligibility criteria.

Factors affecting PM and NO_x biomass boiler emissions

During its monitoring exercise, Gastec[34] noted that many biomass boilers were observed to give levels of smoke emission from the chimney. Evidence from the boiler manufacturers show that most modern biomass boilers will not exceed the stated levels when tested in laboratory conditions. However, research in Europe shows that emissions rise with inefficient schemes[31].

PM emissions are affected mainly by the following factors[42]:

- Air flow: decreasing air-to-fuel ratio during primary combustion while increasing air-to-fuel ratio during secondary combustion could significantly reduce PM emissions;
- Moisture content: high moisture content of the feedstock could lead to higher PM emissions;
- Boiler operation: low load operation could lead to increased PM emissions and incomplete combustion;
- The fuel particle size: small particle size could lead to higher PM emissions; and
- Presence of alkali in fuel could lead to increased PM emissions.

Fuel, thermal and prompt NO_x emissions are affected mainly by the following respective factors:

- Presence of nitrogen in the fuel, e.g. energy crops that are grown with nitrogen fertilizer will generate higher NO_x emissions;
- High combustion temperatures (>1,300°C) promote thermal NO_x. However, in small-scale biomass boilers capable of furnace temperature control (via flue gas recirculation or otherwise) combustion will typically occur at <1,200°C, thereby reducing NOx formation;
- Maintaining sub-stoichiometric conditions during primary combustion could reduce prompt NO_x formation.

Modern boiler designs usually incorporate primary and/or secondary abatement technologies in order to limit the formation of NO_x, and maintain PM emissions under the threshold. Table 7 and Table 8 show the main abatement technologies for small domestic and commercial boilers. As can be seen, multi-cyclones are typically the most cost effective method of meeting PM limits, whereas primary abatement technologies as part of the system design are typically the most cost effective method of meeting NO_x limits. Note that there are other secondary abatement technologies for controlling NO_x not listed in Table 8, such as selective non-catalytic reduction (SNCR), but these are typically designed for large combustion plants rather than smaller biomass boilers.

Table 7: PM abatement technologies small domestic and commercial boilers[32]

Abatement Technology	Type of abatement technology	Description	Reduction Efficiency	Capital Cost (£) of boilers <300kW$_{th}$
Multicyclones	Secondary	Multiple cyclones which use gravity and centrifugal force to gather particles on the wall of the cyclones.	PM_{10} 50-75% $PM_{2.5}$ up to 10%	340 – 620
Electrostatic precipitators (ESP)	Secondary	An electric charge is passed through the flue gas flow charging PM and causing it to move towards a collection plate which must be maintained with regular cleaning.	PM_{10} & $PM_{2.5}$ >90%	Very expensive
Filtration	Secondary	Dust filters consisting of either fabric or ceramic material	PM_{10} & $PM_{2.5}$ 99%	3,900 – 13,500

Table 8: NO_x Abatement technologies for small domestic and commercial boilers[32]

Abatement Technology	Type of abatement technology	Description	Reduction Efficiency	Capital Cost (£)
Staged Combustion	Primary	Restricts oxygen levels in the first stage of combustion and maintaining a lower temperature level in the second stage of combustion	Up to 50%	Incorporated in boiler design
Automated process control systems	Primary	Consists of monitoring the temperature and oxygen levels to ensure optimum conditions for reduced NO_x formation during combustion	Can limit NO_x emissions to 65-100 g/GJ net thermal input	Incorporated in boiler design
Flue gas recirculation	Primary	Reuse of waste gases to lower the combustion temperature and reduce oxygen levels	Up to 15%	Incorporated in boiler design
Selective Catalytic Reduction (SCR)	Secondary	Injection of a chemical reagent (ammonia based) into the gas stream at the point of highest temperature in the combustion chamber. The reagent changes the composition of NO_x to molecular nitrogen and water.	Up to 40%	690 – 3,000 (boiler below 300kW$_{th}$)

6.4 Feedstock testing and certification

There is wide range of biomass feedstock available that can be burnt in biomass boilers. However, the feedstock must be close to the specification of the boiler otherwise it could cause blockages, inefficient operation, condensation in the flue, automatic shutdown of the equipment and emissions problems. To facilitate selection and equipment compliance, a set of European biomass fuel standards has been developed, and fuel quality assurance schemes have been set up to ensure compliance with these standards by the suppliers accredited under these schemes[43].

As mentioned in Section 6.2, the great majority of non-domestic (44%) and domestic (88.2%) boilers acredited under the RHI scheme use wood pellets as feedstock. The ENplus certification scheme was developed to define and ensure constant quality of wood pellets – Table 9 shows the threshold values of the most important parameters for quality classes A1, A2 and B. Whilst most pellet boiler manufacturers require use of A1 to meet the emissions certificate, there is anecdotal evidence that a percentage of pellets used in the commercial and domestic market are not A1[32].

Table 9: Threshold values of the most important pellet parameters[44]

<table>
<tr><th>Property</th><th>Unit</th><th colspan="2">ENplus A1</th><th colspan="2">ENplus A2</th><th colspan="2">ENplus B</th></tr>
<tr><td>Diameter</td><td>mm</td><td colspan="6">6 ± 1 or 8 ± 1</td></tr>
<tr><td>Length</td><td>mm</td><td colspan="6">3.15 < L ≤ 40 2)</td></tr>
<tr><td>Moisture</td><td>w-% ar</td><td colspan="6">≤ 10</td></tr>
<tr><td>Ash</td><td>w-% db</td><td colspan="2">≤ 0.7</td><td colspan="2">≤ 1.2</td><td colspan="2">≤ 2.0</td></tr>
<tr><td>Mechanical Durability</td><td>w-% ar</td><td colspan="3">≥ 98.0 5)</td><td colspan="3">≥ 97.5 3)</td></tr>
<tr><td>Fines (< 3.15 mm)</td><td>w-% ar</td><td colspan="6">≤ 1.0 4) (≤ 0.5 5))</td></tr>
<tr><td>Temperature of pellets</td><td>°C</td><td colspan="6">≤ 40 6)</td></tr>
<tr><td>Net Calorific Value</td><td>kWh/kg ar</td><td colspan="6">≥ 4.6 7)</td></tr>
<tr><td>Bulk Density</td><td>kg/m³ ar</td><td colspan="6">600 ≤ BD ≤ 750</td></tr>
<tr><td>Additives</td><td>w-% ar</td><td colspan="6">≤ 2 8)</td></tr>
<tr><td>Nitrogen</td><td>w-% db</td><td colspan="2">≤ 0.3</td><td colspan="2">≤ 0.5</td><td colspan="2">≤ 1.0</td></tr>
<tr><td>Sulfur</td><td>w-% db</td><td colspan="3">≤ 0.04</td><td colspan="3">≤ 0.05</td></tr>
<tr><td>Chlorine</td><td>w-% db</td><td colspan="3">≤ 0.02</td><td colspan="3">≤0.03</td></tr>
<tr><td>Ash Initial Deformation Temperature 1)</td><td>°C</td><td colspan="3">≥ 1200</td><td colspan="3">≥ 1100</td></tr>
<tr><td>Arsenic</td><td>mg/kg db</td><td colspan="6">≤1</td></tr>
<tr><td>Cadmium</td><td>mg/kg db</td><td colspan="6">≤ 0.5</td></tr>
<tr><td>Chromium</td><td>mg/kg db</td><td colspan="6">≤10</td></tr>
<tr><td>Copper</td><td>mg/kg db</td><td colspan="6">≤10</td></tr>
<tr><td>Lead</td><td>mg/kg db</td><td colspan="6">≤10</td></tr>
<tr><td>Mercury</td><td>mg/kg db</td><td colspan="6">≤ 0.1</td></tr>
<tr><td>Nickel</td><td>mg/kg db</td><td colspan="6">≤10</td></tr>
<tr><td>Zinc</td><td>mg/kg db</td><td colspan="6">≤100</td></tr>
</table>

Units: ar = as received, db = dry basis, w-% = % weight. Notes:

1) ash is produced at 815°C.
2) a maximum of 1% of the pellets may be longer than 40mm, no pellets longer than 45mm are allowed.
3) at the loading point of the transport unit (truck, vessel) at the production site.
4) at factory gate or when loading truck for deliveries to end-users (Part Load Delivery and Full Load Delivery).
5) at factory gate, when filling pellet bags or sealed Big Bags.
6) at the last loading point for truck deliveries to end-users (Part Load Delivery and Full Load Delivery).
7) equal to ≥ 16.5 MJ/kg as received.
8) the amount of additives in production shall be limited to 1.8 w-%, the amount of post-production additives (e.g. coating oils) shall be limited to 0.2 w-% of the pellets.

The quality requirements under ENplus as listed above are now based on the standard for solid biofuels ISO 17225-2.

Quality assurance is dealt with in standard BSI BS EN 15234 – 'Solid biofuels - Fuel quality assurance Part 1: General requirements' which guarantees solid biofuel quality through the supply chain. Additional parts to the standard have been developed to describe fuel quality assurance for pellets (Part 2), briquettes (Part 3), wood chips (Part 4), firewood (Part 5) and non-woody pellets (Part 6) for non-industrial use.

In the UK there are two quality assurance schemes, namely HETAS and Woodsure. Both schemes provide reassurance to buyers that the feedstock being supplied has been accredited as quality compliant by an independent third party.

HETAS is a Government recognised scheme that assesses producers against European solid biomass fuel standards and it covers firewood, wood briquettes and pellets, wood chips and hog fuel. Producers can gain a Quality Assured Fuel Status through HETAS. Its allow the consumers to identify suppliers who have been accredited as operating a quality assurances scheme compliant with the fuel standards. HETAS is also the UK's approved certifying body for the ENplus in the UK. This scheme ensures that pellet quality is managed throughout the entire supply chain. The UK Pellet Council holds the licensing rights for the scheme in the UK and, through their website, certified ENplus producers and traders can be found (http://www.pelletcouncil.org.uk/consumer-information).

Similarly, Woodsure assesses the quality of wood chips, wood pellets and briquettes, hog fuel and firewood against ISO, EN and Önorm standards (The Austrian Standards Institute). All documentation is submitted to HETAS for approval. An interactive map showing all UK woodfuel suppliers currently approved under the Woodsure Certification Scheme can be seen at: http://woodsure.co.uk/woodsure-certified-fuel-suppliers/.

The main European technical standard for solid biofuels is 'BSI BS EN ISO 17225-1: Solid biofuels – Fuel specifications and classes, Part 1 General requirements' for feedstocks originating from forestry and arboriculture, agriculture and horticulture residues, aquaculture and blends and mixtures. The standard includes the specification of properties for briquettes, pellets, wood chips and hog fuels, log wood and firewood, sawdust, shavings, bark, bales of straw, reed grass and Miscanthus, and thermally treated biomass (mild form of pyrolysis/torrefaction) among others. The standard makes reference to several technical standards, describing methods for sampling and analysis of fuel properties, such as:

- BSI BS EN ISO 16559, Solid biofuels — Terminology, definitions and descriptions;
- BSI BS EN ISO 16948, Solid biofuels — Determination of total content of carbon, hydrogen and nitrogen;
- BSI BS EN ISO 16967, Solid biofuels — Determination of major elements;
- BSI BS EN ISO 16968, Solid biofuels — Determination of minor elements;
- BSI BS EN ISO 16993, Solid biofuels — Conversion of analytical results from one basis to another;
- BSI BS EN ISO 16994, Solid biofuels — Determination of total content of sulfur and chlorine;

- BSI BS EN ISO 17828, Solid biofuels — Determination of bulk density;
- BSI BS EN ISO 17829, Solid biofuels — Determination of length and diameter for pellets;
- BSI BS EN ISO 17831-1, Solid biofuels — Determination of mechanical durability of pellets and briquettes — Part 1 Pellets;
- BSI BS EN ISO 17831-2, Solid biofuels — Determination of mechanical durability of pellets and briquettes — Part 2: Briquettes;
- BSI BS EN ISO 18122, Solid biofuels — Determination of ash content;
- BSI BS EN ISO 18123, Solid biofuels — Determination of the content of volatile matter;
- BSI BS EN ISO 18134-1, Solid biofuels — Determination of moisture content — Oven dry method — Part 1: Total moisture — Reference method; and
- BSI BS EN ISO 18134-2, Solid biofuels — Determination of moisture content — Oven dry method — Part 2: Total moisture — Simplified method.

Additional parts to BSI BS EN ISO 17225 have been developed to describe graded solid biofuel products for non-industrial use (Part 3, 4, 5 and 7) and industrial use (Part 2 and Part 6).

- Part 2: Graded wood pellets;
- Part 3: Graded wood briquettes;
- Part 4: Graded wood chips;
- Part 5: Graded firewood (log wood);
- Part 6: Graded non-woody pellets;
- Part 7: Graded non-woody briquettes.

A draft by ISO TC 238 (BS EN ISO 17225-8) for Graded thermally treated and densified biomass fuels, which would cover torrefied pellets and briquettes, is currently in the process of being finalised.

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7 Glossary

AR / ar	As received
CHP	Combined Heat and Power
CO	Carbon monoxide
CO_2	Carbon dioxide
CV	Calorific Value
DB / db	Dry basis
DECC	Department of Energy and Climate Change
EPC	Engineering Procurement Construction
EPR	Environmental Permitting Regulations
ESP	Electrostatic precipitators
ETI	Energy Technologies Institute
FIT	Feed-in-tariff
GJ	Gigajoule
HHV	Higher Heating Value – defined as defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products
Kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
K_2O	Potassium oxide
LHV	Lower Heating Value – defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered
LTHW	Low Temperature Hot Water
mg	milligram
mm	Millimetre
MTHW	Medium Temperature Hot Water
MW	Megawatt
N	Nitrogen
Na_2O	Sodium oxide
NIEA	Northern Ireland Environment Agency

NO_x	Nitrogen oxides
NRW	Natural Resources Wales
OEM	Original Equipment Manufacturer
ORC	Organic Rankine Cycle
PAH	Poly-aromatic Hydrocarbons
PM	Particulate Matter
POM	Particulate Organic Matter
RHI	Renewable Heat Incentive
RPM	Rotations per minute
SCR	Selective Catalytic Reduction
SEPA	Scottish Environmental Protection Agency
SNCR	Selective non-catalytic reduction
SO_x	Sulphur oxides
TRL	Technology Readiness Level
UK	United Kingdom
V	Volt
WB	Wet basis