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Biomass Boiler Systems for LTHW Heating and DHW

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List of Abbreviations

AHU	Air Handling Unit
BEMS	Building and Energy Management System
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Services Engineers
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DECC	UK Department of Energy and Climate Change
DHW	Domestic Hot Water
ESRU	Energy Systems Research Unit at the University of Strathclyde
GCV	Gross Calorific Value
kWhth	Kilowatt Hour Thermal
LTHW	Low Temperature Hot Water (70-90ºC)
NOx	Nitrous Oxides
Ofgem	UK Office of the Gas and Electricity Markets
PM_{10}	Particles of equivalent diameter 10µm or less
RH%	Relative Humidity (%)
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator

Abstract

The aim of this dissertation is to investigate the requirements for good practice in design and operation of biomass boiler system for space heating and DHW. Biomass boiler systems can provide a cost effective method for reducing the cost and environmental impact of heating in buildings. Biomass used for heat could represent a particularly effective strategy given that space heating accounts for a significant proportion of the UK's energy use, however certain key differences between biomass and fossil fuel boilers are the subject of frequent misunderstanding due to the superficial similarities between the two combined with a comparatively low level of deployment of the technology in the UK. Poor design and operation of biomass boiler systems not only increases running costs but can also result in harmful emissions to the environment. The research method for this thesis involved a literature review outlining the current state of the technology, followed by two case studies, one design based and one involving troubleshooting an existing installation's poor performance. The first case study dealt with a site with potential for installation of a retrofit biomass boiler system for space heating and DHW, working through the design process required to size a biomass boiler system for a calculated heat load. The second case study was a practical evaluation of an existing biomass boiler system which was exhibiting poorer than expected performance and included recommendations for measurement techniques particular to biomass boiler systems. The main findings of these studies were that biomass boiler systems should be sized as a single boiler/thermal store combination to meet a percentage of annual heat demand; arrays of biomass boilers should be avoided in most cases due to capital cost and operational issues. The benefits of biomass boiler systems are lower fuel costs and lower emissions than equivalent fossil fuel systems; poorly running biomass boiler systems can, however, result in harmful emissions of CO, NOx and particulates as well as poorer than expected financial benefits, so monitoring and evaluation of biomass boiler systems must be carried out at the commissioning stage and periodically during normal operation to ensure the system operates within its design expectations.

1. Introduction

1.1. Background

Space heating accounts for almost 40% of total non-transport energy use in the UK according to DECC (2010a) figures, yet less than 1% of this demand was met by renewable sources, excluding electrical heating, in 2008 (DECC, 2010b). For non-domestic users, CO_2 emissions are taxed through the Climate Change Levy (CCL; see 'Legislation' section below). Fossil fuel prices can be expected to rise due to diminishing reserves and worldwide political instability. There are therefore two drivers to improve heating systems in buildings; to reduce CO_2 emissions and to reduce the direct cost of heating (Moss, K.J. 2006). In order to realise carbon emissions reductions goals, it would seem sensible to attempt to both reduce demand, and to utilise less carbon-intensive heating methods. A number of options are outlined below:

- Demand reduction through better insulation, airtightness and reducing ventilation losses; this is progressive and ongoing through the tightening of modern Building Regulations. This option does not exclude other solutions, although practical considerations must be taken into account for retrofit applications.
- De-carbonise grid, use electric heating; this is a long term solution, reliant on the actions of others, i.e. electricity producers and TSOs.
- Use locally available renewable energy generation to provide heat; e.g. solar thermal, small scale wind; this is dependent on the available resource, and can entail high capital cost and low reliability/despatchability. Site surveys must be carried out to avoid inappropriate application but in some instances this approach may be useful in providing auxiliary supply where the full demand cannot be met.
- Use of more efficient natural gas fired boilers (e.g. condensing boilers) ; this can be an effective short term solution utilising existing technology, however it is not suitable for all applications, e.g. high heating system flow/return temperature differences & those remote from the gas grid. Price and availability is likely to be an issue in the future as the resource dwindles. Although this represents a low risk option in the short term, the future is less predictable.
- District heating schemes or CHP where suitable demand exists.

- Identification of alternative heating fuels, such as from waste, or renewable biofuels such as straw, wood chips or pellets; these may be considered in particular where the installation is remote from the gas grid or where the fuel would otherwise have to be sent to landfill which is becoming an expensive solution.

The choice of options to reduce emissions and costs will be influenced by a number of factors and therefore will be largely site dependent. This study focuses on the application of wood burning biomass boilers for LTHW space heating and DHW.

The DECC (2010c) provides the following background information on renewables used for heat production:

- Around 14% of renewable sources were used for heat generation in 2009.
- Renewables used to generate heat declined to a low point in 2005 but since then increased by 62% to 966 thousand tonnes oil equivalent
- The decline was mainly due to tighter emissions controls discouraging on-site burning of biomass, especially wood waste by industry
- Domestic use of wood accounts for 39% of all renewables used for heat; plant biomass is the second largest component, at 21%.

The general trend in renewables used for transport, electricity generation and heat production is shown in Figure 1-1.

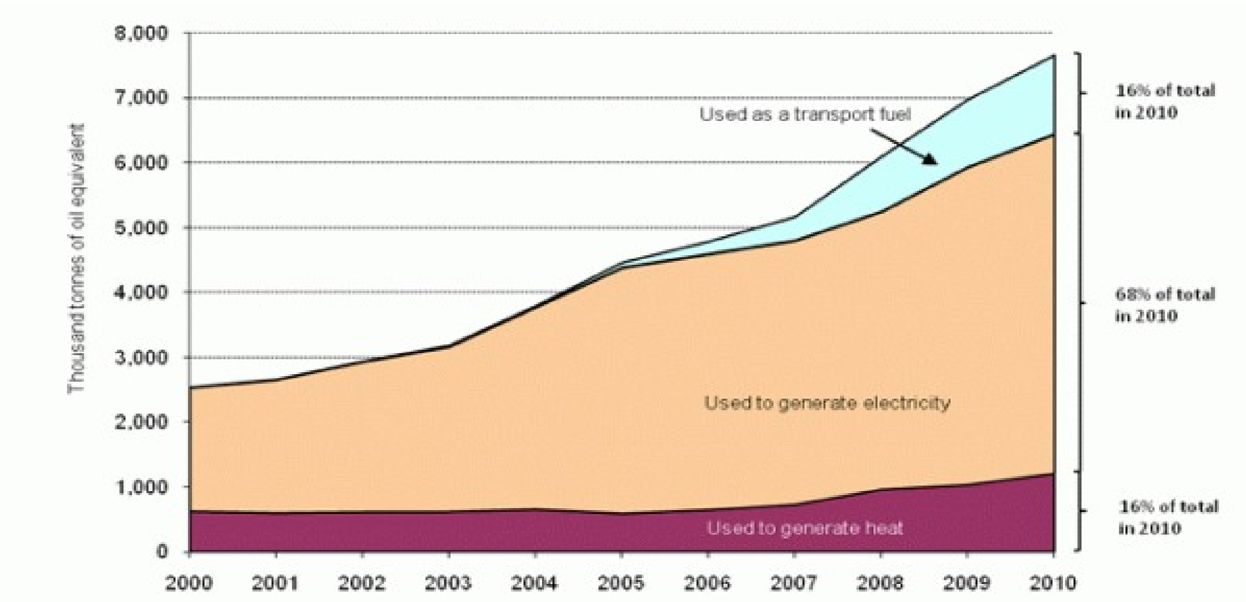

Figure 1-1: UK Renewable Energy Use Trends 2000-2010

Source: DECC (2010c)

Some biomass system manufacturers offered their views (CIBSE, 2009) on how the technology might be deployed in the future:

George Fletcher, Technical Sales, Veissmann, predicts most benefit will be found off the gas grid and in industrial waste wood applications. Domestically, he expects biomass to only be viable in district heating, however states, 'during the next 10 years we would expect to see many more pellet boilers installed in larger and also in older domestic properties.'

Andy Owens, technical sales manager, Hoval, stresses it will be important to consider control practicalities such as heat load throughout year, to minimise cycling by buffer vessel sizing and integration with auxiliary e.g. fossil or solar thermal systems.

Tom Lelyveld, AECOM consulting engineers, suggests there is scope to combine biomass with solar thermal to allow for a summer shutdown of the biomass boiler.

1.2. Biomass Boilers

Biomass boilers are characterised by high capital costs (due mainly to the need for solid fuel handling, storage, and size of boiler due to low energy density of fuel), and low turn-down ratios in comparison to traditional fossil fuel boilers. They can, however, offer significant carbon emission reductions, and lower fuel costs, particularly when competing with fuel oil as would be the case at sites off the gas grid. The specific characteristics of biomass boiler operation are discussed in the subsequent report, along with the site conditions that would make installation of a biomass boiler most favourable.

As with any new application of an engineering solution, there is currently a lack of knowledge about biomass boiler design and operation. Biomass boilers operate in a similar way to traditional solid fuel boilers, but with some key differences which mean they must be properly integrated with existing systems and controlled correctly to give optimal performance. Biomass boilers will also typically require more operator interaction than a fossil fuel boiler, so training of staff on site is required to ensure the biomass boiler system performs as expected.

1.3. Fuel Availability

Some industrial processes produce 'waste' biomass which may be utilised locally as fuel, however for most installations a reliable source of imported biomass, such as wood chips or wood pellets is needed. This may present a problem if there is significant uptake, as although wood is a renewable resource, it is also finite.

The vast majority of biomass wood fuel used at present in Scotland is wood chip rather than wood pellet - 56%/3% in 2009, despite the greater complexity of plant operation and storage issues (Forestry Commission Scotland, 2010). UK wide provisional figures for 2008 are shown in Figure 1-2. The advantages of wood pellets versus wood chip are discussed in Chapter 2.1.

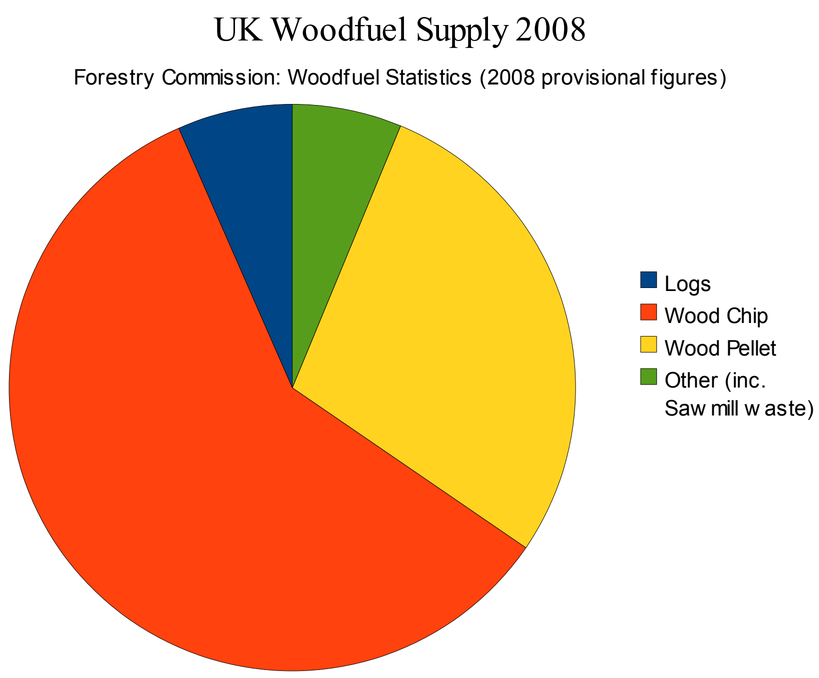

Figure 1-2: UK Woodfuel Supply 2008

Source: (Forestry Commission, 2009)

There has, however been a rapid increase in wood pellet production to meet growing demand from the sector; Forestry Commission (2011) figures reported a 67% increase from 118,000 tonnes to 197,000 tonnes in UK pellet & briquette production from 2009 to 2010 , and a number of initiatives have been undertaken by the Forestry Commission in the UK and Scotland as well as by the Scottish and UK governments to increase the availability of wood for use as a biofuel. Problems of supply may however arise if large scale wood burning or co-firing power plants are to be introduced; this is not expected to be the best use of the resource in Scotland according to the Wood Fuel Task Force (WFTF). Proposals mentioned in the WFTF 2011 Report (WFTF, 2011) include four 100-200MWe plants by Forth Energy and Peel Energy's proposals for a co-firing plant at Hunterston. These large scale projects would require imported wood pellets from the USA, Russia or South America, however the market is uncertain, especially if countries such as the USA choose to increase their reliance on wood biomass, as is likely to be the case.

Due to this uncertainty of global and local supply of woody biomass, the WFTF recommends discouraging large scale plants for electrical generation which could cause supply problems:

> 'The Task Force believes that biomass policy, rather than making a dash for biomass through a series of large scale electricity only power stations, should encourage the incremental growth of the biomass industry, focussing on heat and combined heat and power, and avoiding lock in of the resource to a small number of large plants.' - (WFTF, 2011, p11)

1.4. Environmental Impact

The burning of biomass can release potentially harmful by-products into the environment if steps are not taken to mitigate their impact. A list of common pollutants is given below along with some suggestions for their mitigation.

- Metal Oxides - The most harmful pollutants can be produced from waste wood which is essentially impure; low melting point metals and other contaminants should ideally be removed from waste wood prior to burning.
- Cl - Wood biomass has an environmental advantage over other sources of biomass such as straw as it contains low concentrations of chlorine which results in less fouling in boilers burning wood vs straw
- NOx - Burning wood in excess air can potentially release nitrous oxides as well as increasing sensible heat losses in the flue gas; careful control of the fuel/air mix is required to avoid this
- CO - Poor combustion efficiency, caused either by supplying insufficient air or by poos fuel/air mixing can result in harmful CO being produced rather than CO_2; if a boiler is not performing well, high CO levels in the flue gas are an obvious sign of this
- Particulates - solid particles from the char and ash are a major source of pollution from burning any solid fuel. These can be removed from the flue gases by mechanical separation e.g. in a cyclone or filter, or by electrostatic means. Some research has also suggested turbulence in the secondary air can be used to remove most particulates before they reach

the flue (Wiinikka, H., Gebart, R., 2004). Different fuel feed systems can also influence the rate of particulate emissions (Verma et al. 2011), and particulate emissions are generally minimised by modern boiler designs

1.5. Legislation

The UK and Scottish governments have introduced a number of schemes to promote biomass use and CO_2 emissions reduction. From a commercial point of view the most significant are the Climate Change Levy (CCL) and Renewable Heat Incentive (RHI). Capital grants have also been introduced in some instances. Emissions are also controlled by legislation. The various initiatives are outlined below.

Renewable Heat Incentive (RHI)

The RHI is essentially a heating equivalent to the Feed in Tariff (FIT) for renewable electricity production. Currently the RHI is due to come into force on the 1st of September 2011 in the UK for non-domestic installations. Producers of renewable heat from biomass are guaranteed payments per kWhth for 20 years (subject to metering requirements) dependent on the installed capacity of the boiler. The rate is to be set at 2.6p/kWhth for boilers above 1MW installed capacity, with 'Tier 1' rates of 7.6p/kWhth for up to 200kW and 4.7p/kWhth 200-1000kW; 'Tier 2' rates are 1.9p/kWhth for boilers up to 1MW. The 20 year guarantee will likely have a major positive impact on the ability of companies and local authorities to secure funding for biomass heating projects. The heat produced to qualify for RHI payments must meet metering criteria set out by Ofgem and unintended consequence of the RHI may be that fuel metering also improves; as a result biomass boiler systems may be better operated than perhaps has been the case up until now due to improved worker training.

Other Initiatives

- CCL introduced in 2001 to replace the Fossil Fuel Levy, is a tax on electrical and fuel use by non-domestic customers UK wide; biomass systems are exempted from the CCL
- CRC Energy Efficiency Scheme
- Biomass Action Plan for Scotland, Scottish Executive, 2007
- Scottish Biomass Heat Scheme may provide grant support for biomass system installation (see 'Useful Web Links' at the end of this document)

This list is not exhaustive and a number of smaller schemes may be available in particular regarding capital grants for specific geographical areas. The 'Useful Web Links' section at the end of this document provides resources with further information on the various schemes available.

Emissions

Emissions from biomass boilers in the UK are generally governed by the Clean Air Act and the Local Authority. NOx and particulate (PM_{10}) emissions are the main pollutants of concern for biomass. Where waste wood is burned, the Waste Incineration Directive (WID) may also be applicable, although boilers burning wood waste which does not contain halogenated organic compounds or heavy metals (caused by some preservative treatments), for example from sawmill waste, are excluded from the WID.

1.6. Project Outline

Aims & Objectives

- To investigate design & operation of biomass boiler systems
- To identify key performance parameters for biomass boilers and thermal stores
- To investigate the differences between expected design performance and performance in practice and the reasons for this
- To provide generalised recommendations for the operation & design of biomass boiler systems

Scope

The main application of biomass boilers investigated is to be pellet & wood chip burning boilers for DHW and space heating in municipal buildings and for greenhouse space heating

Areas of boiler operation & design to be investigated are:

- biomass boiler system design requirements & methodology
- boiler efficiency test procedure
- comparison between design & measured efficiency
- investigation of biomass boiler control systems & comparison with fossil fuel boilers

Methodology

For the project the following work was carried out

1. Literature review of biomass boilers
2. Design method for biomass boiler systems, aided by a case study of a retrofit design for a college campus system
3. Efficiency test, and system troubleshooting, aided by a case study of an existing biomass boiler installation at a plant nursery
4. General conclusions including recommendations for requirements for site monitoring and evaluation

2. Biomass Boiler Systems for Space Heating & DHW

2.1. Fuel

Biomass boilers could be those defined as firing any organic material (such as straw, sawdust, spent grain, etc.) from either a waste or fuel crop source. In comparison to most other plant derived biomass, wood has a high GCV due to its higher fraction of Carbon (around 50% by weight dependent on species and source), and lower NOx emissions and residue production due to lower levels of Nitrogen, Chlorine and other ash forming elements. This report will focus on biomass boilers burning either wood chip or wood pellets. Wood burning does not result in the harmful dioxin emissions associated with for example straw, or the sulphurous emissions that result from coal burning (Chagger et al., 1998), however burning waste wood may contain other chemicals such as chlorine or low melting point metals dependent on its source (Sandberg et al., 2011). Wood pellets (which can be made from a variety of wood waste or fuel crop sources) have the advantage of easier storage (due to regular shape and low moisture content), easier transport within the boiler due to regular size and greater ease of flow, as well as more predictable combustion characteristics when compared with wood chip due to lower moisture content and manufacturing quality assurance. Wood chip will have the lower cost where it is available, but storage and combustion are affected by the higher moisture content. A system burning wood pellets may also be more reliable and require less maintenance in the long term due to the higher fuel quality. Wood chip characteristics such as particle size and moisture content are classified in the draft European Standard CEN/TC 335.

Key practical considerations for wood biomass fuel are:

Wood Pellets:

- Pellets must not be damaged in transit or delivery (e.g. by high pressure blown hose delivery), as this may result in high levels of dust

Wood Chip:

- Moisture must be controlled during transportation & storage to prevent biodegradation
- Storage of high moisture content wood chip can result in composting, heat production, and spore producing moulds which may require P3 filter dust mask to be worn when working with the chip

- The chip must be kept free of dirt or stones which could damage equipment

Whilst there are similarities between coal fired boilers and biomass boilers since both burn solid fuel, differences in physical and chemical properties between wood and coal result in different combustion characteristics:

- wood/biomass has a lower energy density, 10-17MJ/kg vs. 36MJ/kg GCV of coal
- wood/biomass has a higher moisture content
- wood has a lower density
- wood/biomass has a higher volatile content 70-80% vs 10-50% by weight
- different minerals result in different ash content (this will vary for both coal and biomass dependent on source); burning biomass may result in fouling problems due to more alkaline ash (Annamali & Wooldridge, 2001) , but would generally result in lower volumes of char

The first two listed differences will result in biomass boilers requiring to handle more fuel and be more physically massive than a similar rated fossil fuel boiler, increasing capital costs. The second two listed differences seem to result in a higher temperature in the freeboard and lower temperature in the char than is the case in coal fired boilers (Tarelho et al. 2011). This means that biomass burning may be more sensitive to variations in moisture content, which is a concern since biomass will vary as any biological organism does; the use of manufactured wood pellets seeks to minimise this variation, however pellet quality quality can vary significantly from one manufacturer to another according to conversations with biomass boiler operators.

Combustion Mechanism

Since solid fuel does not burn directly, the combustion process within the boiler can be characterised into a number of distinct phases, where solids and gases react separately. A summary of the combustion mechanism is shown in Figure 2-1.

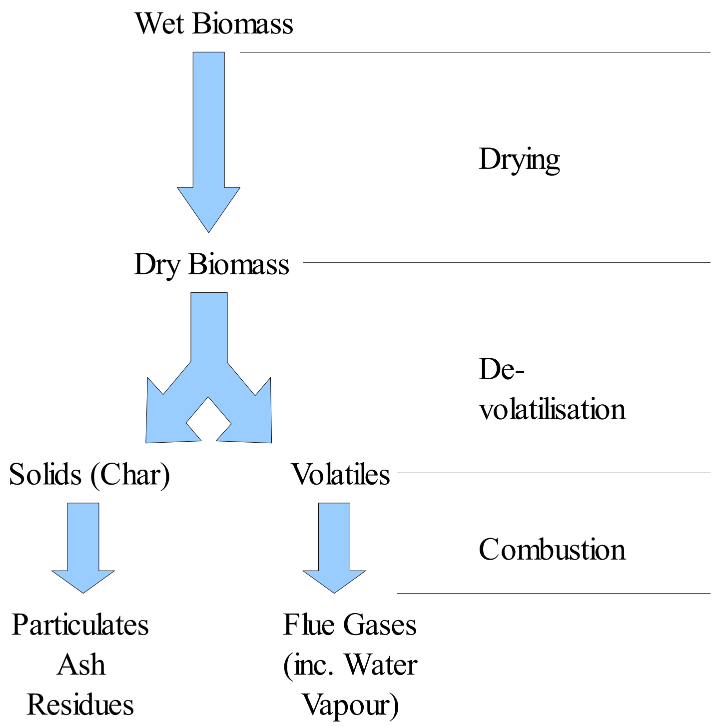

Figure 2-1: Combustion Mechanism for Solid Biofuel

Although this gives a basic outline of the process, the exact mechanism of combustion for biomass fuels is complex and not fully understood, especially for wet fuel. It is possible that pyrolysis may take place if there is insufficient oxygen for combustion. It can be understood however that the water and volatile fraction of the biomass will have a significant effect on the process. The drying and devolatilisation phases will depend on the boiler type and fuel moisture content, with some boiler types more tolerant of wet fuel due to more efficient drying mechanisms, as described in Section 2.3.

Fuel Delivery

Much of the increased capital cost of biomass boilers as opposed to gas or oil boilers relates to the delivery, storage, and handling of a bulky biodegradable fuel. A good outline of the variety of methods and their practical considerations is available from the Carbon Trust (2009) guide for biomass heating users; this document is referred to as 'CTG012' in subsequent text. These fuel delivery options are outlined in Table 2-1.

Delivery Option	Suitable Fuel	Delivery Payload
Flexible hose from tanker	pellet (chip with specialist equipment)	pellet=medium chip=small
Bulk bags	pellet or chip	very small
Tipper trailer	pellet or chip	pellet = large - very large chip = medium
Scissor lift tipper trailer	pellet or chip	chip=medium
Tipper truck & blower trough	chip	small
Hook lift/Ro-Ro bins	chip	medium-large
Front loader	chip and bales	very small
Walking floor trailer	chip	very large

>1t= very small, 1-6t = small scale, 6-10t medium 10-14t large, 15+ very large

Table 2-1: Fuel Delivery Methods

A comprehensive description of the fuel delivery methods is available in CTG012. Selection will be based upon a number of practical considerations; the decision process is outlined below:

1. What is the rated size of the boiler?
2. What is the fuel type (i.e. chip or pellet)?
3. What space is available for delivery vehicles?
4. What manpower is available on site?
5. What size & type of storage is available on site?
6. What fuel extraction system is to be used?
7. Choose preferred method(s), estimate fixed & operating costs and repeat if necessary

Fuel Storage

CTG012 characterises storage methods as above ground, below or partially below ground, building integrated, or containerised removal types. The key considerations for a selected storage type are:

- Dust control
- Moisture Control
- Delivery access available
- Structural design

- Ease of inspection
- Ease of delivery to plant
- Safety & security of fuel & workers
- Building design considerations (e.g. electrical supplies, Building Regulations etc.)

Once again, the type of storage selected will be site specific. Typical decision process outlined below:

1. What type of fuel is to be used (chip or pellet)?
2. What delivery type is preferred?
3. What space is available?
4. What is the distance to the plantroom?
5. What are the ground conditions if subterranean storage has been selected?
6. Are there any visual considerations?
7. Estimate costs & repeat if necessary

Often the main concerns when considering a biomass installation at an existing site, many of which may be remote rural sites with poor infrastructure, will be space for fuel storage and determining a suitable route for delivery trucks while attempting to minimise the amount of civil engineering work required.

Fuel Extraction

Fuel can be transported to the boiler from where it it stored by a variety of methods. The main aims will be to ensure fuel volume supplied to the boiler is controlled to maintain efficiency and meet the desired load, and to ensure safety by preventing ignition of the fuel outside the boiler (termed 'burn-back'), often by means of a flap valve. A minimum of two systems are needed to prevent burn back, one of which must operate without mains electricity (BS EN 15270:2007). Available space on site and distance between the boiler and fuel store will also have an influence on fuel extraction method selection. Fuel extraction methods are summarised in Table 2-2.

Type	Fuel	Scale
Fuel Hopper	chip or pellet	small
Sweeping Arm	chip or pellets	small - medium
Sweeping Auger	chip or pellet	large
Hopper	pellet (or grain)	small-large
Walking Floor	chip or pellet	very large

Table 2-2: Fuel Extraction Methods

2.2. Boiler Operation Strategy

In order to maximise efficiency whilst minimising emissions of particulates, CO and NOx compounds, combustion within the boiler is controlled by regulating the supply of fuel and air; the optimal air/fuel mix must be supplied to minimise particulate and NOx emissions and heat wastage. The addition of excess air will influence the efficiency of the system in two ways (Menghini et. al., 2007); firstly by controlling the degree of combustion of the fuel through stoichiometry, and secondly by removing heat from the system through convection. Too little air supply will result in unburnt fuel and subsequent increased CO emission, whereas too much air will lower efficiency and may increase NOx emissions. It is also possible that too much excess air will increase CO emissions, as too much air can result in poor mixing of the combustion air with the fuel, even where it is stoichiometrically excessive. Different designs are used to achieve these aims; common boiler types are discussed in the next section.

Biomass Boilers typically operate in a number of distinct modes:

- Slumber Mode. The boiler must burn a small amount of fuel when there is no heat demand to avoid the need for re-ignition using auxiliary power (electricity)
- Full Flame. More fuel is added and the boiler warms up to supply demand
- Normal Operation. Under load the boiler burns fuel to meet desired demand
- Cool Down. If the boiler must be shutdown, e.g. for maintenance then it will require time to cool down.

2.3. Boiler Types

Three main types of biomass boiler are currently used for space heating and DHW ; Stoker Burners, Underfed Stokers, and Moving Grate Boilers (Palmer, D. 2011). Fluidised bed combustors are frequently used for larger installations for example in co-firing with coal in power generation. The choice of boiler type will be dependent on fuel type, scale and various practical considerations.

Both the Underfed Stoker and Moving Grate boiler types introduce fuel and primary air at the base of the boiler, with secondary air blown down from above; these can be controlled separately.

Moving Grate Boilers

In a moving grate boiler the biomass burns in a fixed bed on a moving grate which transports the fuel from fuel inlet to the ash discharge; the boiler is internally lined with refractory material such as fire brick which directs heat onto the fuel. An electrical burner is used to bring the fuel to ignition. Fuel is fed in from the auger onto a moving grate (this can be either travelling, vibrating, or reciprocating), where it is dried and combusted as it travels along the grate. Ash is automatically removed at the end of the grate. Primary air is added below the grate, and secondary blown in from above. Figure 2-2 shows a typical moving grate boiler.

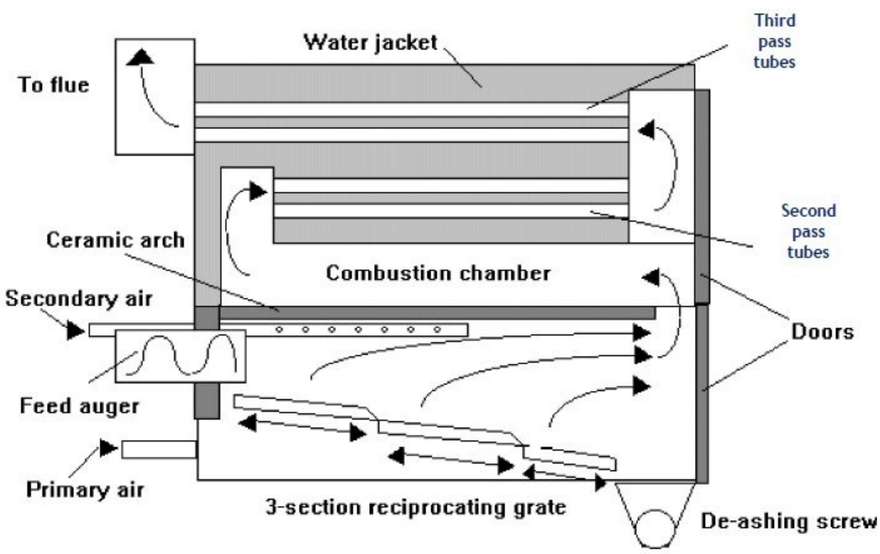

Figure. 2-2: Moving Grate Boiler Diagram (Palmer, D. 2011)

Major operational characteristics are the low turn down ration due to the high inventory of fuel on the grate, and high thermal inertia due to the fire brick lining. The design does however allow a high level of automation and can cope with a variety of fuels.

Underfed Stoker Boilers

The underfed stoker boiler is similar to the moving grate boiler, however the fuel is fed in from below the combustion chamber by the fuel auger to a fixed grate. This simpler design reduces cost, however flame out may occur if slag is allowed to build up on top of the fuel. This type of boiler also has a high thermal inertia due to fire brick lining as with moving grate boilers.

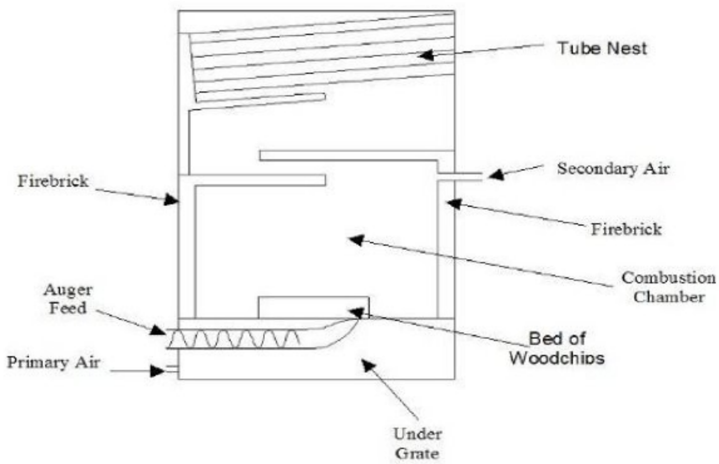

Figure. 2-3: Underfed Stoker Boiler Diagram (Palmer, D. 2011)

Stoker Burner Boilers

The Stoker Burner boiler is a simple design, with a single air blower introducing air around the burner head enclosure where it is heated before flowing through air holes before the combustion chamber to provide primary air below the fuel and secondary air above the fuel (i.e. primary and secondary air cannot be separately controlled). Ash must be removed manually. This boiler type is less suited to burning wet fuel, but has a lower thermal inertia than other types and higher turn down ratios. Due to the lack of automation, these boilers may be more labour intensive, requiring manual fuel extraction and ash removal.

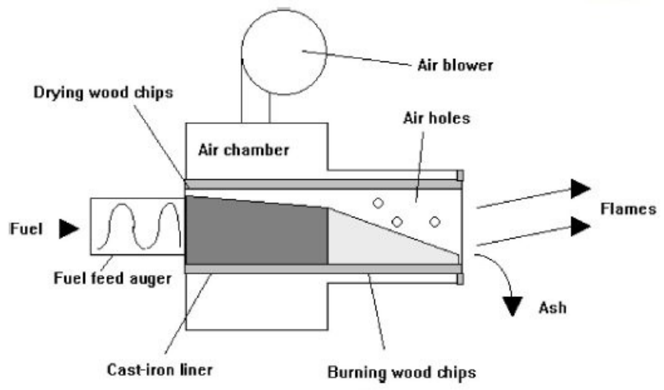

Figure. 2-4: Stoker Burner Boiler Diagram (Palmer, D. 2011)

Fluidised Bed Boilers

Fluidised bed boilers have been developed to control harmful emissions from burning coal without the need for expensive post-combustion treatment. They allow solid fuels to be burned with higher efficiencies associated with gas fuels at lower temperatures, by reducing particle size so that the solid may be suspended in a flow of gas (usually air or nitrogen), to produce a 'fluidised bed' of solids which will react more easily than a fixed bed. The lower emission temperatures can be advantageous as it reduces NOx emissions. As regards biomass, this type of boiler is common in coal co-firing power plant applications and has a good tolerance of varying fuel types. Start up times for fluidised bed combustors are far in excess of the other designs discussed and this combined with high capital cost makes this type of boiler unsuitable for LTHW supply in buildings, so could be considered outwith the scope of this research. If burning of biomass in larger plant becomes more popular in the future we could expect some development of fluidised bed biomass boilers, as technical feasibility has been confirmed by a number of studies (Diego et al. 2001).

The main boiler types are summarised in Table 2-3.

Type	Advantages	Disadvantages
Stoker Burner	Simple design reduces cost & responsive to load variations with TDR of 4:1 or better	Very sensitive to fuel quality, poor air control may lead to CO emissions. Require manual ash removal.
Underfed Stoker	Tolerant of MC up to 50%, good air control	high thermal inertia/slow response to load variations with TDR of 2:1 at best, poor ash removal may cause burner to flame out.
Moving Grate	Good mixing of fuel gives good combustion characteristics and tolerance to different fuel qualities	design complexity increases costs, high fuel loading gives slow response to load variations , high thermal inertia
Fluidised Bed	High combustion efficiency and low emissions, tolerant to different fuel types after particle size reduction	Design complexity increases costs. Long start up period, lack of technology maturity for pure biomass

Table 2-3: Biomass Boiler Types

Generally the moving grate boiler is preferred in larger LTHW heating and DHW installations due to superior operational qualities and higher level of automation, however capital cost makes installation at smaller scale less financially viable.

2.4. Biomass Boiler Performance Evaluation

Biomass boilers have two characteristics which will result in variation in performance from one site to the next, and variation in the performance of one boiler from one day to the next. The first is the higher level of human interaction required when compared with conventional fossil fuel boilers, and the second is the variation in fuel quality inherent in any natural product; we are burning fuel which has been grown in the ground rather than produced at a refinery. Worker training and monitoring of fuel quality are requirements which are often overlooked, but crucial to biomass boiler performance. These considerations are investigated in more detail in Chapter 4.

As previously mentioned, efficiency of the combustion and heat recovery may be optimised by controlling the air supply and flow regimes within the boiler. Software methods involving the use of Computational Fluid Dynamics (CFD) have been investigated recently, for instance to optimise the geometry of the furnace at the design stage (Menghini et al., 2007).

Emissions of particulates, which may become an environmental concern with increased uptake of the technology, can also be controlled by operating parameters rather than flue gas removal in e.g. filters or cyclones; a study in Sweden found that turbulence in the secondary air zone could reduce the transfer of particulates from the primary zone into the flue gas, and that the effect of 'total air factor' varied dependent on the air flow regimes within the furnace; i.e. that emissions could be controlled by optimisation at the design stage (Wiinikka & Gebart, 2004).

Proper site monitoring and evaluation is required to compare design and actual performance metrics and identify problem areas. BS 845-1:1987 describes methods for calculating efficiency, both directly using heat meters for measured heat in and heat out, and indirectly by calculating individual losses from sensible heat loss in flue gases, losses due to unburnt fuel, losses due to moisture content of fuel/enthalpy of water in flue gases, and radiative, convective and conductive heat losses from the boiler. Accurate calculations will depend upon reliable data collection, e.g. correctly located sensors, and accurate and conscientious measurement of fuel used and analysis of spent fuel, which can be particularly problematic in biomass boiler applications where employee motivation and training are key.

2.5. Biomass Boiler Issues

The main operational problems with biomass boilers burning a variety of biomass from straw and biofuel crops arise from fouling and trace metal emissions (Saidur et al 2011 pp 2283-2285), however as previously mentioned, wood chip and pellet fuels, where not produced from waste wood, have a low concentration of these pollutants, so only particulates may be expected to require removal from flue gases where combustion efficiency is good. For wood burning biomass boiler systems, the main considerations will centre around the volume of fuel required, the physical size of the boiler for a given rating, and the low turn down ratios and thermal inertia of the boiler. A strategy to overcome the problems of low turn down ratio and thermal inertia in order to meet demand is discussed in the following section.

2.6. Site Integration - Heat Load

For maximum efficiency, a biomass boiler supplies a constant load year round, moreso than gas boilers due to the lower 'turn down ratio'. Whereas a fossil fuel boiler can load follow, a biomass boiler cannot, so in order to meet a varying demand profile it is desirable to hydraulically decouple it from the load so that the biomass boiler is not directly supplying heat to the load; most commonly this is done by installing a thermal store. More constant loads such as those found in buildings with a large domestic hot water load e.g. hotels, swimming pools, with less demand for space heating (i.e. well insulated), as this will reduce seasonal variation in demand will reduce the required size of thermal store and allow a greater percentage of demand to be met by the biomass boiler. Applications to process heating may also be suitable, but this was deemed outwith the scope of this report. Buildings with high space heating demand in winter, intermittent operation and a cooling load in summer (e.g. a poorly insulated office building), would not be best served by a biomass boiler. A key initial step in the sizing of biomass boilers is to construct a design load profile which the boiler must be expected to meet. Since most loads for space heating or hot water in buildings will feature a start-up peak and overnight zero demand, a buffer vessel or thermal store would be required in order for the boiler to operate with minimal cycling, and it may be desirable to run an auxiliary fossil fuel boiler to cope with sharp peaks in demand or periods of low demand in summer for instance.

In calculating the heat load for a building, the designer must take into account the local climate and determine fabric heat losses, infiltration & ventilation losses, solar gains, casual gains from occupants and equipment, as well as DWH requirements based on building use as well as the occupancy profile of the building. At initial planning stages estimates may be used, with more accurate data required for detailed design.

A typical load profile for a building with short occupancy is shown in Figure 2-6.

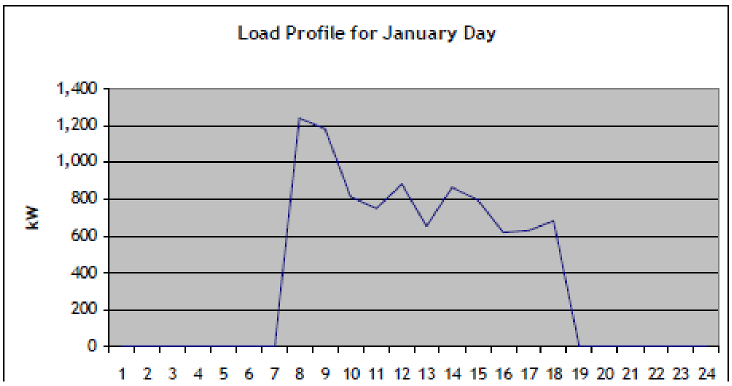

Figure 2-6: Typical Building Heat Load

Source: (Palmer, D., 2011)

Load matching using Thermal Stores/Accumulators

As previously mentioned, biomass boilers cannot load follow in the same way as a gas or oil boiler. One way to allow a biomass boiler to meet a varying demand profile is to install a thermal store. The boiler supplies heat to the thermal store, and the thermal store provides heat to the load, but the boiler does not heat the load directly. As well as allowing the heat demand of the load to be met, this will also minimise cycling which can reduce efficiency and boiler lifetime/reliability. An auxiliary fossil fuel boiler may be required to meet peak demand if the load is very dynamic. It is common for buffer tanks to be used to store heat on start up and shutdown and to avoid overheating in solid fuel boilers, however the buffer vessel is not the same as the thermal store.

Whereas in a buffer tank set up, the purpose of the buffer vessel is to store heat on start up and shutdown to avoid wasting heat and to avoid flow temperature reaching boiling point, the main purpose of the thermal store is to even out the peaks in demand to allow a smaller sized boiler (i.e. one not sized for peak load) to supply the load. The high capital cost of biomass boilers, combined with physical size, low turn down ratios and high thermal inertia makes combination with a thermal store the most efficient setup for most applications.

Previous knowledge of fossil fuel boilers has been based on a boiler cycled to meet demand, so research into control algorithms and best configuration for biomass boilers is ongoing, with no CIBSE guidance yet published. Mathematical modelling of the interaction between the boiler and the thermal store such as carried out by Stritith et al. (2004) could be used to improve the design and optimise sizing of the thermal store.

Sizing of the boiler will also differ from conventional fossil fuel boilers which are sized for peak demand, or indeed over sized in order to achieve short heat up period and hence minimise fuel costs. Since biomass boilers need not meet peak demand, they can be sized in combination with the thermal store depending on the heat profile of the load, and the percentage of demand which may be met will be dependent on the hourly load profile, not just on peak demand. ESRU and the Campbell Palmer Partnership (CPP) developed a Biomass Boiler Sizing Tool which was then contracted to The Carbon Trust which allows users to size boilers and thermal stores to suit building design loads; the tool is described in more detail in Chapter 3.1 . Often it may be possible to size a boiler to meet as little as 40% of the peak design load, with a large thermal store to make up the difference. Sizing in this way can potentially reduce capital cost of the installation and improve performance by allowing the boiler to operate under a high load for extended periods. The biomass boiler can be combined with fossil fuel boilers used either as auxiliary boilers to help meet peak demand, or sized for peak load as back-up boilers to improve system reliability (often it may be sensible to have modular fossil fuel boilers which are able to operate as both auxiliary and back-up boilers). Operation and design of thermal stores is described in the following section.

2.7. Thermal Stores

As described in the previous section, thermal storage vessels can be utilised in biomass heating systems to reduce the required rated boiler size and to reduce cycling during operation. Thermal stores are often used in Solar Heating applications, or with electric heaters which take advantage of lower overnight tariffs. The thermal store used for biomass boilers is often simply a well insulated water tank; heat is transferred to and from the store directly by mass transfer, as opposed to indirectly though a heating coil as is sometimes the case in the other systems mentioned. Thermal stores can be either 2 port or 4 port configurations; 2 port being the cheaper to install and 4 port being easier to control and therefore easier to run efficiently if operated correctly. Typical schematics for both configurations are shown in Figures 2-7 and 2-8.

4 Port Thermal Store

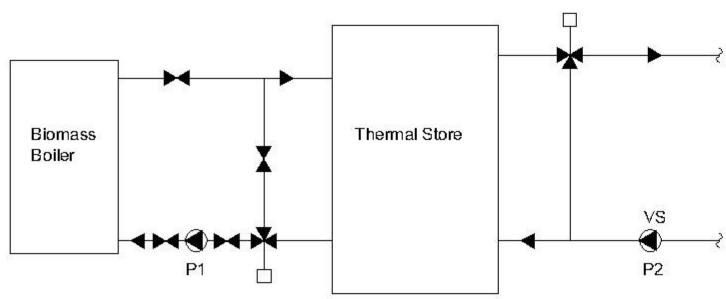

Figure 2-7: 4 Port Thermal Store

Hot water from the boiler is fed into the top of the tank, with cooler water returning to the boiler from the bottom; once the thermal store has been charged, hot water is fed from the top of the tank to the heat load, and cooler water returning from the load is fed to the bottom of the tank. Fully modulating mixing valves control flow.

Provided mixing can be avoided once the thermal store has been charged, the operation of a 4 port thermal store can be defined in three stages:

1. Charge (Pump 1 Operates): The boiler supplies water to the thermal store, until desired temperature within the tank has been achieved.
2. Normal Operation (Pumps 1&2 Operate): The thermal store accepts hot water from the boiler and discharges hot water to the load simultaneously. A thermocline within the tank separates the upper region feeding inlet hot water from the boiler to the heat load from the lower region feeding return water from the load to the boiler. The thermocline will move upwards as the hot water volume in the tank decreases.
3. Discharge (Pump 2 Operates): Once the thermal store contains sufficient hot water to meet the remaining heat demand for the period of operation (normally the working day for the building), the boiler may be switched to slumber mode and the thermal store supplies the heat load.

2 Port Thermal Store

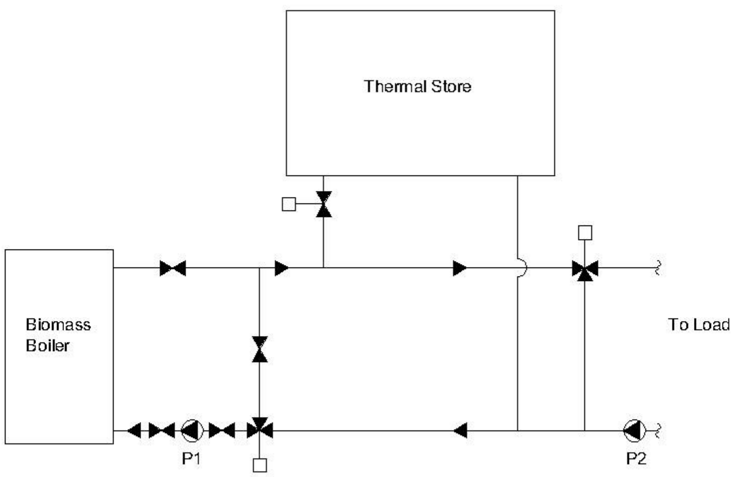

Figure 2-8: 2 Port Thermal Store

In the 2 port configuration, pump P2 is rated higher that pump P1, and should be controlled by a variable speed controller or modulating 3 port mixing valve. In the case of the 2 port design, the boiler will typically be controlled to maintain the temperature of the thermal store at its set point when there is a demand from the load, but the discharge of the thermal store cannot be controlled directly. Although 2 port thermal stores present a lower capital cost solution than 4 port thermal stores, further study would provide a better understanding of their operation.

Buffer Vessel

These can be compared with a buffer vessel configuration such as the one shown in Figure 2-9.

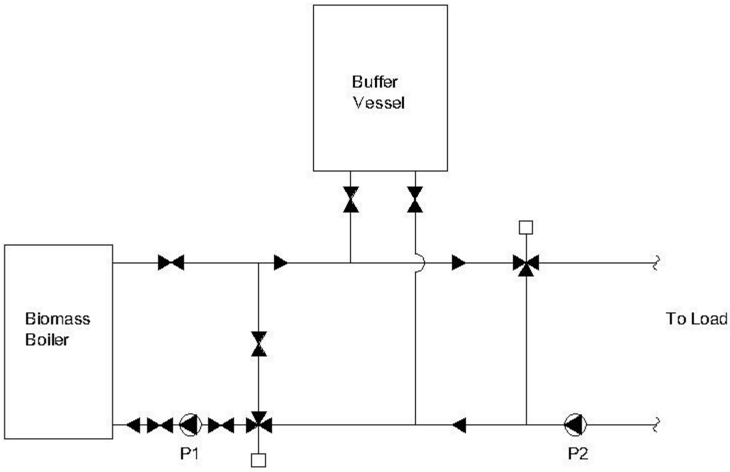

Figure 2-9: Buffer Vessel

In a standard buffer vessel configuration, the buffer vessel does not contribute to peak load: pump P2 is rated for boiler output the same as pump P1, and the purpose of the buffer vessel is to store hot water from start up and shut down to prevent overheating and to improve efficiency. During normal operation, water flows directly from the boiler to the load, bypassing the buffer vessel, whereas if the vessel was a thermal store, water would flow from the boiler to the thermal store and then to the load during normal operation.

Auxiliary boilers may feed the thermal store rather than feeding the load directly; the control system must be designed in such a way that the biomass boiler is fired in preference to auxiliary boiler to reduce fuel costs and stratified temperature sensors on the thermal store are desirable to this end, as well as to monitor thermal store stratification. Where the turn down ratio of the auxiliary boilers is suitable, and where the load profile has a short period of peak demand, it might be preferable to have the thermal store connected only to the biomass boiler with auxiliary boilers feeding the load directly.

Stratification

Thermal stores used in biomass boiler systems should be large enough that instantaneous mixing cannot be expected within the tank; stratification will occur, and this can be controlled and maintained once a steady inlet temperature from the boiler, above the temperature within the thermal store, is achieved. Maintaining stratification within the tank means that a single tank can effectively carry out the duty of storing heated water from the boiler, and return water from the heat load, which would otherwise require two separate tanks (Dincer, I. & Rosen, M. A., 2002, p 260). This elegant solution keeps capital and operating costs to a minimum through its simplicity and the lack of complex control pumps, valves etc.

De-stratification can be caused by a number of mechanisms which tanks must be designed and operated to avoid:

- Fluid mixing caused by turbulent inlet streams. Operating conditions should be chosen to avoid this
- Conduction from cold fluid to hot fluid through tank walls. The tank walls should be as thin as possible and of low thermal conductance to avoid this
- Conduction from cold fluid to hot fluid directly; the presence of a thermocline in the fluid can reduce the impact of this.
- Heat losses from the tank to external atmosphere. The tank should be well insulated and located within the building envelope where possible. Thermal bridges should be avoided in the construction.

Where stratification occurs and software modelling of thermal store behaviour is to be carried out it may be useful to model the thermal store as a series of layers, with energy balances carried out between each layer. In order to monitor the performance of a thermal store it is advantageous to have temperature sensors arranged up the height of the tank to measure stratification.

Tank Design & Operation

An aspect ratio of between 3 and 4 seems to give reasonable trade off between cost and performance, and the tank should be constructed of a material with a thermal conductivity close to that of water (Dincer, I. & Rosen, M. A., 2002, p295). Vertical tanks are therefore recommended for best stratification, however horizontal stores may be required where space concerns are an issue, and these can be cheaper due to lower structural demands on the vessel. Horizontal thermal stores installed at a variety of sites seem to exhibit satisfactory stratification in practice (conversation with D. Palmer, 8th August 2011). The size of thermal store required for biomass boiler applications presents a problem both for structural design, available plant space, and economically, so the best design may not necessarily be the ideal theoretical one. In practical terms, over sizing of the thermal store in anticipation of future increase of demand where it is likely may be worthwhile, as due to it's large size and the cost of purchase and installation (in particular where space is at a premium), it is unlikely to be possible to change the thermal store after it has been installed.

Some efforts have been made with regards to thermal stores for Solar Heating for example, to control stratification within the tank by modifying fluid flow within the tank using a porous manifold, such as in work carried out by Brown & Lai (2011), however as the aim of biomass boiler is to avoid cycling, control by maintaining constant inlet temperature should be sufficient for this application. Care must be taken in design and operation to avoid turbulence at the inlet from the boiler. Mixing caused by the inlet flow can be minimised by reducing inlet velocity, by increasing pipe diameter and/or adding a diffuser at the inlet.

Thermal Store Performance Evaluation

The most obvious performance evaluation of a thermal store is to measure direct efficiency from knowledge of heat input and heat export, however heat meters can be expensive to install. Heat loss from the thermal store can be measured from surface temperature readings and ambient temperature data. It is also useful, as previously mentioned, to have stratified temperature sensors installed so that the degree of stratification can be monitored. Dincer, I. & Rosen, M. A., (2002) provide an exhaustive list of performance parameters for thermal stores, focussing in particular on exergy and the importance of grades of energy rather than simple efficiency measures, however it is the author's opinion that in practical applications, monitoring of the heating system as a whole and minimisation of losses from the thermal store by insulation and location within the building fabric where possible, along with stratified temperature sensors, will prove sufficient in commercial applications where time and cost may override the pursuit of idealised design.

2.8. Major Differences Between Fossil Fuel and Biomass Systems

The previous sections have discussed the main characteristics of biomass boiler systems for space heating and DHW. Due to the the superficial similarities between biomass boilers and fossil fuel boilers, ignorance of crucial design and operational factors may prove a barrier to effective deployment of the technology. The major differences between biomass and fossil fuel systems are therefore outline below:

- Fossil fuel boilers are modulated to meet demand, biomass boilers cannot follow a varying demand directly
- Biomass boilers should be hydraulically independent of the heat load where the demand varies; this can be achieved by means of a thermal store
- Fossil fuel boilers are sized for peak demand; biomass boilers must be sized in conjunction with a thermal store to meet varying demand
- Whereas a gas boiler may be oversized to achieve a short heating period, a biomass boiler should be undersized to achieve a long heating period under high load
- Biomass boilers should not be expected to meet the full demand in most cases; they can be combined with auxiliary fossil fuel boilers to significantly lower fuel costs however
- Auxiliary fossil fuel boilers may be required to meet short periods of peak demand, or in summer months when there is minimal demand
- Capital costs and physical size of biomass boilers are greater for a given rating- this must be taken into account when determining required plant room space and when sizing the biomass boiler
- Biomass boilers require greater fuel storage space due to lower energy density of fuel
- Biomass fuel is significantly cheaper than fossil fuel. Whilst this is an obvious advantage, it can result in poor running efficiency due to lowering operator motivation to minimise fuel use

3. System Design

3.1. Introduction

The biomass boiler system design process consists of a number of distinct stages:

1. Budget for the project should be set, and for comparison running cost of existing system determined in retrofit cases, or cost of installation & expected running cost for equivalent conventional system determined in the case of new build projects.
2. A heat load profile for the site must be determined
3. The boiler and thermal store must be sized to meet the load
4. Installation and running costs of the Biomass Boiler system should then be estimated

This process can be either for preliminary investigation, or for detailed design dependent on the accuracy of the data and assumptions used. The level of uncertainty in available data must be taken into account, particularly regarding the design heat load profile if direct measured data is not available.

Budget and costs will be dependent on the organisation; knowledge of past utility bills will be useful in order to determine the economic benefit a biomass boiler system might result in. Generally, biomass boiler systems will incur higher capital costs, with lower running costs and potential benefits in terms of climate change levy and RHI income as described in previous sections. The RHI is expected to have a significant impact of the viability of biomass boiler systems. Technical design stages are described in the following sections.

Biomass Boiler System Sizing

As previously mentioned, sizing a biomass boiler system does not simply entail sizing the boiler for peak demand as would be the case for a fossil fuel boiler; the boiler and thermal store must both be sized in combination dependent on whether an optimal sized thermal store is desired to minimise the size of the biomass boiler, whether the thermal store size must be limited, and dependent on the nature of the design heat load profile. A software program such as the Biomass Boiler Sizing Tool (BBST), developed by the University of Strathclyde, Campbell Palmer

Partnership (CPP) and subsequently contracted to the Carbon Trust may be used to compare different sizing options.

BBST Overview

The BBST is a macro enabled Excel based program which completes the biomass boiler system design process in a number of modules:

- Demand Module – heat profile data is added in one of four ways- from direct heat meter measurement, from heating bill data, from an external simulation program, or using an internal calculator based on basic input data and assumptions (see notes below)
- Financial Inputs – cost data such as available grants, maintenance costs etc. are entered in this module. The tool is designed to be able to take account of capital grants and income from the RHI
- Fuel Selection – the tool can be used for either wood chip or wood pellet boilers
- Fuel Data – data on characteristics of the fuel such as fuel calorific value, moisture content and unit costs are supplied by the user or from default data
- Biomass System Sizing – boiler type, fuel extraction system and sizing strategy (i.e. for minimal buffer vessel, optimal boiler/thermal store combination, or limited thermal store size where site practical considerations limit the space available for the thermal store) are selected
- Biomass Boiler System Sizing Results I – different sizing combinations of biomass boiler and thermal store can be examined
- Thermal Storage Vessel – thermal storage vessel specifications can be input here
- Capital Cost Specification – either from default tool data or user's own data
- Biomass Storage – different storage options (e.g. sloping floor, silo) can be compared in this section
- Biomass Boiler System Sizing Results II – this outputs data on predicted energy use, emissions savings and costs for the system selected previously
- Report – the tool can generate a printable report with system information and economic outcomes

The modules within the tool can be used iteratively to obtain the desired solution. Full explanation of the tool is available from the Carbon Trust website.

BBST Demand Module

In order to size the biomass boiler and thermal store, knowledge of the dynamic variation in heat requirements is vital as previously mentioned. Knowledge of the design heat load profile is often the major source of uncertainty in the design, so all assumptions and data sources should be documented, especially where directly measured data is not available.

There are a number of different methods to predict heat load profiles within the BBST; users can input demand from utility bills, heat meter measurements, or through calculation within the tool or using an external energy simulation tool. The tool uses data on material losses, casual gains from occupants, lighting and equipment, as well as DHW demand dependent on occupancy and use, however this is recommended for use mainly at the preliminary stage and in the current version at time of writing (Version 4.6.3), multiple buildings must be externally aggregated. There is also no provision as yet for non-conventional building demands such as greenhouse heating or swimming pool heating. Multiple buildings, greenhouses and swimming pools are expected to be included in future revisions, as these loads can be well suited to biomass heating systems.

In order to examine sensitivity to fuel prices, fuel cost and inflation rate can be varied within the tool. There is however, no way to model fuel price escalation based on historical and predicted future data other than through variation of the inflation rate.

Provided the expertise and input data is available, energy simulation software (such as ESRU's ESP-r) can be used to provide more reliable heat load profiles. It should be noted that the demand profile input from simulation program is for the design day only; the BBST will then scale this to an annual basis based on the other parameters chosen in the Demand Module (for example insulation level, DHW requirements etc.).

ESP-r Overview

ESP-r is a dynamic energy simulation program developed by Energy Systems Research Unit (ESRU) at the University of Strathclyde. It can be used to assess a wide range of building performance characteristics and meets CIBSE requirements for thermal load calculations; for biomass boiler design it's most useful function is to obtain an expected heat load profile based on the heat losses and gains for a building or group of buildings which can then be used within the BBST.

3.2. Case Study A Introduction

As part of this project, the sizing of a biomass boiler system for Lews Castle College in Stornoway, Isle of Lewis was investigated. The site consisted of an educational campus with three buildings; Facilities, Engineering, and Rural. An existing oil fired boiler system with 2x 825kW boilers supply the facilities building and two 325kW oil fired boilers supply the Engineering & Rural buildings. Energy use data was available for the buildings on an annual basis and a report by the Greenspace Research Unit at Lews Castle College (LCC 2010), henceforth referred to as the 'LCC Report', was available which provided information on building construction and use from a site survey. Further information was also available from an MSc thesis by Cheng, A. H. Y. (2010). Due to time and budget constraints, a site survey was not possible as part of this thesis, so these two documents, as well as CAD files made available by the college were relied upon for input data. The possibility of supplying the campus space heating and DHW requirements from a biomass boiler system was investigated as recommended in the LCC Report Section 7.2.4. The LCC Report suggested chipping wood on site, however a survey of available local wood would be required to confirm the feasibility of this and it was considered at this stage that a more reliable option would be the use of imported wood pellets so only this option was explored within this study. The choice of either wood pellet or wood chip will influence the fuel cost and the storage required, however a moving grate boiler was chosen which could fire either type of fuel if desired. Confirmation of fuel availability would be required for a full feasibility study.

This case study was for a proposed installation, and it was decided to compare performance of an existing fuel oil boiler system with a theoretical one recommended and sized using the Biomass Boiler Sizing Tool in order to evaluate the benefits of installing a new biomass boiler system for space heating and DHW.

Although the LCC Report detailed a site survey of the buildings for the college, the required hourly demand data was not available as part of the report. For boiler sizing an hourly schedule of heat demand is needed in order for the BBST to give reliable results; where measured data was not available, assumptions were made as determined below. In order to estimate the required heat load for the boiler, material heat losses, losses from ventilation and infiltration, as well as casual gains from occupants, lighting and equipment were estimated as described in the following sections and an ESP-r model constructed for each of the buildings to give a design day space heating demand profile as described in Chapter 3.3. DHW demand was calculated within the BBST as described in Chapter 3.5.

Model Resolution

Due to the location of the college, it was not considered that solar gains would be significant factor for space heating. It was also considered that a model with surface area and volume equal to the college would be sufficient, and internal air flow and geometry would not have a significant effect on overall hourly heat demand.

Methodology

The first step was to obtain a heat demand profile using Esp-r Software and standard techniques as described in the CIBSE Guide (CIBSE, 1986) and BS 6880-1:1988 for space heating using LTHW systems.

Once a reliable heat load profile was obtained, the system was sized using the BBST and some indicative financial results examined.

3.3. Case Study A Heat Load Calculation Using ESP-r

Facilities Building Model

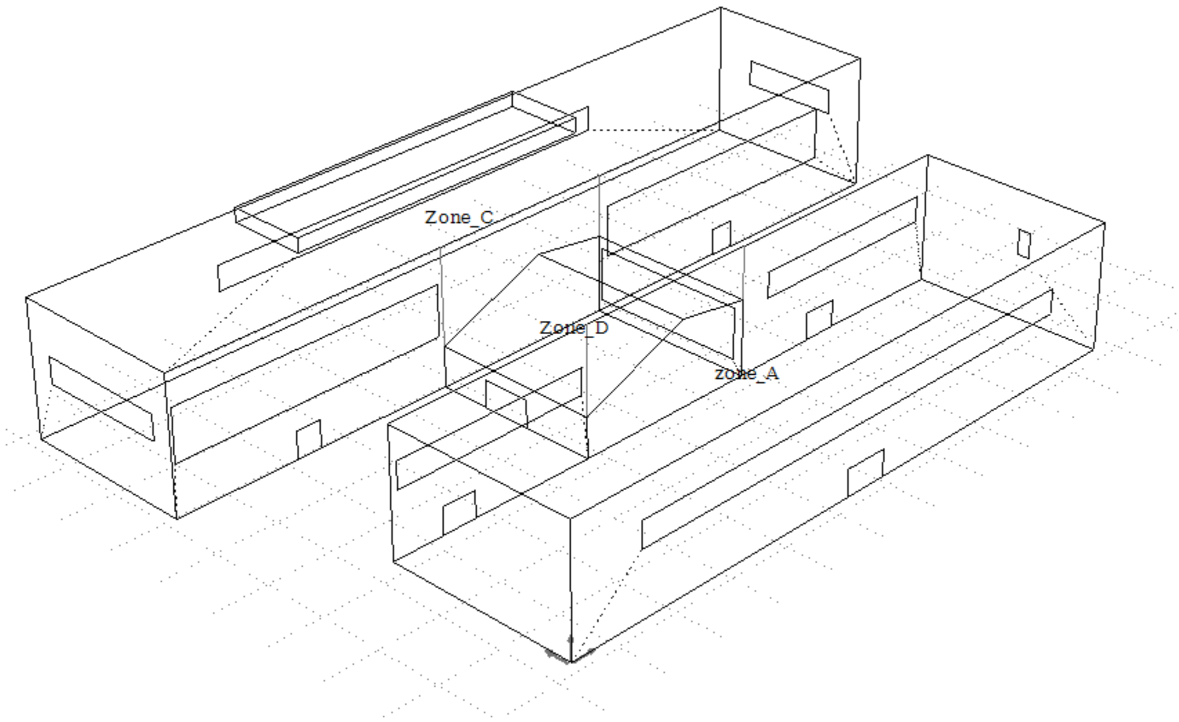

Figure 3-1: Facilities Building Model

A three zone model was constructed in ESP-r. Geometric information was obtained from the CAD drawings available, and information on construction materials from the LCC Report (LCC pp53-58). The following U-values were then calculated for the Facilities Building:

External Walls:0.89W/m^2 K Zone A, 1.44W/m^2 K Zone C, 0.48W/m^2 K Zone D

Ground Floor: 0.44W/m^2 K

Roof: 0.51W/m^2 K Zone A, 0.63W/m^2 K Zone C, 0.2W/m^2 K Zone D

Glazing:2.8W/m^2 K

Doors: 3.3W/m^2 K

No schedules of occupant levels or number of PCs were available so these were estimated from the CAD files. Full data assumptions for casual gains are given in Appendix A Table A-5.

Casual gains from lighting were estimated to be 5W/m^2 on each floor; Zone C represented 3 floors and Zone A 2 floors, so the base levels for casual gains from lighting were 15W/m^2 in Zone C, 5W/m^2 in Zone D and 10W/m^2 in Zone A.

A base level of infiltration of 1ach/hr was assumed at all times, with mechanical ventilation increasing this during occupied periods to the overall air change rates described in the Simulation Schedule below. Mechanical ventilation was assumed to supply air at the design room temperature with heat emitters (radiators) offsetting building heat losses. For the purposes of the ESP-r model both heat supplied to the AHU and to the heat emitters are calculated together to give sensible heat load, since the air supply is modelled as scheduled air flow regardless of whether it is heated by the LTHW system heat emitters or the AHU heating coil.

The zones were controlled independently to maintain 20ºC using an ideal basic controller. This type of controller is useful when the objective is to calculate heat demand loads rather than simulate heating systems and is not generally sensitive to time step length (Hand, J. W., 2010).

Engineering Building Model

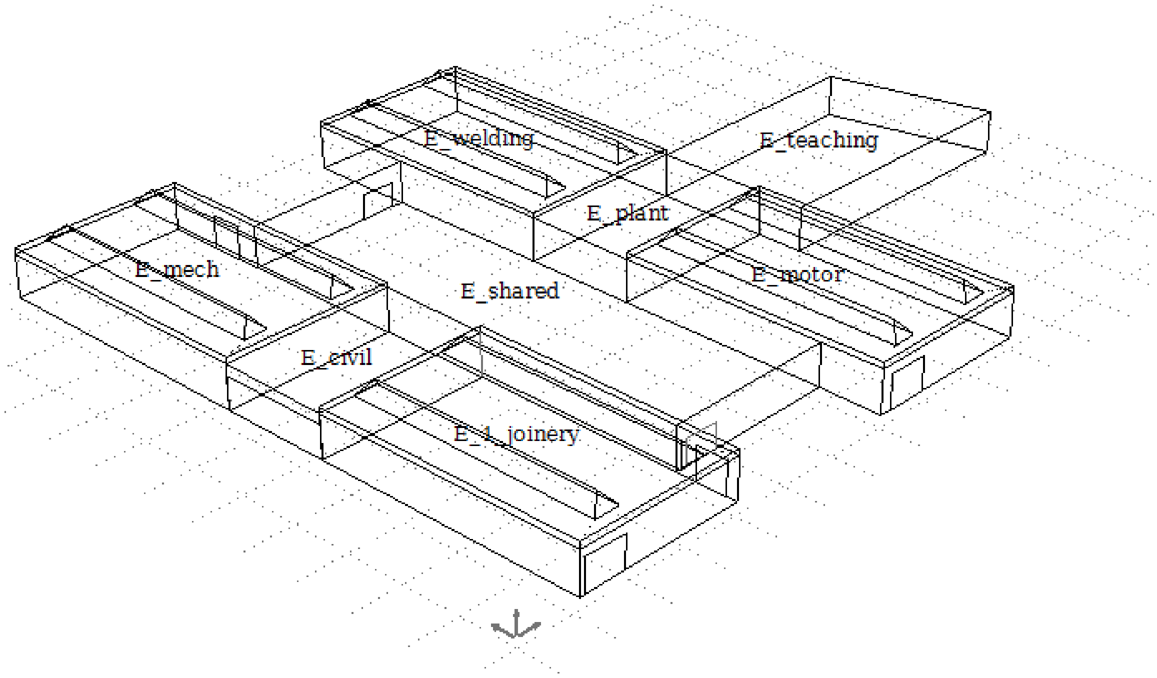

Figure 3-2: Engineering Building Model

An eight zone model was constructed in Esp-r for the Engineering Building. Geometric information was obtained from the CAD drawings available, and information on construction materials from the LCC report (LCC pp53-58). The following U-values were then calculated for the Engineering Building:

External Walls:1.3W/m^{2}K

Ground Floor: 0.44W/m^{2}K

Roof: 0.75W/m^{2}K in workshops and teaching space, 3.4W/m^{2}K in shared area

Glazing: 5.9W/m^{2}K (skylight)

Doors: 3.3W/m^{2}K

There was however a lack of clarity over the as fitted CAD drawings and information on materials of construction in the LCC Report; a full site survey would be required to inform the model for accurate results for this building in particular. Casual gains and infiltration/ventilation were estimated in the same way as for the Facilities Building and casual gains assumptions are detailed in Appendix A Table A-6. Each zone was controlled separately in the same way as the Facilities Building except for the Plantroom which was set as a free floating control zone (i.e. it was not expected that the Plantroom would be heated) with casual gains from equipment as outlined in the Table 3-1.

Rural Studies Building Model

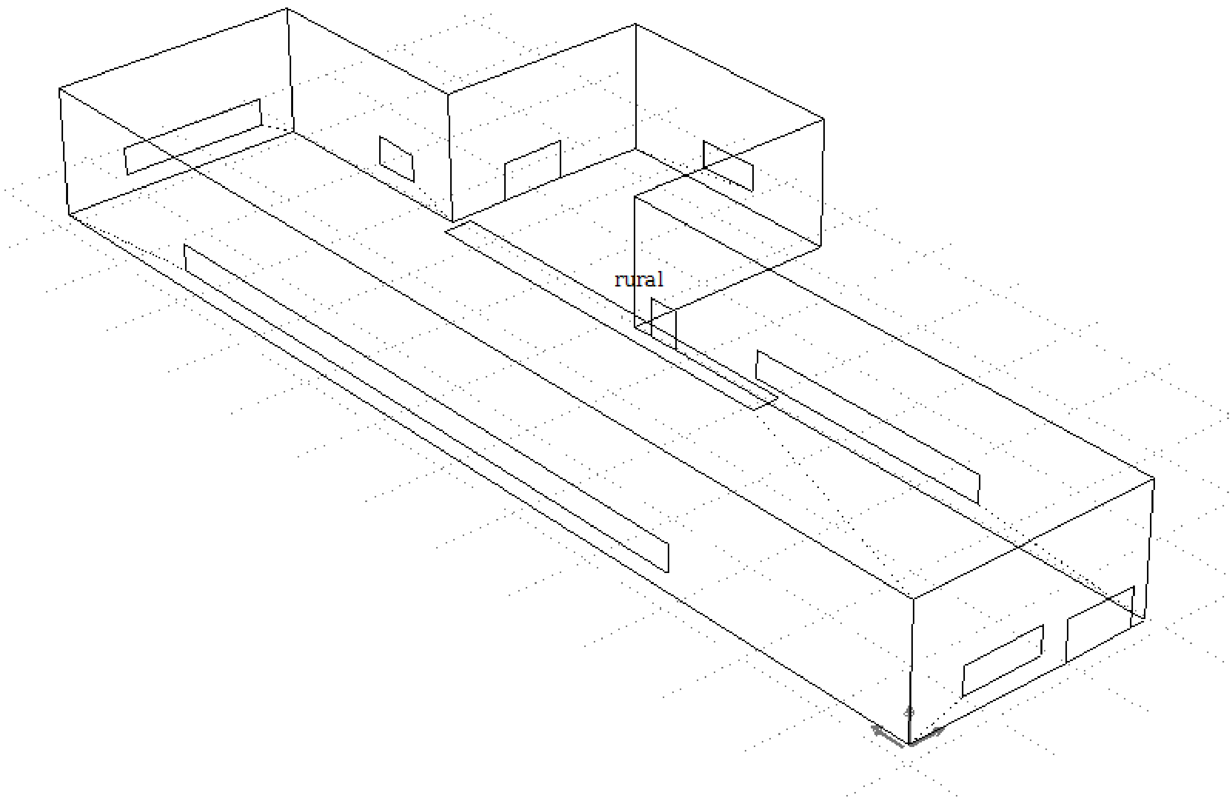

Figure 3-3: Rural Studies Building Model

The Rural Studies building was modelled as a single zone. There was some difficulty in ascertaining all dimensions due to a lack of available CAD drawings. The only available CAD drawing for this building was a ground floor plan, however the previous site survey information in the LCC Report referred to a two floor building, so assumptions were made of a floor to ceiling height of 5m and window heights of 1.2m. Once again a full site survey is recommended to inform a more accurate model. Casual gains and infiltration/ventilation were estimated in the same way as for the Facilities Building and are detailed in Appendix A Table A-7.

Control, ventilation and casual gains were assumed to be as with the other buildings. U values from the information in the reports were calculated as below:

External Walls: $1.4W/m^2K$

Ground Floor: $0.44W/m^2K$

Roof: 0.64W/m^{2}K

Glazing: 2.8W/m^{2}K

Doors: 3.3W/m^{2}K

Simulation Period

The simulations were run for the year 2010. Based on the calendar information available from the college website, it was assumed that the building was heated for the following dates, 9am-5pm, with lighting from 6am:

Monday 4th January-Friday 2nd April

Monday 19th April-Friday 11th June

Monday 6th September-Friday 15th October

Monday 25th October-Friday 24th December

These assumptions would require confirmation for more accurate design; in particular heating may be required for night classes outside of normal working hours, however no data on the frequency or length of these was available.

Climate Data

Climate, in particular ambient temperature, will have a significant impact on space heating requirements. Unfortunately no climate data for Stornoway itself was available; data was however available for Lerwick in the Shetland Isles, along with some data for a part of Lewis outside Stornoway. Full information on the climate data used is detailed in Appendix A. A comparison was made between the available data for Lerwick and Lewis in Figures 3-4, 3-5 and 3-6.

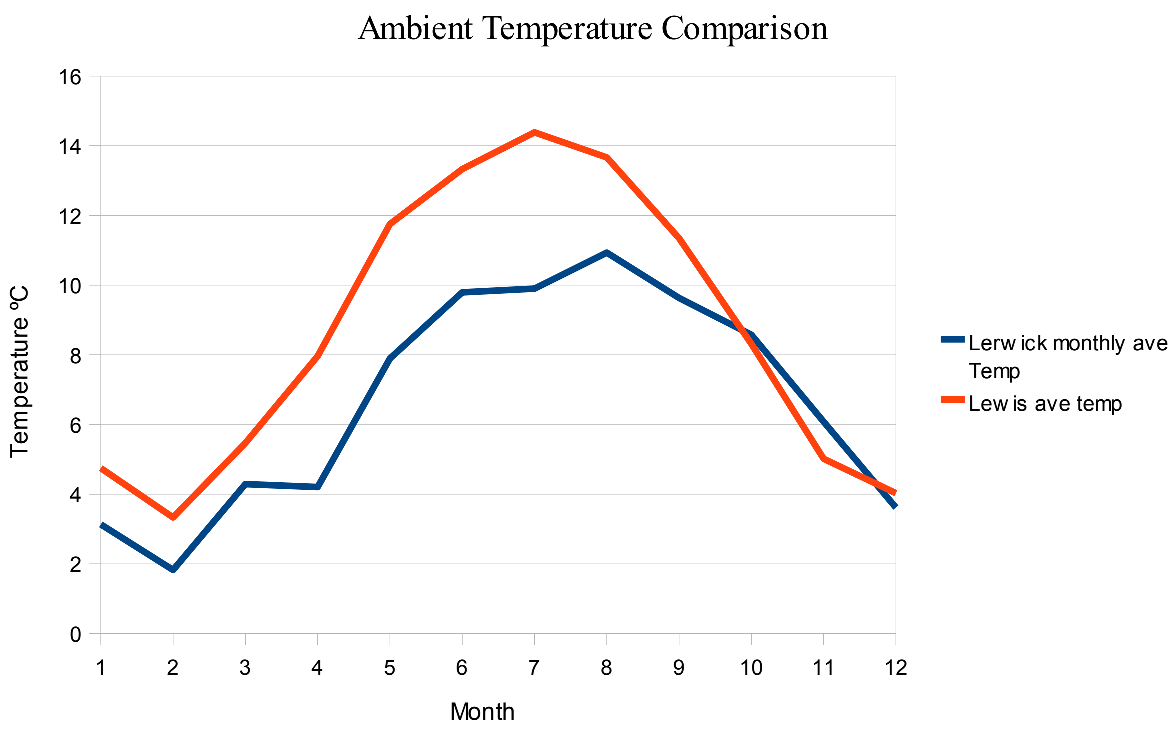

Figure 3-4: Ambient Temperature Comparison between Lerwick and Lewis

Lewis can be seen from Figure 3-4 to be significantly warmer, particularly during the summer months. Since ambient temperature is likely to have the greatest impact on space heating requirements, the data available for Lewis was collated and imported into a custom ESP-r climate file for the project.

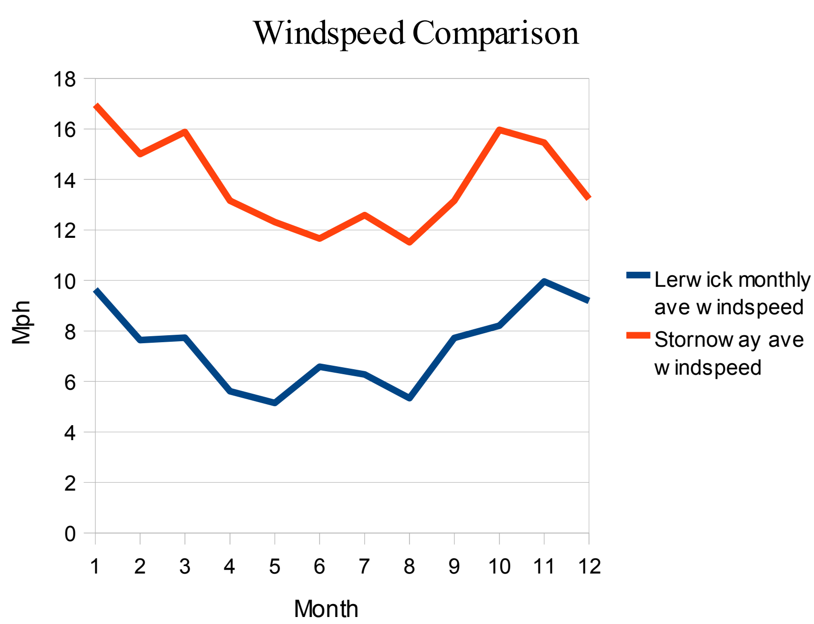

Figure 3-5: Windpseed Comparison between Lerwick and Lewis

From the data available, shown in Figure 3-5, it seems that Stornoway may be significantly windier. It should be noted the location of the weather station on Lewis is on an exposed headland. Wind speed also typically varies significantly by the minute and from year to year; the Lerwick data is from a single year (1978), whereas the Stornoway data is averaged data from 2010, 2009 and 2008. It is likely that the relative windspeed could be quite different; the trend over the year is similar for both islands however. Since no flow networks were used in the model, the impact of windspeed on the heat load was considered low enough that the Lerwick data would be sufficient.

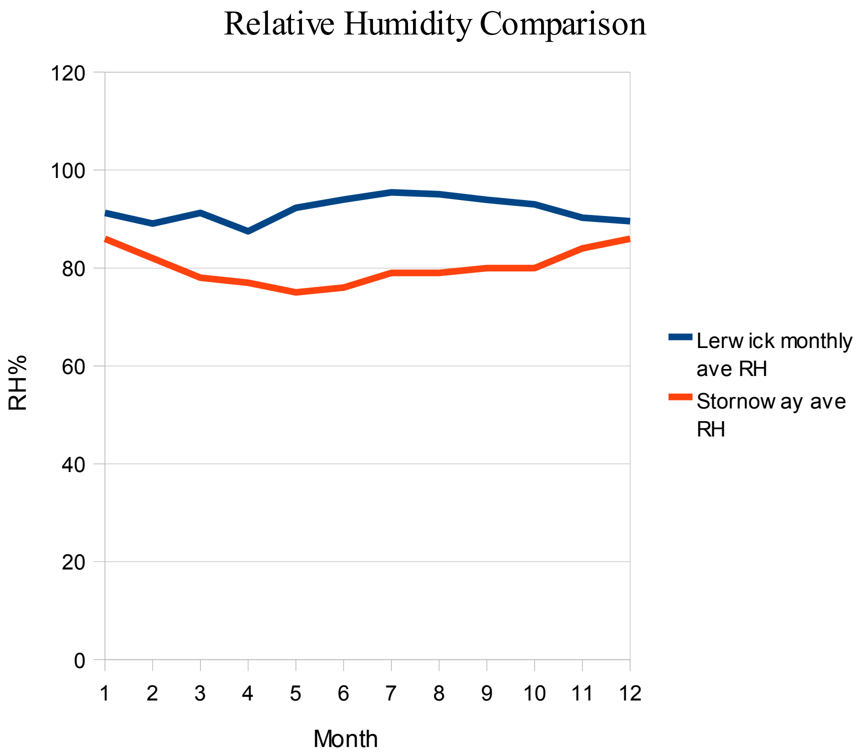

Figure 3-6: RH% Comparison between Lerwick and Lewis

Relative humidity was significantly higher for Lerwick based on the data shown in Figure 3-6. It was considered that the values for Lerwick were consistently quite high for what might be expected (varying little from around 95% for the entire year), however once again the Lerwick data was similar enough to be sufficient given it's low expected impact on heat load results.

Uncertainty Analysis

Due to the uncertainties and assumptions required for the heat load calculation, the simulation was run for a variety of different scenarios as outlined in the Table 3-1. Base rates for casual gains are shown in Appendix A.

		Facilities Building	Engineering Building	Rural Studies Building
Simulation A	Ventilation Rate when occupied	4ach/hr	4ach/hr	4ach/hr
	Equivalent Persons	122	81	154
	Equivalent PC's	128	0	8
	Equipment Gains	base	base	base
Simulation B	Ventilation Rate when occupied	3ach/hr	3ach/hr	3ach/hr
	Equivalent Persons	122	81	154
	Equivalent PC's	128	0	8
	Equipment Gains	base	base	base
Simulation C	Ventilation Rate when occupied	2ach/hr	2ach/hr	2ach/hr
	Equivalent Persons	122	81	154
	Equivalent PC's	128	0	8
	Equipment Gains	base	base	base
Simulation D	Ventilation Rate when occupied	4ach/hr	4ach/hr	4ach/hr
	Equivalent Persons	134.2	89.1	1.12
	Equivalent PC's	140.8	0	1.18
	Equipment Gains	base +10%	base +10%	base +10%
Simulation E	Ventilation Rate when occupied	4ach/hr	4ach/hr	4ach/hr
	Equivalent Persons	146.4	97.2	184.8
	Equivalent PC's	153.6	0	9.6
	Equipment Gains	base +20%	base +20%	base +20%

Table 3-1: Case Study A Simulation Schedule

Note 'ventilation rate when occupied' in Table 3-1 is the total air change rate, including both infiltration and ventilation. 4Ach/hr was chosen as the base rate (the CIBSE Guide Table B2.3 recommends 4-6ach/hr for offices and a minimum 8.3l/s per person for schools). The value of 4ach/hr is quite high, however construction was thought to be poor quality and it was possible that this level of ventilation existed due to high occupancy, poor ventilation control, leaky construction or a combination thereof.

Casual Gains from people were assumed to be 90W sensible and 25W latent as would be expected for sedentary office work at 20ºC (CIBSE, 1986) except in the workshop areas of the Engineering Building where values of 100W sensible and 45W latent were used as for light factory work (CIBSE 1986). Gains from PC's were assumed to be 100W each, 14% radiative, 86% convective (CIBSE 1986).

'Simulation A' was also carried out for a number of different climates in order to show the sensitivity of the heat load to varying climate data, and the results of this are detailed in the following section.

Design day heat load data was chosen for an averaged winter day to take account of daily variation in climate.

3.4. Case Study A Heat Load Results

Results were averaged for five winter days (Tuesday 5th, Wednesday 6th, Thursday 7th and Friday 8th January and Friday 24th December, 2010) to obtain the campus heat load profile shown in Figure 3-7.

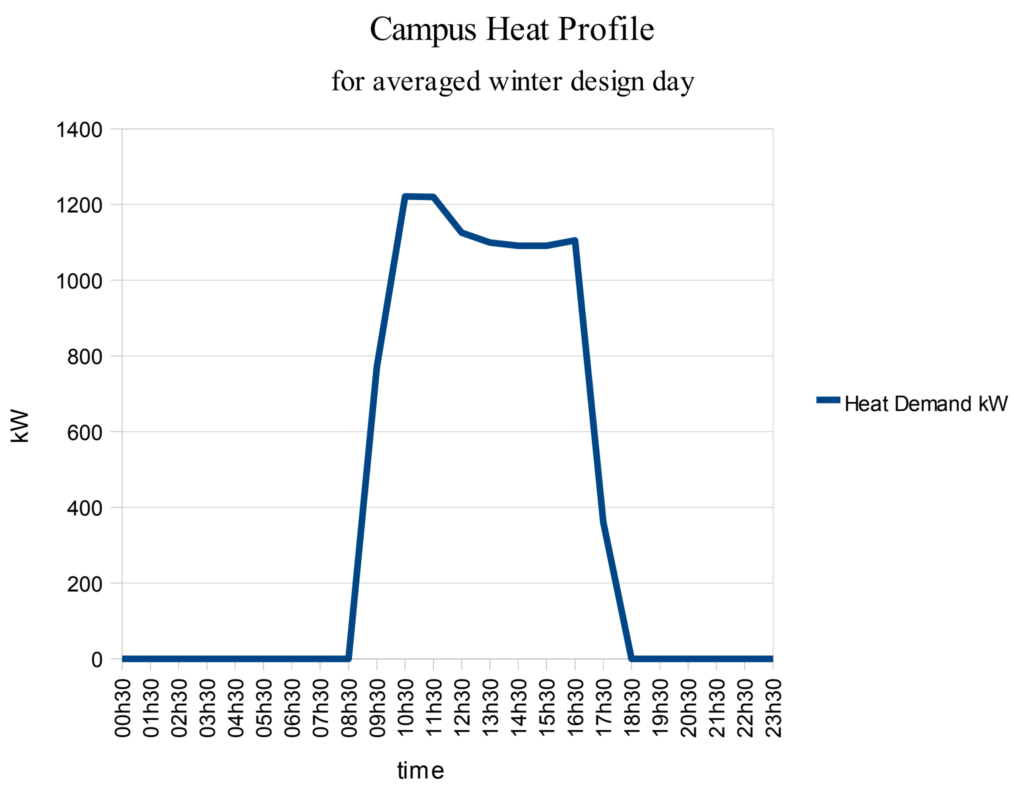

Figure 3-7: Campus Heat Load Profile

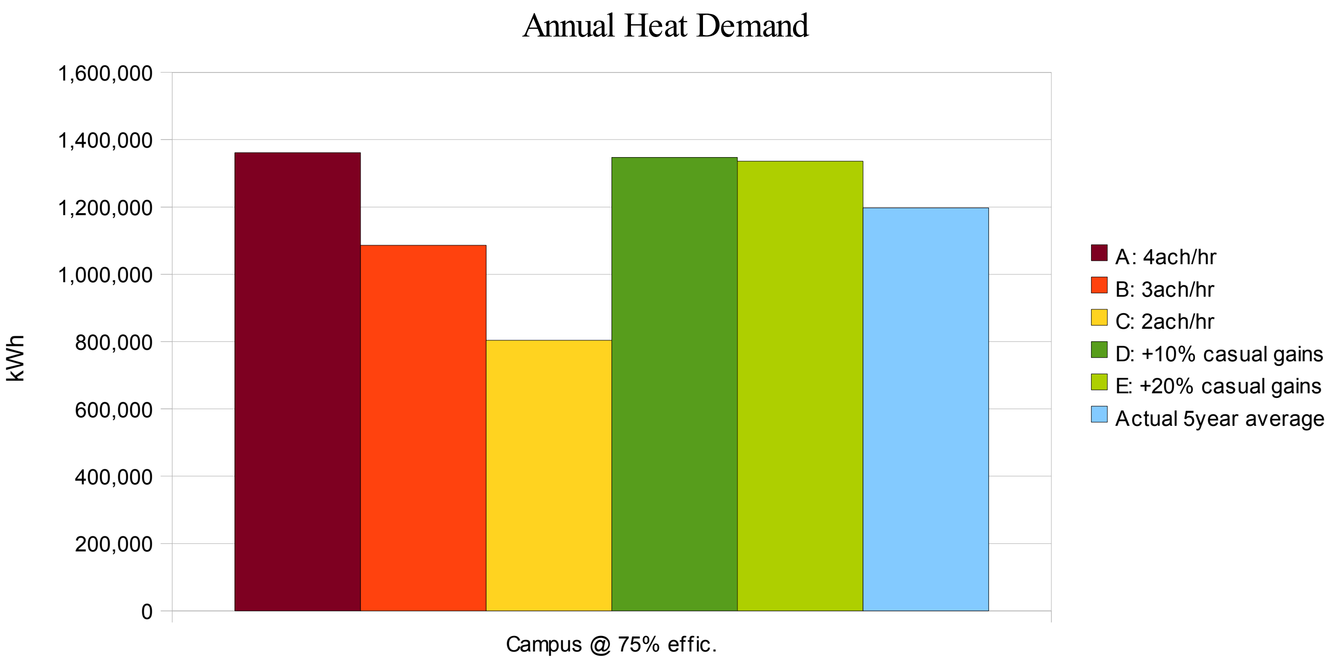

Figure 3-8: Campus Annual Heat Demand

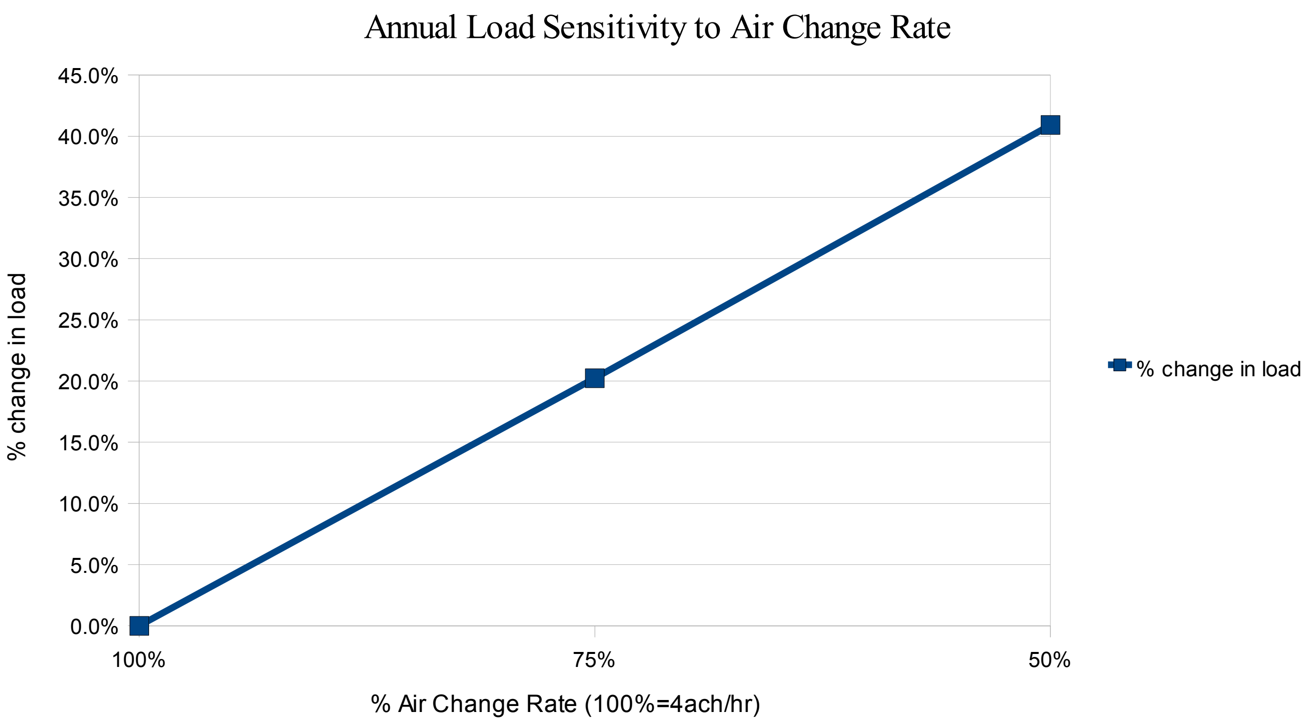

Figure 3-9: Annual Load Sensitivity to Ventilation Rate

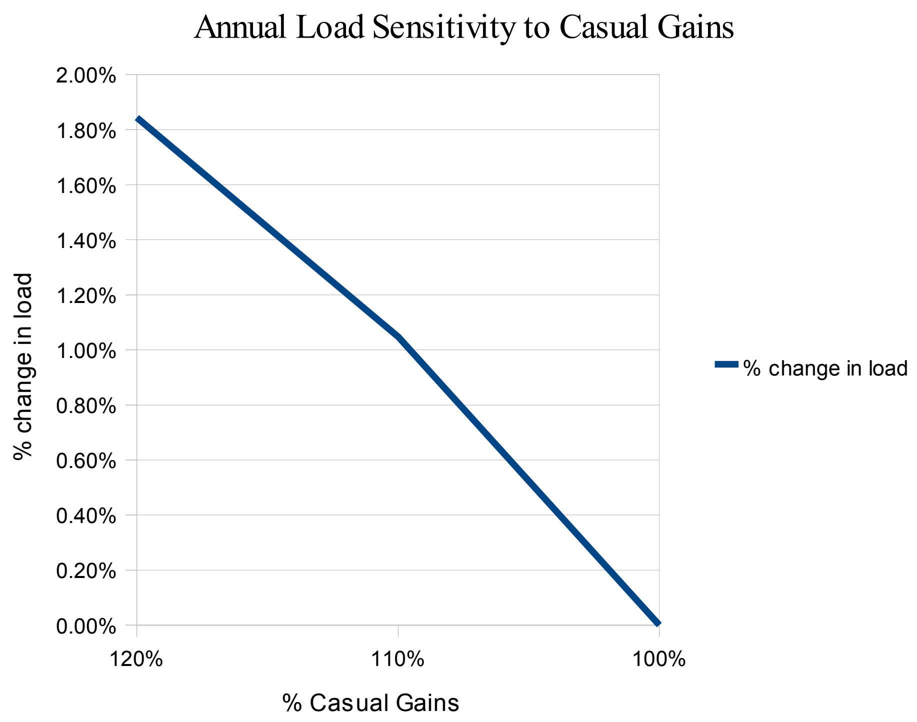

Figure 3-10: Annual Load Sensitivity to Casual Gains

Building	Lewis	Dublin	Dundee	Oban
Facilities Building	494,733	394,580	449,826	413,212
Engineering Building	331,234	257,576	296,612	269,240
Rural Building	195,193	158,330	180,482	166,712
Campus	1,021,160	810,486	926,920	849,164

Table 3-2: Annual Heat Demand kWh

HDD	Lewis	Dublin	Dundee	Oban
Average/Day	8.9	7.29	8.6	7.76
Total Annual	3249.6	2662.6	3139.6	2831.2

Table 3-3: Climate Data

Results Discussion

The buildings show general trends in heat load demand profiles as expected in Figure 3-7, with a peak in the mornings to heat the building up to temperature and demand dropping throughout the day due to rising ambient temperatures and casual gains from lighting, equipment and occupants.

The BBST scales a typical winter 'demand day' profile in order to calculate annual demand, however it was also thought useful to scale demand within ESP-r at this stage to compare results with known utility bills in order to check model validity (see Figure 3-8).

Campus heat demand per HDD of the model was calculated to be 418.99kWh/HDD based on a system with 75% seasonal efficiency, which compares well with the figure calculated in previous work of 411.12kWh/HDD (Cheng, A.H.Y., 2010), which was around 20% higher than the actual average demand.

The sensitivity analysis results are outlined in Figures 3-9 and 3-10; we would expect the main contributors to heat demand to be material losses (which will vary with ambient temperature) and losses due to ventilation and infiltration. It can be seen that air change rate has a significant impact on the results. Although casual gains will reduce the heat load to some extent, the heat load is not very sensitive to changes in casual gains due to occupants and equipment, and the assumptions outlined in Table 3-1 were thought reasonable. The higher combined ventilation & infiltration rate of 4 air changes per hour when occupied was chosen as the basis for the sizing of the boiler system; although this gives an annual load 14% higher than the 5 year average actual value based on a 75% heating system seasonal efficiency, this is within the acceptable error margin for this stage of design. 4 air changes per hour is a high ventilation rate, and the reasons for this assumption are outlined under the 'Uncertainty Analysis' heading in Chapter 3.3. A site survey would be recommended in order to confirm the accuracy of this and other assumptions used in the calculations.

The chosen '4 air change per hour' model was also used for simulations using a variety of different climate databases in order to show the sensitivity to ambient temperature which will affect both material losses and ventilation/infiltration heating requirements. The results of these simulations are shown in Table 3-2. Heating degree days comparison for the climates used are shown in Table 3-3 (a full monthly breakdown for each location is available in Appendix A). The difference between Lewis and Dublin's annual heat load for instance is over 20%; this illustrates the importance of reliable climate data in the design process.

Dependent on which day is chosen, the heat profile can vary widely, with Dublin colder on 5th January than Lewis for example, as can be seen from the heat load profiles shown in Figure 3-11, therefore it was decided to average five typical winter days to obtain the heat profile for use in the BBST.

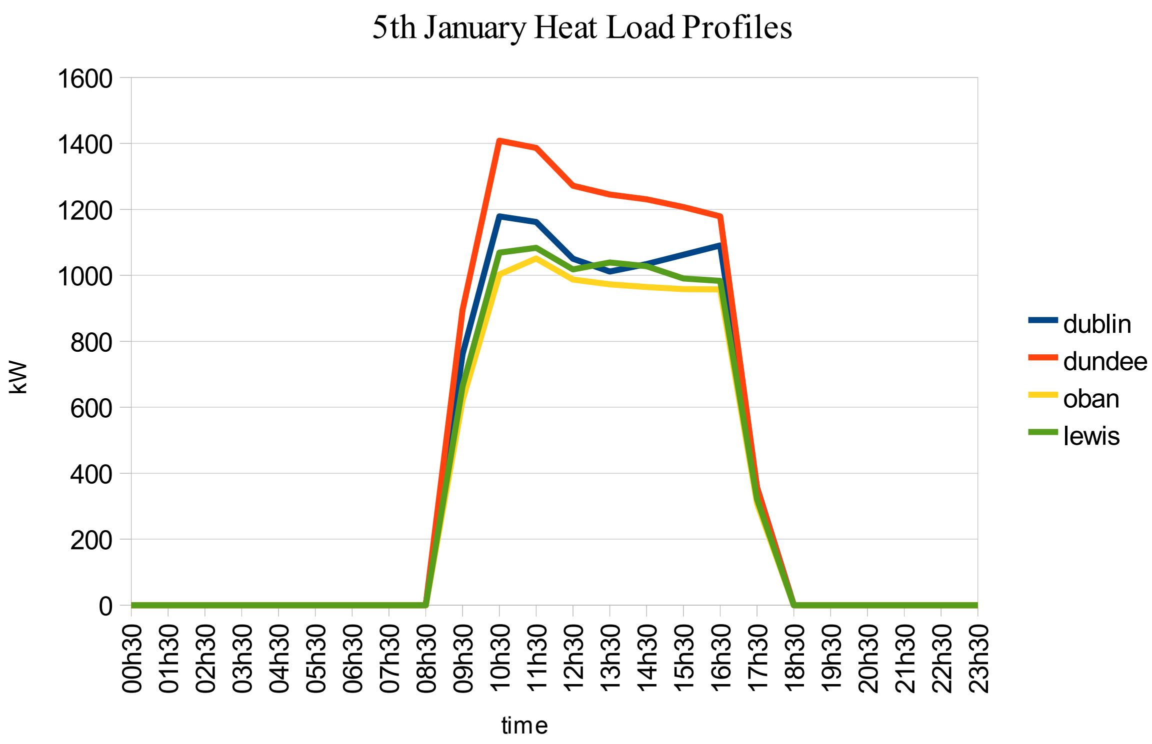

Figure 3-11: 5th January Heat Load Profiles

Further Validation Results

An idealised heating/cooling control system was used for the simulations, with a heating set point of 20ºC and cooling set point of 24ºC. This would not take account of any inefficiencies in the heating system, however since the aim of the simulation was to obtain a heat load requirement for the building, this was deemed an appropriate modelling approach. In order to validate the simulation results against actual fuel use data available, it was however necessary to make an assumption of heating system seasonal efficiency. Boiler Efficiency test results were available (Cheng, A.H.Y., 2010), and these gave the instantaneous efficiencies shown in Table 3-4.

	Rated Size (kW)	Measured Effic.
Boiler 1	850	82.00%
Boiler 2	850	87.40%
Boiler 3	325	62.30%
Boiler 4	325	72.10%
weighted average		79.86%

Table 3-4: Existing Boiler Efficiency

Source: (Cheng, A.H.Y., 2010)

If we expect pipe and equipment losses of around 5%, then it would seem reasonable to expect that seasonal efficiency will not exceed 75%. The seasonal efficiency assumption of 75% is used here to validate the simulation results against known fuel bills for the existing oil boiler system and is not relevant to the biomass boiler system sizing other than to validate the model; a figure of 85% seasonal efficiency was used to size the new biomass boiler system using the BBST as discussed in Chapter 3.5; the heat load profile calculated and shown in Figure 3-7 is a demand profile only.

In order to check the validity of the energy simulation model, the simulation was run for a full calendar year in order to compare with the available actual fuel use data and Energy Performance Certificates (EPC's) available from the LCC Report. Table 3-5 compares the heat demand results for each building with the EPC figures.

	Annual Heat Demand (kWh)	Floor Area (m^2)	Heat Demand (kWh/m^2)	EPC assumed total (kWh/m^2)	EPC calculated total (kWh/m^2)
Facilities Building	494,733	4,965	100	150	138
Engineering Building	331,230	2,928	113	418	330
Rural Building	195,193	2,237	87	130	123

Table 3-5: Comparison of Simulation and EPC Energy Use

Source: (Cheng, A.H.Y., 2010)

Both EPC figures overestimate the actual demand of the building. If we expect around 50% of the total demand to be required for space heating (Cheng, A.H.Y., 2010), then the heat demand for each building seems reasonable, although the Engineering Building heat demand seems quite low whilst heat demand for the Facilities and Rural Studies buildings are quite high.

A further check was carried out by comparing the campus heat demand from the simulation and therefore expected oil use (calculated at 11.7kWh/litre from http://www.biomassenergycentre.com) with the actual oil use based on a 5 year average. Comparison can then be made between actual oil use and a system of 70% and 75% seasonal efficiency as shown in Table 3-6.

	Annual Heat Demand (kWh)	Oil Use (litres)
Facilities Building	494,733	42,285
Engineering Building	331,230	28,310
Rural Building	195,193	16,683
Campus	1,021,156	87,278
Campus @ 70% effic.	1,458,794	124,683
Campus @ 75% effic.	1,361,541	116,371
Actual (5yr average)	1,197,272	102,331

Table 3-6: Comparison of Simulation and Actual Energy Use

The error between simulation figures at 70% and 75% seasonal efficiency and actual fuel use was 22% and 14%, which is within the level of accuracy required in order to investigate the possibility of a biomass boiler system. More information on ventilation schedules, material losses (including thermal bridges) and occupancy profiles would be required to improve the resolution of the model and obtain the more accurate results required for detailed design.

3.5. Case Study A Sizing Using BBST

The BBST was then used to give boiler sizing options for the given demand profile. From the ESP-r simulation results the design heat demand profile shown in Table 3-7 was obtained.

Time	Heat Demand kW
00:00	0
01:00	0
02:00	0
03:00	0
04:00	0
05:00	0
06:00	0
07:00	0
08:00	0
09:00	770
10:00	1,221
11:00	1,220
12:00	1,125
13:00	1,099
14:00	1,091
15:00	1,091
16:00	1,105
17:00	362
18:00	0
19:00	0
20:00	0
21:00	0
22:00	0
23:00	0

Table 3-7: Heat Load Profile for Campus (averaged Winter design day)

DHW requirement

In order to estimate the DHW requirement, the BBST estimates demand based on building use and occupancy. CIBSE Guide Table B4.8 (CIBSE, 1986) suggests an average of 6litres/day/person for an educational building. The tool calculated DHW demand of 8kW based on an average occupancy of 357 people; this is quite low when compared to 16kW for an office building and 262kW for a hotel (CIBSE Guide Table B4.8 suggests 8litres/day/person for an office building and 137litres/day/person for a hotel).

Ventilation

Although ventilation and infiltration were used in the ESP-r simulation, the BBST also requires an input for ventilation rate; the data from ESP-r represents a single design day, however the BBST scales this to an annual basis based on user's input data. The BBST used a ventilation rate of 12litres/person when occupied to scale to an annual basis. Since this figure is not used for calculating the design day load profile, the sizing result is not sensitive to this value when inputting data from a simulation program.

Other Assumptions

A seasonal efficiency of the biomass boiler system of 85% was assumed; this would represent a newly installed well running system. Default values within the tool were used for most of the financial inputs including capital costs. Fuel oil was assumed to cost 60p/l, electricity 12p/kWh, and wood pellets £165 per tonne delivered (equivalent to 4p/kWh). Sensitivities to price were noted as part of the discussion in Chapter 3.7.

3.6. Case Study A Sizing Results

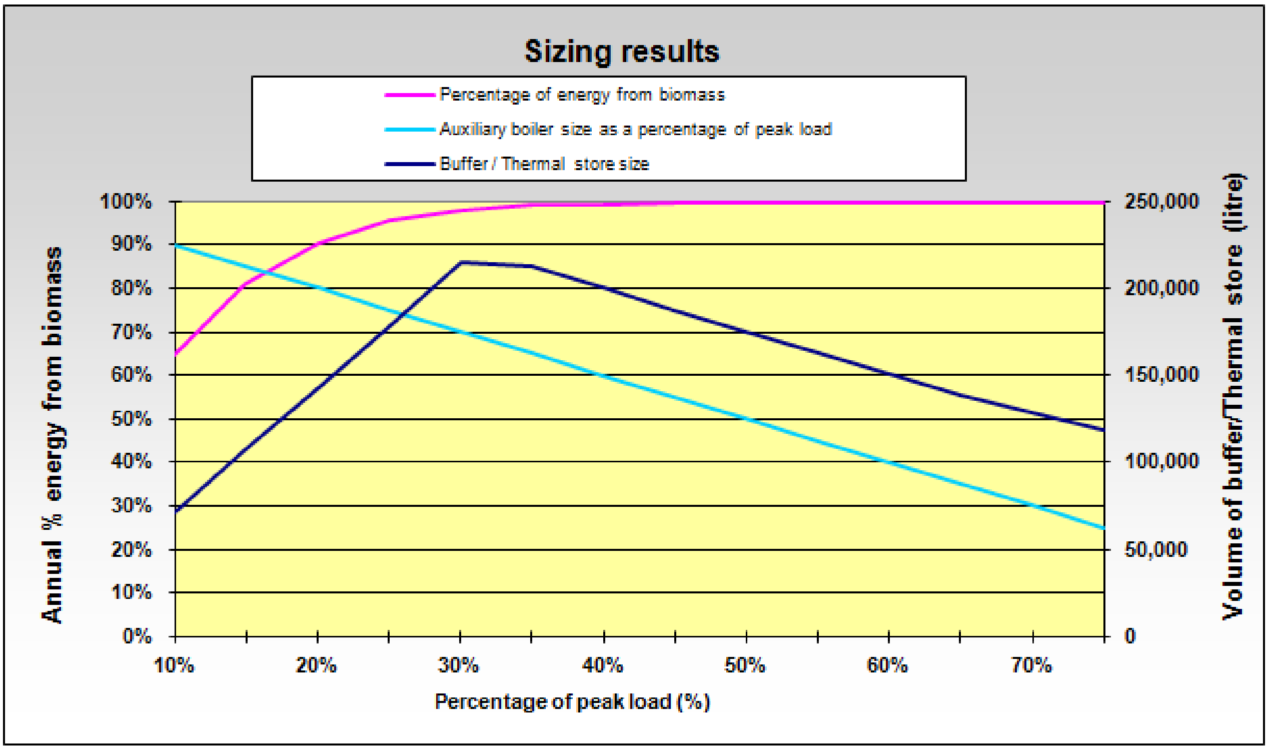

Figure 3-12: Biomass Boiler System Sizing

Boiler rated size	thermal store size (litres)	% heat from biomass	Estimated Capital Cost	Paypack
300kW	175,700	95.2%	£370,591	8.6
200kW	117,200	84.6%	£260,976	6.7
140kW	82,000	70.3%	£192,097	5.8
122kW	71,400	64.5%	£170,737	5.5

Table 3-8: BBST Sizing Results

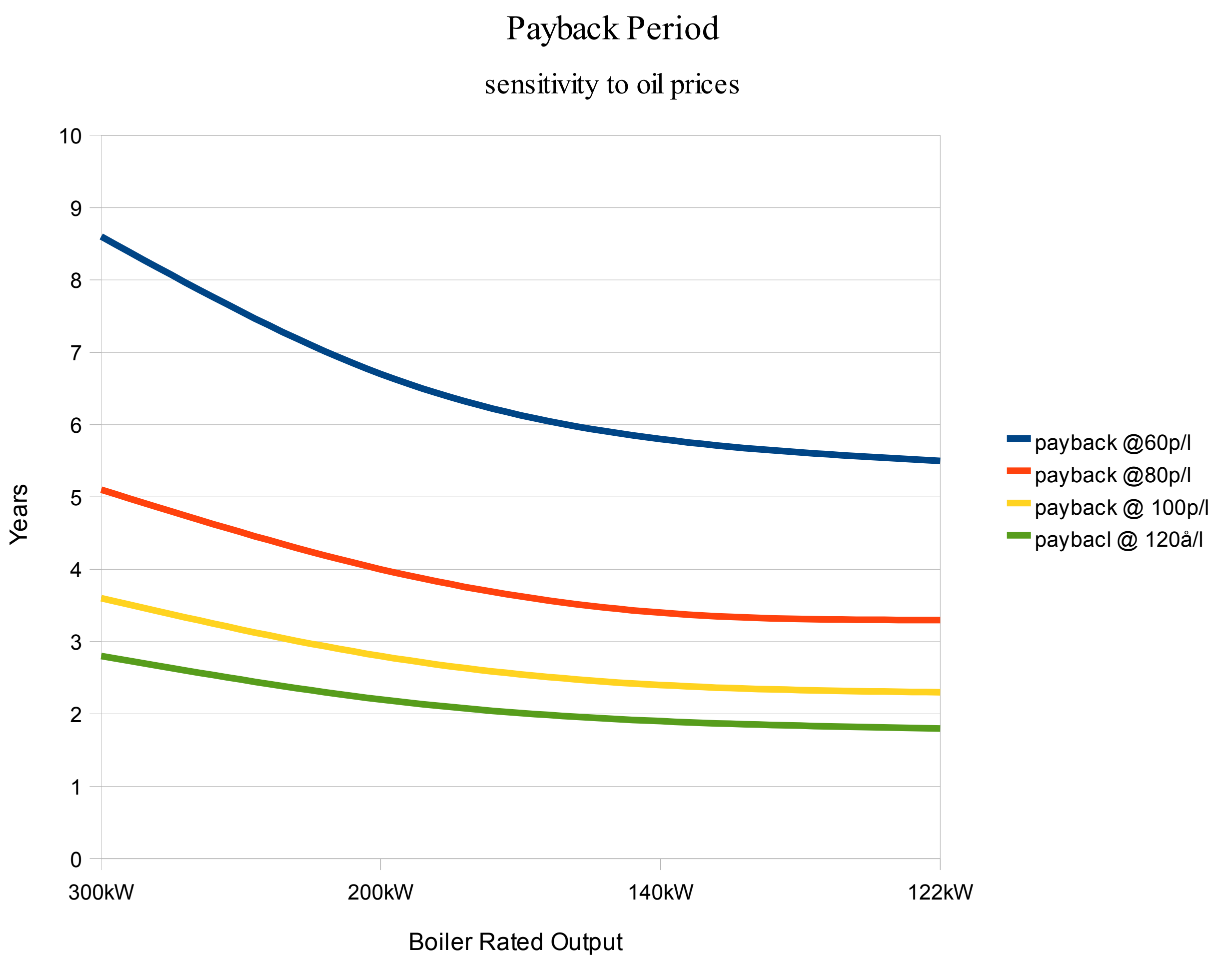

Figure 3-13: Sensitivity to Fuel Oil Price

Sizing Results Discussion

The BBST suggested a boiler sized for 10% of peak demand and thermal store sized at 71,400litres would be the most cost effective option. It should be noted that the payback period results are dependent upon the default assumptions within the tool and actual capital costs can vary significantly; quotes from biomass boiler providers would be required for accurate results, and rising costs for fuel oil and electricity would also influence the payback period. Sensitivity to fuel price is shown in Figure 3-13. As expected, the larger rated boiler size, the greater the sensitivity to fuel oil price, however capital cost is still the greatest influence on financial viability. For the Case Study, standard values from the tool for capital costs and it was assumed that no capital grant scheme would be available. The high capital cost of biomass boiler systems (in some cases as much as ten times the cost of an equivalent fossil fuel system) means that the result is very sensitive to the capital cost assumption. It was not found that payback period was sensitive to either electricity price or increasing the inflation rate for fuel oil; there is not facility within the tool to represent exponential increases in fuel oil prices which might be expected with diminishing reserves.

It is interesting to note from Table 3-8 that the most cost effective option is to supply only 64.5% of demand from biomass, using a 122kW rated biomass boiler. The small boiler size recommended suggests that the load profile of the college, with short heating period per day, low DHW demand and summer shutdown, is not the best suited to application of biomass boiler technology, although due to the fuel savings in comparison with fuel oil and the RHI, a small system could still provide acceptable financial payback. If capital grants were available a larger system may be viable. The high ventilation rate used may also result in quite high demand for the design day; a higher proportion of demand might be met by the biomass boiler system than suggested in the sizing results, and the accuracy of the heat load calculation will influence the accuracy of the sizing results as previously noted.

The method of sizing for a percentage of peak demand with a thermal store to make up the difference is quite different from sizing technique for a conventional fossil fuel boiler which may be over-sized for peak demand in order to heat the space quickly and minimise fuel costs. Perhaps the existing system of 2x850kW and 2x325kW was sized for this, with two duty boilers and two backup boilers, although it was not possible to confirm this from the information available. It was also noted that the LCC Report recommended a biomass boiler array of 3 boilers rated at 200kW, 300kW and 600kW in order to meet the varying demand profile (LCC p109); this illustrates how common misunderstanding of biomass boiler sizing technique is. Due to the high capital cost and large size of biomass boilers, arranging a number of boilers in an array like this does not make financial sense, and in any case the slow response to control of biomass boilers mean that such a system would never function efficiently or effectively in practice. The variation in the load should be dealt with by the addition of the thermal store rather than having a number of smaller boilers, and the system must be sized as a combination of boiler and thermal store. Sizing the biomass boiler as a stand alone unit without the thermal store would most likely result in a sub optimal system, which is why a software tool such as the BBST is so useful in the proper design of biomass boiler systems as it facilitates the iteration process.

3.7. Case Study A Recommendation & Summary

The college is remote from the gas grid and currently heated by oil boilers so we might expect a biomass boiler system to reduce heating fuel costs. Despite the intermittent nature of the campus heat demand, initial estimates suggest payback periods of less than ten years and in fact as low as 5.5 years are possible for a number of boiler sizing options if matched with a suitable thermal store dependent on the assumptions used.

If the biomass boiler system was installed, the existing setup could be integrated to use one 325kW boiler and one 850kW boiler as an auxiliary, with the other 325kW boiler either removed or retained to provide back up if reliability were a concern.

Although some Plant Room space would be freed up by removing one 325kW boiler, oil boilers are much smaller for a given rating so additional plant space will be required for the biomass boiler. It was not envisaged from the CAD drawings available that it would be possible to locate the thermal store within the building envelope, so an outdoor horizontal thermal store was specified, sacrificing some performance in order to achieve a practical solution. Additional costs may also be involved in creating a new boiler room for the biomass system which have not been fully accounted for in the tool.

These results give an initial indication that a biomass boiler system may be beneficial, however more detailed data is required in order to improve the accuracy of the heat demand profile used. It is possible that the heat load profile over or under estimates demand. Quite a high ventilation rate was assumed, which the results are very sensitive to, and the operating hours , heating season and casual gains may vary from those assumed. A full site survey would be required to improve the accuracy of these estimates and carry out detailed design. This could either inform the ESP-r energy simulation model, or involve installation of heat meters to measure demand. The heat meter option may be the more accurate, however the site survey and improved ESP-r model may prove the cheaper option as heat meters can cost around £2000 each and a number of these may be needed to monitor the load for the desired period dependent on the heating system pipework configuration on site.

The load profile of the college, as noted in Chapter 3.6 is not particularly suitable for biomass boiler system, and further benefit might be envisaged from a district heating system perhaps involving the nearby hotel which would have a high DHW demand year round; further study would be required to investigate this.

4. System Monitoring and Evaluation

The previous section describes a theoretical design process to size the biomass boiler and thermal store to meet a desired demand profile, however biomass boilers do not always perform as expected. The systems specified for Lews Castle College assume a seasonal efficiency of 85% but the economic outcome would be different if this efficiency was not achieved in practice. Reasons for poorer than expected performance in practice will vary by site, however the level of staff training will have an influence, as will natural variations in fuel quality. Chapters 4.1 & 4.2 describe the various requirements for boiler efficiency testing. In Chapters 4.3 through 4.6, a case study of the performance of a biomass boiler system at a plant nursery is described.

Biomass boiler systems have much lower fuel costs and require much higher levels of operator interaction than equivalent fossil fuel systems; the former may lower operator motivation to run the boiler efficiently and the latter may lower operator ability to run the boiler efficiently if adequate training has not been provided. The operation strategy required for biomass boiler systems also runs contrary to that required of fossil fuel boilers, gas boilers in particular. Whereas a fossil fuel boiler might be oversized and modulated in order to achieve a short heating period and thereby minimise fuel costs, biomass boilers must be run with minimal cycling to minimise fuel costs. At the commissioning stage, and periodically during the operational lifetime of the system, the system should be monitored and evaluated to ensure it performs to specification. Recommended testing and data monitoring is described in this section.

4.1. Biomass Boiler Efficiency Test Procedure

There are two ways to measure boiler combustion efficiency; directly, by measuring the heat produced by a given amount of fuel of known GCV, or indirectly by measuring individual losses. The direct method is quicker and simpler to complete, however it is less useful in troubleshooting boiler performance and less accurate than the indirect method. In the indirect method, each source of inefficiency is measure separately. This means that the overall measurement of efficiency will be less sensitive to errors in the measurement of individual losses, and also that individual sources of inefficiency can be identified and examined to effectively troubleshoot poor boiler performance.

Indirect Method:

According to BS 845-1:1987

> 'For the purposes of this standard, steady state conditions shall be deemed to have been reached, for solid fuel fired boilers with continuous fuel and ash flows and for liquid and

gaseous fuel fired boilers, when over a period of 1 h immediately before the test, drift in exit gas temperature does not exceed ± 10 K/h from the mean value.'

In practice it may not be possible to run the boiler at steady state for the time required by the standard other than at the commissioning stage, due to time and operational constraints.

The following parameters must be known or measured for the duration of the test in order to carry out the calculation of indirect efficiency described in BS 845-1:1987

- Mass Flow Rate, GCV and moisture content of fuel
- Carbon & Hydrogen content of fuel
- Combustion supply air temperature
- Flue gas temperature
- Volume of CO_2 & CO (or CO_2 and O_2) in flue gas
- Quantity & carbon content of ash and riddlings
- Quantity & carbon content of grit and dust
- Boiler flow water temperature
- Surface area & insulation thickness and quality of boiler
- Ambient temperature

From these parameters it is possible to calculate losses due to sensible and latent heat in the flue gases, losses due to unburnt fuel in the flue gases and in the solid residues, as well as losses from the boiler by radiation, convection and conduction. Methods for measurement of these parameters are discussed in Chapter 4.2.

An 'Efficiency Calculator' spreadsheet was constructed to determine boiler indirect efficiency from these parameters according to the equations given in BS 845-1:1987; the use of a spreadsheet tool was deemed advantageous as not all parameters can be easily or accurately measured in practice so some sensitivity analysis would be required. Some discussion of the loss calculation is shown in Chapter 4.4.

4.2. Measurements

All measurements should be made in accordance with BS 845-1:1987 as outlined in this chapter. Where this may not be possible in practice, an 'alternative method for test' has been suggested.

Fuel Mass Flow Rate

BS Approved Method: direct weighing by manufacturer approved method.

Alternative Method for Test: Calibration of fuel supply rotary screw auger for fuel volume, calculate weight of fuel supplied using fuel density.

GCV of Fuel

BS Approved Method: Bomb Calorimeter Test (detailed in BS 7420:1991) for specified reference conditions

Fuel Moisture Content

BS Approved Method: Oven Dry Method. (detailed in BS EN 14774:2009) Particle size reduced to 1mm or less (detailed in CEN/TS 14780), minimum 1g sample size, preferably mechanically mixed. Dried in controlled drying oven at 105 +/- 2 ºC, 3-5 ach/hr until constant weight, with dessicant to prevent absorption of moisture from atmosphere to sample before weighing. Weigh scale with accuracy of +/- 0.1g. Weigh rapidly after drying. Note: wood may contain other volatiles other than water which could influence the accuracy of the result from this method.

Alternative Method for Test: As per standard method but using a microwave oven in place of controlled drying oven. Comparison can be made with a moisture content meter if desired. This will inevitably be less accurate than the standard method, however could still be useful in a practical situation where time is at a premium and proper apparatus may not be available.

Flue Gas CO_2, CO%, dry basis

BS Approved Method:

BS 845-1:1987 states,

> '5.8.2 For measurement of exit gas CO, CO_2 and O_2 content, a hole shall be provided, as near as practicable to the final heat transfer surfaces of the boiler, in the

ducting or boiler casing, as appropriate, the diameter being just large enough to accommodate a gas sampling probe. Any gap shall be sealed against air ingress.

NOTE It is desirable to lag the gas exit duct with approximately 50 mm of rock wool from the boiler outlet to approximately one duct diameter downstream of the hole.

5.8.3 The gas sampling probe shall be located in close proximity to the temperature sensor in order to avoid errors.

NOTE It is advantageous to use a combined temperature sensor support tube and gas sampling probe.

5.8.4 The probes for both temperature measurement and gas sampling shall be of sufficient length to traverse the duct. Prior to the test period readings shall be taken at the centre of the cross section of the duct and at a minimum of four other representative points and then averaged.

NOTE If it is found that a single position gives readings representative of the average, this position may be used for subsequent observations provided that the firing conditions remain unaltered.'

Alternative Method for Test: Many sites may have access to a Combustion Air Measurement Set which is either permanently installed or used as a hand held device. This should be used according to manufacturers instructions.

Flue Gas Temperature

BS Approved Method: BS 845-1:1987 states

'5.8.1 The exit gas temperature shall be measured by using a probe comprising a fine wire thermocouple with the tip left bare (see BS 4937-20) supported in a small bore tube, in conjunction with a digital indicator, or by using one of the alternative instruments given in Table 1, compensating where necessary for the cold junction.

NOTE A fine wire thermocouple used in conjunction with a digital indicator responds rapidly to changes in temperature. A chart recorder may be used to show the peaks in exit gas temperature but the digital indicator can be used also for this purpose if an observer is employed to plot temperature and time.'

Alternative Method for Test: A Combustion Air Measurement Set will normally measure flue gas temperature as well as the CO_2 & CO levels as mentioned previously.

Combustion Air Temperature

BS Approved Method: Fine wire thermocouple as per other temperature measurements, or other instrumentation used as per manufacturers guidelines.

Hot Water Flow Temperature

BS Approved Method: instrumentation used as per manufacturers guidelines.

Alternative method for test: Where heat meters have been installed these will normally be capable of giving a temperature reading, as well as flow rate and calculated heat output.

Boiler Heat Loss Parameters

Measured Parameter: Ambient Temperature, Insulation thickness, surface area

BS Approved Method: Calculation based on surface area and insulation values.

Alternative Method for Test: Boiler surface temperature may be measured using infra red thermometer and heat loss calculated from literature tables.

General Notes:

The measurement interval should be synchronised for all parameters where at all possible (e.g. where the manpower is available). Often boiler surface temperature may not vary significantly during the test period and losses from the boiler surface may be considered steady state for the duration of the test if this is the case.

Carbon Content of Solid Residues: The method to determine this is described in BS 1016-106:1996; the procedure requires specialised laboratory equipment that may not be available and measurement of losses from solid residues is particularly problematic for biomass boilers from a practical point of view (due partly to natural variation in fuel properties and lack of provision for sampling by operators). Some manufacturers methods for boiler efficiency testing in fact routinely ignore or make assumptions for losses due to solid residues, i.e. they calculate only flue gas losses rather than combustion efficiency.

Overall, the major losses are expected to be from sensible heat, latent heat, and unburnt gas in the flue gases, so the final result should not be overly sensitive to errors in calculation of losses from solid residues however this should be checked as part of the sensitivity analysis when testing.

4.3. Case Study B Introduction

Tests were run on the biomass boiler system at a plant nursery supplying space heating to greenhouses to evaluate performance and identify possible improvements. Some information available from previous testing at the site suggested that the boiler was running at below normal efficiency but provided no further information so this case study attempted to identify the possible reasons for poor performance. The risk assessment carried out for the test day is provided in Appendix B. The tests ran from 12:30 until 14:15 on the 8th August and the following parameters were measured:

- Heat delivered from boiler (MWh) measured from Carbon Trust installed heat meter readings
- Boiler surface temperature from infra red thermometer reading on site
- Fuel delivered to boiler measured by calibration of rotary valve turns to calculate kg fuel
- Flue gas CO_2, CO and temperature measured by combustion measurement set

Other values assumed for the test were:

- Gross Calorific Value of wood pellet fuel assumed to be 17kJ/kg (from http://www.biomassenergycentre.org.uk)
- Energy conversion rate for fuel assumed 4.8kWh/kg (from http://www.biomassenergycentre.org.uk)
- Moisture content of fuel, 10% assumed (measurement from sample to follow)
- Combustion air supply temperature assumed to be 16ºC on day of test

A schematic of the system is shown in Figure 4-1 (not all valves and pumps shown for clarity)

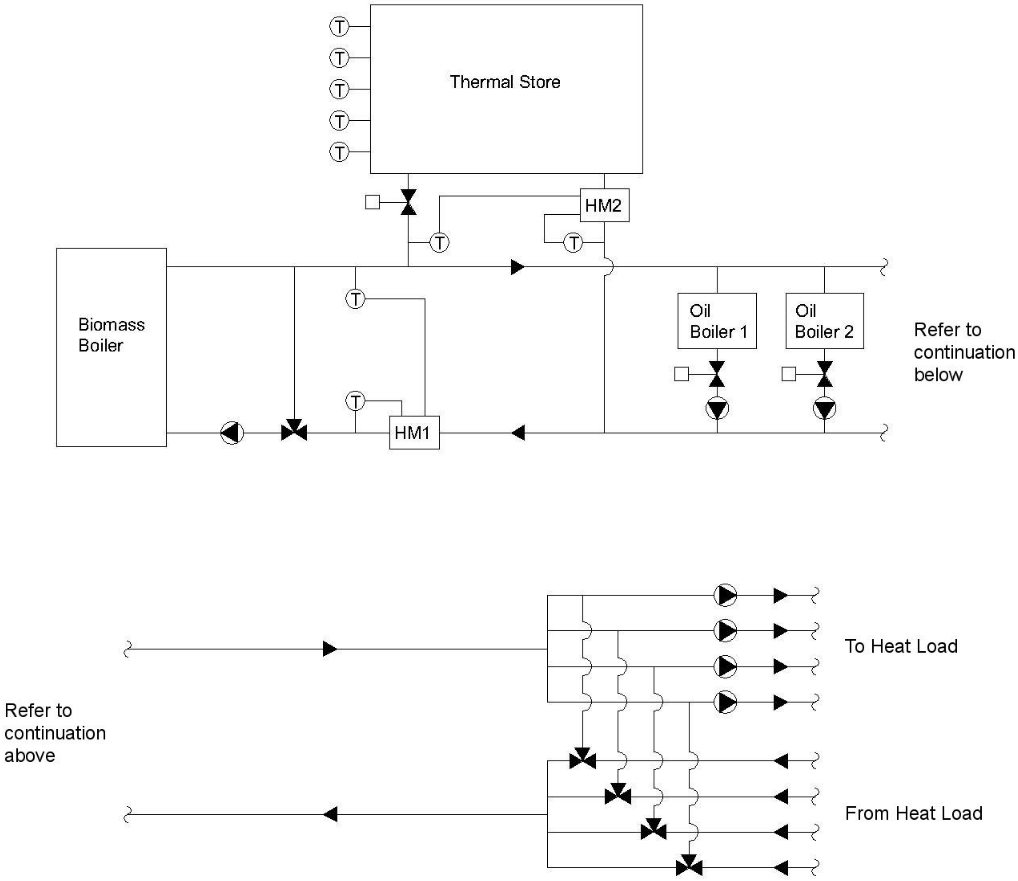

Figure 4-1: Case Study B Heating System Schematic

The boiler flue (not shown) passes through a cyclone to remove particulates and a variable speed fan before the gas is ejected to atmosphere via the external stack flue. Heat Meters HM1 and HM2 were installed by a contractor for the Carbon Trust, however access to logged data was not available and there were issues with the usefulness of their readouts, as noted in Chapter 4.7.

Rotary Valve Calibration

The rotary valve was calibrated for kg fuel per turn by direct weighing of the wood pellets collected from 1 1/3 turns of the valve. This provided a value of 3.63kg pellets per full turn.

Boiler Operation During Test Period

From 12:30-13:10 the boiler was running in slumber mode

From 13:10 - 13:17 the pumps were turned on to run the boiler at full load, however this was not reached

From 13:17-13:46 the boiler ran in slumber mode

From 13:46-13:55 the boiler temperature was increased to 83ºC on the boiler control panel to allow the boiler to run at full load

From 13:57-14:15 the boiler ran in slumber mode

Control Systems

There are a number of control systems associated with the heating system on the site.

- Fuel supply to the boiler is controlled via the SCADA system in response to temperature sensors in the greenhouses
- There are five temperature sensors on the thermal store; when the temperature at each of the sensors from the top down drops below the set point (i.e. as the thermal store discharges), it fires the boilers in the order: Biomass Boiler, Oil Boiler 1, stage 1, Oil Boiler 1, stage 2, Oil Boiler 2, stage 1, Oil Boiler 2, stage 2.
- Excess air to the boiler is controlled by the local boiler control panel in response to the fuel supply rate.

It was noted that the SCADA system boiler temperature reading for the biomass boiler was consistently higher than the reading on the boiler's own control panel by around 6ºC.

4.4. Case Study B Calculations & Test Results

Direct Efficiency Results

Time	HM1 reading (MWh)	kWh supplied
12:30	17697.6	0
13:10	17697.7	100.00
13:19	17697.8	100.00
13:30	17697.9	100.00
13:38	17698	100.00
13:48	17698.1	100.00
13:55	17698.2	100.00
13:57	17698.2	0.00
14:00	17698.3	100.00
14:05	17698.3	0.00
14:07	17698.4	100.00
14:13	17698.5	100.00
Total Heat Supplied (kWh)		900.00

Table 4-1: Heat Supplied by Boiler

time	rotary valve turns	fuel weight kg	fuel input kWh
12:30	1.333	4.84	23.23
12:46	1.333	4.84	23.23
12:58	1.333	4.84	23.23
13:10	1.333	4.84	23.23
13:12	3.2	11.62	55.77
13:13	3.2	11.62	55.77
13:14	3.2	11.62	55.77
13:15	3.2	11.62	55.77
13:16	3.2	11.62	55.77
13:17	3.2	11.62	55.77
13:18	1	3.63	17.43
13:20	1	3.63	17.43
13:22	1	3.63	17.43
13:24	1	3.63	17.43
13:47	4.71	17.12	82.16
13:48	4.71	17.12	82.16
13:49	4.71	17.12	82.16
13:50	4.71	17.12	82.16
13:51	4.71	17.12	82.16
13:52	4.71	17.12	82.16
13:53	4.71	17.12	82.16
13:54	4.71	17.12	82.16
13:57	1	3.63	17.43
13:59	1	3.63	17.43
14:13	0.333	1.21	5.80
	Total Fuel Energy Supplied (kWh)		1195.22

Table 4-2: Fuel Supplied to Boiler

From Tables 4-1 & 4-2, Direct Efficiency can be calculated:

direct efficiency=energy supplied by boiler to load / fuel energy supplied to boiler (4-1)

=900/1195.22

=75.3%

Indirect Efficiency Results

The Combustion Measurement Set readings for the test period are given in Appendix B Table B-1. The indirect efficiency results were calculated using standard methods outlined in BS 845:1987 based on the gross calorific value of the fuel with assumptions made for losses in solid residues; major losses were calculated using equations 4-2, 4-3 & 4-4, however there is no data in the British Standard for biomass fuels. The values for the Siegert Constant k_{gr} and constant k1 required for calculation of losses from sensible heat in the flue gas and unburnt fuel (i.e. CO) in the flue gas were available in literature (Spiers, H.M. 1961) and various flue gas measurement set manufacturers handbooks. A method for their calculation based on fuel properties is also given in BS 845-1:1987 and shown in equations 4-5 & 4-6. The literature values however, do not seem to correspond with the values obtained using equations 4-5 & 4-6, and their values gave unlikely results when used to calculate efficiency. It was also noted that a number of Combustion Measurement Set manufacturer's manuals give an erroneous value for the carbon and hydrogen content of wood of at 97%/3%- the carbon content of wood varies between 45-55% dependent on species (Ragland, K. W., Aerts, D. J., 1991) and a value of 50% carbon and 6% hydrogen is normally used. The values given in the literature, and the ones calculated using the standard equations are shown in the Table 4-4.

$$L1 = \frac{k_{gr}(t3 - ta)[1 - 0.01(L4 + L5)]}{VCO_2}$$ sensible heat losses in flue gases (4-2)

$$L2 = \frac{(mH_2O + 9H)(2488 - 4.2ta + 2.1t3)}{Q_{gr}}$$ losses due to enthalpy of water in flue gases (4-3)

$$L3 = \frac{k1\,VCO[1 - 0.01(L4 + L5)]}{VCO_2 + VCO}$$ losses due to unburnt fuel in flue gas (4-4)

Where the constants were calculated from:

k_{gr}= (253 x [C])/Q_{gr} (4-5)

k1= 1.25 x [C] - 55 (4-6)

The symbols have meanings a shown in Table 4-3.

t3	flue gas temperature	°C
ta	air inlet temperature	°C
L4	losses due to unburnt fuel in ash and riddlings	%
L5	losses due to unburnt fuel in grit and dust	%
VCO_2	vol CO_2 in flue gas	% dry basis
VCO	vol CO in flue gas	% dry basis
C	Carbon content of fuel	% by mass
mH_20	Moisture content of fuel	%
H	hydrogen content of fuel	% by mass
Q_{gr}	GCV of fuel	kJ/kg

Table 4-3: Variables for Loss Calculations

It was noted that in the equation for losses due to unburnt fuel in the flue gas in the BS 845-1:1987, there is a misprint, with '1' printed as 'l'; this mistake is repeated in Appendix B of the BS. There is no constant 'l' and all values of 'l' were assumed to be '1' instead. The constants k_{gr} and k1 from BS 845-1:1987 may also be referred to as k1 and k2 or by some other notation in some flue gas measurement set manufacturers handbooks so care must be taken with their use. All notation used in this research is based on BS 845-1:1987.

	Fuel data from literature					Fuel data from calculation	
	H%	**C%**	**k_{gr}**	**k1**	**Qgr**	**k_{gr}**	**k1**
wood	6.0	50.0	0.64	6	17,000	0.74	7.50
coal	4.0	96.0	0.62	63	39,484	0.62	65.00
heavy fuel oil	11.5	88.5	0.48	53	46,219	0.48	55.63
light fuel oil	13.0	87.0	0.51	54	44,250	0.50	53.75

Table 4-4: Constants required for BS 845-1 Indirect Efficiency Calculation

The major losses in this type of boiler were then calculated using both sets of constants and results are shown in figures 4-2 and 4-3.

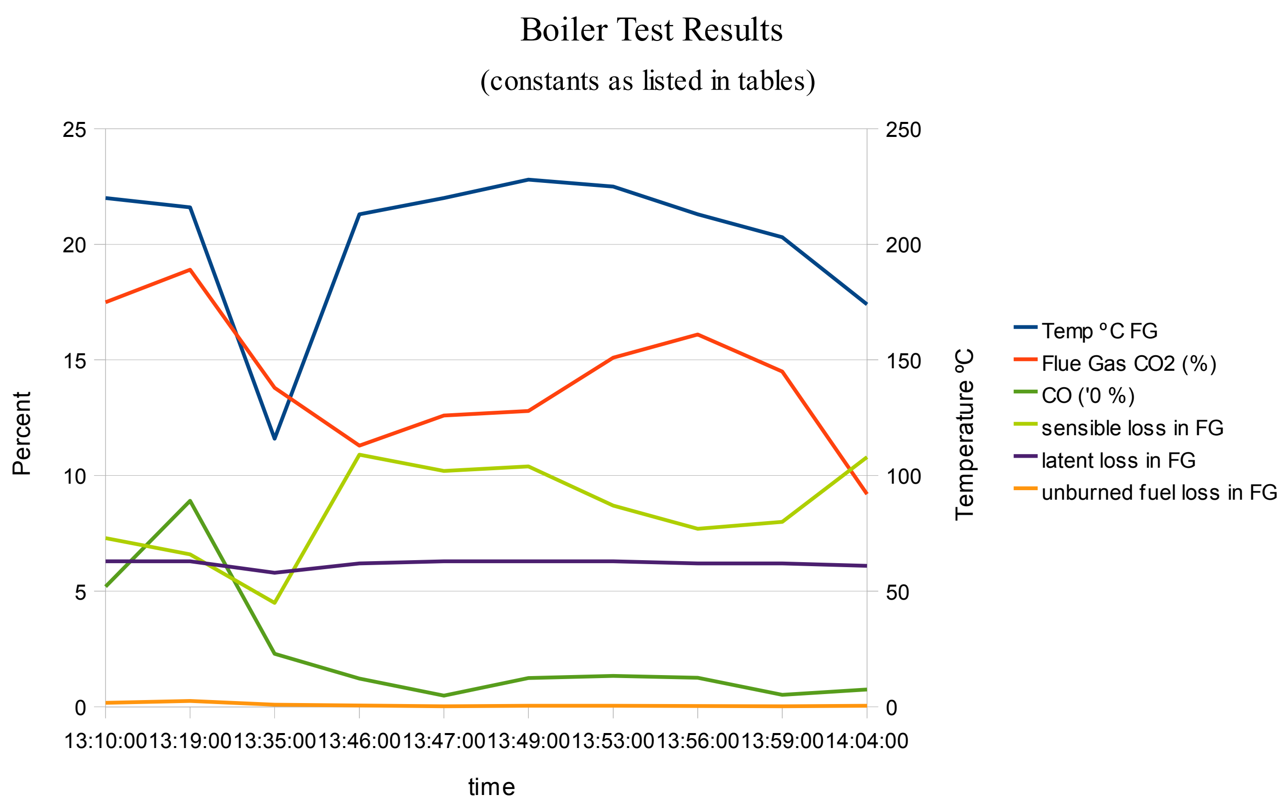

Figure 4-2: Boiler Test Results using literature constants kgr and k1

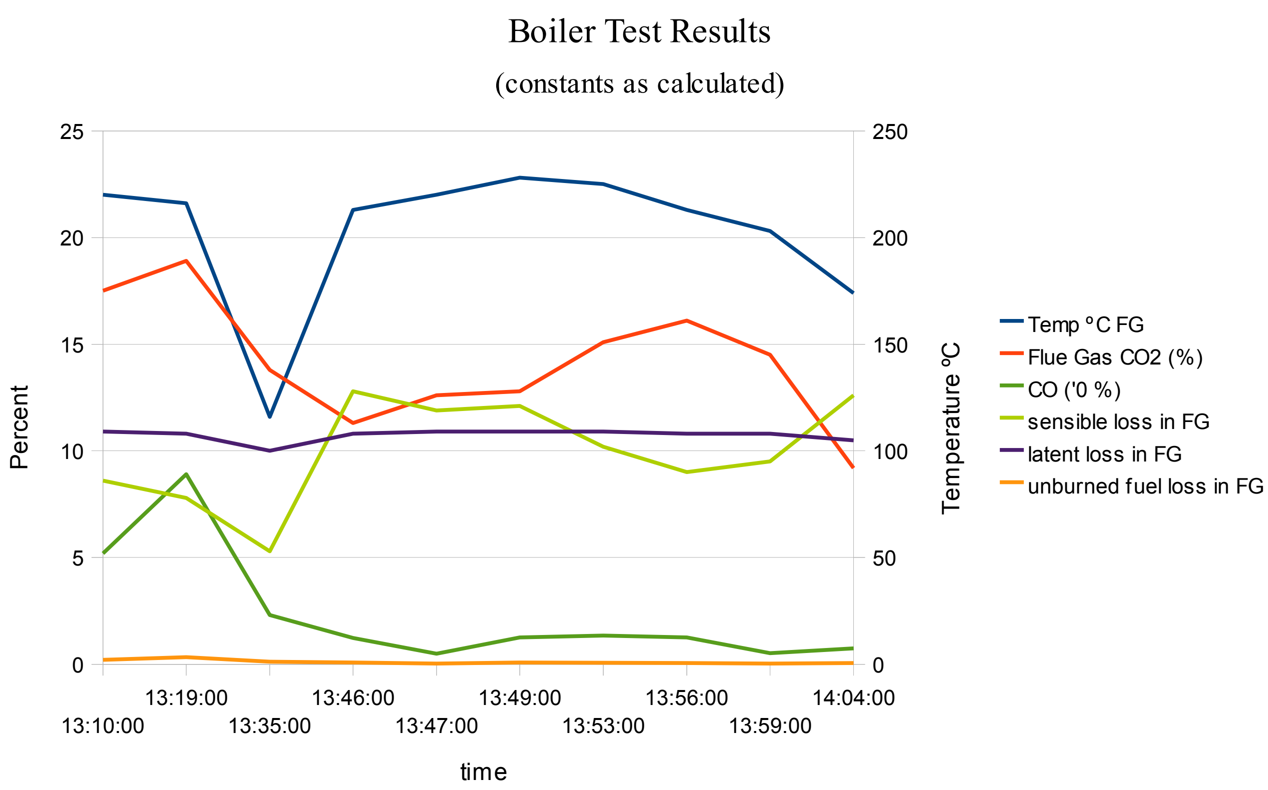

Figure 4-3: Test Results using calculated values for constants kgr and k1

The results for indirect efficiency for both sets of constant are shown in Table 4-5, along with time weighted value for the test period and correction factors for those losses not included elsewhere.

Time	Efficency % (constants as listed in tables)	Efficiency % (constants as calculated)
13:10	86.2	80.3
13:19	86.8	81.1
13:35	89.6	84.6
13:46	82.8	76.3
13:47	83.5	77.2
13:49	83.3	76.9
13:53	85.0	78.8
13:56	86.1	80.1
13:59	85.8	79.7
14:04	83.1	76.8
time weighted average	86.05	80.23

Table 4-5: Indirect Efficiency

Losses Not Measured

Boiler surface temperatures did not exceed 44ºC on lagged surfaces and 62ºC on unlagged surfaces, indicating losses by convection, conduction and radiation from the boiler were acceptable.

Table 3, Appendix C of BS 845-1:1987 gives expected losses from radiation, convection and conduction for standard boiler types and we could expect 0.5% for the boiler tested.

In the absence of laboratory resources to test the losses from unburnt fuel in the solid residues, these losses were assumed to be 2% based on the boiler type and size (Spiers, H. M., 1961) and the results were not found to be sensitive to this assumption.

A screenshot from the plant nursery SCADA system is shown in Figure 4-4 for the period preceding the test , and it was noted that the clock on the SCADA was 1hr and ten minutes slow (i.e. 12:00 on screen = 13:10)

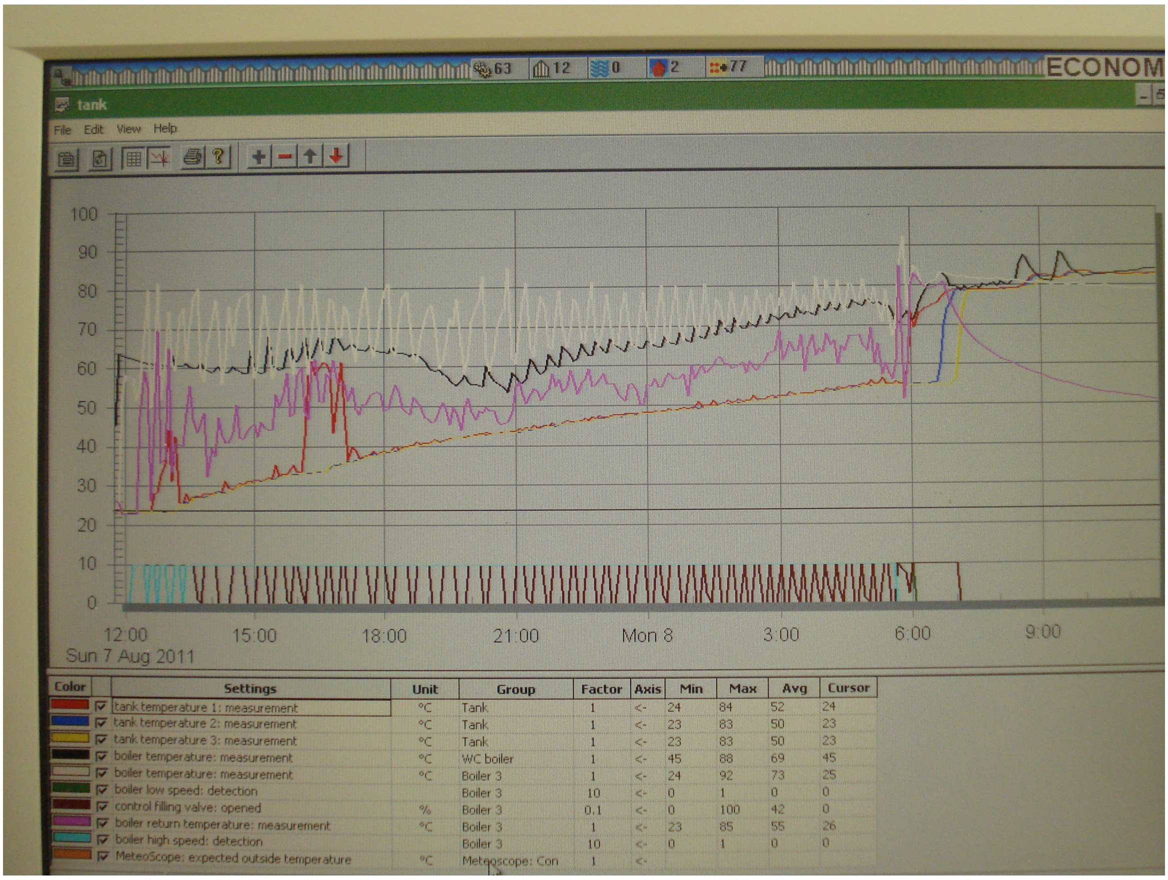

Figure 4-4: Case Study B SCADA Screenshot

4.5. Case Study B Results Discussion

Direct Efficiency

Due to issues with time step synchronisation and low resolution of heat meter data, it was not thought a useful level of accuracy could be achieved by calculating direct efficiency on a time-step basis, so direct efficiency was calculated for the duration of the test (which included periods of slumber and full load over 1hr 45mins) based on the rotary valve fuel weight calibration and the cumulative heat delivered to the load from HM1. Issues with the data available from HM1 are discussed in the later section on Test Limitations in Chapter 4.6. The value of 75.3% measured during the test suggests a lower combustion efficiency was being achieved in practice compared to what might be expected for a boiler operating well. The BBST uses 85% heating system seasonal efficiency as a default value, so it important to consider the effect of reduced efficiency at the design stage and to attempt to avoid reduced efficiency during operation. Data obtained from a biomass boiler provider suggested that this model of boiler should operate with a constant efficiency of 90-91% from 20% to 100% load, so it was clear the boiler was not performing as expected. Indirect efficiency measurements can be useful in identifying the source of poor performance.

Indirect Efficiency

The flue gas was sampled as it left the boiler, before the cyclone. After the cyclone there was a variable speed fan, which made obtaining a steady reading from the flue gas analyser impossible as it never operates at steady state. For this reason, losses were calculated for each flue gas temperature reading as shown in Figures 4-2 and 4-3 . Indirect efficiencies are shown in Table 4-5.

As mentioned previously, there are practical problems associated with the measurements required to estimate losses associated with solid residues from biomass boilers, however it was possible to analyse the flue gases on site and come to some conclusions about boiler performance from this. Reasonable assumptions for losses due to unburnt solid residues and convective, radiative and conductive losses from the boiler are listed in Chapter 4.5 under the 'Losses Not Measured' heading. The boiler is generally in a good state of repair, with no indication of overly poor insulation or poor air tightness which could lead to excessive heat losses from the boiler.

Losses were calculated from flue gas analysis, with a correction factor added for 'losses not measured' of -2.5%. from these assumptions Absolute values for indirect efficiency from the tests may not prove to be accurate as a result of these assumptions and other mentioned below, however sources of inaccuracy have been identified where possible and it was still possible to identify possible sources of poor operation from the results.

As mentioned in the previous results section, there is some doubt over the accuracy of constant values for wood fuel available in the literature. The figures calculated using the figures from the authors values for the constants are slightly higher than the measured direct efficiency of the test period- 75.3% direct efficiency compared with a corrected indirect efficiency of 77.7% as opposed to 83.6% using the literature constants when the correction factor of -2.5% is applied to the results in Table 4-5. The literature constants underestimate losses from sensible and latent heat, and unburnt fuel in the flue gases (see Figures 4-2 and 4-3).

The losses due to latent heat of water in the flue gases are more or less constant, dependent on moisture content and hydrogen content of fuel; the value is highly sensitive to hydrogen content, as can be seen from equation 5; in the absence of the resources for full laboratory chemical analysis of the fuel the absolute values for efficiency should be viewed with this in mind. The constants used in the loss calculations, and therefore the final absolute value, are also sensitive to the gross calorific value of the fuel; as previously noted, it was not possible within the time or resource constraints of the test to carry out a bomb calorimeter test on the fuel fired. The value of 17MJ/kg for wood pellets used (from http://www.biomassenergycentre.org.uk) is at the higher end of the range that might be expected, particularly taking into account the operator's observations on fuel quality listed below, and a lower GCV would give a lower value for indirect efficiency.

It was noted that the boiler was burning wood pellets, rather than the wood chips which it normally burns, and that these pellets were considered by the operator to be of low quality. It is possible that excessive fines may be present in the combustion chamber, or that fouling may be an issue. Although it is impossible to determine this from the test carried out, it may be worthy of future investigation. Another concern is that the moisture content of wood pellets is below that of wood chip, so the fuel being burned will travel more slowly on the grate than is required for efficient combustion since it requires a shorter drying period (refer to Figure 2-1 for an overview of the combustion mechanism). The impact of this would require further investigation, however it is possible that the longer residence time of ash in the system could increase fouling, or that the losses due to unburnt solid residues may not be as assumed. The incorrect fuel selection could also contribute to the high flue gas temperature as wood pellets have a higher GCV than wood chip (17MJ/kg compared to around 11MJ/kg) so the combustion may be giving off more heat than the system is being operated for for. Further investigation, including repeating the test with wood chip fuel, is recommended as there were no indications that the boiler had been adjusted to accept different fuel.

What was apparent from the test was that there was an excessive volume of CO present in the flue gases even at full load; this is generally caused by unburned volatiles, i.e. incomplete combustion, where 'wood gas' (CO and H_2 mix produced by carbon containing biofuels heated in presence of an insufficient stoichiometric quantity of oxygen) is carried over into the flue gases as lost energy. This could either be caused by excessive fuel supply to the boiler, insufficient air supply, or poor mixing within the combustion chamber. As shown in Appendix B Table B-1, CO levels of up to 0.89% were observed in the flue gases with the boiler at full load, compared to expected levels of 0.1% or less for a boiler running well according to BS 845-1:1987.

Fuel supply by the rotary valve and screw auger is controlled via the SCADA system in response to the heat load required. Air supply is set on the boiler control panel and is controlled by this in response to the fuel supplied. Mixing between the air and fuel within the combustion chamber is essentially an aspect of boiler design geometry, although poor mixing might be caused by excessive fines in the fuel or fouling, or by high levels of excess air.

Excessive fuel supply is unlikely to be an issue here, as the direct efficiency figures suggest that the fuel supplied is not being burned completely.

The boiler Control Panel indicated excess air in the flue gas of between 4-11% throughout the test. This should be sufficient to give better combustion efficiency than was observed; this is measured by a lambda sensor connected to the control panel, and since these are prone to inaccuracy and failure, it could be that the sensor is reporting an incorrect value for O_2 concentration and replacement of this sensor is one possible recommendation for improved operation. It is also possible that too much excess air is being supplied; this could result in poor mixing in the combustion chamber, hence CO emissions from unburnt fuel, and also increased sensible heat losses in the flue gas (flue gas temperature was observed to be above design values, as noted below).

It was not possible during this test to analyse performance within the boiler (for example combustion distance on the grate, combustion temperature, or impact of fouling), and there are practical issues associated with this. Some suggestions to investigate this would be to examine the boiler internally during shutdown, or consult maintenance records, to investigate whether fouling is a major problem, or to repeat this test with wood chip or higher quality wood pellets which produce less dust than the wood pellets burned during this test and compare performance. Fouling may also be diagnosed from an abnormally high pressure drop on the flue gas side; data may be available from the boiler manufacturer to measure this. Combustion temperature could be measured if a pyrometer was available.

It was clear from the results that the greatest loss was from sensible heat in the flue gases. Data obtained from a biomass boiler provider gave flue gas temperatures for this type of boiler which do not exceed 170ºC at 50% load , 180ºC at 80% load , and 195ºC at 100% load. The measured flue gas temperatures under load varied between 203-228ºC during the test period. The reasons for this cannot be determined from the test data available, however it is clear that this is a source of inefficiency. It is possible that the heat exchanger section of the boiler is not performing well, either due to fouling on the tubes, too low an air or water flowrate through the heat exchanger, or as a result of too high a return water temperature to the boiler. Further investigation, in particular of the boiler return temperature, is recommended.

SCADA screenshot

Figure 4-4 shows the readout from the SCADA for the time preceding the test. The white line shows boiler temperature for 'Boiler 3', which is one of the auxiliary oil burning boilers and the black line 'WC Boiler' is the biomass boiler temperature. At the start of the period, with the thermal store temperature below 30ºC, the auxiliary boiler is required as expected. The tank temperatures 1,2 and 3 are stratified temperature readings, with temperature 1 at the top of the tank firing the biomass boilers and the others firing staged oil boilers as described in the previous section. It can be seen that once temperature sensor 1 reaches 60ºC at around 16:30 on the Sunday (SCADA time), the biomass boiler goes into slumber mode, but the faster responding oil boiler 3 is still firing until Monday 7am (SCADA time) when the deeper temperature sensor 3 reaches 80ºC. The control system seems to perform as it has been set up, however if it's aim is to burn cheaper biomass in preference to oil, it doesn't achieve this during summer operation. It was also noted that the biomass boiler temperature reading on the SCADA was around 6ºC higher than the reading on the boiler's own control panel. The fact that the boiler control panel and the SCADA system have different readings for temperature of the boiler suggest that these separate systems are probably not coordinated properly which could result in reduced performance. The control of the system by different methods could perhaps be rationalised so that all control is via the SCADA system, rather than using the boiler control panel for individual parameters (i.e. air supply and boiler temperature).

Unfortunately there is no reading for the return temperature to the biomass boiler. It is possible that as the thermal store heats up it may be raising the return temperature to the biomass boiler. This could be contributing to the high flue gas temperature noted previously.

4.6. Case Study B Summary

Observations

- High CO readings in the flue gas indicate the fuel is not being burned completely
- O_2 readings of 4-11% excess on the boiler control panel indicate that fuel should be burned efficiently; it is possible the lambda sensor is giving an incorrect reading for O_2
- Poor mixing may be occurring within the combustion chamber resulting in lower than expected combustion efficiency
- The boiler may be set up to burn wood chips with a moisture content of around 30%. even though it is burning wood pellets with a moisture content 10%. It must be confirmed that the operating parameters are suitable for the fuel being burned

- High flue gas temperatures indicate poor heat transfer efficiency. This may be due to fouling, high airflow, or high boiler return temperature
- The control setup for the heating system requires further investigation, in particular regarding placement of flow temperature sensor on the biomass boiler and biomass boiler return temperature

Recommended further investigation

- The control system must be surveyed to confirm it is operating as intended, in particular it must be confirmed that the return temperature to the biomass boiler is within design specification
- The lambda sensor for O_2 measurement in the biomass boiler control panel may require to be replaced; air flow through the boiler should be measured to confirm it is within design specifications
- Fuel supply, oxygen supply and flow temperature of the biomass boiler should be controlled from a single controller if possible
- It must be confirmed that operating conditions are suitable for the fuel type being fired
- Fouling of the biomass boiler and heat exchanger should be investigated
- Flowrate of water through the boiler must be measured and compared with design values

Test Limitations

There were a number of practical limitations in carrying out this test which resulted in deviation for the BS 845-1:1987 recommended procedure. As previously noted, the absolute values for efficiency should be viewed with this in mind, however useful conclusions can be made if the limitations listed are taken into account.

- Steady state as defined in BS 845-1:1987 as 1hr of operation with variation in exit gas temperature less than +/-10K from mean value was not achieved during the test.
- Due to time limitations, it was not possible to run the test for minimum recommended 2 hours at each operating load.

Data resolution proved to be a problem for this test, as is often the case when information on dynamic performance is required as opposed to monthly or annual billing data. HM1 measured heat delivered by the boiler in MWh only; while this may be acceptable for calculations on a monthly or annual basis, it is of limited use for this kind of diagnostic testing. There were effectively only 12 sample points within the test period for heat delivered, as can be seen in Figure 4-5; the fuel supplied sample points, by contrast, represent the exact amount of fuel energy supplied per minute, subject to the accuracy of the rotary valve calibration and 4.8kWh/kg fuel conversion used, also shown in Figure 4-5. In order to evaluate dynamic control system performance, accurate time step data is crucial. Flow meters can be expensive (as much as £5000), so it makes economic sense to set them up to provide high resolution data when required to obtain full benefit from their installation. HM2 measured bi-directional heat flow to and from the thermal store and summed the result, so the readout showed double the heat supplied by the thermal store, minus losses which as a result could not be calculated so was not of use. Heat meters calculate the heat flow by measuring temperature and mass flowrate, however neither of these readings were available on screen at this installation; it was not possible to determine the reason for this. Little information is being measured and recorded by the heat meters on site compared to what is technically possible.

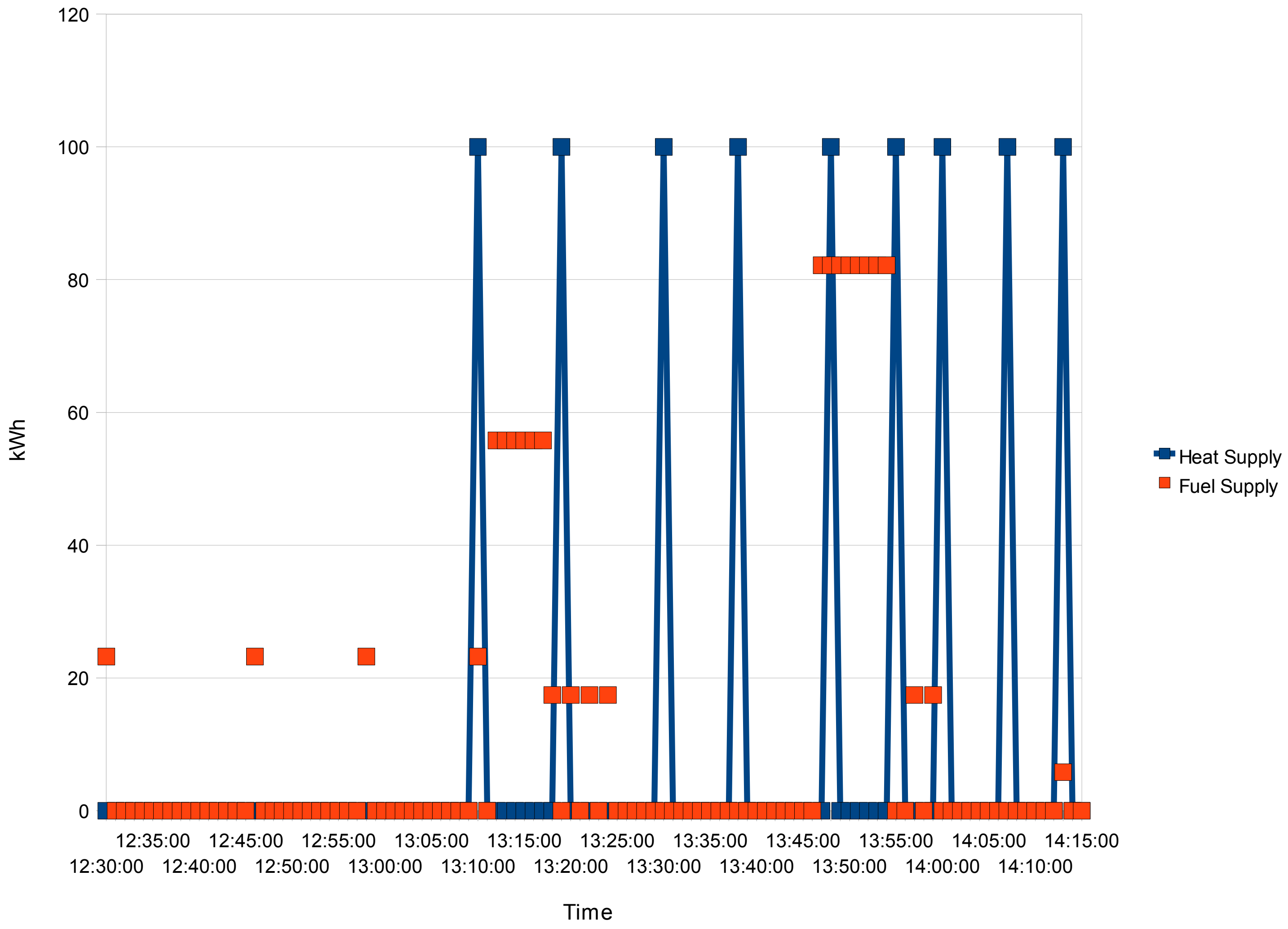

Figure 4-5: Case Study B Fuel Data

4.7. Monitoring & Evaluation Issues

In addition to testing boiler combustion efficiency, it is also recommended that heat flow throughout the system is monitored; this can be useful for whole system investigations, and also as a means of measuring losses from the thermal store.

Heat meter placement is crucial; this requires full knowledge of system design and operation. Heat meters must be installed in the relevant section of pipe to measure flow to and from the relevant piece of plant, without significant losses between the plant item and the meter; meters must be lagged after installation and incorrectly placed heat meters shall likely prove to be useless.

The level of data resolution required for accurate dynamic performance evaluation is much higher than that which is often collected and logged. It is fairly common for data on temperatures, heat flows etc. to be available from the BEMS system, however it is rarely logged, and where it is this is often only on a monthly or annual basis as one would log utility bills. This is often the result of constraints on staff time, however once automatic data logging is set up it should require little intervention from the operator. In order to understand how the system responds to changes in heat load or ambient conditions, we must have readings at time-steps of around 15mins or less; this data should then be logged for the full period which the system is in use (e.g. for a full year) to check data validity and to observe the impact of changing climate and maintenance conditions. Boiler systems will often perform quite differently during summer and winter due to the varying heat load, so in order to evaluate seasonal performance, year round data is essential. Biomass boiler systems may also experience a degradation in performance over time due to fouling; full period data on performance would allow this to be identified and changes to maintenance intervals recommended where required. In the case of boiler efficiency testing, BS 845-1:1987 recommends time-steps of 10mins or less for temperature measurements, 5mins for heat carrier temperature and 1min or less for flow measurements. Time step measurements should be synchronised where at all possible to provide an accurate representation of dynamic conditions.

4.8. Recommended Monitoring & Evaluation Requirements

Heat Flow Metering

- heat meters measuring temperatures, flow rates and hence heat flow rate kWh
- heat meter data logged at required resolution (e.g. 1hr time-steps or better) for required period (e.g. year)
- flowrates and temperatures should be measured using the heat meters where available to confirm boiler is operating within it's design parameters

Climate Data

- ambient temperature data at required resolution (e.g. 1hr time-steps or better) for required period (e.g. year)

Heat Load monitoring

- heat meters to measure heat delivered to load

- temperature sensors to evaluate how well the control system maintains the required set point temperatures

Boiler Efficiency monitoring

- Periodic (annual) measurement of boiler instantaneous efficiency is recommended
- Periodic air tightness checking of boiler & flue
- Accurate record keeping of fuel use & fuel quality (major variations in fuel quality are an inherent problem for biomass, less so for wood pellets than wood chip)

Thermal Store monitoring

- in the case of stratified thermal stores, temperature sensors at relevant positions within the tank (only practical at installation)
- heat metering on all ports of the thermal store to allow measurement of heat delivered to/from load and boiler as well as heat losses from the store

5. Overview of Biomass Boiler Systems

Biomass Boiler Systems are most suited to:

- buildings with high DHW demand in constant use
- buildings with year round heating demand
- any other load which might allow them to operate under high load for extended periods

Biomass Boiler Systems are characterised by:

- slow response to control
- lower fuel costs & lower emissions than fossil fuel equivalents
- higher capital cost and size

Biomass Boiler System Design requires:

- accurate heat load data
- proper sizing of the boiler & thermal store to meet design criteria
- careful integration with existing boilers

Biomass Boiler Systems may perform less well in practice than design due to:

- poorly understood system configuration
- poorly designed or operated control systems
- poor control integration with auxiliary boilers
- poor quality fuel due either to manufacturing or storage failings
- natural variation in fuel quality when burning wood chip
- failed or incorrectly placed sensors
- excessive cycling caused either by poor control or unsuitable thermal load profile
- poor maintenance leading to material heat loss or fouling
- poor combustion efficiency caused by inadequate air/fuel ratio or air/fuel mixing
- poor heat exchanger performance due to incorrect temperatures or flowrates

- human factors; because fuel costs are so much lower than for fossil fuel boilers, operators may lack the motivation to maintain a biomass boiler running efficiently, which can result in an increase in pollution due to increased CO, NOx and particulate emissions. A greater degree of interaction with the boiler during normal operation also requires a certain degree of worker training which is not always taken into consideration

6. Conclusion

6.1. Summary

Biomass represents a useful renewable resource with many potential uses in power generation and heat production. The resource is however finite and due to the relatively low level of penetration in the UK, the fuel production infrastructure, in particular for pellet production, is still growing to meet demand. A number of large scale electrical generation projects which have been proposed could have a detrimental effect on the availability of fuel. A more efficient use of wood chips and pellets in the UK would be to burn the fuel for CHP or for space heating and DHW in larger, in particular municipal, installations. Space heating alone accounts for a large proportion of UK primary energy use in buildings and biomass heating systems could significantly reduce the cost and CO_2 emissions impact of space heating, particularly in locations distant from the gas grid where oil boilers may be replaced.

The aim of this research was to identify the key design and operational requirements for effective deployment of biomass systems for LTHW space heating and DHW.

A design procedure was described for sizing the boiler and thermal store required for LTHW space heating and DHW, aided by a case study for an educational campus (Case Study A); this research was discussed and presented in Chapter 3.

Monitoring and evaluation of biomass boiler systems was discussed in Chapter 4. There can be many reasons for poor performance and the monitoring requirements are outlined here. A case study of an installed system at a plant nursery was used to investigate the performance of a system in practice (Case Study B). Tests were a carried out on a boiler in order to identify the cause of lower than expected combustion efficiency; the results of these tests are detailed in Chapter 4.4, and discussed in Chapter 4.5.

The case studies used highlighted some common misunderstanding concerning design and operation of biomass boiler systems.

6.2. Design Considerations

The key difference between fossil fuel boiler systems and those burning wood chip or pellets regards how the system is sized. Fossil fuel boilers are normally sized for peak load, or over sized to achieve fast heat up and hence short operational period; fossil fuel boilers firing gas or liquid fuel are cycled to meet the demand profile of the load. Biomass boilers on the other hand have characteristically slow response to control due to the nature of the fuel and boiler design and cycling is to be avoided. They will often be required to be combined with a thermal store to hydraulically decouple them from the load. The boiler and thermal store are sized together dependent on the heat load demand profile. This is best achieved using software methods such as the Biomass Boiler Sizing Tool (BBST) developed by the University of Strathclyde and Campbell Palmer Partnership for the Carbon Trust. Case Study A involved the use of energy simulation program ESP-r to estimate a demand profile, followed by use of the BBST to size a suitable boiler and thermal store for the calculated load. It was noted that the load calculations contained more assumptions than would be desired for detailed design, although the results were suitable for an initial indication of the feasibility of a biomass boiler system. Previous research had recommended an array of three biomass boilers for the site used in Case Study A, however this was found to be far from an ideal solution for various practical reasons such as size and cost, as well as failing to take account of the operational characteristics of biomass boilers such as slow response to control. Due to the performance characteristics and high capital cost and size of biomass boilers, a single boiler should be combined with a single thermal store to meet varying demand with auxiliary or backup fossil fuel boilers as required; whereas a fossil fuel boiler system might consist of an array of different sized boilers to cope with periods of peak or low demand, it is not feasible to specify more than one biomass boiler in the majority of cases.

Since the biomass boiler is not sized for peak demand, the time varying nature of the heat load demand profile is more important in calculating what proportion of the demand can be met from biomass and hence what the payback period of the installation might be, as well as to provide an accurate estimate of CO_2 emission reduction. A large part of Case Study A consists of the calculations required to determine the design day heat load profile for this reason. The level of data available and assumptions made will determine what level of accuracy is possible in the sizing calculation, and as previously stated, more resources would be required to carry out a full site survey for the college used as Case Study A if detailed design of a biomass boiler system were to go ahead.

6.3. Operational Considerations

Biomass boilers should be able to achieve high efficiency of 90% or better where the installation and control system design has been carried out properly for a suitable load. Case Study B illustrated that this is not always the case in practice. Performance of biomass boiler systems can vary widely, due to natural variations in fuel quality, and the higher level of human interaction required when compared with fossil fuel systems. The monitored data available for many sites will be on a monthly or annual basis since most operators will be concerned with utility bills rather than dynamic performance so efficiency testing may be required to evaluate performance. It was also noted that the relatively low cost of fuel for biomass systems can demotivate operators from accurately monitoring performance as fuel bills will often be lower than for a fossil fuel system even for a poorly running system, particularly where the fuel is regarded as waste wood. Poor performance will not only lead to higher running costs, but will increase the emissions of pollutants such as CO, NOx and particulates so good performance is desirable for environmental reasons and to avoid breaking emissions regulations as well as to achieve greater fuel economy. In order to evaluate performance, dynamic performance data is required, in some cases with measurements taken at 10 minute intervals or less. This information may already be available from the BEMS, however it is rarely logged, and the requirements for data measurement are outlined in Chapter 4.8. It is possible that as a result of the heat metering requirements of the Renewable Heat Incentive (RHI) due to come into force on 1st September 2011 in the UK, the general standard of monitoring biomass boiler systems will improve, as the financial benefits will be more directly apparent to system operators and worker training or contracted services will be required to qualify for the RHI.

6.4. Recommendations

Recommendations for biomass boiler system design and operation are summarised below

- Calculation of the design heat load profile is crucial in sizing the boiler and thermal store combination, as well as estimating financial and emissions benefits
- The biomass boiler system should not be expected to deliver 100% of heat requirements in most cases.
- Biomass boilers are most suited to year round constant heat loads such as greenhouse heating or buildings with high DHW requirements such as swimming pools, hotels or hospitals. Intermittent heat loads will require a larger thermal store and it may not be possible to meet a high percentage of demand from biomass; minimal summer demand may necessitate a summer shutdown and supply from a non biomass auxiliary system.
- A single biomass boiler and thermal store combined with auxiliary or back up fossil fuel boiler or boilers is likely to provide the most cost effective solution; arrays of biomass boilers should not generally be viewed as a solution to meet a varying demand profile

- At the commissioning stage, as well as periodically during normal operation, biomass boiler systems must be monitored to ensure they are operating at an acceptable efficiency. Failure to do so can result not only in higher fuel costs but in harmful emissions, possibly breaking regulations
- Site operatives require adequate training to deal with the higher level of worker interaction required with a biomass boiler system in comparison with a similar rated output fossil fuel system

6.5. Further Study

In the course of this research, areas for further study were identified which could prove useful in providing better understanding of biomass boiler systems. Some areas for further study include:

1. Optimal system configuration regarding interaction between the biomass boiler and the thermal store, in particular for two port thermal stores. Some mathematical modelling of the system could be combined with site measurements to provide better understanding of the best control algorithms and the flow of the heating medium through the system
2. The application of biomass boiler systems to specific heat loads which may prove suitable e.g. swimming pool heating, greenhouse heating and for process industries with potential waste streams which could be used for fuel, such as the food, paper and timber industries as well as brewers or distillers. It is understood research into swimming pool and greenhouse heating applications is currently underway at ESRU.
3. The Biomass Boiler Sizing Tool (BBST) summarised in Chapter 3.1 provides limited options for examining sensitivity to fuel price; the ability to model predicted escalation of fuel prices would be useful in sizing systems for fossil fuel scarcity
4. A full site survey of the college used for Case Study A is required to verify the data used and remove assumptions made in order to provide a more accurate recommendation and detailed system design, as well as an investigation into fuel availability. Opportunities for district heating to supply more suitable loads where they exist, such as greenhouses, swimming pools, or a nearby hotel, may be worthy of further investigation.
5. Further investigation is required at the site used for Case Study B- some recommendations for the measurements required are detailed in Chapter 4.7. In particular the interaction between the boiler and thermal store, including boiler return water temperature, must be

better understood in order to evaluate system performance. There may be potential to combine this with recommendation 1

Overall, biomass boiler technology has the potential to contribute significantly to the UK's targets for reduction in CO_2 emissions as well as providing a clear financial benefit in many cases, however the potential for deployment of poorly specified or operated biomass boiler systems is high and could potentially cause new emissions problems as well as damaging the reputation of the technology. The author hopes that this research, and the areas suggested for further study, can contribute to a better understanding of biomass boiler systems and result in higher standards in their design and operation.

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BEAT2 - Biomass Environmental Assessment Tool - http://www.biomassenergycentre.org.uk/portal/page?_pageid=74,153193&_dad=portal&_schema=PORTAL [Accessed 27th June 2011]

The Biomass Boiler Sizing Tool used in Chapter 3.5 is available as a free download from the Carbon Trust website from http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/biomass/pages/biomass-tool.aspx [Accessed 8th September 2011]

ESP-r and MERIT are available as a free download from the ESRU site at http://www.esru.strath.ac.uk/software.htm [Accessed 8th September 2011]

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Appendices

Appendix A: Case Study A Data

Climate Data

Lerwick: Climate data from Merit software

Stornoway: Data for temperatures and windspeeds was obtained from http://www.hebwx.co.uk

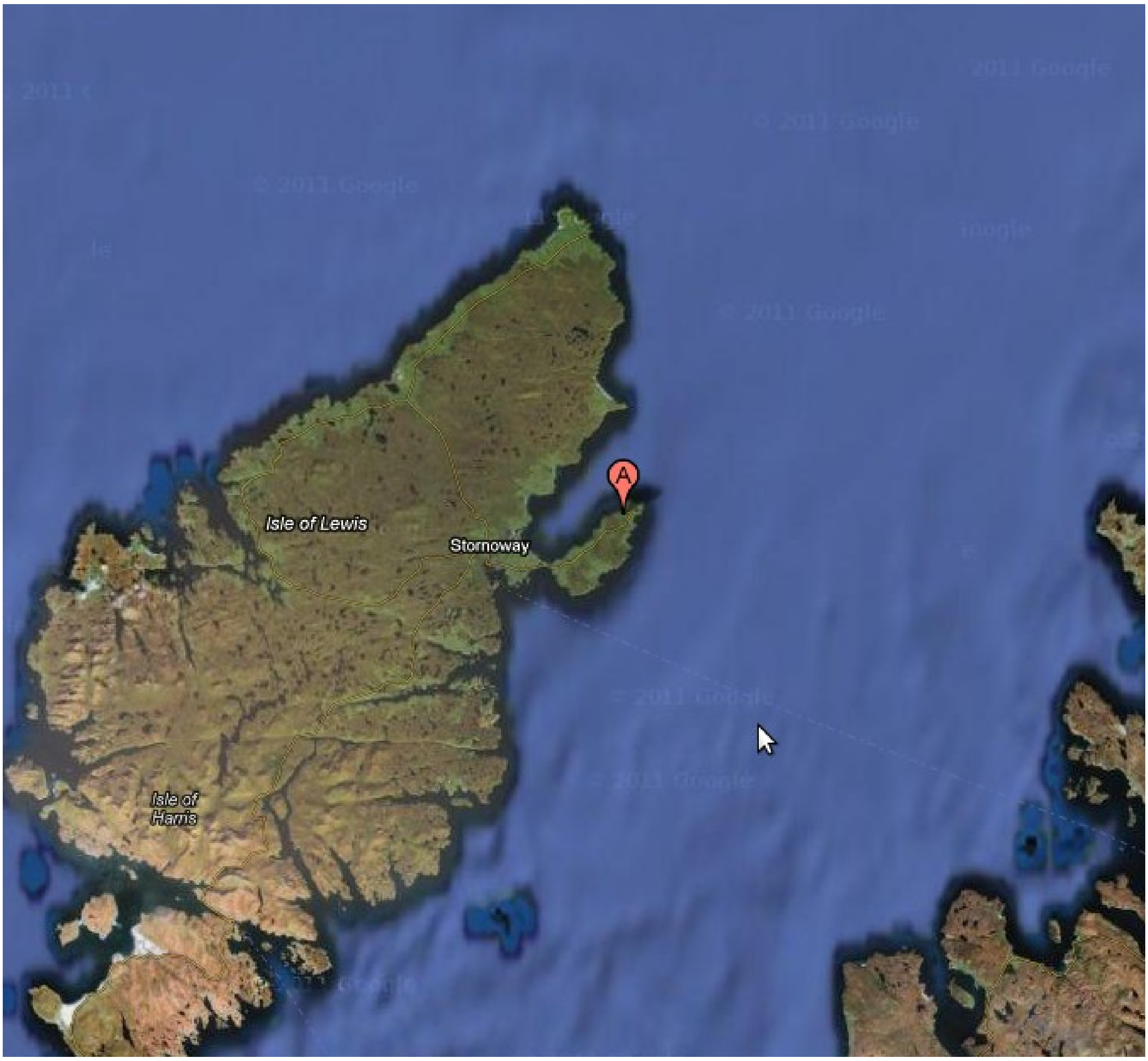

Figure A-1: Hebwx Lewis Weather Station Location

Source: Google Maps

The weather station location is shown in figure A-1. The location is less than 500m from the coast and the weather station is run as 'a hobby', however full information is available on the website and the readings broadly agree with data available elsewhere (for example http://www.climatetemp.info/united-kingdom/stornoway.html). Data for ambient temperature and windspeed for 2010, 2009 and 2008 was averaged to give the readings used. Data for 2007 was discounted as this appears to have been the start up year and there was little correlation between this year and the rest, showing temperatures too high and windspeed too low to be reliable (e.g. max temperature in March of 30.4C, windspeed 6.6 knots). Martin Collins, the site operator noted by email that

> 'I should mention that I live 7 miles east of Stornoway and the conditions here can differ to those in the town. This is mainly because we are at the end of a peninsula and surrounded on three sides by water. As a result we can see higher wind speeds, less rain and we occasionally suffer from sea fog which reduces the air temperature. Overall the conditions are similar but it may be worth noting.'

The data for relative humidity was taken from http://www.climatetemp.info/united-kingdom/stornoway.html The source of this website's data was not determined, however there was enough similarity between the figures for windspeed and temperature to suggest the data was reliable enough for the accuracy of the simulation and the RH% data seemed believable from the author's personal experience.

Heating and cooling degree day data is shown in Tables A-1 through A-4. Lewis data was taken from the weather station shown in Figure A-1, Oban, Dundee and Dublin Data from the ESP-r database. Lerwick data used with the Lewis ambient temperature data was sourced from the software program MERIT, which was also developed by ESRU and is available from the same source as ESP-r.

56.4N 5.5W: 1994 DN

Degree day analysis: heat base at 17°C & Cooling at 21°C

			Heating DD	Cooling DD
Month:	1	avg/day	12.18	0
Month:	1	total	377.52	0
Month:	2	avg/day	11.93	0
Month:	2	total	334.09	0
Month:	3	avg/day	11.48	0
Month:	3	total	355.82	0
Month:	4	avg/day	8.93	0
Month:	4	total	267.82	0
Month:	5	avg/day	6.39	0
Month:	5	total	198.08	0
Month:	6	avg/day	4.58	0.09
Month:	6	total	137.48	2.67
Month:	7	avg/day	2.9	0
Month:	7	total	90.03	0.15
Month:	8	avg/day	3.37	0
Month:	8	total	104.45	0
Month:	9	avg/day	4.72	0
Month:	9	total	141.56	0
Month:	10	avg/day	6.44	0
Month:	10	total	199.58	0
Month:	11	avg/day	9.66	0
Month:	11	total	289.66	0
Month:	12	avg/day	10.81	0
Month:	12	total	335.13	0
		Total:av/day	7.76	0.01
		Annual total	2831.2	2.8

Table A-1: Climate data: Oban

Source: ESP-r database

53.4N 6.3W: 2001 DN

Degree day analysis: heat base at 17°C & Cooling at 21°C

			Heating DD	Cooling DD
Month:	1	avg/day	11.22	0
Month:	1	total	347.82	0
Month:	2	avg/day	12.18	0
Month:	2	total	340.9	0
Month:	3	avg/day	10.19	0
Month:	3	total	315.81	0
Month:	4	avg/day	8.49	0
Month:	4	total	254.78	0
Month:	5	avg/day	6.49	0
Month:	5	total	201.2	0
Month:	6	avg/day	3.75	0
Month:	6	total	112.58	0.05
Month:	7	avg/day	1.99	0.06
Month:	7	total	61.65	1.98
Month:	8	avg/day	2.61	0
Month:	8	total	80.97	0
Month:	9	avg/day	3.89	0
Month:	9	total	116.7	0
Month:	10	avg/day	6.53	0
Month:	10	total	202.46	0
Month:	11	avg/day	9.81	0
Month:	11	total	294.33	0
Month:	12	avg/day	10.76	0
Month:	12	total	333.42	0
		Total:av/day	7.29	0.01
		Annual total	2662.6	2

Table A-2: Climate data: Dublin

Source: ESP-r database

56.5N 3.0W: 1980 DN

Degree day analysis: heat base at 17°C & Cooling at 21°C

			Heating DD	Cooling DD
Month:	1	avg/day	13.33	0
Month:	1	total	413.1	0
Month:	2	avg/day	13.71	0
Month:	2	total	383.75	0
Month:	3	avg/day	11.39	0
Month:	3	total	353.04	0
Month:	4	avg/day	10.49	0
Month:	4	total	314.79	0
Month:	5	avg/day	7.27	0
Month:	5	total	225.51	0
Month:	6	avg/day	4.93	0
Month:	6	total	147.93	0
Month:	7	avg/day	3.28	0.04
Month:	7	total	101.58	1.31
Month:	8	avg/day	2.86	0.06
Month:	8	total	88.6	1.81
Month:	9	avg/day	4.11	0.01
Month:	9	total	123.2	0.26
Month:	10	avg/day	9.3	0
Month:	10	total	288.37	0
Month:	11	avg/day	10.98	0
Month:	11	total	329.52	0
Month:	12	avg/day	11.94	0
Month:	12	total	370.2	0
		Total:av/day	8.6	0.01
		Annual total	3139.6	3.4

Table A-3: Climate data: Dundee

Source: ESP-r database

60.0N 1.0E: 2010 DN

Degree day analysis: heat base at 17°C & Cooling at 21°C

			Heating DD	Cooling DD
Month:	1	avg/day	12.86	0
Month:	1	total	398.75	0
Month:	2	avg/day	13.62	0
Month:	2	total	381.34	0
Month:	3	avg/day	11.22	0
Month:	3	total	347.88	0
Month:	4	avg/day	9.95	0
Month:	4	total	298.48	0
Month:	5	avg/day	8.31	0
Month:	5	total	257.69	0
Month:	6	avg/day	4.75	0
Month:	6	total	142.43	0
Month:	7	avg/day	4.27	0
Month:	7	total	132.27	0
Month:	8	avg/day	4.46	0
Month:	8	total	138.13	0
Month:	9	avg/day	5.1	0
Month:	9	total	152.93	0
Month:	10	avg/day	7.48	0
Month:	10	total	231.85	0
Month:	11	avg/day	11.58	0
Month:	11	total	347.35	0
Month:	12	avg/day	13.57	0
Month:	12	total	420.55	0
		Total:av/day	8.9	0

Table A-4: Climate data: Lewis

Source: Hebwx Weather Station (See Figure A-1)

Casual Gains Data

The assumptions for occupancy and PC usage for Case Study A are shown in Tables A-5 through A-7.

	Room	Expected max. occupancy	PCs
Floor 0	classroom	10	
	int room1	2	
	int room2	2	
	sdudent services	2	2
	photocopy room	1	1
	senior manager	1	1
	principal sec	1	1
	principal sec	1	1
	first aid	1	
	bursaries	1	1
	finance1	1	1
	finance2	1	1
	board room		
	Art & craft 1	3	
	Art & craft 2	3	
	plant room		
Floor 1	IT room1	10	10
	senior manager	1	1
	IT room2	10	10
	classroom	10	
	software tech	2	2
	calss conf	10	
	sec IT room	10	10
	hardware tech	1	1
	library	5	2
	IT room3	10	10
	staffroom	2	
	office	1	1
	IT room4	10	10

total	112	66

Table A-5: Facilities Building Casual Gains

Zone	Expected max. occupancy	Equip. (W)
joinery	10	200
civil	13	200
mech	10	200
shared proj	30	200
welding	10	200
plant	0	100 sensible/50 latent, 24 hours a day
teach2	26	200
motorvehicle	19	200
Total	118	N/A

Table A-6: Engineering Casual Gains

Room	Expected max. occupancy	PCs
naut studies	12	
staff base c c	0	
net mending	10	
Agri /7 horti	12	
tut room1	4	
tut room 2	4	
science lab	13	
oftti	10	
postgrad	2	
head of dep	1	1
classroom	10	
shop	2	
staff base ma a a	0	3
weavers	10	
staff base m b j	3	
comm classroom	15	
comm classroom	15	
Arts & crafts	18	2
staff base d n c	0	2
naut studies chartroom	13	

Total	154	8

Table A-7: Rural Studies Building Casual Gains

Appendix B: Case Study B Data

Time	Temp °C FG	Flue Gas CO_2 (%)	Flue Gas CO (ppm)	CO (%)
13:10	220	17.5	5201	0.52
13:19	216	18.9	8904	0.89
13:35	116	13.8	2300	0.23
13:46	213	11.3	1228	0.12
13:47	220	12.6	490	0.05
13:49	228	12.8	1254	0.13
13:53	225	15.1	1345	0.13
13:56	213	16.1	1260	0.13
13:59	203	14.5	523	0.05
14:04	174	9.2	751	0.08

Table B-1: Case Study B Combustion Measurement Set Readings

Plant Nursery	**Risk Assessment**
TASK / ACTIVITY:	Measurement of boiler performance - 8/8/11

TASK DESCRIPTION:

This risk assessment covers the measurement of the performance of the onsite Biomass Boiler.

A test set requires to be installed on the boiler flue. This will be done using a step ladder.

Measurements to be taken from heat meters on wall.

Moisture content of fuel to be tested.

Main Hazards:

Crushing		Direct electrical contact		Hot ambient temperature	✓
Cutting / shearing		Indirect electrical contact	✓	Cold ambient temperature	
Trapping	✓	Fire / explosion		Asphyxiation / drowning	
Slips / trips	✓	Lifting / handling		Localised hot surface(s)	✓
Falls from height	✓	Fatigue / stress		Localised cold surface(s)	

Figure B-1: Case Study B Risk Assessment (part 1)

Please specify other risks not covered above:

None.

PERSONS EXPOSED:

Employees	✓	Visitors		Maintenance staff	
Public		Contractors	✓	Other:	
Vulnerable Groups		Cleaners		Please specify	

CURRENT CONTROL MEASURES:

- ✓ Only specifically authorised competent employees are permitted to be involved in the testing of the boiler.
- ✓ Only specifically and formally trained employees are permitted to operate the plant.
- ✓ Where work at heights are required they will be carried out from safe working platforms erected by competent persons.
- ✓ Site has been assessed and suitable first aid provision ensured.
- ✓ All staff will be made aware of this risk assessment and method statement prior to starting.

Are the risks adequately controlled? please specify the level of risk before additional controls are implemented:			**Yes** ✓	**No**	
HIGH		MEDIUM		LOW	✓
ADDITIONAL CONTROLS REQUIRED: TO BE IDENTIFIED AFTER SPECIFIC SITE ASSESSMENT					None.
Nothing further to report					
Please specify the level of risk after the additional controls have been implemented:					
HIGH		**MEDIUM**		**LOW**	✓

NOTES:

ASSESSOR'S NAME: _xxxxxxxxxxxxxx___ _ **DATE:** _8/8/11____

SIGNATURE: __________________ **REVIEW DATE:** __n/a_________ _

JOB TITLE: _Biomass Installer__

Figure B-2: Case Study B Risk Assessment (part 2)