Department of Mechanical Engineering

Technical and Economic Feasibility of Using Waste Wood as Biomass Fuel for Small Scale Boiler and CHP in Solway Precast, Scotland

Author:

Setta Verojporn

Supervisor:

Professor John Counsell

A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Energy: Renewable Energy Systems and the Environment

2011

Copyright Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Setta Verojporn Date: 9 September 2011

Abstract

Renewable energy has been widely used in power generation and household applications, its use in industry is way more concerned in terms of its stability and reliability to meet the manufacturing process energy demand according to the uncertainty of renewable technologies. Manufacturing industries are considered the major energy consumption sector in Scotland. Therefore it is important that this sector is developing in a sustainable way in emerging economies to reduce greenhouse gas emissions and the use of conventional fuels.

The objective of this work is to investigate technical and economic feasibility of using waste wood as biomass fuel in precast concrete site. This study looks at the precast concrete process and its energy use with particular focus on Solway Precast. A review of small scale biomass boiler and CHP that would be suitable for the case study was undertaken. And a tool was created to analyse the economic and environmental performance between selected wood waste boilers and CHPs for this case study and other type of manufacturing processes. This tool allows the user to quickly calculate the economic and environmental performance using the thermal and electrical demand profile, boiler or CHP technological specification, the operation mode, the costs, financial incentives and other financial factors.

Different wood boilers and CHP that can be applied in this case study were analysed using the tool. This study indicates that suitable biomass boilers or CHP can demonstrate economic and environmental benefits. Wood fuel CHPs can give more long term profit than wood fuel boilers in this analysis but with longer payback period. The quantity of CO2 emission reduction from biomass CHP is also more than boilers in this analysis. However, the initial cost of the biomass CHP is much more expensive than boilers of the same size. Therefore investing in biomass CHP obviously has more risks than boilers due to the higher initial cost of the CHP.

Acknowledgements

I would like to thank Prof. John Counsell for his valuable advice, support, and guidance to me throughout the duration of my project.

I would also like to thank Dr. Paul Strachan, he has been kindly helping, supporting, and advicing me from the beginning to the end of this MSc course.

To Ali Sheikh. Mark Young, Andy Gillon, and everyone at Solway Precast for their friendly support and assistance getting the data and information throughout the duration of this project.

My classmates and friends who have been supporting me directly or indirectly to overcome any problems during this MSc course and this project.

Table of Contents

ABSTRACT ..... **II**

ACKNOWLEDGEMENTS ..... **III**

TABLE OF CONTENTS ..... **IV**

LIST OF FIGURES ..... **VII**

LIST OF TABLES ..... **IX**

1. INTRODUCTION **1**

1.1 Background 1

1.2 Research Focus 3

1.3 Overall Research Aim and Individual Research Objectives 5

2. LITERATURE REVIEW **7**

2.1 Introduction 7

2.2 Precast Concrete 8

2.2.1 Introduction *8*

2.2.2 Precast Concrete Process *9*

2.2.3 Energy Use *11*

2.2.4 Environmental Impact in Precast Concrete Production *12*

2.3 Biomass 14

2.3.1 What is Biomass *14*

2.3.2 Wood Waste as a Biomass Fuel *16*

2.4 Small Scale Wood fuel Conversion Technology 24

2.4.1 Combustion *25*

2.4.2 Gasification *30*

2.5 Small Scale Wood Fuel Power Generation Technology 33

2.5.1 Internal Combustion Engine *34*

2.5.2 Stirling Engine *34*

2.5.3 Organic Rankine Cycle (ORC) engine *35*

2.5.4 Micro-turbine *35*

2.6 Financial Incentives 36

2.6.1 Renewable Heat Incentive (RHI) *36*

2.6.2 Feed-In Tariffs (FITs) *37*

2.6.3 Renewable Obligation Certificates (ROCs) *37*

2.6.4 Other Grants and Support Schemes *39*

3. THE BIOMASS BOILER AND CHP TOOL 40

3.1 INTRODUCTION 40

3.2 AIMS AND OBJECTIVE 41

3.3 LIMITATION 42

3.4 CELL COLOUR CODING 43

3.5 THE BIOMASS BOILER AND CHP TOOL STRUCTURE 43

3.5.1 Energy Demand *43*

3.5.2 Wood Fuel *48*

3.5.3 Biomass boiler and CHP Specification *50*

3.5.4 Comparing Biomass Boiler and CHP *52*

3.5.5 Results *57*

3.5.6 Results comparison *58*

3.6 DETAIL CALCULATION AND ANALYSIS OF THE TOOL 60

3.6.1 Energy demand *61*

3.6.2 Wood fuel *63*

3.6.3 Biomass boiler and CHP specification *66*

3.6.4 Comparing Biomass Boiler and CHP *71*

3.6.5 Results *84*

3.6.6 Results comparison *85*

4. THE CASE STUDY 87

4.1 INTRODUCTION: BACKGROUND OF SOLWAY PRECAST 87

4.2 ENERGY DEMAND 88

4.2.1 Electrical Energy Demand *88*

4.2.2 Thermal Energy Demand *90*

4.2.3 Fuel consumption and CO_2 Emissions *92*

4.3 WOOD WASTE AT SITE 93

4.4 BIOMASS IN SOLWAY PRECAST 94

4.4.1 Thermal Demand Profile *94*

4.4.2 Electrical Demand Profile *98*

4.4.3 Wood Fuel *99*

4.4.4 Biomass Boiler and CHP Specification *103*

4.4.5 Financial Incentives and Parameters *113*
4.4.6 Results and Analysis *115*
4.5 Overall Results and Analysis 123

5. CONCLUSION 124

5.1 Conclusion 124
5.2 Further Investigation 126

REFERENCES 127

APPENDIX 1: FINANCIAL RESULTS 133

APPENDIX 2: MONTHLY BIOMASS CONSUMPTION 147

List of figures

Figure 1: Basic precast concrete production process 9
Figure 2: The effect of moisture content on the lower heating value of wood (kWh/kg) (ELECTROWATT-EKONO (UK) LTD , 2003) 19
Figure 3: Main Biomass Energy Conversion Routes (Turkenburg, 2000) 24
Figure 4 : Basic Process Flow for Biomass Combustion (Knoef et al., 1999) 25
Figure 5: The typical efficiency of the CHP compared to traditional heat and power generation (Self Energy UK, 2009) 33
Figure 6: Input and Output Cells 43
Figure 7: Choosing demand characteristic 43
Figure 8: Manually enter the hourly demand data 44
Figure 9: Generating hourly energy demand profile 44
Figure 10: Result of the first step of generating hourly demand profile 45
Figure 11: Result of the second step of generating hourly demand profile 45
Figure 12: Result of the third step of generating hourly demand profile 46
Figure 13: Example of hourly demand profile result in January 46
Figure 14: Input area for existing energy information 47
Figure 15: Input area for wood waste information 48
Figure 16: Wood waste summary table 49
Figure 17: Input area for extra wood needed to purchase information 49
Figure 18: Input area for biomass boiler and CHP information 50
Figure 19: Wood fuel choosing area 52
Figure 20: Biomass boiler and CHP choosing area 53
Figure 21: Choosing operation mode area 53
Figure 22: Choosing operation mode and operation time area 54
Figure 23: Results in choosing biomass boiler and CHP subsection 55
Figure 24: Tool Methodology 60
Figure 25: Thermal efficiency at range of operating capacity 72
Figure 26: Heat to power ratio at range of operating capacity 76
Figure 27: Solway Precast (Barr Ltd, n.d.) 87
Figure 28: Moulding Workshop (Barr Ltd, n.d.) 87
Figure 29: On-site Batching Plant (Barr Ltd, n.d.) 87
Figure 30: Cement Silo 89
Figure 31: Conveyor Belt 89

Figure 32: Vibrating Process 89
Figure 33: Kerosene tank 91
Figure 34: Kerosene heaters in the factory 91
Figure 35: Kerosene heater in the office 91
Figure 36: Wood waste at Solway Precast site 93
Figure 37: Thermal demand settings of the tool for Solway Preacast 96
Figure 38: Hourly thermal demand profile of pre-stressed beds in Solway Precast for one year 96
Figure 39: Thermal Energy Usage by Type of Demand (kWh) 97
Figure 40: Thermal Energy Usage by Type of Fuel (kWh) 97
Figure 41: Electrical demand settings of the tool for Solway Preacast 98
Figure 42: Hourly electrical demand at Solway Precast site for one year 98
Figure 43: Data entered in the wood fuel section for the 1st case 100
Figure 44: Data entered in the wood fuel section for the 2nd case 101
Figure 45: Wood waste summary for both cases 101
Figure 46: REFO 80 (Teisen Products Ltd, n.d.) 104
Figure 47: REFO 80 composition (Teisen Products Ltd, n.d.) 104
Figure 48: HT boiler with accumulator tank (Teisen Products Ltd, n.d.) 107
Figure 49: HT boiler composition (Teisen Products Ltd, n.d.) 107
Figure 50: BG 25 CHP (Talbott's Biomass Generators Ltd, n.d.) 108
Figure 51: Example day of 1st operation method for HT 50 and HT 80 boilers with accumulator tank 110
Figure 52: Example day of 2nd operation method for HT 50 and HT 80 boilers with accumulator tank 111

List of tables

Table 1 : Carbon emissions of different fuels per unit of energy (Biomass Energy Centre, 2003) 14
Table 2 : Fuel prices per kWh (Biomass Energy Centre, 2011) 15
Table 3: Estimate of total wood waste arisings in the UK (The Waste & Resources Action Programme, 2005) 16
Table 4: Wood Fuel Lower Heating Value (ELECTROWATT-EKONO (UK) LTD, 2003; Biomass Energy Centre) 18
Table 5: Ash content from wood fuel (Eleotrowatt-ekono (UK) ltd, 2003) 20
Table 6: Table of tariffs support for biomass in renewable heat incentive 36
Table 7: Banding provision (Office of Gas and Electricity Markets, 2011) 38
Table 8: Monthly electricity consumption in kWh 90
Table 9: Monthly quantity of kerosene ordered in litres 90
Table 10: Monthly quantity of gas oil ordered in litres 90
Table 11: Wood fuel characteristics 99
Table 12: Thermal energy demand-supply matching results 116
Table 13: Electrical energy demand-supply matching results 119
Table 14: Financial results 120
Table 15: Equivalent CO_2 emission results for one year 122
Table 16: Table 15: Equivalent CO2 emission reduction results for 30 years 122
Table 17: 1st case financial result 133
Table 18: 2nd case financial result 135
Table 19: 3rd case financial result 137
Table 20: 4th case financial result 139
Table 21: 5th case financial result 141
Table 22: 6th case financial result 143
Table 23: 7th case financial result 145
Table 24: Monthly biomass consumption in kg 147
Table 25: Monthly biomass consumption in m^3 147

1. Introduction

1.1 Background

Renewable energy has been targeted to meet an equivalent of 100% electricity demand and 11% of heat demand by 2020 in Scotland. Besides, the greenhouse gas emissions also have been targeted to reduce at least by 42% by 2020 (The Scottish Government, 2011). Increasing renewable energy and reducing greenhouse gases in the growing economy are a huge challenge. Involving sectors are obliged to contribute in terms of technology, economy, politic, social characteristics as well as our way of life.

There are four main end demand sectors which are domestic, transport, industry and services sector in decreasing level of energy consumption in Scotland.

Manufacturing industries use approximately 35% of total energy used by all sectors in Scotland in 2002. Industrial energy usage was mainly linked to production of food and drink, paper, chemical and engineering in Scotland. Meanwhile, mineral industries such as cement counts for a smaller proportion of the total industrial energy usage (AEA Technology, 2006). On the other hand, the cement industry produces large amount of CO_2 emissions, of which 50% is from the chemical process, 40% from burning fuel, and the rest are from electricity and transport uses (World Business Council for Sustainable Development, 2002).

Despite the fact that renewable energy has been widely used in power generation and household applications, its use in industry is way more concerned in terms of its stability and reliability to meet the manufacturing process energy demand. The lack of electricity or heat during the ongoing process can the increase in cost of production and affect the machines in dysfunctions the process. Moreover, the production operation, management and scheduling may need to be changed according to the uncertainty of renewable technologies in order to maintain reliability and efficiency of the process.

Precast concrete is the ready-made concrete product produced by casting and curing it under controlled environment. It is formed into certain shapes and transported to the construction site. The precast concrete plant uses electricity and heat depending on the process. Due to the closely monitoring in the manufacturing site, the precast concrete has been well strengthened than construction site-casting.

Barr limited incorporating Solway Precast Concrete is committed to keep improving the environmental performance and minimizing the impact of their activities. They approached the University of Strathclyde in order to develop in a sustainable way by reducing the CO_2 emissions while maintaining or improving economic benefit. Renewable technology had been using at Barr Limited prior to this thesis focusing on the usage of landfill gas. This thesis will propose and compare biomass technologies to generate electricity and heat that would be suitable for Solway Precast Concrete (Concrete Manufacturing Site) energy demand. Which it will also reduce the CO_2 emissions and fossil fuel consumption at the site. Return on investment, capital costs, maintenance costs, grid connection costs will also be analysed.

1.2 Research Focus

Nowadays, renewable energy interests public, private and government sectors due to its potentiality to reduce greenhouse gas emissions and replacement of conventional fuels. It is important that industrial sectors are developing in a sustainable way in emerging economies. Renewable energy can be applied in industrial as long as industrial sectors are encouraged to take this step and prepared to take on the long term commitment to renewable and climate friendly technologies. However, it would only be possible if firms have the financial capacity or support to invest in the particular renewable technologies. Moreover, the knowledge and state-of the-art technologies need to be well established. Firms that have financial capacity should set examples to others to follow the steps.

The main focus of the study of this thesis is to look at the feasibility of wood waste biomass technologies for a precast concrete plant. Scalable framework for biomass boiler, and combined heat and power in precast manufacturing process will also be made to be adaptable for other type of industrial manufacturing process.

Wide range of wood waste biomass conversion technologies will be considered to be able to sufficiently supply heat and electricity for the precast concrete manufacturing process and an office building of Barr Limited Solway Precast Concrete at Barrhill, Scotland. The decision of biomass technologies would be based on costs, financial and reduction of CO_2 benefits, and more importantly, applicable of the particular technologies at the site. To make the best use of proposed biomass technologies, the process energy demand must be reduced as much as possible to reduce unnecessary costs for oversize the renewable energy options. Nonetheless, this thesis will not focus on this issue due to the time limitation and numerous options to improve energy efficient at this site.

Since the precast concrete process have a lot of wood waste products from shuttering used for concreting and moulding process, it can be used as an important fuel source instead of being disposed of at a cost to the company. It is significant to know that the landfill option is also available for wood waste. However, the cost of sending waste wood or any other materials to the landfill site are increasing every year. And it is also involved with fuel in transportation which it would increase the CO_2 emission to the atmosphere. These issues make the alternative uses of wood waste becoming more attractive and interested. The efficient use of this by-product is a basic essential for industrials (Action Renewables, n.d.). Therefore, in this thesis, wood waste is taken into account in the calculation of the renewable energy potential. Due to the need of heat and electricity at the site, the comparison between wood waste boiler and wood waste CHP will be analysed to compare energy performance, energy savings, capital costs, maintenance costs and applicability to install. Also the benefits from renewable incentive schemes for heat and electricity would be analysed.

This thesis will set out the tool not only for precast concrete manufacturing process, but also other type of industrial manufacturing process to use renewable energy. Reduction in the amount of electricity imported from the grid, conventional fuels and CO_2 from renewable technologies will financially benefit the industries and the country itself due to the reduction of power generated as a whole. This case study would also set the example for other small industrials that want to use wood waste as a biomass fuel to make long term profit and improve environmental performance.

1.3 Overall Research Aim and Individual Research Objectives

The overall aim of this research is to integrate wood waste biomass technologies into precast concrete manufacturing process without impact on the quality and delivery of the precast concrete product. However, in order to understand energy demand for precast concrete manufacturing process it is really important to gain an insight into understanding the process itself and the heat and electricity required for the process as well as the office at the site. The heat and electricity demand will be matched with range of biomass boiler and CHP technologies regarding to energy performance, demand-supply matching, financial benefits and environmental impacts. Further, this research will assess the biomass boiler and CHP technologies that would be suitable for the case study (Solway Precast). The wood waste boiler at the site would be the first thing to be analysed following by biomass combined heat and power technologies. The case study chapter contains the details of research strategy, the energy demand data collection at the site, techniques to be used to analyse that energy demand data and strategy for renewable energy generation in Solway Precast.

Specifically, within the background of higher education, the objectives of this research are to:

1. *Understand the precast concrete process and energy used in this*
2. *Investigate the feasibility of using waste wood as a biomass fuel for heat and combined heat and power (CHP) in this precast concrete plant case study*
3. *Evaluate the potential financial benefits and CO_2 reduction of biomass in the case study*
4. *Create a scalable tool for precast manufacturing process which can be adapted for other type of manufacturing processes*

For the purpose of each of the above objectives, objectives 1 focus on the existing technology of the precast concrete process for the case study and heat and electricity use in each of the process. Objectives 2 and 3 will make the key comparisons to biomass energy technologies for the precast concrete process, especially in wood waste boiler and wood waste CHP. Objective 4 will make this thesis be useful for other type for industries.

This research work will contribute the establishment of wood waste energy production technologies not only for precast concrete industries, but also other industries. Firstly, by reducing the CO_2 emissions in to the atmosphere and the electricity import from the grid for the case study. Secondly, by critically examining existing wood waste boiler and wood waste CHP, allowing a meaningful comparison in performance, capital costs, operating costs, maintenance costs and long-term financial benefits. Thirdly, by providing a tool that can be adapted to implement to other industries.

The next chapter will be issues and related literature review, beginning with an investigation of precast concrete manufacturing process.

2. Literature Review

2.1 Introduction

This literature review section will observe the main issues surrounding renewable energy for the industrial sector, especially in the precast concrete process. The outline of this literature review will focus on objectives 1 and 2 as set out in the introductory chapter. However objectives 1, 2 and 3 will be met again in the case study chapter for collecting energy data and it will compare many aspects in wood waste energy technology for the Solway Precast. While the final objective, objective 4, will be derived from the results and conclusions of objective 1, 2 and 3:

1. *Understand the precast concrete process and energy use in this*
2. *Investigate the feasibility of using waste wood as a biomass fuel for heat and combined heat and power (CHP) in this precast concrete plant case study*
3. *Evaluate the potential financial benefits and CO_2 reduction of using biomass in the case study*
4. *Create a scalable tool for precast manufacturing process which can be adapted for other type of manufacturing processes*

By discovering the above areas of literature, the background information of precast concrete process and biomass fuel for boiler and CHP will be extensively studied. Typical precast concrete manufacturing processes will be explored in order to understand the energy used in each process. Similarly, the existing technologies of renewable energy will also be explored to find the most suitable technologies for the case study. Importantly, the number of key parameters that influence the decisions of choosing renewable energy technologies will be studied and analysed.

At the end of the literature review chapter, it is hoped that an in-depth understanding of the mentioned issues will be demonstrated. The reader will have a better understanding of the precast concrete process and renewable technologies that would be suitable for this process.

2.2 Precast Concrete

2.2.1 Introduction

Precast concrete is concrete that is casted and formed into a particular shape, then allowed to become solid by curing process in a controlled environment before being delivered to a construction site. On the contrary, on-site casting concrete is being done on construction sites. With precast concrete production, the concrete is well casted, formed, and cured because of the close monitoring process and the controlled environment in the precast plant. Moreover, the mould that is used in precast concrete can be reused again for a certain amount of time before they have to be eliminated. The strength of the precast concrete can be improved by reinforced concrete (casting concrete with reinforcement of steel), or pre-stressed concrete (high-strength pre-stressing tendons are used instead of steel). In practice, the process predominantly depends on the type and shape of the concrete product. Therefore the process has to be managed to optimize the product. Nevertheless, the main process consists of mixing, casting, curing, storing and transporting. The basic materials in the precast concrete process are Portland cement, water, aggregates, admixtures, reinforced steel, and woods (Elhag et al., 2005).

The precast concrete industry has existed for more than 150 years and has largely reduced the costs of the construction site, and also construction time which therefore improves the quality and performance of the construction site (Chen et al, 2009 cited in Elhag et al, 2005, p.10). As a result, precast concrete products are used in a wide range of constructions from houses and buildings with big infrastructures such as bridges, football stadiums, etc.

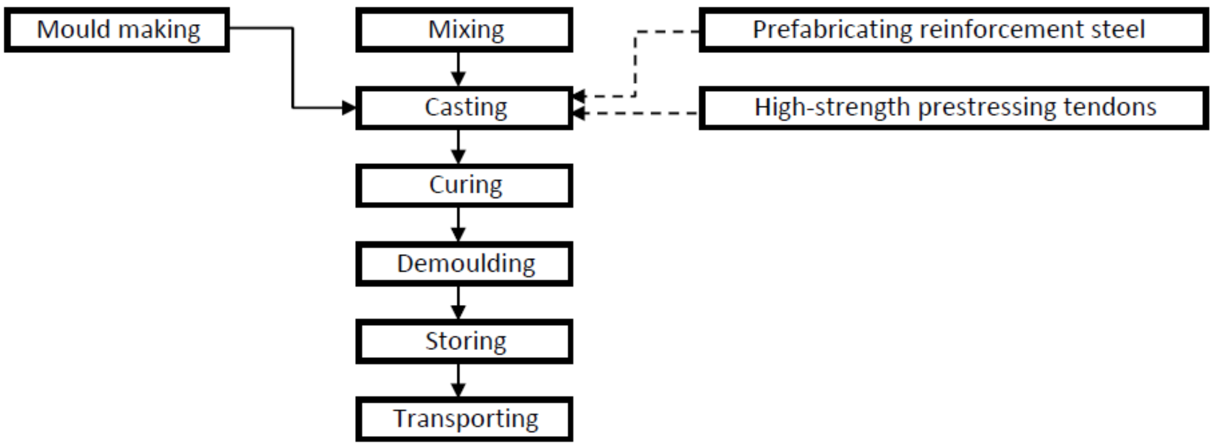
The precast concrete industry is more sustainable than on-site casting in the sense that it takes less input, such as concrete and mould, for the same amount of concrete product (The Concrete Centre, 2009). The process can be more sustainable if recycled and reused materials are being applied. The by-product of the process, for instance, wood waste from unusable moulds can be used as a biomass fuel to create heat or electricity.

Following this first introductory section, the remainder of this chapter will describe the production process, the energy used, and the environmental impact of the precast concrete product.

2.2.2 Precast Concrete Process

The basic production process of precast concrete in the plant consists of mixing, mould making, casting, curing, de-moulding, storing and transporting. These processes are illustrated in the figure below.

Figure 1: Basic precast concrete production process



<u>Mixing</u>

The mixing or batching of concrete includes factors such as the ratio of the mixtures and the speed of the mixers. Concrete mixtures consist of Portland cement, water, sand (fine aggregate), small stone or gravel (coarse aggregate), and admixtures. The ratio of these mixtures depends on the application of concrete product. In the precast concrete plant, mixing machines (concrete mixing plant) are used. These mixtures are then transported and batched in a large concrete mixing plant before casting them into moulds (Elhag et al., 2005).

<u>Mould Making</u>

Precast concrete moulds can be constructed of various materials but mainly from concrete, steel, wood or fibreglass. The type of material depends on their frequency of usage. The amount of time that steal mould can be reused is more than that in wood and fibreglass moulds. Wood and fibreglass moulds can be reused approximately 40 to 50 times, while steel and concrete moulds can be used almost ceaselessly (ASCENT, 2007).

Casting

The casting process involves the pouring, compacting and levelling of concrete into moulds (Hu, 2006). After placing the concrete into the moulds by hopper or crane, the concrete is then vibrated by a vibrator to consolidate and to make the concrete compact. The reinforcement steel and pre-stressing tendons have to be inserted before pouring the concrete, if such strengthening technologies are needed.

Curing

The curing process is to prevent water evaporating from the concrete too quickly. Since water is the most important element for the hydration reaction, it will directly affect the strength of the concrete. This hydration reaction can take days or weeks therefore the curing process must be conducted at an appropriate time in order to achieve concrete strength, water tightness, abrasion resistance, volume stability and durability (Cement Concrete & Aggregates Australia, 2006). Only during the period when concrete is gaining strength does it need to be cured. The typical process is to prevent loss of moisture from the concrete by covering the concrete with an impermeable membrane or continuously wetting the exposed surface of the concrete. However, the concrete in the precast process can gain compressive strength by accelerating the curing process. The methods of accelerated curing are physical processes (conduction/convection, electrical resistance curing, or pressure steam curing), mineral admixture (silica fume or fly ash), and chemical admixtures (calcium, super plasticizers or self-consolidating concrete) (Vollenweider, 2004).

De-moulding

The de-moulding process is the process of stripping the moulds or the frame and removing the concrete. Concrete has to reach the strength required in the curing process before it removed from the mould and is strong enough to prevent the concrete product from being damaged, overstressed or distorted with regards to the de-moulding equipment used (CONSTRUCT, n.d.).

The method of de-moulding depends on the size and the shape of the concrete product, as such cranes and machines might be used if necessary.

Storing

After the de-moulding process, the concrete products are placed in the stockyard or the storage room to achieve delivery strength. Forklifts or trucks are used to transport the concrete product from the de-moulding area to the stockyard.

Transporting

The precast concrete product is transported to the construction site.

2.2.3 Energy Use

The energy demand in the precast concrete process is determined by various factors related to the production system used, product range manufactured, production capacity, and location. The range of energy consumption in a precast plant is around 350 – 1113.2 MJ (97.2 – 309 kWh) per cubic metre of concrete product (Elhag et al., 2005). As mentioned before, this wide gap of energy use in a precast plant may have too many dependent variables to be more specific.

In the precast concrete process, electricity is used to supply machines in different processes and building services. In the mixing process, electricity is used to transport all the concrete mixtures to the mixer via a conveyor belt or pipe using a motor. It is also used in mixing and batching where a machine is used to combine all the mixtures together, thus creating the concrete. Prefabricating reinforcement steel and the mould making process also needs electricity which is supplied to the equipment used for cutting, trimming, bending, seaming and welding the materials (steel, wood or fibreglass). Moreover, electricity is used to operate cranes and hoppers to cast the concrete into the mould, and is used to supply the concrete vibrator in the casting process. Electricity may be used in the curing process if the electrical resistance curing is being used.

Besides space heating, thermal energy is usually used for the concrete to achieve its potential strength and durability in the curing process. Vollenweider (2004) stated that there is a relationship between the rate of compressive strength and curing temperature in concrete. Increasing the curing temperature will increase the strength of the concrete. There are various methods to increase the curing temperature in this process including simple convection by hot water or oil through a mould, framework or pipe, electric resistance heating by reinforcement steel, and pressure steam. The convection and pressure steam method requires boilers to produce heat. The source of thermal energy can be generated from electricity, biomass, gas or fuel oil.

Apart from electricity and thermal energy, transportation (to the construction site) has a significant impact on the overall energy used in the precast process (Elhag et al., 2005). Depending on the weight and size of the precast concrete product and the length of the delivery, the fuel used in transportation can be the largest portion of energy usage. Transportation includes the delivery of the cement, aggregates, and admixtures to the site, as well as the process of delivering the waste from the precast concrete process.

Precast concrete plants need energy in the form of electricity to supply the production plant, and thermal energy for the curing process and space heating. The electricity can be imported from the grid or generated by natural gas, biomass, or from the plant itself while the thermal process can be generated from the electricity, natural gas, biomass or fuel oil. Meanwhile, these two forms of energy, electrical and thermal, make it possible to develop a combined heat and power system. However, the concurrency and the capacity of these two energy demands have to be considered; this depends on the particular precast concrete plant.

2.2.4 Environmental Impact in Precast Concrete Production

Environmental impact in precast concrete production is mainly associated with the cement content and the transportation (Bijen, 2002 cited in Elhag et al, 2005, p.4). Cement manufacturing and transportation has a significant impact on the environment because of the CO_2 emissions of the cement production and the delivery of the heavy and big precast concrete products to the construction site. The average amount of CO_2 emitted by the production of cement is about 880 kg/tonne (Gilbert, 2005 cited in Elhag et al, 2005, p.5). The use of conventional fuels in transportation of the precast concrete product also plays a big part in CO2 emissions. This problem is not easily to tackle and improve, if the location of the precast concrete plant is far from all the construction sites. However, good logistical transport operations can help solve this problem.

However, there are other aspects that can easily reduce the environmental impact from the precast concrete production: which are waste and energy consumption in the precast concrete plant.

Recycling and reusing the by-products of precast concrete plants assures the reduction of waste from the precast plant itself and also from other manufacturers. The reusing of slag (from steel manufacturing) can be mixed with cement, water, aggregate, and admixture to strengthen the concrete over a long period (American Concrete Pavement Association, 2003). Slag mixing with cement also reduces the amount of cement, which in turn reduces the CO_2 emissions (ASCENT, 2007). Furthermore, precast concrete panels, forms and moulds can be reused again many times depending on the type of materials. The reuse or recycle of waste not only reduces the environmental impact, but also saves on cost or even increases profit. Instead of delivering waste from the precast plant to the landfill, reusing and recycling waste can be a better choice. The Landfill tax penalises poor use of waste materials meaning that companies that have more waste will have to pay more, and also the cost of transportation of the waste to the landfill site. Additionally, the landfill tax tends to increase as time goes on (Deloitte, n.d.). The worn and obsolete wood can be used as biomass fuels to create energy, which in turn reduces the amount of conventional fuels used and electricity imported from the grid. Even concrete can be recycled as fill or road base (ASCENT, 2007).

All the materials used in precast concrete production are local to the United Kingdom. This makes the UK self-sufficient in concrete production (The Concrete Centre, 2009). However, the increase in economic growth might stop the UK from being self-sufficient in the future. Therefore the level of mineral extraction needs to be considered as well. A reduction of environmental impact and cost of producing precast concrete can support the UK economy as well as UK environment.

2.3 Biomass

2.3.1 What is Biomass

Biomass is a biological material from organic substances or living organisms that can be converted to an energy form. These materials usually come from virgin wood, energy crops, agricultural residues, food waste and industrial waste. Energy obtained from these sources can replace or reduce the use of conventional fuels such as oil, natural gas, coal and electricity (which is generated by these conventional fuels). Increasing the use of biomass is not only able to decrease CO_2 emissions, but also decrease the amount of money for buying or importing the conventional fuels for private sectors or a country as a whole. The table below shows the CO2 emitted by full combustion of some conventional and biomass fuels, per unit of energy.

Table 1 : Carbon emissions of different fuels per unit of energy (Biomass Energy Centre, 2003)

Fuel	Approx. life cycle CO_2 emissions	
	kg / GJ	kg / MWh
Hard coal	134	484
Oil	97	350
Natural gas	75	270
LPG	90	323
Electricity (UK grid)	150	530
Electricity (large scale wood chip combustion)	16	58
Electricity (large scale wood chip gasification)	7	25
Wood chips (25% MC) Fuel only	2	7
Wood chips (25% MC) Including boiler	7	25
Wood pellets (10% MC) starting from dry wood waste	4	15
Wood pellets (10% MC) Including boiler	9	33
Grasses/straw (15% MC)	1.5 to 4	5.4 to 15

From table 1, biomass fuels CO_2 emissions are far less than conventional fuels. Moreover, the next table shows the typical prices of fuel per unit of energy.

Table 2 : Fuel prices per kWh (Biomass Energy Centre, 2011)

Fuel	Price per unit	kWh per unit	Pence per kWh
Wood chips (30% MC)	£ 90 per tonne	3,500 kWh / tonne	2.6p / kWh
Wood pellets	£ 185 per tonne	4,800 kWh / tonne	3.9p / kwh
Natural gas	4.1p / kWh	1	4.1p / kwh
Heating oil	56p per litre	10 kWh / litre	5.6p / kwh
LPG (bulk)	54p per litre	6.6 kWh / litre	8.2p / kwh
Electricity	13.0p / kWh	1	13.0p / kwh

The cost of biomass fuel is not cheaper when compared to the cost of conventional fuels. This is because biomass fuels need to be purchased. If waste, wood and agricultural residues were obtained from industries by-products, these costs would be lower.

There are a number of energy production technologies for many different types of biomass fuel. Biomass fuel can be converted by thermo and/or chemical and bio-chemical conversion technologies to produce energy. Biomass is considered an inexhaustible fuel source as it can be grown over and over again. Furthermore, it can be grown all over the world. However, biomass releases a certain amount of CO_2 emissions into the atmosphere when it is burned, not as much as fossil fuels, but in order to balance the amount of CO_2 emissions, biomass sources need to be grown in the same amount to absorb the CO_2 emissions from the atmosphere. Biomass usually comes from grain, sugar and oil crops, all of which are foods. Despite the increasing energy consumption demand, the increasing demand for food still exists, hence the balance of crop for energy, crop for food must be put into place. Aside from that, waste, wood and agricultural residues can be utilised to produce energy instead of eliminating them or throwing them away where they will end up in landfill sites.

Nonetheless, biomass energy production technologies have considerable investments due to their immature technologies compared with conventional fuel energy production technologies. Capital costs of biomass energy production technologies are also higher than those of gas and oil fired due to the nature of the fuel sources (Kellet, 1999). Therefore, it is extremely important to understand and be able to choose suitable types of biomass technology in order to make energy efficient and financially benefit from it.

2.3.2 Wood Waste as a Biomass Fuel

Biomass is any organic material that can be converted into energy. Biomass energy comes from wood, waste wood, agricultural waste materials, animal waste, agricultural processing plant wastes and wastes from the community.

Waste wood can be obtained from various types of sources such as municipal waste, construction, demolition, commercial and industrial waste. According to The Waste & Resources Action Programme (2005), it was estimated that the total waste wood arising in the UK is about 10,586,000 tonnes per annum. This figure indicates the large amounts of energy that could be produced from wood waste. The table below shows the total wood waste separated by sectors.

Table 3: Estimate of total wood waste arisings in the UK (The Waste & Resources Action Programme, 2005)

Waste Stream	In the UK (Thousand Tonnes per Annum)
Municipal Waste	1,065
Commercial and Industrial	4,481
Construction and Demolition (an average of the maximum and minimum estimates)	5,040
Total Wood Waste	10,586

There are various options to deal with wood waste. It can be reused, recycled, energy recovered or disposed. The way in which wood waste can be dealt with depends on the quantity and the quality of the wood. Waste wood has been conventionally seen as an inconvenient material that has to be disposed of. Landfill disposal is the easiest way to deal with waste wood. It is also suitable for all types of waste wood in terms of quality and quantity. However, it is not the most desirable option as the number of landfill areas is growing each year, therefore this scarcity of landfill areas might increase the landfill fee in the future. The cost per tonne of sending waste wood or other waste to landfill has also been increasing over the past decade (Department for Environment, Food and Rural Affairs, 2008). Moreover, landfill taxes have been increasing over the years. The landfill tax was £ 24 per tonne in 2007 and 2008, and it has been increasing at a rate of £ 8 per tonne from 2008 to 2011 (Department for Environment, Food and Rural Affairs, 2008).

Another option would be using waste wood as a biomass fuel. This option is strongly influenced by the quantity and quality of the waste wood. Producing energy from waste wood can help reduce the electricity imported from the grid as well as heat from conventional fuel. Therefore, producing energy from wood waste would result in a long term cost reduction (wood fuels price can be cheaper than conventional fuels (£ per kWh)) and CO_2 emissions would be reduced. On the other hand, the capital costs of technologies for producing biomass are more expensive than that of conventional fuel.

Waste wood usually has one advantage over virgin wood; waste wood has a lower moisture content from the process than that of virgin wood (Department for Environment, Food and Rural Affairs, 2008). Wood chip made from waste wood can be used in normal wood chip boilers with suitable moisture and ash content. The characteristics of wood waste such as moisture content, heating value, ash content, size, and contaminant have to be well considered before choosing the suitable biomass conversion technology.

Moisture Content

Moisture content of biomass fuels is an important consideration for energy generation. If the moisture content of biomass is very high, such as in pulp, starch or yeast (where the moisture content of about 80-90%) (Penn State College of Agricultural Sciences, 2010), it is not appropriate for incineration. However it can be put through a process of compression (dewatering) to reduce the moisture content prior to incineration, or an anaerobic treatment process to produce biogas. In the case of fresh green wood, moisture content is about 50% (Penn State College of Agricultural Sciences, 2010). However, it also depends on the species, age, growth area and the part of the tree. One option to reduce moisture content is to store biomass fuel in a controlled environment to decrease the moisture content. Another option is to store and dry it by heat radiation. As for waste wood, the moisture content is usually less than that in fresh wood, and the value is likely to be less than 20% (National Association of Forest Industries, 2006). The moisture content of waste wood from industrial, residential, municipal, institutional, or commercial backgrounds depends significantly on which process they went through, and whether the wood fuel has been drying throughout that process.

Heating Value (Calorific Value)

Each type of biomass gives different amounts of energy depending on the chemical elements and percentage of moisture it contains. The heating value or calorific value of biomass indicates the total amount of heat released per unit weight of biomass being burned (kJ/kg). These can be expressed in two terms: higher heating value and lower heating value. The high heating value (gross calorific value) is the total amount of heat energy derived from burning biomass fuels including the latent heat of vaporisation of water in biomass fuel. The low heating value (net calorific value) is the total amount of heat energy derived from burning biomass fuel excluding the energy required to evaporate the water that accumulates in the biomass fuel (Kauriinoja, 2010).

As mentioned before, the heating value of a biomass fuel type can vary significantly depending on the species of wood and moisture content. Even the heating value of some species of biomass fuel can vary depending on the different climatic and geographical conditions when grown (Biomass Energy Centre, 200-). The table below gives an example of lower heating values of different types of wood at specific range of moisture content.

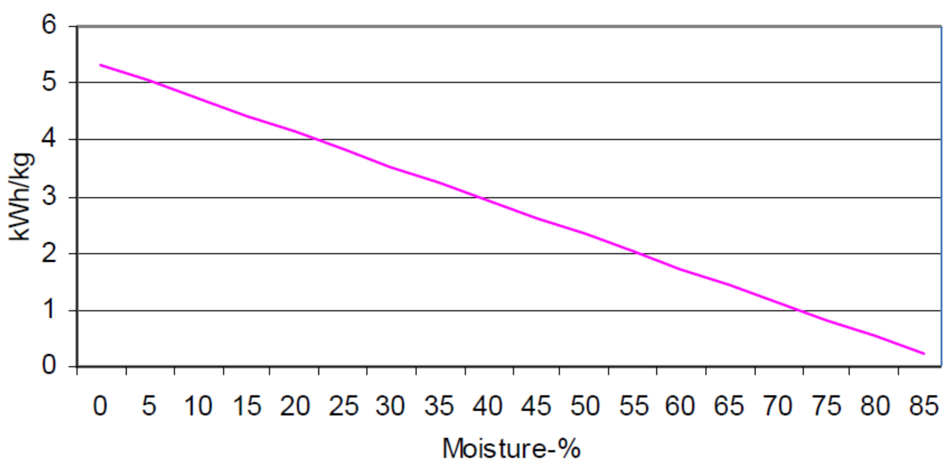
Table 4: Wood Fuel Lower Heating Value (ELECTROWATT-EKONO (UK) LTD, 2003; Biomass Energy Centre)

Wood Fuel	**Lower Heating Value (Net Calorific Value) (kWh/kg)**
Wood chips (30% MC)	3.5
Wood chips (20% MC)	4.22
Forest wood chip dry (40% MC)	2.89
Forest wood chip fresh (55% MC)	2
Log wood (stacked - air dry: 20% MC)	4.1
Wood (solid - oven dry)	5.3
Wood pellets	4.8
Wood waste (18-25% MC)	≈4
Poplar wood (5-15% MC)	4.72 - 5.27
Willow wood (12% MC)	4.72 - 5.27

Plywood residue (5-15% MC)	4.16 – 4.72
Logging residue chips (50-60% MC)	1.67 - 2.5
Whole tree chips (45-55% MC)	1.67 - 2.5
Log chips (40-55% MC)	1.67 - 2.78
Stump chips (30-50% MC)	1.67 – 3.05
Soft wood bark (50-65% MC)	1.67 - 2.5
Birch bark (45-55% MC)	1.94 – 3.05
Wood Residue chips (10-50% MC)	1.67 – 4.16
Uncoated Wood (15-30% MC)	3.33 – 4.16

In wood fuel, the heating value has a linear relationship with moisture content. Increasing the moisture content decreases the heating value because the part of heat energy released is used to vaporise the water within the wood fuel. The figure below shows the lower heating value (net calorific value) compared with moisture content.

Figure 2: The effect of moisture content on the lower heating value of wood (kWh/kg) (ELECTROWATT-EKONO (UK) LTD , 2003)



The high moisture content will decrease the lower heating value of the biomass fuel and in turn affect the fuel efficiency, as well as the size of the boiler. Therefore a more expensive boiler has to be installed, if the moisture content is high.

Ash Content

Inorganic materials of biomass fuels or waste wood that cannot be burned will turn into ash, which is called ash content. Ash will remain in the process after burning. Each type of biomass has different proportions of ash content. These inorganic materials can exist as part of the organic structure of the biomass fuel, or it can be added to the biomass fuel via processing, harvesting, or handling (Livingston, 2007). Most wood waste contains considerable inorganic materials depending on the process that they have undergone, this can affects the efficiency in the wood waste conversion system. A few examples of the main ash-related problems of a biomass conversion system in furnace and boilers are (Livingston, 2007):

- Larger particle of ashes that fall through the bottom during the combustion process are called bottom ash, these ashes need to be handled and dispose of from the furnace. Bottom ashes can be recycled as fertilizer, road construction or landscape materials.
- Smaller particles that are carried with the flue gas are called fly ash. High amounts of fly ash impacts the performance of the flue gas cleaning equipment such as the filter or cyclone and it can stick on the furnace and the heat exchanger surface, which, in turn, reduces the efficiency of the plant.
- The formation of some chemical compounds in the ash can produce slag that will decrease boiler components and other components' life spans.

The exact amount of ash content and its effect largely depends on the type of waste wood, which process they went through, and the biomass conversion technology involved. The following table gives some examples of the amount of ash content in wood.

Table 5: Ash content from wood fuel (Eleotrowatt-ekono (UK) ltd, 2003)

Wood Fuel	Ash content in dry matter in percentage of total weight
Plywood residue	0.4-0.8
Logging residue chips	1-3
Whole tree chips	1-2
Log chips	0.5-2
Stump chips	1-3
Wood Residue chips	0.4-1
Uncoated Wood	1-5

Size

Waste wood has to be cut or chipped into an appropriate size before being uses in a biomass boiler or CHP. This not only helps improve the efficiency of the boiler, but it also eases the handling, transporting, and storing of waste wood. Smaller sized wood waste has a larger surface area than bigger sized wood waste of the same weight, therefore it can release moisture more quickly than the bigger sized wood waste (Penn State College of Agricultural Sciences, 2010). As a result, it has a better burning efficiency. The smaller sized of waste wood need less space for handling, transporting, and storing compared to the bigger sized of waste wood, which in turn reduce the cost of these factors. However, the cost of size reduction has to be considered too. The size of the wood fuel should comply with the technological requirements of the biomass boiler or CHP.

If the wood waste needs to be chipped, there are three main design technologies to produce wood chip: disk chippers, drum chipper, and screw chipper (Biomass Energy Centre, n.d.). A disk chipper is suitable for solid pieces of wood waste and provides a better quality of chip size than drum chipper. While a drum chipper is more suitable for small pieces of wood waste, but it might provide some oversized wood chips. A screw chipper or cone chipper is also suitable for solid pieces of wood waste, and produces high quality and uniformed sized chips (Spinelli & Hartsough, 2000) however it typically more expensive than disk chippers (BioRegional Development Group, 2006).

Wood Fuel Storage

Wood fuel storage purpose is to keep or improve the wood fuel characteristics before feeding them into energy conversion technologies. If the moisture content of the wood fuel (solid pieces of wood or wood chips) reaches the requirements of the particular biomass boiler or CHP, it is important to keep it in a dry controlled environment. If the moisture content of the wood fuel is still too high, it needs a further drying process in storage. Storing the wood fuel in a dry environment with well design natural ventilated air would be enough, if the wood fuel does not need to be dried in a short period of time. Mechanical ventilation and heating can be used to dry the wood fuel more rapidly, but it also increases the overall energy consumption and capital cost (Macmillan, 2001).

Besides the methods of drying the wood fuel, the size of the storage is also essential. The storage size must be big enough to be able to store and deliver the wood fuel all year round. It is obvious that the bigger s storage facility is the better in terms of the amount of wood fuel it can store. Moreover, bigger storage can reduce wood fuel delivery frequency to the site, which reduces the transportation cost of wood fuel. However, bigger storage will increase more capital cost. Therefore, the optimum size of the storage needs to be evaluated with the rate of wood waste being produced from the process, rate of wood fuel consumption, wood fuel transportation cost, and the storage cost (Biomass Energy Centre, n.d.).

The position of the storage should be designed to make it convenient for delivery vehicles to access it. The height level of the storage system is also important especially for wood chips. Above ground storage must be coupled with the hoppers or tools to elevate the wood fuel from the vehicle to the storage, if the height of the storage is above the transportation vehicle. Underground storage eases the delivery of wood chips from the vehicle, removes the building structure, and provides more space above the ground. However, the cost of underground storage is likely to be more than above ground. The ventilation and heating system is also more complicated to install if it is needed (Millar, 2006).

Contaminant

Contaminant in waste wood is an important issue to be overcome in order to have safe and successful use of waste wood as a biomass fuel. Wood waste by manufacturing, processing, construction and demolition or other industries may have received some kind of treatment, contaminant or heavy metal. The wood waste that is contaminated with chemical matter has limitations of use as biomass. Wood waste can be viewed in different ways, mainly separated into hazardous wood waste and non-hazardous wood waste.

Waste wood has stricter regulations when being used in energy production than virgin wood (Biomass Energy Centre, 200-). These regulations are for contaminated wood waste from treatments, manufacturing processes, or accidental spills of chemicals. These place wood waste under control of the Waste Incineration Directive (WID) and Pollution Prevention and Control (PPC). These restrictions are set to prevent poisonous emissions from burning contaminated wood. The wood waste is considered hazardous wood waste if it has been treated with the following (TRADA Technology & Enviros Consulting Ltd, 2005):

- Chromated Copper Arsenate (CCA)
- Copper Organics
- Creosote
- Light Organic Solvent Preservatives
- Micro-emulsion
- Paint/strain
- Varnish

The use of contaminated wood waste as mentioned above can be used as a biomass fuel if and only if the appropriate filtering and ash handling process and level of emissions control are applied (TRADA Technology & Enviros Consulting Ltd, 2005).

Heavy metals such as copper, chromium and lead in waste wood can be removed by magnetic force during the wood chipping process. If heavy metals are not removed before energy production process, it will exist in bottom ash and fly ash that needs to be taken care of. The bottom ash can reduce the efficiency of the boiler in the combustion process and it is needed for suitable handling and disposal of ash. The fly ash can contaminate the emissions from energy production, therefore an appropriate filter or cyclone has to be installed to prevent unacceptable emissions.

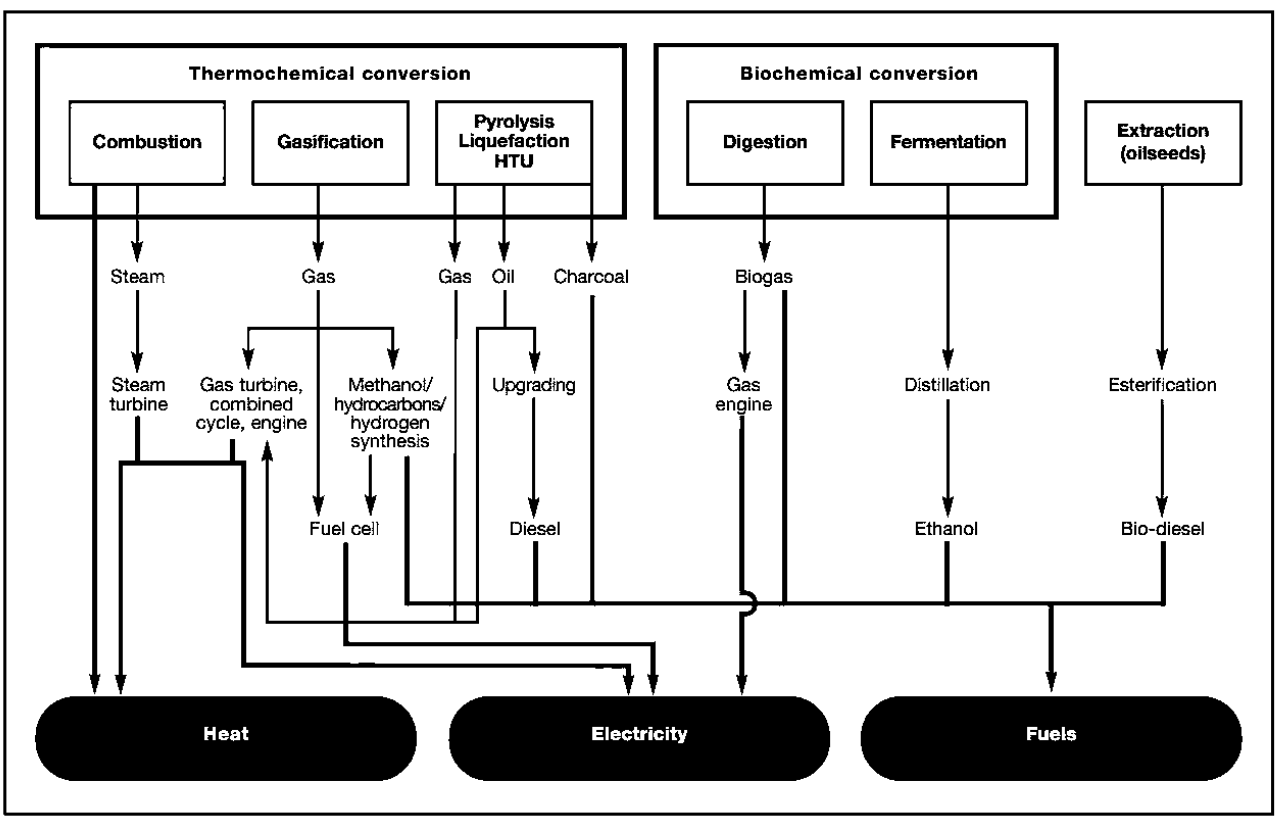
Other contaminants such as halogens and halides could be released in the flue gas emissions therefore, a scrubber or trap has to be installed to reduce or eliminate them. Wood waste that is comprised of more than 1% halogenated organic compounds would be categorised as hazardous waste (Department of the Environment Planning and Environmental Policy Group, 2007). It is essential to counter these issues to prevent harmful emissions and to increase the efficiency of the energy generation technology, but it is also seen as a great barrier to utilise waste wood as biomass fuel.

2.4 Small Scale Wood fuel Conversion Technology

Biomass conversion technology is the first stage of converting biomass fuel into various forms of energy such as heat, flue gas, product gas, biogas, bioethanol, etc. There are a number of technologies to convert biomass to those forms of energy depending on the type and quantity of biomass feedstock, as well as the desired form of energy. Environmental standard and economic issues also have to be considered when choosing suitable biomass conversion technologies.

Not all conversion technologies will be addressed in this chapter. Only the combustion and gasification conversion technology will be focused on because only these two technologies are suitable for small scale wood waste biomass boilers and combined heat and power (CHP), which are well established (Kauriinoja, 2010). The overview principle of conversion technologies will be discussed in terms of technical and availability, small-scale wood waste biomass boilers and CHP. The figure below shows the intermediate energy carriers and final energy products of each conversion technology.

Figure 3: Main Biomass Energy Conversion Routes (Turkenburg, 2000)



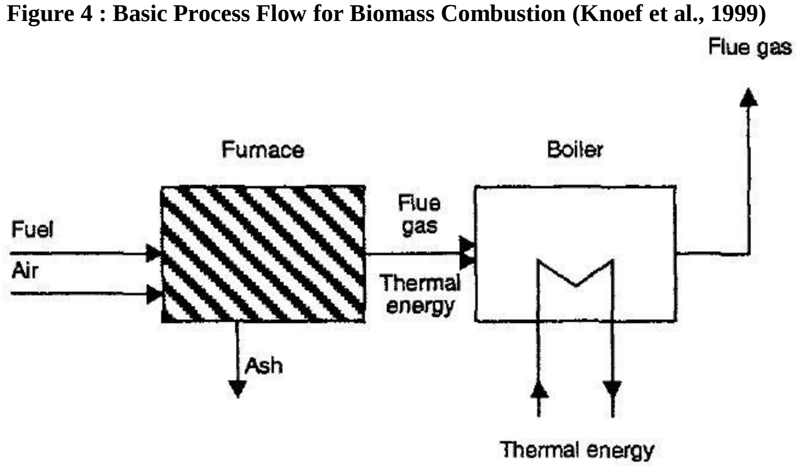
2.4.1 Combustion

Combustion is the most direct conversion process from biomass into usable energy. This direct combustion of biomass fuel creates a chemical reaction between biomass fuel and oxygen, resulting in heat output. Biomass fuel is burned completely when there are three main criteria: sufficient air, a good mixture of fuel and air, and a high combustion temperature. Because this technology is straightforward and easy to implement, it is the oldest and most well established technology compared to the others biomass conversion technologies. Biomass direct combustion systems are commercially available from a few kW up to more than 100 MW (Nussbaumer, 2003). The overall efficiency is significantly high for generating heat. The power production would be efficient, if combined heat and power technology is implemented. Biomass fuels that are usually used in direct combustion is paper, wood, straw, miscanthus, switch grass, etc.

Principles

The combustion process can be divided into two sections which are the furnace (the place where the fuel is burned) and the heat exchanger (the place where the heat from the flue gas in transferred to other energy carriers, such as water, steam, or air) (Knoef et al., 1999).

Figure 4 : Basic Process Flow for Biomass Combustion (Knoef et al., 1999)



The flue gas coming out of the furnace can be used for space heating, water heating or steam raising(generate electricity) via different types of heat exchangers. Thus, combustion furnace and heat exchangers are available in different designs, depending on their end-use energy requirement, biomass properties and characteristics. In general, combustion process of biomass occurs in the furnace releasing hot flue gas. This hot flue gas is the heat output product from the furnace. The type of furnace can be differentiated by the flow conditions of the bed in the furnace. Two main types of furnaces are the fixed bed combustion and fluidized bed combustion.

Fixed bed Combustion Systems

Fixed bed systems are the most widely spread technology for biomass combustion technology (Knoef et al., 1999). Fixed bed systems are distinguished by the types of grates and the way the biomass is supplied to the furnace. It includes the grate-fired system and the underfeed stoker system. This section will give an overview of the most frequently used furnace type for small-scale biomass technology.

- *Grate-Fired System*

Biomass will be fed into the combustion chamber, where it is most likely to lay on the grate and be burnt to ashes. There are various ways to feed biomass into the combustion chamber, manually or automatically, where biomass is supplied above or under the grate. These technologies are appropriate for biomass fuels with a high moisture content, of different sizes, and high ash content (Vos, 2005).

  - *Fixed-Grate System*

This system is suitable for small scale (Obernberger, 1998). The grate is fixed in place (often sloped) in the combustion chamber. Biomass may enter by gravity from the top of the grate. Primary air is supplied under the grate for the combustion of the material that remains after being burnt (char) and biomass. Secondary air is supplied above the grate for the combustion of the volatile gases (fuel gas from burning biomass). The newly added biomass fuel will be repeatedly burnt by heat from the char combustion. Ash can be manually removed or automatically removed below the grate (Knoef et al., 1999).

- *Moving Grate Furnaces*

In this system, the grate is in a horizontal or inclined position and will be moved by the drive gears (usually by hydraulic cylinder) (Van Loo & Koppejan, 2003). Flow directions of the fuel and the flue gas can be counter-current flow, co-current flow, and cross-flow.

In counter-current flow, the flame is in the opposite direction of the feeding fuel, is suitable for wet bark, wood chips, or saw dust. In co-current combustion, the flame is in the same direction as the feeding fuel, is suitable for waste wood or straw. In the cross-flow, the flame is removed in the middle of the furnace, is suitable for wet and dry biomass (Van Loo & Koppejan, 2003).

Biomass fuels enter by the screw feeders on the grate at one end. Biomass on the grate will be transported along to the other side and burned as well. Biomass fuels will be burned into ashes, when the grate is at the other end. Ash will fall towards the bottom and be removed (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007).

In moving grate furnaces, mixture of wood fuels can be burned, but not wood fuels, straw, cereals and grass together due to the different combustion behaviour of each biomass fuel. Moreover, high ash and moisture content biomass can also be used in this technology (Nussbaumer, 2003).

- *Travelling Grate Furnaces*

Travelling grate furnace is made of grate bars moving in circle in the combustion chamber (Van Loo & Koppejan, 2003). Biomass fuels enter into the grate by screw feeders or spreader stokers. Spreader stokers feed biomass into the furnace above the reaction zone. Heavier biomass particles will fall further than the lighter biomass particles from the spreader stokers. Very light and small biomass particles will be burnt above the reaction zone on the grate. The grate will move in the opposite direction of the feeding biomass. This method will let heavy and large biomass stay longer on the grate to be burnt (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007). This system can burn wood chips and wood pellets in constant combustion conditions (Vos, 2005).

- *Underfeed Stokers*

Underfeed stokers are usually suitable for small-scale systems and mostly used for wood chips and small biomass particles (Van Loo & Koppejan, 2003). This technology is a relatively cheap and safe option for biomass combustion (Nussbaumer, 2003). Biomass fuels are fed into the combustion chamber and the grate by a screw conveyor from below. The pressure from the feeding system pushes the biomass fuels upward. This will lead to a volatile substance being contained in the fuel vapour and into the upper part to make it easier to ignite and burn up completely (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007). Ash from biomass fuel combustion will be pushed to the ash removal by air and small particles flowing with the flue gas and will be extracted by the cyclone. However, it is not feasible to burn high ash content biomass as this can affect the airflow and lower the quality of combustion (Van Loo & Koppejan, 2003).

This technology has an advantage of being easier to control in partial-load behaviour than other technologies, since load changes can be achieved quickly and easily by fuel feed supply (Van Loo & Koppejan, 2003).

- *Fluidized bed Combustion Systems*

In fluidised bed combustion systems, air will flow throughout a layer of a non-combustible material bed. The system includes a combustion chamber with the non-combustible bed inside (heat transfer medium). This non-combustible bed is fluidised by blowing air beneath the chamber. This method increases the efficiency of the biomass combustion because of the intensive mixing between biomass fuel, bed, and air, resulting in high specific heat transfer (Van Loo & Koppejan, 2003).

There are two types of fluidised bed combustion systems, which is the bubbling fluidised bed and circulating fluidised bed. The difference between these two technologies is the air velocity blowing beneath the chamber. In the bubbling fluidised bed, the air with a velocity of 1-2.5 m/s will only move the bed (usually sand). While in the circulating fluidised bed, the air velocity (5-10 m/s) is higher than that in the bubbling fluidized bed, resulting in all the small and light particles in the chamber flowing up along with the heat flue gas (Obernberger, 1998). The cyclone is used to extract such particles from the heat flue gas and send it back to the chamber. This way the large and heavy particles will be burnt until they become small and light, thus the complete combustion is rather easily done and it gives the flexibility of fuel properties, sizes and shapes. Moisture content and ash content usually accept up to 60 and 50 percent respectively (Obernberger, 1998). Bubbling fluidised bed and circulating fluidised bed boilers are usually used in large-scale applications (Nussbaumer, 2003).

2.4.2 Gasification

Biomass gasification is the process that turns solid fuel into fuel gas, producer gas or syngas, by heat process (thermal conversion). Producer gas is a gas that can be used as fuel consisting of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4) (Sanderson & Feltrin, n.d.). The combustion of the producer gas provides heat that can be used in heating, water heating, and electricity generation (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007). Moreover, producer gas can also be used as a fuel in gas combustion engines or even modified diesel engines. The biomass gasification process can be divided into four processes.

1. Drying process: The moisture content in biomass fuel will be reduced by heat from the combustion zone of a reactor.
2. Pyrolysis process: This is the first step of burning biomass fuel by the heat from the combustion zone. Organic compounds in biomass fuels will erupt in a solid, liquid and gas.
3. Combustion process: The process of biomass fuel is burned in the reactor; air is blown into the reactors where it then reacts with solid fuel which is derived from the pyrolysis process.
4. Reduction process: Many reactions occur in which carbon monoxide (CO) and hydrogen (H_2) are produced as producer gases. This is the second step so that the combustion air is controlled.

Biomass gasification systems are mainly used in the present and can be divided into three systems. The difference of the various gasifiers is the way in which the fuel is transported into the gasification stage. These are: updraft, downdraft, and fluidised-bed gasifiers technologies are commercially available (Sinjab, 2009).

- *Updraft or Countercurrent Gasifiers*

An updraft gasifier is the simplest type of gasifier and it has been used for a long period of time. Biomass fuel is fed into the top of the stove and the air is passed through from the bottom of the reactor. When the air goes into the combustion area, a reaction occurs producing carbon dioxide and water. The gas from the combustion zone reaches a high temperature as it goes into the reduction zone. In this area, carbon dioxide and water will react with carbon to make the carbon monoxide and hydrogen as the main component of the producer gas. The producer gas will flow into the area where the temperature is lower than in the reduction zone. Then the high temperature producer gas will flow into the layer of moist biomass in order to evaporate the water contained in the biomass. As a result, the producer gas temperature from the furnace is low (Knoef et al., 1999).

Producer gas contains tar as the contaminant, which is due to the efficiency of the gasification process. A more efficient process would contain less tar in the producer gas. However, tar has to be removed before using producer gas in a boiler or gas combustion engine. (Food and Agriculture Organization of the United Nations, 1986)

- *Downdraft or Cocurrent Gasifiers*

Downdraft gasifiers have been used since World War 2 and are still widely used today (Overend, 2004). This technology is particularly designed to eliminate tar in producer gases. Biomass fuel is fed from the top of the reactor and air is drawn through from the top or the sides, by a group of nozzles (tuyers) whereas producer gas comes out from the bottom. The zones are similar to the updraft gasifier, but the order of the process is different. On the way down to the bottom, the component in the biomass fuel must pass through a glowing bed and turn into hydrogen, carbon dioxide, carbon monoxide and methane (Knoef et al., 1999).

Composition of the tar in the producer gas from the downdraft gasifiers is less than 10% tar from the updraft gasifier. However, there are high amounts of ash and dust particles in the producer gas. Thus this technology is not suitable for high ash content or moisture content biomass. It might make the combustion process slower and lose pressure inside the furnace (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007).

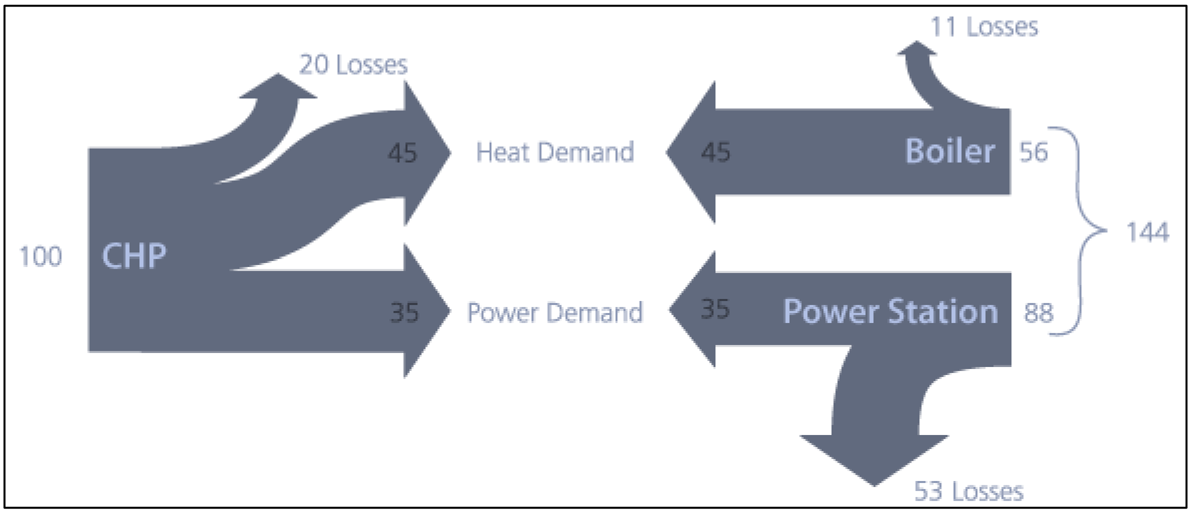
- *Fluidized-Bed Gasifiers*

  With three of the gasifiers mentioned above, the operation depends solely on the chemical properties and size of the biomass fuel. Fluidised-bed gasifiers were originally developed to solve such problems (Knoef et al., 1999). In this technology, air flows throughout the chamber with hot sand bed and biomass fuel. Biomass fuel is fed into the bubbling fluidised bed or circulating fluidised bed depending on the airflow velocity from the bottom of the chamber. Biomass fuel will be burnt and mixed quickly with the bed material, resulting in continuous pyrolysis. Fluidised-bed gasifiers have the advantage of flexibility in biomass characteristics and sizes due to high combustion efficiency. However, this technology is more complex than others mentioned and more expensive (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007), therefore this technology is mostly suitable for large scale operation power plants (Knoef et al., 1999).

2.5 Small Scale Wood Fuel Power Generation Technology

Combined heat and power technologies (CHP) can produce heat and electricity from the same source. The CHP efficiency can easily reach 80-90%, because thermal energy normally lost in the process of producing electricity is utilised in many forms such as process steam, hot water, or hot air (Alakangas & Flyktman, 2001). CHP systems (if well designed) are capable of dramatically reducing carbon footprints and fuel bills. The installation of the CHP should be based on thermal energy demand not electrical energy demand due to the fact that it is easier to export the electrical energy surplus to the grid rather than dissipate or utilise thermal energy surplus (Biomass Energy Centre, 2009).

Figure 5: The typical efficiency of the CHP compared to traditional heat and power generation (Self Energy UK, 2009)



Small scale biomass CHP technologies are not as mature as larger scale biomass CHP (Biomass Energy Centre, 2009). Commercially available small scale biomass CHP is very limited, due to economic and technical issue (Dong et al., 2009). Therefore the cost of small scale biomass might be expensive, and the efficiency might not be as high as larger biomass CHP.

Many technologies have been researched and developed for small scale biomass CHP. This includes the conversion technology that converts biomass to hot water, hot air, steam, or gas mentioned earlier in this chapter. Another conversion technology that has to be considered is the transforming of those products from the first conversion to heat and power.

Dong, Liu, & Riffat (2009) and Alakangas & Flyktman (2001) stated that direct combustion and gasification processes combined with small sized steam turbines are normally for large scale biomass CHP. In large scale, this technology is commercially available and traditional. The heat to power ratio dramatically increases when the system size decrease because of the inefficiency of small steam cycles and losses. The gasification process can be used with gas turbines and micro-turbines, but it is also suitable for large scale biomass CHP (Biomass Energy Centre, 2009). Many of the current small scale biomass technologies are still under research and development, and are immature however, some are already established

2.5.1 Internal Combustion Engine

Internal combustion engines use gas products from the gasification process to produce heat and power. The down-draft gasification process is the majority process for used with internal combustion engines. It has several advantages such as a short start-up and shut down time, and good load-following, but it is noisy (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007). This technology requires good, clean gas in order to operate the internal combustion engine to its potential. The filer, cyclone or tar remover must be put in place before letting the gas product into the engine. The commercial biomass CHP system using internal combustion engine capacity ranges from 10 kW_e to 100 kW_e, and it can give low heat to power ratio as 2:1 or 1:1 (Biomass Energy Centre, 2009).

2.5.2 Stirling Engine

Unlike the internal combustion engine, the Stirling engine is an external combustion engine. The heat from the combustion process or the combustion of product gas from the gasification process is transferred to the engine to create work and then drive the turbine. The gasification process would be a better option due to the purity of the gas in order to avoid erosion and corrosion of the engine. In this engine, the combustion process takes place outside the engine (U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007). The heat is transferred to the engine by a heat exchanger. This process gives some advantages such as more complete combustion of the wood fuel, which in turn emits lower emission. Stirling engines are commercially available from 1 kW_e to 75 kW_e with a heat to power ratio around 4:1 (Biomass Energy Centre, 2009).

2.5.3 Organic Rankine Cycle (ORC) engine

Organic Rankine cycle operation is similar to steam turbines, but the water working fluid is replaced by a low boiling point working fluid such as silicone oil, freon, or an organic solvent. The system can work in much lower temperatures than the steam turbine. For this reason, an ORC engine is more suitable for small scale biomass CHP and gives higher efficiency than using water (Dong et al., 2009). The lower operating temperature also lowers the cost of the material and insulation. ORC engines are commercially available from about 350 kWe to 3,500 kWe and they are successfully demonstrated with heat to power ratio of around 5:1 (Biomass Energy Centre, 2009).

2.5.4 Micro-turbine

Gas turbines are commercially available in large scale biomass CHP, and the efficiency of these turbines reduces with size. Therefore in recent years, many studies have focused on downsizing such turbines whilst maintaining electrical efficiency and also instantaneously improving economic viability. The micro-turbine can be driven with flue gas or air. Therefore micro turbines can be combined with direct combustion technology. This technology has to comply with a compressor to raise the gas or air pressure to the required value before being transferred to the turbine. ORC engines are commercially available from about 30 kWe to 250 kWe with a heat to power ratio of around 3:1 (Biomass Energy Centre, 2009; U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007).

2.6 Financial Incentives

2.6.1 Renewable Heat Incentive (RHI)

Renewable heat incentive has been set up to promote the use of renewable technologies to create heat. The purpose of the renewable heat incentives is to increase the proportion of non-domestic sectors heat generated from renewable technologies (Department of Energy and Climate Change, 2010). Due to the high capital costs of renewable technologies, this scheme will compensate by paying money to non-domestic sectors for every kWh of heat generated by renewable technology.

Renewable heat incentives will support biomass, biomethane, biogas used on site, solar thermal, heat pumps etc., but not fossil fuel CHP, co-firing CHP, or solar transpired panels. Some of the technologies will be eligible for certain output capacities. More details of the renewable heat incentive eligibility of renewable technologies can be found in the department of energy and climate change website. The heat that will be taken into account in this scheme has to be useful heat used for water, process, or space heating.

Table 6: Table of tariffs support for biomass in renewable heat incentive

Tariff name	Eligible technology	Eligible sizes	Tariff rate (pence/ kWh)	Tariff duration (Years)	Support calculation
Small biomass	Solid biomass; Municipal Solid Waste (incl. CHP)	Less than 200 kW_{th}	Tier 1: 7.6 Tier 2: 1.9	20	Metering Tier 1 applies annually up to the Tier Break, Tier 2 above the Tier Break. The Tier Break is: installed capacity x 1,314 peak load hours, i.e.: kW_{th} x 1,314
Medium biomass		200 kWth and above; less than 1,000 kW_{th}	Tier 1: 4.7 Tier 2: 1.9		
Large biomass		1,000 kW_{th} and above	2.6		Metering

For biomass, the small size and medium size mentioned in the above table will fall under a ‘tiered’ tariff structure. Tier 1 tariff allows installations to receive support until they reach the 15 % of annual heat load, which is the 1,314 x installation capacity. Subsequently tier 2 tariff will support the remaining thermal energy generated.

2.6.2 Feed-In Tariffs (FITs)

Feed-in Tariffs have been created to promote the use of renewable technologies for electricity generation. The purpose of the feed-in tariffs is to increase the proportion of all sectors’ electricity being generated from renewable technologies. This scheme will give three financial benefits, which are the payment for electricity generated, exported, and saving from using electricity produced.

The generation tariffs will pay for every kWh of electricity generated. The export tariff will pay for every kWh of electricity exported to the grid and any renewable technologies can obtain support by the generation tariffs and export tariff as long as the production capacity is less than 5 MW. However some renewable technologies such as biomass, liquid biofuels, biogas, tidal and wave power, and geothermal energy are excluded from this scheme (Feed-In Tariffs Ltd, 2011).

The Energy Act defines that the mentioned excluded renewable technologies could be eligible for this scheme, but the government has not included them yet (Feed-In Tariffs Ltd, 2011).

2.6.3 Renewable Obligation Certificates (ROCs)

Renewable obligation certificates have been created to increase the percentage electricity created by renewable technologies for each licensed electricity supplier. Renewable obligation certificates are issued by Ofgem for each MWh of electricity generated by renewable technologies. Theses certificates can be traded to the licensed electricity supplier. The licensed electricity suppliers have to pay a selling price (£/ROC) for each certificate from the electricity generators, if they cannot reach the percentage of electricity supplied from renewable technologies set by the renewables obligation. If the licensed electricity suppliers do not have enough ROCs, they have to pay the buy-out price (£/MWh) to the buy-out fund.

This scheme helps renewable technologies generators to increase their incomes by selling their ROCs to licensed electricity suppliers. This scheme runs for one year but it could be reissued with ROCs for twenty years as long as it is before 31 March 2037 (Office of Gas and Electricity Markets, 2011).

There are many definitions and factors to define eligibility under this scheme for each renewable technology. The details of renewable technologies eligible for this scheme can be found in department of energy and climate change website.

The table below shows the amount of ROCs given per MWh of electricity generated by biomass.

Table 7: Banding provision (Office of Gas and Electricity Markets, 2011)

Technologies	**Level of support (ROCs/MW)**
Co-firing of biomass	0.5
Co-firing of energy crops, Co-firing of biomass with CHP, Standard gasification or pyrolysis	1
Co-firing of energy crops with CHP, Dedicated biomass	1.5
Anaerobic digestion, Advanced gasification or pyrolysis, Energy crops (with or without CHP), Dedicated biomass with CHP, Microgeneration	2

The ROCs are only applied to the eligible electricity output of the renewable technologies defined by RO Order. Usually eligible output is the gross output subtracted by input electricity. Input electricity is all the electricity used in generation of electricity including operating of generators, fuel handling and preparation, maintenance, etc.

2.6.4 Other Grants and Support Schemes

- Energy Saving Scotland – Small Business Loans

  Loans from £ 1,000 to £ 100,000 with 0% interest rate can be given to businesses to install renewable energy technologies. This scheme is for businesses in Scotland that are defined as small and medium-sized Enterprise, private sector, and non-profit organisation.

- The Enhanced Capital Allowance (ECA) scheme

  This scheme allows businesses to claim 100% first year qualifying capital allowances against the taxable profit in the investment year. This scheme only supports new and unused equipment and this equipment has to meet the energy-saving criteria issued by the Energy Technology Criteria List.

- EU Emissions Trading System (EU ETS)

  This scheme allows companies to trade the CO_2 emissions allowance to other companies, if their CO_2 emissions do not exceed the level of emissions allowance. However, if their emissions exceed the allowance, they have to buy more allowance from another company or pay the buy-out price.

3. The Biomass Boiler and CHP Tool

3.1 Introduction

The previous chapters gave the background overviews of using wood waste as biomass fuel, the conversion technologies of biomass boilers as well as the combined heat and power (CHP) technologies. The significant environmental advantages of using biomass to produce heat or electricity is that it does not increase the net amount of carbon dioxide (CO_2) in the Earth's atmosphere, only if we produce enough biomass to balance this usage. It will make the absorption of CO_2 in the production of new biomass equal to the amount of CO_2 produced by burning biomass. Besides, biomass has lower sulphur content than many fossil fuels. This means that the use of biomass will reduce the greenhouse gases (Greenhouse effect) as opposed to the use of conventional fossil fuels. However, biomass needs more storage space, because of the lower calorific value of biomass compared to that of conventional fossil fuels, it requires larger storage space than the fossil fuels to heat evenly. Providing and collecting biomass to be used constantly all year round has to be well managed sufficiently to provide heat or electricity needed. Therefore, developing ways to store and transport biomass is very important and necessary.

This helps us to choose appropriate biomass boilers and CHP to use from existing wood waste. Moreover, it also gives us ideas of the environmental impact of using and not using wood waste as a biomass fuel. After examining many mentioned aspects of using wood waste as biomass fuel, we can conclude that using waste wood as a biomass fuel has more criteria and regulation that has to be fulfilled and approved in order to have the maximum economic and environmental benefit. The commercially available technologies to convert wood waste to thermal energy are more developed and widespread than that of CHP technologies in small-scale. Small-scale biomass electricity generation has a relatively low efficiency. Therefore CHP technologies will not be suitable, if the heat generated from CHP is not used profitably. Besides Renewable Heat Incentives, the electricity generation for CHP can have other benefits such as Feed-in Tariffs or Renewable Obligation Certificate as mentioned before.

Most of the industrial applications that require process heat can obviously have the benefit of using their wood waste by-product to produce heat. As for wood waste CHP, the technologies are more expensive than that of the boiler. The detailed energy demand and energy supply have to be considered with the benefits from costs, fuel saving, and financial incentives to be able to compare the economic and environmental performance between the wood waste boiler and the wood waste CHP.

3.2 Aims and Objective

The aim of this tool is to analyse the economic and environmental performance between selected wood waste boilers and CHPs at a particular site. This tool allows the user to quickly calculate the economic and environmental performance using the thermal and electrical demand profile, technology specification, the operation mode, the costs, financial incentives and other financial factors. This tool is a preliminary decision support analysis tool that can be used for those who are investigating and investing in wood waste boiler and CHP.

Specifically, within the background of higher education, the objectives of this tool are to:

1. Specify the important parameters regarding the biomass boiler and CHP performance
2. Generating thermal and electrical hourly demand profile
3. Provide a tool for the analysis of economic and environmental performance between selected wood waste boilers and CHPs
4. Compare the economic and environmental performance between selected wood waste boilers and CHPs

For the purpose of each of the above objectives, objective 1 focuses on identifying the important parameters for biomass boilers and CHP to use for calculation in this tool. Objective 2 focuses on generating thermal and electrical demand either from a constant or variable demand. Objectives 3 and 4 will make the key comparisons of biomass energy technologies, especially in wood waste boiler and wood waste CHP.

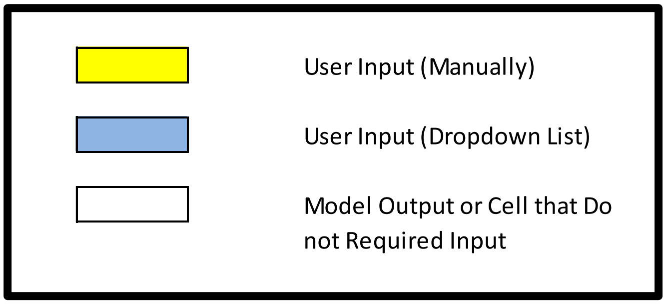
3.3 Limitation

1. This tool can be used for woody biomass either from forestry or waste. For the case of wood waste, waste has to contain 100% wood because this tool assumes that all the contaminant has already been taken out of the waste. However, the mixture of different type wood can be used in this tool.
2. As for the boiler and CHP technical specification, they have to be suitable for producing thermal and/or electrical energy from wood only. And the technologies should be made for solid wood biomass not for biogas or bioliquid.
3. This tool does not consider holiday dates during the year.
4. The thermal and electrical energy demand profile set by the user will be the same for the project lifetime.
5. The thermal storage in this tool is a sensible heat storage designed to help improve the performance of biomass boilers and CHP. The user cannot change the system type to latent heat storage or bond energy storage system. This tool provides the basic calculation for this thermal storage system. Since the thermal storage calculation largely depends on the heating circuit and control configuration, an exact calculation for one specific setting and technology would be inaccurate.
6. Wood storage size calculation will be neglected in this tool due to the many parameters involved. Wood waste by-product from the manufacturer is varying throughout the year. Further investigation is needed to calculate the storage size. However, the tool will provide the monthly fuel consumption of biomass fuel in the result section.
7. The tool has a number of specific inputs; therefore it is really important to fill in the accurate data in order to have an acceptable range of results.
8. The final figure results of this tool should be looked as estimated figures. There are some parameters that are estimated or not considered in this tool such as the fixed inflation rate over a 30-year period and the energy demand that will be the same every year.

3.4 Cell Colour Coding

The user only types data into the yellow cell provided, and chooses the data from the dropdown list in the dark blue cell. All other cells that do not require input are in the white cell and other colours.

Figure 6: Input and Output Cells



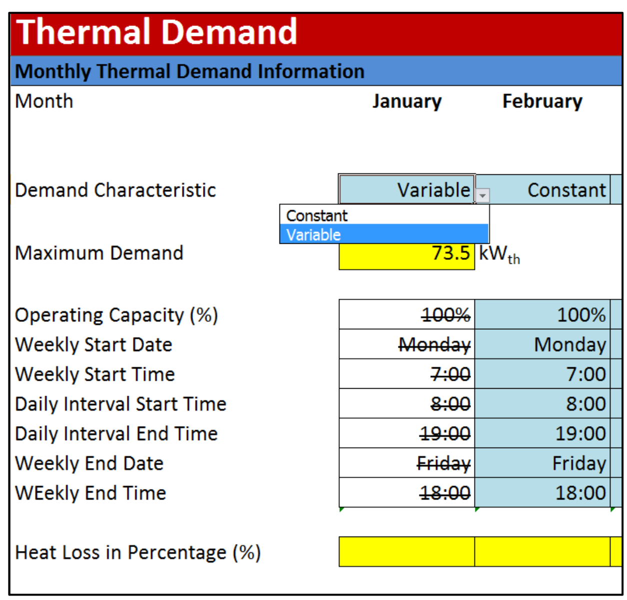
3.5 The Biomass Boiler and CHP Tool Structure

This tool can be divided into five main sections, which are energy demand, wood fuel, biomass boiler and CHP specifications, comparing the biomass boiler and CHP results, and results comparison.

3.5.1 Energy Demand

Energy demand section allows the user to enter hourly thermal and/or electrical energy demand for further calculation in this tool. If the user already has the hourly energy demand profile, the user can manually enter the hourly thermal and/or electrical energy demand by choosing "Variable" in the demand characteristic dropdown list for each month.

Figure 7: Choosing demand characteristic



Then user can manually enter the hourly demand data in the space provided below the spreadsheet.

Figure 8: Manually enter the hourly demand data

Hourly Thermal Demand Profile				
Date	Hour	Hourly Heating Demand (kW_{th})		
		Constant	Manually	Real
1-Jan-10	0:00		12	12.00
1-Jan-10	1:00		14	14.00
1-Jan-10	2:00		16	16.00
1-Jan-10	3:00		20	20.00
1-Jan-10	4:00		18	18.00
1-Jan-10	5:00		18	18.00
1-Jan-10	6:00		20	20.00
1-Jan-10	7:00		18	18.00
1-Jan-10	8:00		19	19.00

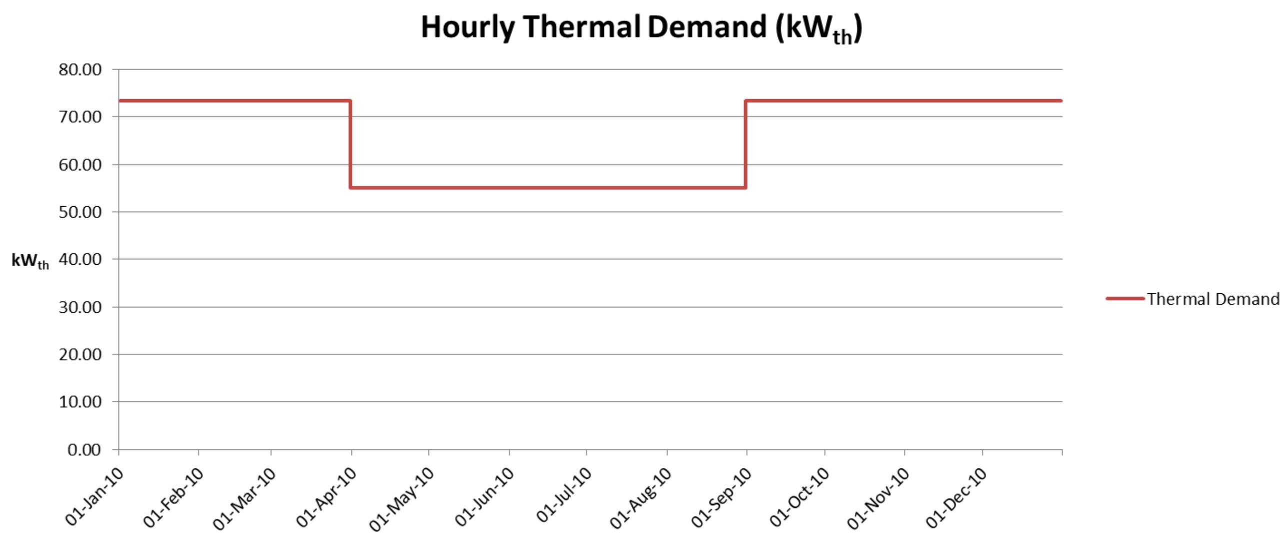
Otherwise user can generate the hourly energy demand profile by choosing constant in the demand characteristic dropdown list and choosing the maximum demand in a year in kW.

Figure 9: Generating hourly energy demand profile

	Thermal Demand		
	Monthly Thermal Demand Information		
	Month	January	February
	Demand Characteristic	Constant (Constant / Variable)	Constant
	Maximum Demand	73.5	kW_{th}
1st Step	Operating Capacity (%)	100%	100%
3rd Step	Weekly Start Date	Monday	Monday
	Weekly Start Time	7:00	7:00
2nd Step	Daily Interval Start Time	8:00	8:00
	Daily Interval End Time	19:00	19:00
3rd Step	Weekly End Date	Friday	Friday
	WEekly End Time	18:00	18:00
4th Step	Heat Loss in Percentage (%)		

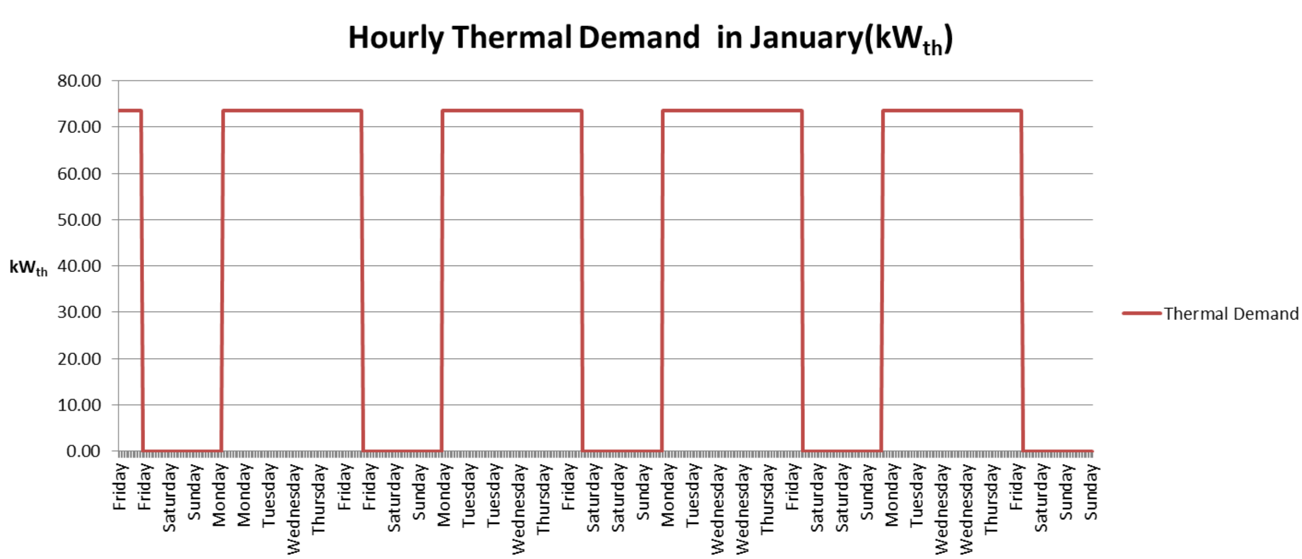
There are four steps to generate energy demand profile. First step, user can adjust the constant demand throughout the year in each month. For example in the graph below, in December (winter) the heat demand is at maximum so it is set to 100%, while in July (summer) the heat demand is at half of the maximum demand so it is set to 50%.

Figure 10: Result of the first step of generating hourly demand profile



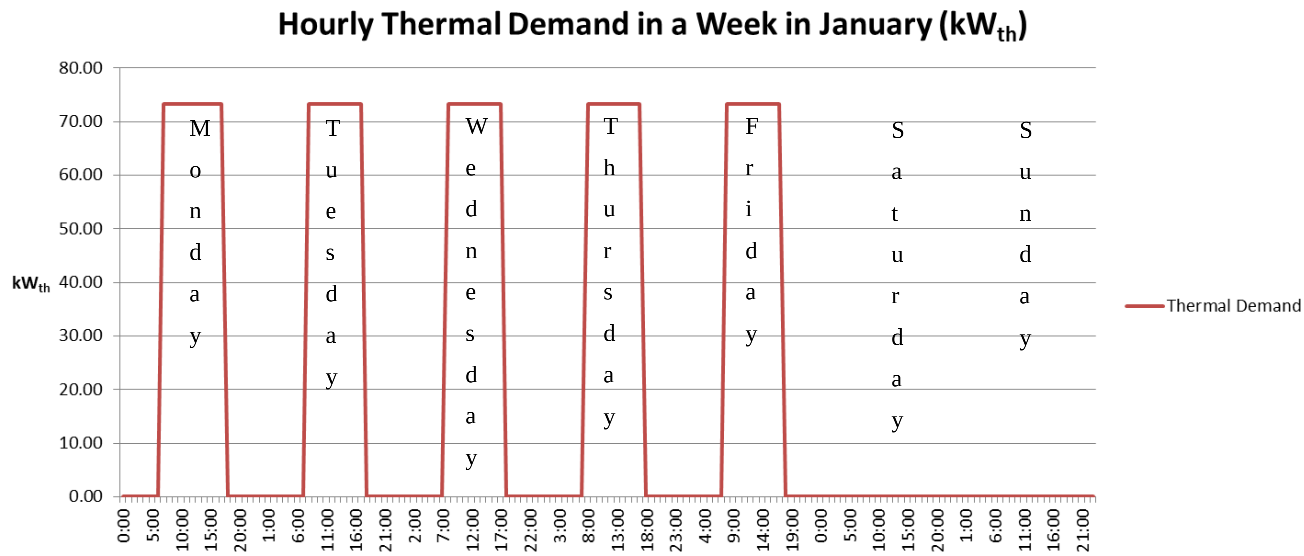
As for the second step, the user can choose the day and time that demands occur and end in every week for each month. For example in the graph below, in January the demand occurs at 7:00am on Monday and ends at 18:00 on Friday.

Figure 11: Result of the second step of generating hourly demand profile



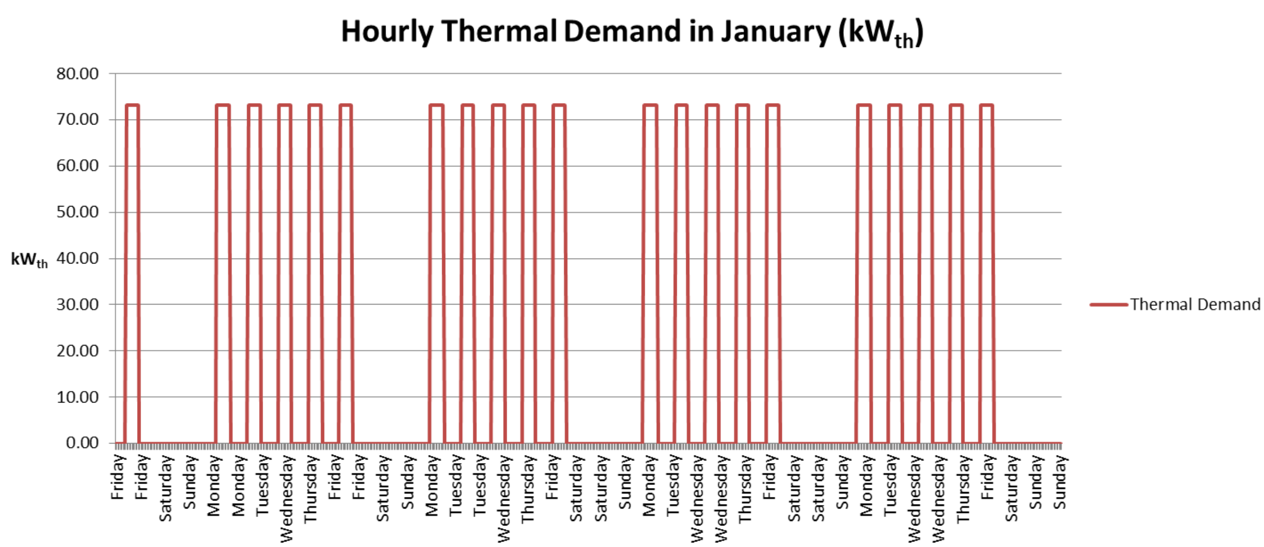
Thirdly, the user can choose the time that demands occur and end every day of every week in each month. For example in a week in January, the demand occurs at 7:00am on Monday and end at 18:00pm on Friday. Then the demands occur at 8:00am to 19:00pm from Tuesday to Thursday.

Figure 12: Result of the third step of generating hourly demand profile



And this is the example of hourly thermal demand result for January.

Figure 13: Example of hourly demand profile result in January



The user has to repeat these steps for every month in one year to get the hourly demand profile for one year. Finally in the fourth step, user can enter the average heat loss in percentage for each month. This will increase the hourly heat demand according to the input for each month.

This demand generation method is to help user that does not have the hourly energy demand data, but has some ideas about how the energy is being used throughout the year. This energy demand data can represent the approximate hourly energy usage or approximate hourly energy that needs to be supplied by the biomass boiler or CHP.

After this, user has to fill the existing thermal and electrical energy supply information at the site in the designated area. The list of required information is:

1. Type of heating Supply Fuel
2. Lower heating value of the supply fuel (kWh/Litre)
3. Fuel price (£/Litre)
4. Boiler efficiency existing at the site in percentage
5. CO_2 emission factor for fuel (kgCO_2/Litre)
6. Electricity supply source
7. Electricity price rate (£/kWh)
8. CO_2 emission factor for electricity imported (kgCO_2/kWh)

Figure 14: Input area for existing energy information

Electrical			Thermal		
Annual Electricical Energy Demand	523,398.00	kWh	Annual Themal Energy Demand	444,123.75	kWh
Electricity Supply Source	Grid		Heating Supply Fuel	Kerosene	
			Lower Heating Value	10.35	kWh / Litre
Electricity Price Rate	0.10	£ / kWh			
Annual Fuel Cost	52,339.80	£	Fuel Price	0.57	£ / Litre
			Boiler Efficiency	70.00	%
CO_2 Emission Factor	0.59	kg CO_2 / kWh	Annual Fuel Consumption	61,300.72	Litre
Annual CO_2 Emission	310,730.92	kg CO_2	Annual Fuel Cost	34,941.41	£
			CO_2 Emission Factor	3.01	kg CO_2 / Litre
			Annual CO_2 Emission	184,650.04	kg CO_2

3.5.2 Wood Fuel

This section allows the user to enter wood fuel to use in the biomass boiler and CHP. It is mainly divided into two parts. The first part is wood waste. The user can enter one type of wood or a mixture of wood in this tool. This sector is really important because the rate at which the wood will be consumed and the price are based on the wood fuel characteristics. The user can define four different wood waste fuel cases. In each case, mixed or single type of wood waste can be chosen.

First of all, user enters the name, chooses the type of wood in the dropdown list, and specifies the total amount of waste wood available at site per annum. Then the user enters the type of wood, mass percentage (weight proportion of mixed wood), moisture content, ash content (dry basis), fuel density (dry basis), lower heating value (dry basis), and CO_2 emission factor as input. Finally, the tool will calculate the ash content (as received), fuel density (as received), and lower heating value (as received).

Figure 15: Input area for wood waste information

1st Wood Fuel Case

Name	Precast Concrete Site	
Type	Mixed Type of Wood	
Available at Site	150,000.00	kg / year

Type of Wood	Percentage (%)	Mositure Content (%)	Ash Content (%)		Fuel Density (kg/m^3)		Lower Heating Value (kWh/kg)		CO_2 Emission Factor (kg·CO_2/kg)
			Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	
Pine	50	20	100	80	100	125	5.138888889	3.622511111	
Plywood	50	20	0.6	0.48	20	25	5.277777778	3.733622222	
				0		0		0	
				0		0		0	
				0		0		0	
				0		0		0	
				0		0		0	
				0		0		0	
				0		0		0	

The tool will summarise the waste wood fuel characteristics in the bottom table, after the user completes the information.

Figure 16: Wood waste summary table

Wood Waste Summary							
Name	Mositure Content (%)	Ash Content (%) (%)	Fuel Density (kg/m^3)	Lower Heating Value (kWh/kg)	CO_2 Emission Factor (kg·CO_2/kg)	Available at Site (kg)	Price per kg (£)
Precast Concrete Site	20	40.24	75	3.678066667	0	150,000.00	0
b	15	35.3	81.42857143	6.10855	0	150,000.00	0
c	15	35.3	81.42857143	6.10855	0	150,000.00	0
d	15	35.3	81.42857143	6.10855	0	150,000.00	0

The second part is the extra biomass that needs to be purchased for each waste wood case. This part was created in the case that energy from waste wood is not enough to supply the thermal energy demand throughout the year. Therefore, the user needs to purchase extra wood fuel to support the shortfall of waste wood fuel. The inputs are similar to those in waste wood fuel except for the price per kg delivered that has to be entered.

Figure 17: Input area for extra wood needed to purchase information

Extra Biomass Needed to Purchase									
For Wood Waste	Mositure Content (%)	Ash Content (%)		Fuel Density (kg/m3)		Lower Heating Value (kWh/kg)		CO2 Emission Factor (kg·CO2/kg)	Price per kg Delivered (£)
		Dry Basis	s Receive	Dry Basis	As Received	Dry Basis	As Received		
a	30	100	70	100	142.85714	7	4.1671		1
b		0.6	0.6	20	20		0		1
c			0		0		0		1
d			0		0		0		1

The meaning of each parameter and the calculations involved will be described later in the appendix 3.

3.5.3 Biomass boiler and CHP Specification

After specifying the wood fuel characteristics of a particular site, the next step is to choose the suitable biomass boiler and CHP to supply the energy demand. Then 10 or less suitable biomass boiler and/or CHP information can be inserted in the bottom table of this section. The information required is:

Figure 18: Input area for biomass boiler and CHP information

Biomass Boiler, and Combined Heat and Power (CHP)	
Boiler or CHP	Boiler + Thermal Storage
Manufacturer	Farm2000
Manufacturer Model	REFO 80 + Thermal Storage
Electrical Consumption	10.00
Conversion Technology	combustion
Power Generation Technology	-
Maximum Thermal Output (kW_{th})	75.00
Efficiency at 75-100% Load (%)	94.00
Efficiency at 50-75% Load (%)	75.00
Efficiency at 25-50% Load (%)	50.00
Efficiency at 0-25% Load (%)	30.00
Maximum Power Output (kW_e)	~~25.00~~
Heat to Power Ratio at 100% Load	~~3.20~~
HPR at 50-75% Load	~~4.00~~
HPR at 25-50% Load	~~5.00~~
HPR at 0-25% Load	~~6.00~~
Thermal Storage Size (m^3)	6.00
Thermal Storage Min Temp (°C)	50.00
Thermal Storage Max Temp (°C)	90.00
Fluid Type	Water
Specific Heat Capacity (kWh / kg K)	0.0012
Density of Fluid (kg/m^3)	1,000.00
Average Temp Drop (°C / hour)	1.00
Initial Temperature (°C)	50.00
Capital Cost (£)	20,000.00
Operation and Maintenance Cost (£)	1,000.00

1. Boiler or CHP
2. Manufacturer name
3. Manufacturer model name
4. Electricity consumption for the technology in kW
5. Biomass conversion technology
6. Power generation technology
7. Rated thermal output in kW_{th}
8. Efficiency at 75-100% Load
9. Efficiency at 50-75% Load
10. Efficiency at 25-50% Load
11. Efficiency at 0-25% Load
12. Maximum power output in kW_e
13. Heat to power ratio at 75-100% load
14. Heat to power ratio at 50-75% load
15. Heat to power ratio at 25-50% load
16. Heat to power ratio at 0-25% load
17. Thermal storage size (m^3)
18. Thermal storage min temp (°C)
19. Thermal storage max temp (°C)
20. Thermal storage fluid type
21. Thermal storage fluid specific heat capacity (kWh / kg·C)
22. Density of fluid in thermal storage (kg/m^3)
23. Thermal storage average temp drop (°C / hour)
24. Thermal storage initial temperature (°C)
25. Initial cost (£)

26. Operation and maintenance cost (£)

It is important that user finds a suitable wood waste biomass boiler and CHP to fill in this section based on the understanding mentioned in the literature review chapter. The detailed calculation of each parameter will be described later in the appendix 3.

3.5.4 Comparing Biomass Boiler and CHP

This section of the tool is considered the main section. Type of wood waste, and biomass boiler and CHP specified in the previous section are chosen to compare the economic and environmental performance in this section. The total number of comparison is seven; therefore it has seven cases to be compared. It can compare the same biomass boiler and CHP with different type of wood waste, or the same type of wood waste with different biomass boiler and CHP. This section has eight subsections which are:

1. Annual energy demand

   This subsection indicates the total amount of electrical and thermal energy demand per year in kWh based on the energy demand section.

2. Choose wood fuel

   In this subsection, user is able to choose the type of wood waste specified before. Wood fuel type can be selected from the dropdown list based on the wood waste fuel section. After choosing the wood fuel type, the tool will show the important parameters for that particular wood fuel such as moisture content, ash content, calorific value, fuel cost, and wood fuel available at site.

Figure 19: Wood fuel choosing area

Choose wood Fuel			
		1st Case	2nd Case
Fuel Type		Wood Chips 1	Wood Chips 2
Moisture Content	%	15	10
Ash Content	%	0.7	0.6
Calorific Value	kWh/kg	4	4.2
Fuel Cost (Available at Site)	£ / kg	0	0
Extra Fuel Cost (Need to purchase)	£ / kg	0.09	0.09
wood Fuel Available at Site	kg	150000	150000

3. Choose biomass boiler and CHP

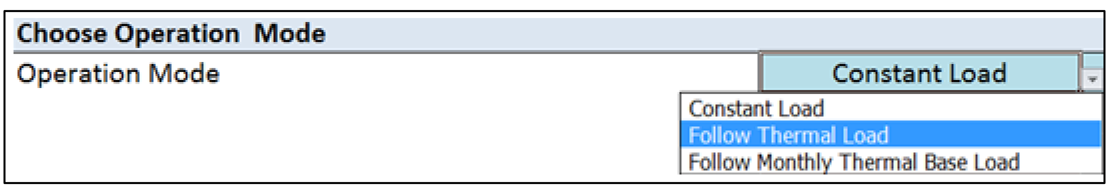
In this subsection, user is able to choose biomass boiler and CHP specified before. The biomass boiler and CHP can be selected from the dropdown list based on the biomass boiler and CHP specification section. The tool will show the biomass conversion technology, power generation technology, and maximum thermal and electrical output after the boiler or CHP is chosen.

Figure 20: Biomass boiler and CHP choosing area

Choose Biomass Boiler and CHP			
		1st Case	2nd Case
Manufacturer Model		REFO 80 + Thermal Storage	BG 25
Boiler or CHP		Boiler + Thermal Storage	CHP
Conversion Technology		combustion	epped moving grate combust
Power Generation Technology		-	turbo-compound heat engine
Maximum Thermal Output	kW_{th}	75	80
Maximum Power Output	kW_e	N/A	25

Then the user has to choose the operation mode for the boiler or CHP chosen. There are three operation modes to choose from, which are constant load, follow thermal load, and follow monthly thermal base load.

Figure 21: Choosing operation mode area



- Constant load operation mode will let the boiler or CHP operate at constant thermal output, if the boiler or CHP is turned on. Users can choose to operate the boiler or CHP at one particular constant output throughout the year or choose to operate at different constant outputs for each month.

- Follow thermal load operation mode will let the boiler or CHP modulate its thermal output following the thermal demand, if the boiler or CHP is turned on.

- Follow monthly thermal base load operation mode will let the boiler or CHP operate at different constant thermal output each month following the thermal base load of each month, if the boiler or CHP is turned on.

After this, users can choose the time to operate the boiler or CHP. It can be operated all year round or by a weekly basis. If the user chooses to operate the boiler or CHP all year, it will run 24 hours for 365 days at a particular set running capacity. If user chooses to operate the boiler or CHP by a weekly basis, it can be set to operate at one particular running capacity for each month. And it also can be turned on and off at a set time every day or every week of each month. There are four steps to operate boiler or CHP by a weekly basis. These steps are similar to those in generating energy demand mentioned before in energy demand section.

Figure 22: Choosing operation mode and operation time area

Choose Operation Mode	
Operation Mode	Constant Load
Operation Time	Weekly Basis
All Year Running Capacity	All Year Weekly Basis
January	
Running Capacity	100%
Weekly Start Date	Monday
Weekly Start Time	0:00
Daily Interval Start Time	0:00
Daily Interval End Time	23:59
Weekly End Date	Sunday
WEekly End Time	23:59
February	
Running Capacity	100%
Weekly Start Date	Monday
Weekly Start Time	0:00
Daily Interval Start Time	0:00
Daily Interval End Time	23:59
Weekly End Date	Sunday
WEekly End Time	23:59

After choosing the biomass boiler and CHP, operation mode, and operation time, this tool will provide information on biomass fuel used, thermal and electrical energy supply-demand matching results for all cases in this subsection based on all the input. The figure below shows the result in this subsection. The detailed calculation of biomass fuel used and energy supply-demand matching will be mentioned later in the appendix 3.

Figure 23: Results in choosing biomass boiler and CHP subsection

Biomass Fuel Used		
Annual Fuel Consumption	kg	125,176
Surplus Biomass Fuel	kg	24,824
Deficit Biomass Fuel	kg	0
Thermal Energy Supply-Demand Matching		
Annual Thermal Generated	kWh	470,663
Annual Thermal Delivered to Load	kWh	444,124
Annual Thermal Energy Surplus	kWh	0
Annual Thermal Energy Deficit	kWh	0
Electrical Energy Supply-Demand Matching		
Annual Electricity Generated	kWh	0
Annual Electricity Delivered to Real Load	kWh	0
Annual Electricity Exported to Grid	kWh	0
Annual Remaining Electricity Required	kWh	589,648

4. CO_2 emissions

In this subsection, the tool will calculate the annual amount of CO2 emissions from biomass for each case, which is usually considered as carbon neutral. However, it can be calculated, if the user enters the CO2 emissions factor in the wood fuel section. Then the tool will give the annual CO2 emissions reduction based on fossil fuel usage for the same amount of electrical and thermal energy produced to load for each case. The detailed calculation of CO2 emissions reduction will be mentioned later in the appendix 3.

5. Costs

The Initial cost represents the costs which is the sum of the design, purchase, construction, installation and grid connection costs of all the elements of the new biomass boiler or CHP system.

The operating and maintenance (O&M) costs are the sum of the annual costs to operate and maintain the new biomass boiler or CHP system.

The initial and O&M costs will be transferred to the result section for further financial calculation.

6. Savings, Grants, Renewable Heat Incentives (RHI), Renewable Obligation Certificate (ROC) and Feed in Tariff (FIT)

This subsection involves the financial benefit or loss for installing the biomass boiler and CHP. It can be separated into three main parts.

Firstly, this subsection calculates the fuel and electricity saving by replacing the existing technology with the biomass boiler or CHP for each case.

Secondly, users can enter the grant or subsidy that is paid for the initial cost of the biomass boiler or CHP. As for the grant that reduces loan interest rate, the user has to manually subtract it from the rate of interest on loan in the next subsection.

Finally, renewable Heat Incentives (RHI), Renewable Obligation Certificate (ROC) and Feed in Tariff (FIT) can be applied and analysed in this tool. Users have to enter all the required information in the designated cell. The detailed calculation of these financial incentives will be mentioned later in the appendix 3.

The savings, grants and financial incentives will be transferred to the result section for further financial calculation.

7. Loan

The model calculates the annual repayment, which is the portion of the total capital cost required to implement the project and that is financed by a loan. The annual repayment is calculated from the rate of interest on loan and number of years to complete the repayment. The detailed calculation of the loan will be mentioned later in the appendix 3.

8. Financial parameters

Users can enter a discount rate (%), which is the rate used to discount future cash flows in order to obtain their present value, as well as the inflation rate (%). The inflation rates that can be entered are biomass fuel price, electricity price, conventional fuel, operation and management cost, RHI, and FIT inflation rate. These parameters will be used to determine the economic performance for each case.

3.5.5 Results

There are seven results for seven cases in seven spreadsheets. This subsection contains the results of the calculations from all the input parameters entered in previous subsections. Supply-demand thermal and electrical energy matching graph is shown at the top of this section for each case. Below that, the net income and cumulative profit is calculated and shown every year for 30 years from the year zero (investment year) to the year thirty mainly based on these parameters:

1. Initial costs,
2. O&M costs,
3. Fuel saving,
4. Renewable heat incentive tariff,
5. Electrical saving,
6. Electricity Incomes from feed in tariff, and
7. Renewable obligation certificate incomes.
8. Grants

All the inflation rates are also applied to calculate more realistic and acceptable results in this section. Moreover, this also gives the amount of biomass available at site, biomass fuel used and CO_2 emissions reduction for each year. All the detail calculations will be described later in the appendix 3. This subsection helps users analyse the detailed economic performance of the biomass boiler or CHP each year.

Below the table, the tool provides the table of monthly fuel consumption of wood fuel in the result section to help design the biomass storage size.

3.5.6 Results comparison

This section gathers and summarises the economic, energy, and environmental performance between seven cases. Users will be able to compare these performances in this section. The economic factors that will be calculated and presented in this section are

- Payback period

  The tool calculates the payback period (years), which represents the length of time that it takes for installing the biomass boiler or CHP to repay the sum of its own investment. The basic analysis of the payback period is that the shorter periods are more desirable than longer periods of payback. This is not the parameter that measures the profits of the case compared to another. Instead, it measures the time required to recover the investment compared to another.

- Cumulative cash flow

  This tool calculates the total profits or losses over 30 years. This is the parameter that measures the profits of the case compared to each other. This is based on the cash flow analysis in the results section.

- Internal rate of return (IRR)

  The internal rate of return is the interest rate provided by the investment over the project lifetime. Alternatively, IRR is the value that makes the net present value (NPV) of net cash flow from the investment equal to zero. This parameter measures the desirability of investments. The basic analysis of IRR is that a higher IRR is more desirable than a lower IRR to undertake the project.

- Net Present Value (NPV)

  NPV is the present money value of the total net cash flow over the project lifetime. If the NPV is positive, it indicates that the project should be invested. Projects that provide the highest NPV are more desirable to undertake the project. However, the NPV alone may have limitations in decision-making; in case the projects with different investments have equal NPV. Therefore other parameters alongside NPV should be taken into consideration to support the decision-making.

- Profitability index (PI)

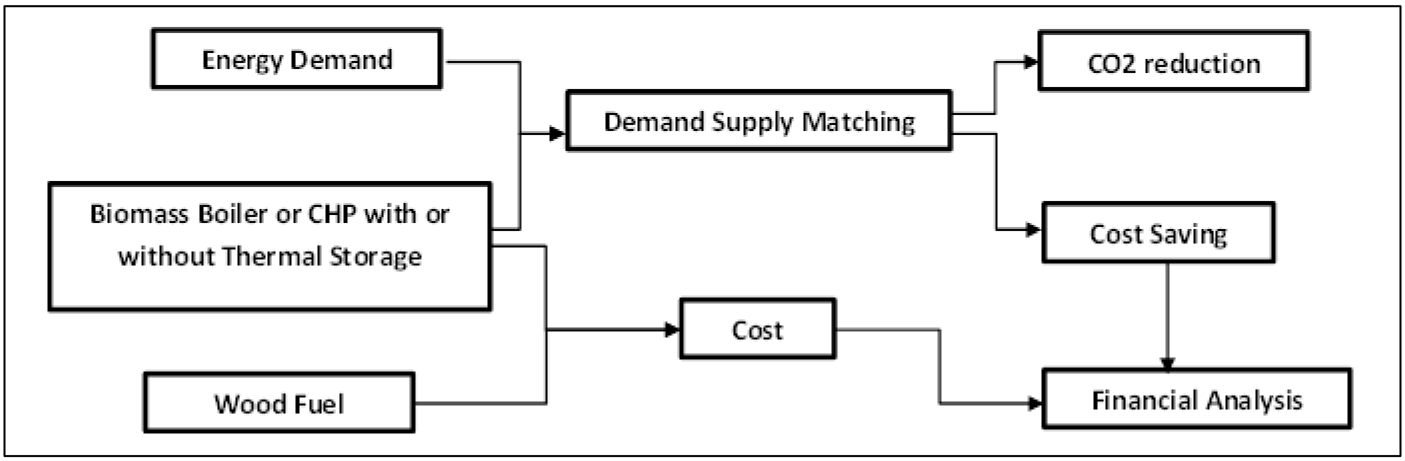
  Profitability index is the ratio of present value of the total net cash inflow to the initial investment (does not include the investment) over the project lifetime. This parameter measures the desirability of investments. The basic analysis of profitability index is that a higher positive PI is more desirable than a lower positive PI to undertake the project. If the PI is less than zero, it is not desirable to undertake the project.

The total thermal and electrical energy generated, delivered to load, surplus, and deficit are calculated and shown here over the project lifetime for each case. The environmental performance results are also shown in terms of equivalent CO2 emission reduction for each case.

3.6 Detail Calculation and Analysis of the Tool

The following are the detailed calculations and analysis which describes the calculations and how the parameters are connected with each other in energy demand, wood fuel, biomass boiler and CHP specification, comparing the biomass boiler and CHP, results, and results comparison section in this tool. The methodology of this tool can be illustrated in the figure below.

Figure 24: Tool Methodology



This figure illustrates the main methodology this tool considers in order to assess the feasibility of using waste wood as biomass fuel for the boiler and CHP.

The first step is to enter or generate thermal and electrical energy demand at the site. Then the user identifies the type of wood fuel to use as a biomass fuel. It was also identified that the different types of wood fuel have a big influence in the energy production.

Then, based on these two key facts with chosen biomass boiler or CHP with or without thermal storage, the tool calculates the energy demand supply matching and all the initial cost involved. After that, CO_2 emissions reduction and cost savings were calculated from the energy demand-supply matching in terms of CO_2 emissions reduction based on fossil fuel usage reduction, and electricity imported reduction.

Finally, the tool will analyse the financial benefit or loss based on the cost and cost savings of selected biomass boiler or CHP and wood fuel.

The calculation of this tool will be based on the methodology of the above figure. And the description will be separated into 6 sectors according to this tool structure.

3.6.1 Energy demand

After the user enters or generates the hourly thermal and electrical energy demand profile (the steps to generate are already described in 4.5.1), these parameters are entered by the user or calculated by the tool.

Heating supply fuel

The user enters the fuel type that supplies heating for existing technology before the biomass boiler and CHP were proposed.

Lower heating value

The low heating value (net calorific value) is the total amount of heat energy from burning fuel excluding the energy required to evaporate the water that accumulates in the fuel. The user enters the lower heating value and selects the suitable unit for the heating supply fuel.

This tool calculates energy based on kWh unit. When there is information of lower heating value in Joules unit, the user can convert to kWh by these formulas.

$$1\ kWh = 3.6\ MJ$$
$$1\ kWh = 3{,}600\ kJ$$
$$1\ kWh = 3{,}600{,}000\ J$$

Fuel price

The user enters the fuel price rate according to the unit given by the tool.

Electricity price rate

The user enters the price of electricity imported from the grid per kWh.

Boiler efficiency

The user enters the efficiency of the boiler for heating of existing technology before proposed biomass boiler and CHP.

Annual fuel consumption

The tool calculates annual fuel consumption from this equation

$$Annual\ fuel\ consumption\ (Unit) = \frac{Annual\ thermal\ energy\ demand\ (kWh)}{Lower\ heating\ value\ of\ fuel\ (\frac{kWh}{unit})\ \times boiler\ efficiency}$$

The unit of the fuel consumption depends on the selected unit in the lower heating value cell by user.

Annual fuel cost

Annual fuel cost is the product of annual fuel consumption and fuel price. This is the estimation of the money spent for supplying fuel from the existing technology. The reason that this figure is just an estimated cost is because the fuel price usually varies throughout the year. But only one particular fuel price is calculated in this tool.

CO_2 emission factor

The user enters CO_2 emission factor for the thermal supply fuel. This figure represents the greenhouse gas emissions converted into kilograms of carbon dioxide equivalent (kg CO_2) per unit of fuel or kWh. Users can find more information on this in the Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting (2011).

Annual CO_2 emission

The tool calculates the total of equivalent CO_2 emission per year by multiplying CO_2 emission factor with the annual fuel consumption.

3.6.2 Wood fuel

After the hourly thermal and electrical energy demands are generated or entered, the user enters the wood waste fuel characteristics. The following parameters are entered and calculated by the user and the tool respectively.

Name

The user enters the name of the waste wood fuel in each case for reference purposes only.

Type

The user chooses the type of wood waste from the dropdown list. Single Type of Wood means that there is only one type of wood characteristic in this wood waste case. Mixed Type of Wood means that there is more than one type of wood characteristic in this wood waste case. Users can enter up to ten wood characteristics when Mixed Type of Wood is chosen.

Available at site

User enters the amount of wood waste available at site per year in kg.

Type of wood

The user enters the type of waste wood fuel in in the table for reference purposes only.

Mass Percentage (%)

The user enters the weight proportion in percentage of each type of wood in the table.

Moisture content (%)

The user enters the moisture content of each type of wood in the table. This value depends on the type of wood and the process it went through.

Dry basis ash content (%)

The user enters the dry basis ash content of each type of wood in the table. Dry basis ash content is the ash content in the wood when it is completely dried (0% moisture content).

Ash content as received (%)

This value is calculated from moisture content and dry basis ash content of the wood with this equation.

$$Ash\ content\ as\ received = Dry\ basis\ ash\ content * (100 - Moisture\ content)\%$$

Dry basis fuel density (kg/m^3)

The user enters the dry basis fuel density of each type of wood in the table. Dry basis fuel density is the fuel density of the wood when it is completely dried (0% moisture content).

Fuel density as received (kg/m^3)

This value is calculated from the moisture content and dry basis fuel density of the wood with this equation.

$$Fuel\ density\ as\ received = \frac{Dry\ basis\ fuel\ density}{(100 - Moisture\ content)\%}$$

Dry basis lower heating value (kWh/kg)

The user enters the dry basis lower heating value of each type of wood in the table. Dry basis lower heating value is the lower heating value of the wood when it is completely dried (0% moisture content).

When the dry basis lower heating value is in MJ/kg unit rather than kWh/kg, the user has to convert the unit by these formulas.

$$1\ kWh = 3.6\ MJ$$

Lower heating value as received (kWh/kg)

This value is calculated from the moisture content and the dry basis lower heating value of the wood with this equation (British Standards Institution, 2010).

$$Lower\ heating\ value\ as\ recieved = \left[Dry\ basis\ lower\ heating\ value\ (\frac{kWh}{kg}) \times (100 - Moisture\ content)\%\right] - (0.006786 \times Moisture\ content)$$

Where 0.006786 is the correction factor of the enthalpy of vaporisation at constant pressure for water at 25°C in kWh/kg.

CO_2 emission factor ($kgCO_2/kg$)

The user enters the CO2 emission factor of each wood type in the table. Normally, this value is zero due to the neutral carbon cycle characteristic of biomass. However, users can enter this figure, if the CO_2 emission from biomass combustion is needed.

Price per kg (£)

The user enters price per kg of the type of wood. This price shows the money spent and chipping wood waste before using it in the biomass boiler or CHP. This price does not include the price of the wood itself, because wood waste is the waste or by-product from manufacture.

Wood waste summary

The tool calculates average characteristic value of all the wood waste types for each case by using mass percentage of each wood waste. For each case,

$$Characteristic\ Value = \sum_{i=1}^{10}(Value_i \ \times Mass\ percentage_i)$$

Price per kg delivered (kg)

The user enters the price per kg delivered of the wood fuel, which transportation cost is already taken into account.

3.6.3 Biomass boiler and CHP specification

After entering the wood fuels for biomass boiler and CHP, the user has to enter the suitable boiler and CHP specification in this sector.

Boiler or CHP

User has to specify the type of energy supply from Boiler, Boiler + Thermal Storage, CHP, and CHP + Thermal Storage from the dropdown list.

Manufacturer

The user enters the manufacturer name for reference purposes only.

Manufacturer model name

The user enters the manufacturer model name for reference purposes only.

Electricity consumption

The user enters the electricity consumption of the boiler or CHP while operating in kW according to the manufacturer specification. This figure will be added to an hourly electrical energy demand load profile for later calculation.

Conversion technology

The user enters the biomass conversion technology of boiler or CHP for reference purposes only. This information helps make the decision on eligibility and tariff level of renewable heat incentives.

Power generation technology

The user enters the power generation of CHP for reference purposes only.

Rated thermal output (kW_{th})

The user enters rated thermal output of boiler or CHP in kW_{th} according to the manufacturer specifications. This figure will be used to calculate the thermal energy supply by the boiler or CHP, and biomass fuel used at different operating capacities, and the renewable heat incentive tariff incomes.

Efficiency at 75-100%, 50-75%, 25-50%, and 0-25% Load

The user enters the thermal efficiency in percentage at range of the operating capacity of boiler or CHP. These figures will be used to calculate the thermal energy supply by the boiler or CHP, and the biomass fuel used at different operating capacities. Normally, the efficiency would be lower when the operating capacity is turned down.

Rated power output in kW_e

The user enters rated power output of CHP in kW_e according to manufacturer specification. This figure will be used to calculate the electrical energy supply by CHP, and help make the decision on eligibility and tariff level of feed in tariff, as well as eligibility and banding of renewable obligation certificate.

Heat to power ratio at 75-100%, 50-75%, 25-50%, and 0-25% load

The user enters heat to power ratio at range of operating capacity of CHP. These figures will be used to calculate the electrical energy supply by CHP at different operating capacity. Normally, the heat to power ration would be higher when the operating capacity is turned down.

Thermal storage size (m^3)

The user enters the size of the thermal storage in cubic metre (m^3) to help increase the performance of the boiler or CHP. This figure will be used to calculate the amount of heat absorbed from the boiler or CHP, and release it to the load. When the size of the thermal storage is in other units rather than cubic metre, the user has to convert the unit by these formulas.

$$1\ cubic\ metre = 1{,}000\ litres$$
$$1\ cubic\ metre = 219.97\ gallon\ (Imperial)$$
$$1\ cubic\ metre = 264.17\ gallon\ (US\ fluid)$$
$$1\ cubic\ metre = 35.3\ cubic\ feet$$
$$1\ cubic\ metre = 1.31\ cubic\ yards$$

Thermal storage min temp (°C)

The user enters the minimum temperature in Celsius that the thermal storage can handle and operate. This temperature represents the limitation of temperature when the thermal storage supplies heat to the load and losses its temperature. This figure is entered to help with the calculation as said before in the limitation of this tool, this tool provides basic calculation for the thermal storage system. Therefore it does not represent the thermal storage in real practice, but the simple one.

When the temperature is in other units rather than Celsius, the user has to convert the unit by these formulas.

Convert from Fahrenheit	$℃ = (°\mathrm{F} - 32) \times \frac{5}{9}$
Convert from Kelvin	$℃ = °K - 273.15$

Thermal storage max temp (°C)

The user enters the maximum temperature in Celsius that thermal storage can handle and operate. This temperature represents the limitation of temperature when the thermal storage absorbs heat from the boiler or CHP and increases its temperature. In practice, the maximum temperature largely depends on the insulation of the thermal storage.

When the temperature is in other units rather than Celsius, the user has to convert the unit by above formulas.

Fluid type

The user enters the type of fluid in the thermal storage for reference purposes only.

Specific heat capacity (kWh / kg·C)

The user enters the specific heat capacity at constant pressure of the fluid in the thermal storage. The specific heat capacity of fluid is the heat required to increase or decrease the fluid temperature by one degree of temperature. This figure will be used to calculate the amount of heat absorb from the boiler or CHP, and releases it to the load.

This tool calculates energy based on kWh unit. When there is information on specific heat capacity in the Joules unit, the user can convert it to kWh by formulas mentioned before in the energy demand section in this chapter.

Density of fluid (kg/m^3)

The user enters the density of fluid in the thermal storage. This figure will be used to calculate the amount of heat absorbed from the boiler or CHP, and releases it to the load.

Average temp drop (°C / hour)

The user enters the average temperature drop in the thermal storage in Celsius per hour throughout the year. This figure represents the heat loss in the thermal storage per hour.

Initial temperature (°C)

The user enters the initial temperature of the fluid in the thermal storage in Celsius. This figure represents the temperature at the start of the calculation. In other words, it shows the temperature of the fluid in the thermal storage right before the 00:00am on the 1^{st} of January since the calculation will always start at 00:00am on the 1^{st} of January in this tool.

Initial cost (£)

The user enters the initial cost, which is the sum of the design, purchase, construction, installation and grid connection costs of all the elements of the new biomass boiler or CHP system.

Operation and maintenance cost (£)

The user enters the operating and maintenance (O&M) costs, which are the sum of the annual costs to operate and maintain the new biomass boiler or CHP system.

3.6.4 Comparing Biomass Boiler and CHP

After choosing the wood fuel and biomass boiler or CHP (the method of choosing biomass boiler and CHP, and their operation mode is described in the previous chapter), the tool will calculate the technical and economic outcomes based on the entered parameter. The technical outcomes are biomass fuel used, thermal and electrical energy supply-demand matching, and CO_2 emissions.

Biomass fuel used

- *Annual biomass fuel consumption*

Annual biomass fuel consumption is the sum of hourly biomass fuel consumption for one year. Biomass fuel used per hour is calculated from the lower calorific value of wood fuel, the thermal output, and the efficiency of that of the thermal output of biomass boiler or CHP.

The equation used for calculate biomass fuel consumption every hour is

$$Biomass\ fuel\ consumption\ (kg) = \frac{thermal\ energy\ output\ (kWh)}{efficiency\ (\%)} \times \frac{1}{lower\ calorific\ value\ of\ waste\ wood\ fuel\ (\frac{kWh}{kg})}$$

Thermal energy output depends on the specification and operation mode at that hour of biomass boiler or CHP.

Efficiency depends on the thermal energy output at that hour compared to the rated thermal output. For example, the boiler rated thermal output is 100 kW, and the boiler thermal output is 70 kW at one particular hour. Therefore its operating capacity is 70% of rated thermal output at that hour. If the user enters the thermal efficiency of the biomass boiler and CHP specification like the following table, the tool will take the thermal efficiency of this boiler at 50-75% load from this table, which is **77%**.

Figure 25: Thermal efficiency at range of operating capacity

Efficiency at 75-100% Load (%)	94
Efficiency at 50-75% Load (%)	77
Efficiency at 25-50% Load (%)	64
Efficiency at 0-25% Load (%)	40

- *Surplus and deficit biomass fuel*

The tool to calculate the annual surplus and deficit biomass fuel is by comparing the annual biomass fuel consumption with the biomass fuel available at the site. If there is surplus biomass fuel, the tool will add it to the following year. If there is deficit biomass fuel, the tool will calculate the cost of purchasing this shortfall of wood waste fuel based on the price per kg delivered input in the wood fuel section.

Thermal energy supply-demand matching

- *Annual thermal energy generated*

Annual thermal energy generated is the sum of hourly thermal output of the biomass boiler or CHP for one year. The hourly thermal output based on specification and operation mode of the biomass boiler or CHP.

- *Thermal Storage*

Before the description of the annual thermal energy delivered to the load of biomass boiler or CHP operate with thermal storage, it is essential to explain how the thermal storage works in this tool and all the calculations involved.

Thermal energy storage would help increase the efficiency of the biomass boiler and CHP by storing excess thermal energy when thermal energy supply exceeds the thermal energy demand, as well as releasing thermal energy when the thermal energy supply is less than the thermal energy demand. Thermal storage allows the biomass boiler or CHP to be operated at maximum efficiency and output, resulting in clean combustion, which extends lifetime of the boiler.

The thermal storage system simulated in this tool is sensible for heat storage systems. In this system, the thermal energy is stored or released by heating or cooling a liquid or a solid. This liquid or solid will not change its phase during the process in this system.

The thermal storage system capacity is given by

$$\begin{aligned} Q &= m \cdot c \cdot \Delta t \\ &= V \cdot \rho \cdot c \cdot \Delta t \end{aligned}$$

Where V is volume, ρ is density, c is specific heat capacity, and Δt is temperature difference between maximum temperature and minimum temperature of the medium.

If the user chooses to couple the biomass boiler or CHP with thermal storage, the user has to enter the volume of the thermal storage (V) in m^3, the specific heat capacity (c) in kWh/ kg·C and density (ρ) in kg / m^3 of the liquid medium. Then from the above equation

$$Q = V \cdot \rho \cdot c \cdot \Delta t$$

$$Q = V \cdot \rho \cdot c \cdot (t_h - t_{h-1})$$

Where t_h is the temperature at time considered, and t_{h-1} is the temperature at 1 hour before.

It can be derived to

$$t_h = t_{h-1} + \frac{Q}{V \cdot \rho \cdot c}$$

At every hour the tool will calculate using this equation and below algorithm.

When the thermal energy supply from biomass boiler or CHP > thermal energy demand, the thermal storage will store energy so Q is > 0. Then the temperature at next hour is

$$t_h = t_{h-1} + \frac{|Q|}{V \cdot \rho \cdot c}, \qquad if\ t_h > t_{max}\ then\ t_h = t_{max}$$

This temperature can be increased until it reaches the maximum temperature set by the user. The thermal energy supply from biomass boiler or CHP will be deducted by this Q.

When the thermal energy supply from biomass boiler or CHP < thermal energy demand, the thermal storage will release energy so Q is < 0. Then the temperature at next hour is

$$t_h = t_{h-1} - \frac{|Q|}{V \cdot \rho \cdot c}, \qquad if\ t_h < t_{min}\ then\ t_h = t_{min}$$

This temperature can be decreased until it reaches the minimum temperature set by the user. Then thermal energy supply from biomass boiler or CHP will be added by this Q.

Moreover, the thermal storage can be set to loss its temperature due to heat loss. The user can set temperature loss of thermal storage per hour.

- *Annual thermal energy delivered to load*

Annual thermal energy delivered to the load is the sum of the hourly thermal energy delivered to the load of the biomass boiler or CHP with or without thermal storage for one year. The explanation of how the thermal storage works and all the calculation involved in this tool is described before. Hourly, thermal energy delivered to the load is calculated by the following algorithm and equations.

If thermal energy supply by the system is more than or equal to thermal energy demand at that particular hour, then

$$Thermal\ energy\ delivered\ to\ load\ (kWh) = Thermal\ energy\ demand(kWh)$$

But if thermal energy supply by the system is less than thermal energy demand at that particular hour, then

$$Thermal\ energy\ delivered\ to\ load\ (kWh) = Thermal\ energy\ supply\ (kWh)$$

- *Annual thermal energy surplus and deficit*

Annual thermal energy surplus and deficit is the sum of hourly thermal energy surplus and deficit of the biomass boiler or CHP with or without thermal storage for one year. Hourly thermal energy surplus and deficit is calculated by the following algorithm and equations.

If thermal energy supply by the system is more than thermal energy demand at that particular hour, then

$$Thermal\ energy\ surplus\ (kWh) = Thermal\ energy\ supply\ (kWh) - Thermal\ energy\ demand(kWh)$$

But if thermal energy supply by the system is less than thermal energy demand at that particular hour, then

$$Thermal\ energy\ deficit\ (kWh) = Thermal\ energy\ demand(kWh) - thermal\ energy\ supply(kWh)$$

Electrical energy supply-demand matching

- *Annual electrical energy generated*

Annual electrical energy generated is the sum of hourly electrical energy generated for one year. Electrical energy generated per hour is calculated from the thermal output, and the heat to power ratio at that thermal output of biomass CHP.

The equation used for calculate electrical energy generated every hour is

$$Electrical\ energy\ generated\ (kWh) = \frac{Thermal\ energy\ output\ (kWh)}{Heat\ to\ power\ ratio}$$

Thermal energy output depends on the specification and operation mode at that hour of biomass CHP.

Heat to power ratio depends on the thermal energy output at that hour compared to the rated thermal output. For example, the CHP rated thermal output is 100 kW, and the boiler thermal output is 80 kW at one particular hour. Therefore its operating capacity is 80% of the rated thermal output at that hour. If the user enters the heat to power ratio in the biomass CHP specification like the following table, the tool will take the heat to power ratio of this boiler at 75-100%load from this table, which is **3.2**.

Figure 26: Heat to power ratio at range of operating capacity

Heat to Power Ratio at 75-100% Load	3.2
Heat to Power Ratio at 50-75% Load	10
Heat to Power Ratio at 25-50% Load	20
Heat to Power Ratio at 0-25% Load	30

- *Annual electricity delivered to real load*

Real load is the electrical demand at the site excluding electrical energy consumed by CHP. Annual electricity delivered to real load is the sum of hourly electricity delivered to real load in one year. Hourly, electricity delivered to the real load and is calculated by following algorithm and equations.

If electrical energy supply by the CHP is more than or equal to the electrical energy demand at that particular hour, then

$$Electrical\ energy\ delivered\ to\ all\ the\ load\ (kWh) = Electrical\ energy\ demand (kWh)$$

Therefore

$$\begin{aligned} &Electrical\ energy\ delivered\ to\ the\ real\ load\ (kWh) \\ &\quad = Electrical\ energy\ demand (kWh) \\ &\quad - electrical\ energy\ consumed\ by\ the\ CHP (kWh) \end{aligned}$$

But if the electrical energy supplied by the CHP is less than the electrical energy demand at that particular hour, then

$$Electrical\ energy\ delivered\ to\ all\ the\ load\ (kWh) = Electrical\ energy\ supply\ (kWh)$$

Therefore,

$$\begin{aligned} &Electrical\ energy\ delivered\ to\ the\ real\ load\ (kWh) \\ &\quad = Electrical\ energy\ supply (kWh) \\ &\quad - electrical\ energy\ consumed\ by\ the\ CHP\ (kWh) \end{aligned}$$

- *Annual electricity energy surplus and deficit*

Annual electrical energy surplus and deficit is the sum of hourly electrical energy surplus and deficit of the biomass CHP for one year. Hourly electrical energy surplus and deficit is calculated by the following algorithm and equations.

If electrical energy supplied by the system is more than the electrical energy demand at that particular hour, then

$$\begin{aligned} &Electrical\ energy\ surplus\ (kWh) \\ &\quad = Electrical\ energy\ supply\ (kWh) - Electrical\ energy\ demand (kWh) \end{aligned}$$

But if electrical energy supplied by the system is less than electrical energy demand at that particular hour, then

$$\begin{aligned}&Electrical\ energy\ deficit\ (kWh)\\&\quad = Electrical\ energy\ demand(kWh) - Electrical\ energy\ supply(kWh)\end{aligned}$$

CO_2 Emissions

- *Annual CO_2 emission from biomass*

The tool calculates amount of equivalent CO_2 emission from biomass for one year by this equation.

$$\begin{aligned}&Annual\ CO_2\ emission\ from\ biomass\ (kg \cdot CO_2)\\&\quad = [Annual\ wood\ waste\ fuel\ consumption\ (kg)\\&\quad \times\ CO_2\ emission\ factor\ of\ waste\ wood\ fuel\ (kg \cdot CO_2/kg)]\\&\quad + [Annual\ wood\ needed\ to\ purchase\ fuel\ consumption\ (kg)\\&\quad \times\ CO_2\ emission\ factor\ of wood\ needed\ to\ purchase\ fuel\ (kg \cdot CO_2/kg)]\end{aligned}$$

CO_2 emission factor is entered in wood fuel section.

- *Annual CO_2 emission reduction*

The tool calculates the amount of equivalent CO_2 emission reduction for one year by this equation.

$$\begin{aligned}&Annual\ CO_2\ \ emission\ reduction(kg \cdot CO_2)\\&\quad = Annual\ CO_2\ \ emission\ reduction\ from\ imported\ electricity(kg \cdot CO_2)\\&\quad + Annual\ CO_2\ \ emission\ reduction\ from\ thermal\ supply\ fuel(kg \cdot CO_2)\\&\quad - Annual\ CO_2\ emission\ from\ biomass\ (kg \cdot CO_2)\end{aligned}$$

when,

$$Annual\ CO_2\ \ emission\ reduction\ from\ imported\ electricity (kg \cdot CO_2)$$
$$=\ CO_2\ emission\ factor\ of\ imported\ electricity\ (kg \cdot CO_2/kWh)$$
$$\times\ [Annual\ electrical\ energy\ demand\ \ of\ exisiting\ technology\ (kWh)$$
$$-\ Annual\ electrical\ energy\ deficit\ of\ new\ biomass\ boiler\ or\ CHP\ system (kWh)\ ]$$

Annual CO_2 emission reduction from imported electricity can be positive or negative value, because the electricity consumption by boiler or CHP is also considered.

,and

$$Annual\ CO_2\ \ emission\ reduction\ from\ thermal\ supply\ fuel\ (kg \cdot CO_2)$$
$$=\ CO_2\ emission\ factor\ of\ thermal\ supply\ fuel\ (kg \cdot CO_2/unit)$$
$$\times \left(\frac{Annual\ thermal\ energy\ delivered\ to\ load\ (kWh)}{LHV\ of\ thermal\ supply\ fuel\ (\frac{kWh}{unit}) \times Efficiency\ of\ the\ boiler\ of\ existing\ technology} \right)$$

Costs

The tool will take and show the initial and O&M cost from the biomass boiler specification sector according to the manufacturers model selected for each case.

Savings, Grants, Renewable Heat Incentives (RHI), Renewable Obligation Certificate (ROC) and Feed in Tariff (FIT)

- *Thermal supply fuel saving*

This is the amount of money saving from installing new biomass boiler or CHP regarding to thermal supply fuel.

$$Annual\ thermal\ supply\ fuel\ saving\ (£)$$
$$= Thermal\ supply\ fuel\ cost\ (equivalent\ supply) (£)$$
$$-\ Annual\ biomass\ fuel\ cost (£)$$

When,

$$Thermal\ supply\ fuel\ cost\ (equivalent\ supply)(£)$$
$$= Thermal\ supply\ fuel\ price\ (£/unit)$$
$$\times \left(\frac{Annual\ thermal\ energy\ delivered\ to\ load\ (kWh)}{LHV\ of\ thermal\ supply\ fuel\ (\frac{kWh}{unit}) \times Efficiency\ of\ the\ boiler\ of\ existing\ technology} \right)$$

Thermal supply fuel cost indicates the amount of money spent on thermal supply fuel to be able to deliver the same amount of thermal energy as to biomass fuel.

, and

$$Annual\ biomass\ fuel\ cost\ (£)$$
$$= [Biomass\ fuel\ comsumed\ at\ site\ (kg)\ \times its\ price(£/kg)]$$
$$+ [Biomass\ fuel\ purchased(kg) \times its\ price(£/kg)]$$

- *Imported electricity saving*

$$Annual\ imported\ electricity\ saving\ (£)$$
$$= \ Imported\ electricity\ price\ (£/kWh)$$
$$\times\ [Annual\ electrical\ energy\ demand\ \ of\ exisiting\ technology\ (kWh)$$
$$- Annual\ electrical\ energy\ deficit\ of\ new\ biomass\ boiler\ or\ CHP\ system(kWh)\ ]$$

Annual imported electricity saving can be a positive or a negative value because the electricity consumption by the boiler or CHP is also considered. The positive value means the user saves some money from installing new biomass CHP system. The negative value means that the user has to spend more money on electricity.

- *Grant*

The user enters the grant or subsidy that is paid for the initial cost of the biomass boiler or CHP. These total grants will deduct the initial cost of installing the new biomass boiler or CHP system.

- *Renewable Heat Incentive*

The explanation of renewable heat incentives is provided in the literature review chapter. Firstly, the user chooses the tiered tariff structure between the single and the double tiered tariff structure. Then the user enters the tariff rate for tier 1, tier 2 (if the double tiered tariff structure is chosen) and the tariff duration in years, if the renewable heat incentive is eligible for the new biomass boiler or CHP system.

Secondly, the tool will calculate the annual tariff income for the tier 1 using the following algorithm and equation.

If single tiered tariff is chosen, then

$$\begin{aligned}&Annual\ tariff\ income\ in\ Tier\ 1\ (1st\ year)\ (pence)\\&\quad = Annual\ thermal\ energy\ delivered\ to\ load\ (kWh)\\&\quad \times Tier1\ tariff\ rate(\frac{pence}{kWh})\end{aligned}$$

But if double tiered tariff is chosen, and

$$1{,}314 \times Rated\ thermal\ output\ (kW) \geq Annual\ thermal\ energy\ delivered\ to\ load(kWh)$$

Then,

$$\begin{aligned}&Annual\ tariff\ income\ in\ Tier\ 1\ (1st\ year)\ (pence)\\&\quad = Annual\ thermal\ energy\ delivered\ to\ load\ (kWh)\\&\quad \times Tier1\ tariff\ rate\ (\frac{pence}{kWh})\end{aligned}$$

Or double tiered tariff is chosen, and

$$1{,}314 \times Rated\ thermal\ output\ (kW) < Annual\ thermal\ energy\ delivered\ to\ load(kWh)$$

Then,

$$Annual\ tariff\ income\ in\ Tier\ 1\ (1st\ year)\ (pence) = 1{,}314 \times Rated\ thermal\ output\ (kW) \times Tier1\ tariff\ rate\ (\frac{pence}{kWh})$$

Thirdly, the tool will calculate the annual tariff income for tier 2 using the following algorithm and equation.

If double tiered tariff is chosen, and

$$1{,}314 \times Rated\ thermal\ output\ (kW) \geq Annual\ thermal\ energy\ delivered\ to\ load (kWh)$$

Then,

$$Annual\ tariff\ income\ in\ Tier\ 2\ (1st\ year)(pence) = 0$$

Or double tiered tariff is chosen, and

$$1{,}314 \times Rated\ thermal\ output\ (kW) < Annual\ thermal\ energy\ delivered\ to\ load (kWh)$$

Then,

$$Annual\ tariff\ income\ in\ Tier\ 2\ (1st\ year)\ (pence) = \{Annual\ thermal\ energy\ delivered\ to\ load\ (kWh) - [1{,}314 \times Rated\ thermal\ output\ (kW)]\} \times Tier2\ tariff\ rate\ (pence/kWh)$$

Finally, the tool will calculate the total tariff incomes by the sum of Annual tariff income in Tier 1 and Tier 2.

- *Renewable Obligation Certificate*

The explanation of renewable obligation certificate is provided in the literature review chapter. The user has to enter the number of ROC per MWh, qualifying percentage and average ROC price, if the renewable obligation certificate is eligible for the new biomass CHP system. Then the tool will calculate the annual ROC income by

$$Annual\ ROC\ income$$
$$= No.of\ ROC\ per\ MWh \times Electrical\ energy\ delivered\ to\ real\ load\ (kWh) \times Qualifying\ percentage \times Average\ ROC\ price(\frac{£}{ROC})$$

- *Feed-in tariff*

The explanation of feed-in tariff is provided in the literature review chapter. The user has to enter the tariff rate for generation, the tariff rate for exporting and the tariff duration for generation, if feed-in tariff is eligible for the new biomass CHP system. Then the tool will calculate the annual tariff income by

$$Annual\ feed\ in\ tariff\ income\ (pence)$$
$$= \left(Electricity\ generated\ (kWh) \times Tariff\ rate\ for\ geneation(\frac{pence}{kwh})\right) + \left(Electricity\ exported(kWh) \times Tariff\ rate\ for\ exporting(\frac{pence}{kwh})\right)$$

- *Loan*

The loan can be applied to this tool, if the user wants to pay the initial cost in regular instalments, or partial repayments. Rate of interest on loan and number of years to complete the repayment has to be entered. Then the tool will calculate the annual repayment for that period by

$$Annual\ repayment = \frac{C \cdot r \cdot (1+r)^n}{(1+r)^n - 1}$$

where C is the values of initial cost subtracted by any grants

n is the number of years to complete the repayment

r is the rate of interest on loan

- *Financial parameters*

The user enters the inflation rates of biomass fuel price, electricity price, conventional fuel, operation and management cost, RHI, and FIT that will increase their value in percentage every year for the project period.

Then user can enter discount rate (%), this value will be calculated in the results comparison section.

3.6.5 Results

Most of the figures in this chapter are taken from the previous sections and are applied with inflation rates involving every year throughout the project lifetime. The annual pre-tax cash flow is calculated by

$$\begin{aligned} Pre\ tax\ cash\ flow \\ &= Thermal\ supply\ fuel\ saving + RHI\ tariff\ income \\ &+ Electricity\ imported\ saving + Feed\ in\ tariff\ income \\ &+ Renewable\ obligation\ certificate\ income - Initial\ costs - O\&M\ costs \end{aligned}$$

Then the tool calculates the cumulative cash flow from annual pre-tax cash flow. These two parameters, cumulative cash flow and pre-tax cash flow, will be used to analyse economic performance of each case in the results comparison section.

The bottom table in this sector contains the monthly biomass fuel used in weight and volume. The monthly biomass fuel used in weight is taken from the sum of hourly biomass fuel used for each month. Then it is divided by fuel density of the wood waste fuel to get the hourly biomass fuel used in volume.

3.6.6 Results comparison

This section calculates and shows the economic, energy, and environmental performance between seven cases. The following parameters are calculated to evaluate the mentioned performance for each case.

- *Payback period*

The tool calculates the payback period based on the cumulative cash flow. It will count the number of years until the cumulative cash flow in the results section turns positive, and returns the value.

- *Cumulative cash flow*

The tool takes the cumulative cash flow at the 30th year in the results section.

- *Internal rate of return (IRR)*

The tool calculates the internal rate of return from the pre-tax cash flow over the project lifetime starting from the investment year (year zero). This tool uses a function in Microsoft Excel to determine the internal rate of return. The calculation of IRR can be shown by this equation

$$0 = \sum_{i=0}^{30} \frac{net\ cash\ flow_i}{(1 + IRR)^i}$$

Alternatively, IRR is the rate that turns NPV to zero.

- *Net present value (NPV)*

NPV is also calculated by using a function in Microsoft Excel using the discount rate, pre-tax cash flow, and the initial cost at year zero. Since the investment year is at year zero and the income starts to come at year one, the initial cost at year zero is added to the NPV result. The calculation of NPV can be shown by this equation

$$NPV = \sum_{i=1}^{30} \frac{pre\ tax\ cash\ flow_i}{(1 + discount\ rate)^i} - Initial\ cost\ at\ year\ zero$$

- *Profitability index (PI)*

PI is calculated by using NPV divided by the initial cost at year zero.

$$PI = \frac{NPV}{Initial\ cost\ at\ year\ zero}$$

- *Energy and environmental performance*

Since this tool assumes the similar thermal and electrical demand profile for every year for 30 years, the total thermal and electrical energy generated, delivered to load, surplus, deficit, and equivalent CO_2 emission reduction over 30 years are calculated by an annual value of mentioned parameters multiplied by 30.

4. The Case Study

4.1 Introduction: Background of Solway Precast

Solway Precast is one of the divisions of Barr Limited, and was established in 1945. This site is located in Barrhill village, South Ayrshire, Scotland. Solway Precast site has an area of around 20 acres, including 10,000 square metres of factory area. Their product range includes terracing/seating units for stadiums, pre-stressed flooring, box culverts, drainage channels, stair flights and landings, bridge parapets, beams, railway products, as well as marine and sea defence.

Figure 27: Solway Precast (Barr Ltd, n.d.)

The site has an on-site batching plant and mould making workshops to produce precast concrete. The cement, wood, steel and aggregates have to be purchased to produce precast concrete at the site.

Figure 29: On-site Batching Plant (Barr Ltd, n.d.)

Figure 28: Moulding Workshop (Barr Ltd, n.d.)

Solway Precast was chosen as a case study because the site has a large amount of wood waste as their by-product. Moreover, the manufacturing of concrete produces large amounts of CO2 throughout the process. Replacement of biomass fuel can enhance the financial and environmental performance at the site. Barr Limited is committed to improving and reducing energy use by improving efficient use of all energy sources, investing in low carbon and sustainable energy efficient technologies, and reducing their environmental impact on the environment.

The site usually operates from Monday to Friday except for some periods that have high demand for products. Electrical energy is imported from the grid, and thermal energy is supplied by purchased kerosene and gas oil. Diesel is also purchased for the site for transportation purposes.

This study included a site visit to the Solway Precast site to collect data such as energy usage, existing technology specification, specific fuel types and fuel usage figures.

4.2 Energy Demand

The energy demand at the Solway Precast site was conducted by gathering the measured data and analysing the energy usage in the precast concrete process.

4.2.1 Electrical Energy Demand

Electricity is used in the office and the factory at the Solway Precast site. It rises and falls throughout the day according to the process in the factory and the number of occupancts in the office.

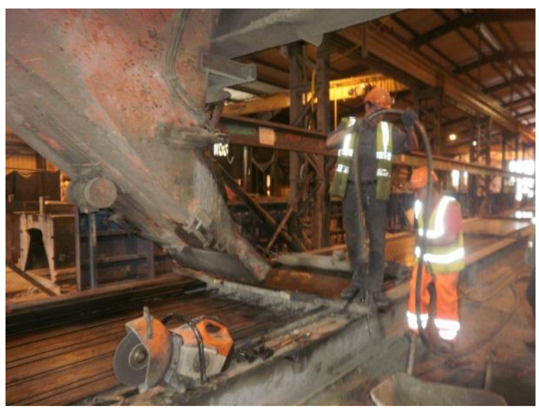
Following the order of the processes, the electricity is used to drive the motor which will in turn run the conveyor belt for delivering the aggregate, slag, and admixture to the mixing and batching machine. It is also used at the cement silo to expel the stored cement, as well as at the water tank to pump the water into the mixing and batching machine. After that the mixing and batching machine, using the electricity, mixes and batches the cement, aggregates, water and admixture until the concrete is ready. The overall process mentioned so far is controlled by computer.

Figure 31: Conveyor Belt

Figure 30: Cement Silo

After the concrete is ready, electricity is used in motors to move the overhead cranes and hoppers to pour the concrete into moulds. At the moulding area, a vibrator is used to consolidate the concrete and to make the concrete compact. Electricity is also used in mould making process to cut, trim, weld, bend, and seam the material like timber and steel.

Figure 32: Vibrating Process



In the office, electricity is used in office appliances. The space heating in the office and the hot water process in the factory use kerosene heaters which also consume electricity.

The electricity demand at the Solway Precast site is monitored every half an hour throughout the year. Since the electricity consumption is measured for the whole site, these figures will be used as an electrical energy demand profile to analyse in demand-supply matching with biomass CHP. The table below shows the monthly electricity consumption in 2010.

Table 8: Monthly electricity consumption in kWh

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40,409	41,582	48,450	42,344	34,909	37,306	39,469	43,050	44,059	50,305	55,666	45,849

4.2.2 Thermal Energy Demand

Thermal energy for space heating and hot water heating at the Solway Precast site use kerosene and gas oil (propane). The amount of the mentioned fuel consumption has never been monitored and measured except for the fuel quantity ordered per month.

Table 9: Monthly quantity of kerosene ordered in litres

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
11,000	15,000	8,000	7,000	6,000	6,000	6,000	0	3,000	9,000	9,000	14,000

Table 10: Monthly quantity of gas oil ordered in litres

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5,000	0	5,000	5,000	3,000	4,500	3,000	4,500	1,000	4,000	10,000	1,000

Therefore, in order to predict the thermal energy demand profile, these fuels have to be analysed in terms of time, duration, and frequency of use in a year.

Two kerosene heaters are used for heating hot water in two pre-stressed beds in the factory during the casting process to increase the strength of the concrete. A kerosene heater also uses for space heating in the office. Two kerosene heaters in the factory have a 36.6 kW thermal output each. The kerosene heater in the office has a 26.4 kW thermal output.

Two kerosene heaters in the factory are turned on for 24 hours 5 days per week except during sub-zero temperatures (such as winter), when they will be turned on at full potential 24 hours 7 days per week to prevent the water in the system from becoming too cold. These heaters are operated at a temperature that ensures concrete achieves the minimum strength in an adequate time. One of the heaters is most likely to operate at half potential during the summer as this will provide sufficient heat whilst not curing the concrete too rapidly. The other operates at full potential during the summer because the water pipe line is much longer, therefore losing more heat.

Figure 34: Kerosene heaters in the factory

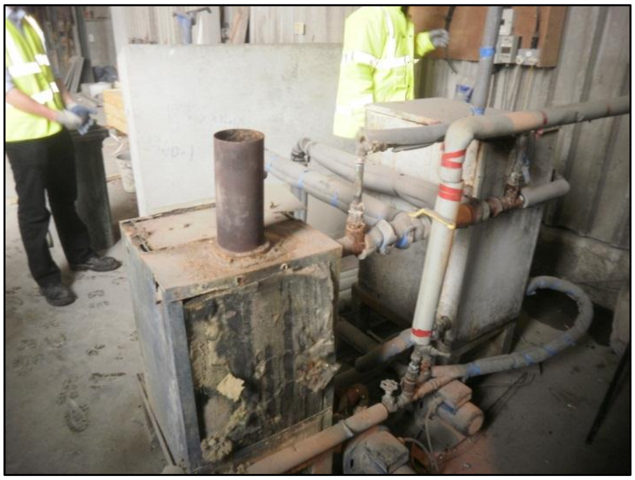


Figure 33: Kerosene tank

The kerosene heater in the office is controlled by thermostat and, the thermostat setting changes throughout the year depending on the ambient temperature. At times during summer, the kerosene heater in the office is turned off completely.

Figure 35: Kerosene heater in the office

Gas heaters are used occasionally when double casting. (2 units simultaneously cast, twice per day) and are also used during winter. There are two gas heaters with a thermal output of 82.43 kW and 102.3 kW. However, the amount of fuel used varies depending on the number of precast units required and the ambient temperature.

4.2.3 Fuel consumption and CO_2 Emissions

The annual electricity imported from the grid at the Solway Precast site was 523,398 kWh in 2010. Assuming the average electricity import price is 10 pence per kWh (A National Statistic Publication, 2011), then the annual electricity cost would be around £ 52,339.8. The CO_2 emission from electricity consumption can be calculated by multiplying the total amount of electricity consumption with the CO_2 emission factor.

$$CO_2\ emission\ from\ electricity\ consumption\ in\ 2010$$
$$= Electricity\ consumption(kWh) \times CO_2\ emission\ factor\ \left(\frac{kgCO_2}{kWh}\right)$$
$$= 523{,}398 \times 0.59368 = 310{,}730.92\ kgCO_2$$

Where the CO_2 emission factor is greenhouse gas emissions converted into kilograms of carbon dioxide equivalent (kg CO2) per kWh. 0.59368 is based on Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting (2011).

The kerosene and gasoil at the Solway Precast site were 94,000 and 46,000 litres respectively in 2010. Assuming the average kerosene and gas oil price is 48.83 and 53.63 pence per litre (A National Statistic Publication, 2011), then the annual kerosene and gas oil cost would be around £ 45,900 and £ 24,699 respectively.

This CO_2 emission factor is 3.0122 $kgCO_2$ per litre for kerosene, and 3.5865 $kgCO_2$ per litre for gas oil. Therefore, CO_2 emissions from kerosene and gas oil in 2010 were 283,146.8 $kgCO_2$ and 164,979 $kgCO_2$ respectively.

So the total $kgCO_2$ emission from electrical and thermal energy consumption is 758,855.92 $kgCO_2$, and the total electrical and thermal energy consumption cost is £ 122,938 in 2010.

4.3 Wood Waste at Site

Woods are purchased for the site for the purpose of constructing moulds. Wood moulds can be reused for a certain amount of time before disposal. In regards to the wood, there are three suppliers: Rowan Timbers (located at Ayr) provides joiners timber which tends to be red and yellow pine as well as plywood. Garnaburn (located at Colmonell) provides stacking timber for the yard which is Douglas fir softwood or other soft pine. Lastly there is Penkiln Sawmill (located outside Wigtown) which provides larger cuts of wood for different purposes. All the sawmills are approved by Forest Stewardship Council (FSC) which means that the trees cut down are from legally designated forest areas.

Figure 36: Wood waste at Solway Precast site

Wood wastage is in the form of solid pieces of wood removed from the mould or the process of making the mould. However, there are some metal materials in the wood such as nails or metal plates which must be taken out before using the wood in the biomass boiler or CHP. Wood waste can be chipped by the chipper to make them suitable for some biomass boilers or CHPs that use wood chips as fuel.

The average total amount of wood waste at the Solway Precast site is 150 tonnes per year. The wood waste is a mixture of red pine, white pine, plywood, Douglas fir, and other soft pine. The exact amount of each type of wood in wood waste is unknown because it has never been monitored or recorded. It also depends on the shape of the mould, which depends on the precast concrete product.

4.4 Biomass in Solway Precast

Since Solway Precast produces wood residues and wood waste, it has a very large potential to replace conventional fuel boilers with biomass boilers and CHP. The following section will point out all the parameters involved at the site that need to be used in the biomass boiler and CHP tool. The thermal energy demand profile has to be generated from the tool based on the knowledge of the heat usage at the site. Electrical demand profile will use the site's data monitored over one year. Subsequently the biomass boilers and CHPs specification will be entered in the tool to observe their economic and environmental performance.

4.4.1 Thermal Demand Profile

The thermal energy consumption at the site is supplied by three sources. Firstly, the two kerosene heaters heat two pre-stressed beds in the factory. Secondly, two gas heaters are used to cure the double casting process, and for space heating during winter in the factory. Thirdly, a kerosene heater is used for space heating to provide a comfortable temperature in the office.

From these three sources of thermal supply, two kerosene heaters used to heat pre-stressed beds consume the biggest proportion of thermal energy consumption. Due to the fact that they operate all day, 5 days a week during summer, and all day, 7 days a week during winter. Two gas heaters only operate occasionally depending on the type of precast product demand, and they also turn on manually when the temperature becomes too low for the employees to work. The kerosene heater in the office is also turned on and off manually during summer and it operates in accordance with the thermostat during winter.

In this analysis, only two kerosene heaters in the factory will be focused on, this is because they are the main thermal energy consumption at the site. Furthermore, these kerosene heaters' operations have a certain operation method hence thermal energy consumption can be more accurately predicted. As for the gas heaters in the factory and the kerosene heater in the office, they largely depend on the precast concrete product type ordered by the customer, and the human factor. The prediction of these heaters might lead to a significantly inaccurate thermal energy demand profile to use in the tool.

Input

As mentioned before, the two kerosene heaters will operate from Monday to Friday during summer, and Monday to Sunday during winter when the temperature decreases to below zero. Both heaters operate at full potential during winter but during summer, only one of them operates at full potential while the other will operate at half potential. This method of operation was put to the kerosene heaters' operator on site. The setting of the full potential operation and half potential operation were found out by the operator experience to get enough strength for the precast concrete product. Based on the specification of the two kerosene heaters in the factory, the maximum thermal energy demand would be 73.2 kW during winter and 54.9 kW during summer. In other words, two kerosene heaters operate at 75% potential in summer compared to their potential during winter.

Data from the met office indicates that the minimum temperature in January, February, and December was below zero in 2010 at the paisley climate station (the nearest climate station to Barrhill) (Met Office, 2011). Therefore, the kerosene heaters operate 7 days a week for these three months. In the summer season between June and September assumption was made due to the higher maximum and minimum temperatures in this period.

According to the above kerosene heaters usage characteristic can be summarised as:

1. In January, February, and December, two kerosene heaters operate at full potential seven days a week.
2. From June to September, only one operates at full potential, and the other operates at half potential for five days a week.
3. Two kerosene heaters operate at full potential for five days a week for the rest of the year.

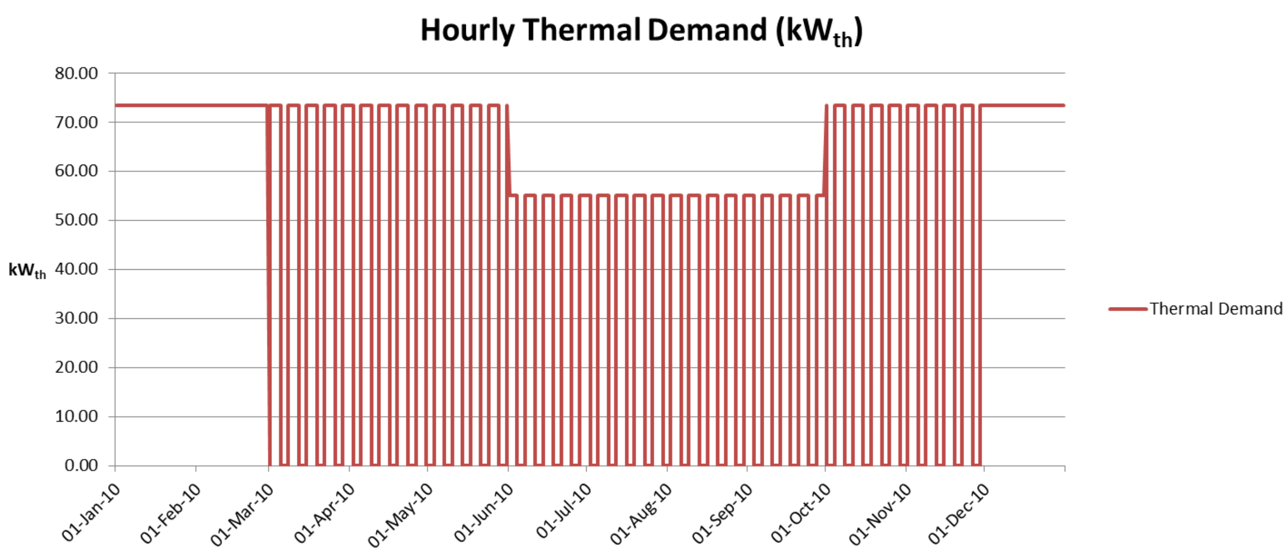
This table shows the settings in thermal demand section of the tool.

Figure 37: Thermal demand settings of the tool for Solway Preacast

Monthly Thermal Demand Information												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Demand Characteristic	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant
Maximum Demand	73.2 kW_{th}											
Operating Capacity (%)	100%	100%	100%	100%	100%	75%	75%	75%	75%	100%	100%	100%
Weekly Start Date	Monday	Monday	Monday	Monday	Monday	Monday	Monday	Monday	Monday	Monday	Monday	Monday
Weekly Start Time	0:00	0:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	0:00
Daily Interval Start Time	0:00	0:00	0:00	0:00	0:00	0:00	0:00	0:00	0:00	0:00	0:00	0:00
Daily Interval End Time	23:59	23:59	23:59	23:59	23:59	23:59	23:59	23:59	23:59	23:59	23:59	23:59
Weekly End Date	Sunday	Sunday	Friday	Friday	Friday	Friday	Friday	Friday	Friday	Friday	Friday	Sunday
WEekly End Time	23:59	23:59	18:00	18:00	18:00	18:00	18:00	18:00	18:00	18:00	18:00	23:59

The hourly thermal demand profile is generated by the tool. The table below shows the graph result of the hourly thermal demand.

Figure 38: Hourly thermal demand profile of pre-stressed beds in Solway Precast for one year



The annual thermal energy demand for two pre-stressed beds is 431,971.50 kWh with a maximum and minimum thermal load of 73.2 kW_{th} and 54.9 kW_{th} respectively. The number of demand hours is 6,374 hours per year.

The amount of kerosene used is calculated by the tool with the assumption of 70% efficiency of the kerosene heaters. The lower heating value of the kerosene is 10 kWh per litre (Biomass Energy Centre, 200-). The kerosene price is £ 0.48 per litre, and the CO_2 emission factor is 3.01 $kgCO_2$ per litre (AEA Technology, 2011). Therefore the total amount of kerosene used for two pre-stressed beds is 61,710.21 litres with the cost of £ 29,620 per year. The total amount of equivalent CO2 emission is 185,883.51 kgCO_2 per year.

It is assumed that the gas heaters in the factory and the kerosene heater in the office at the site have 70% efficiency, using 6.6 kWh per litre as the lower heating value of the propane (Biomass Energy Centre). The pie graphs below shows the proportion of thermal energy usage by type of demand and by type of fuel.

Figure 39: Thermal Energy Usage by Type of Demand (kWh)

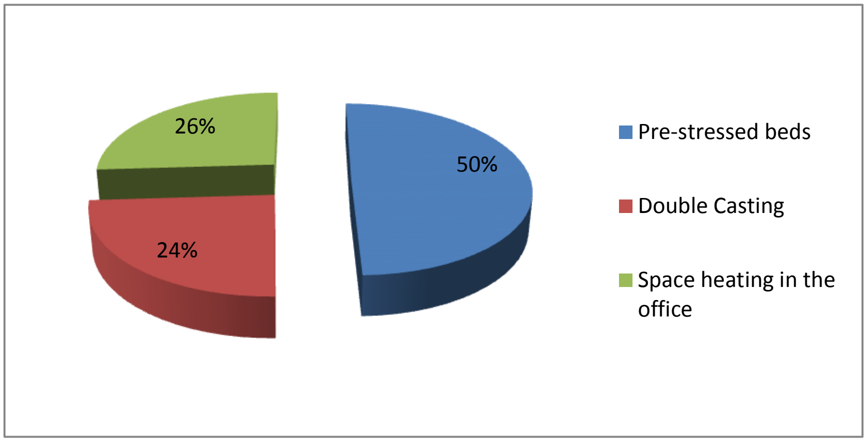
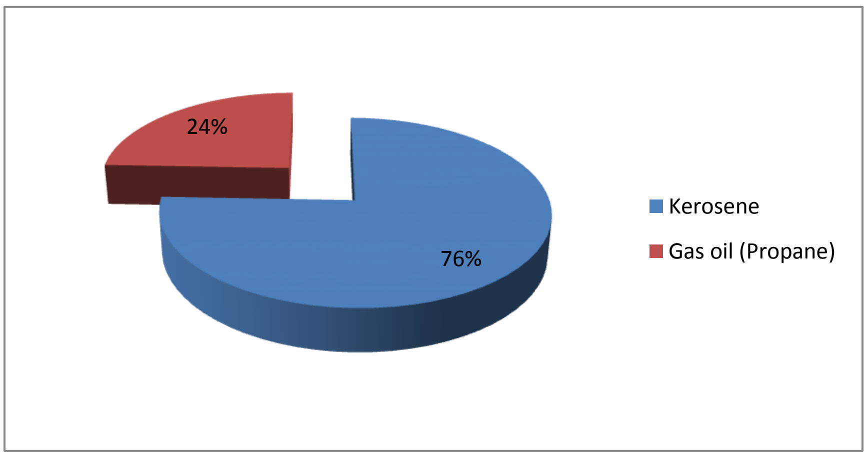


Figure 40: Thermal Energy Usage by Type of Fuel (kWh)



4.4.2 Electrical Demand Profile

The electrical energy consumption at the site is supplied by the grid. The half hourly energy consumption was monitored in 2010. Therefore, the monitored data has been converted to hourly energy consumption and entered into the tool.

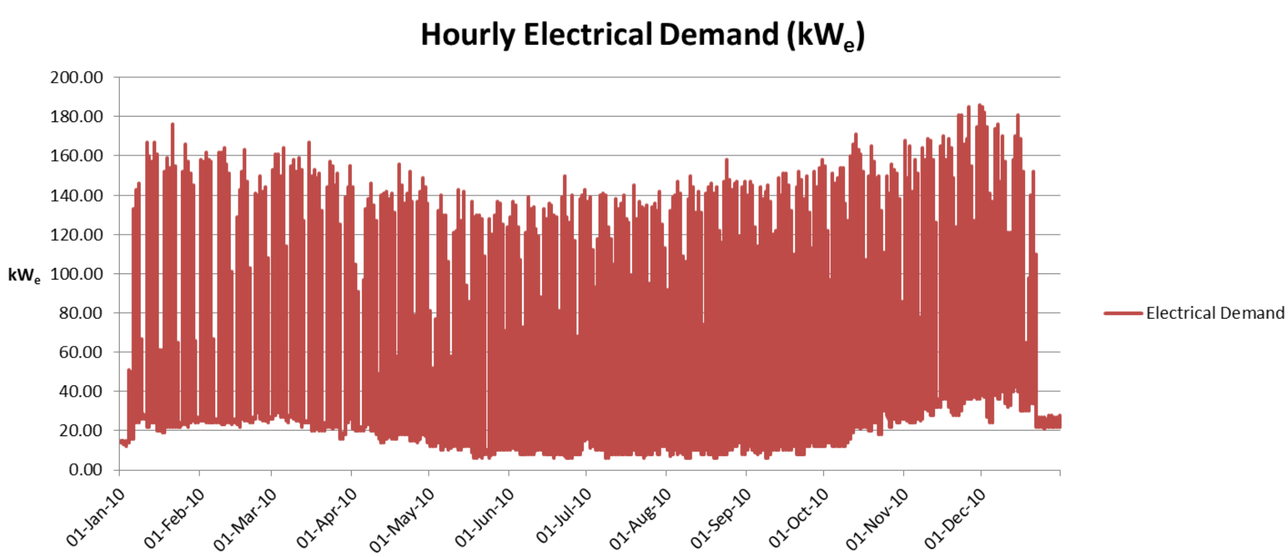
This table shows the setting in electrical demand section in the tool.

Figure 41: Electrical demand settings of the tool for Solway Preacast

Monthly Electrical Demand Information												
Month	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Demand Characteristic	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Variable
	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually	Fill manually
Maximum Demand	0	kW_e										
Operating Capacity (%)	~~100%~~	~~100%~~	~~100%~~	~~100%~~	~~100%~~	~~75%~~	~~75%~~	~~75%~~	~~75%~~	~~100%~~	~~100%~~	~~100%~~
Weekly Start Date	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~	~~Monday~~
Weekly Start Time	~~0:00~~	~~0:00~~	~~0:00~~	~~7:00~~	~~7:00~~	~~7:00~~	~~7:00~~	~~7:00~~	~~7:00~~	~~7:00~~	~~0:00~~	~~0:00~~
Daily Interval Start Time	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~
Daily Interval End Time	~~23:59~~	~~23:59~~	~~0:00~~	~~23:59~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~
Weekly End Date	~~Sunday~~	~~Sunday~~	~~Sunday~~	~~Friday~~	~~Friday~~	~~Friday~~	~~Friday~~	~~Friday~~	~~Friday~~	~~Friday~~	~~Sunday~~	~~Sunday~~
WEekly End Time	~~23:59~~	~~23:59~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~	~~0:00~~

The hourly electrical demand profile is entered by the user. The table below shows the graph result of the hourly electrical demand.

Figure 42: Hourly electrical demand at Solway Precast site for one year



The annual electrical energy demand for the site is 523,398.00 kWh with a maximum and minimum electrical load of 186 kW_e and 6 kW_e respectively. The number of demand hours is 8,760 hours per year.

The imported electricity price is assumed to be £ 0.10 per kWh, and the CO_2 emission factor is 0.59 $kgCO_2$ per kWh (AEA Technology, 2011). Therefore the total cost for electricity at the site is £ 52,339.80 per year. The total amount of equivalent CO2 emission is 310,730.92 $kgCO_2$ per year.

4.4.3 Wood Fuel

The wood waste characteristics are taken from the PHYLLIS database (Energy research Centre of the Netherlands (ECN), n.d.). The table below shows the characteristics of plywood, white pine, yellow pine, Douglas fir, and average mixed waste wood taken mainly from the PHYLLIS database and also other sources.

Table 11: Wood fuel characteristics

Type of Wood	Ash Content (Dry Basis) (%)	Fuel Density (Dry Basis) (kg/m^3)	LHV (Dry Basis) (kWh/kg)
Plywood	2.1	700-800*	4.91
White pine	0.1	450**	5.38
Yellow pine	1.3	450**	5.77
Douglas fir	0.54***	479	5.39***
Mixed waste wood****	1.4	432*****	4.44

* general plywood density taken from CES 2010 Edupack software
** average value of plywood density taken from biomass energy centre website
*** average value of all Douglas firs listed in PHYLLIS database
**** typical mixed wood waste in PHYLLIS database
***** average soft wood density taken from biomass energy centre website

Mixed wood waste in the last row of the table represents the unknown types of wood waste at the site. This data is entered into the wood fuel section in the tool. Wood fuel will be separated into two cases.

The 1st case is a mixture of all the wood mentioned in the above table. They will be cut into appropriate sizes and since the exact proportions of each type of wood is unknown, each will have the same amount in weight. The table below shows the wood fuel setting in the tool for the 1st case.

Figure 43: Data entered in the wood fuel section for the 1st case

1st Wood Fuel Case		
Name	Wood waste pieces	
Type	Mixed Type of Wood	
Available at Site	150,000.00	kg / year

Type of Wood	Mass Percentage (%)	Mositure Content (%)	Ash Content (%)		Fuel Density (kg/m^3)		Lower Heating Value (kWh/kg)		CO_2 Emission Factor (kg-CO_2/kg)	Price per kg (£)
			Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received		
PLywood	20	25	2.1	1.58	750.00	1000.00	4.91	3.51	0.07738	0
White Pine	20	25	0.1	0.08	450.00	600.00	5.38	3.87	0.07738	0
Yellow Pine	20	25	1.3	0.98	450.00	600.00	5.77	4.16	0.07738	0
Douglas Fir	20	25	0.54	0.41	479.00	638.67	5.39	3.87	0.07738	0
Mixed Wood Waste	20	25	1.4	1.05	432.00	576.00	4.44	3.16	0.07738	0
				0		0		0		
				0		0		0		
				0		0		0		
				0		0		0		

The 2nd case is a mixture of all the wood mentioned in the above table. They will be chipped into small wood chips and since the exact proportions of each type of wood is unknown, each will have the same amount in weight. The assumption of softwood fuel density of 195 kg/m^3 will be used in this case (Food and Agricutural Organization of the United Nations, 2004) . The table below shows the wood fuel setting in the tool for the 2nd case. Price per kg is £ 0.0085 per kg, this price indicates the amount of money needed to chip wood fuels (E4tech, 2010).

Figure 44: Data entered in the wood fuel section for the 2nd case

2nd Wood Waste Case		
Name	Wood waste chips	
Type	Mixed Type of Wood	
Available at Site	150,000.00	kg

Type of Wood	Mass Percentage (%)	Mositure Content (%)	Ash Content (%)		Fuel Density (kg/m^3)		Lower Heating Value (kWh/kg)		CO_2 Emission Factor (kg-CO_2/kg)	Price per kg (£)
			Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received		
PLywood	20	25	2.1	1.58	195.00	260.00	4.91	3.51	0.06141	0.0085
White Pine	20	25	0.1	0.08	195.00	260.00	5.38	3.87	0.06141	0.0085
Yellow Pine	20	25	1.3	0.98	195.00	260.00	5.77	4.16	0.06141	0.0085
Douglas Fir	20	25	0.54	0.41	195.00	260.00	5.39	3.87	0.06141	0.0085
Mixed Wood Waste	20	25	1.4	1.05	195.00	260.00	4.44	3.16	0.06141	0.0085
				0.00		0.00		0.00		
				0.00		0.00		0.00		
				0.00		0.00		0.00		
				0.00		0.00		0.00		

The CO_2 emission factors of wood waste are 0.07738 and 0.06141 kgCO_2 per kg for the 1st and 2nd case respectively (AEA Technology, 2011). Even though biomass or wood are considered as neutral carbon emissions, emissions involved in the production, distribution, storage and transport of biomass or wood must be considered. The prices are 0 and £ 0.0085 per kg for the 1st and 2nd case respectively. There is no need to purchase this wood waste since it is the waste from the precast concrete process. However, the cost of making wood chip has to be considered (E4tech, 2010).

Subsequently, the tool calculates average characteristic value of two cases by using mass percentage of each wood waste. The results are shown in the table below.

Figure 45: Wood waste summary for both cases

Name	Mositure Content (%)	Ash Content (%)	Fuel Density (kg/m^3)	Lower Heating Value (kWh/kg)	CO_2 Emission Factor (kg-CO_2/kg)	Available at Site (kg)	Price per kg (£)
Wood waste pieces	25.00	0.82	682.93	3.71	0.08	150,000.00	0.00
Wood waste chips	25.00	0.82	260.00	3.71	0.06	150,000.00	0.01
-	0	0	0	0	0	0.00	0
-	0	0	0	0	0	0.00	0

The only difference between these two cases is the fuel density, since both cases have the same type and amount of wood.

The reason to have two cases is so that the performance of the boiler that is suitable for solid pieces of wood and wood chips can be compared. Moreover, waste wood usually has a moisture content of around 18-25%, and fresh wood usually has a moisture content of around 40% (Department for Environment, Food and Rural Affairs, 2008). Therefore the 25% moisture content will be used to see the range of biomass boiler and CHP performance. The moisture content is used with the assumption that the user has to store the wood long enough in order for it to reach the defined moisture content. The other moisture content value will not be used in this analysis. However, the user can make use of this tool to implement different values of moisture content.

The wood fuel characteristics of extra wood waste and wood chips that need to be purchased in case of a shortfall in wood waste are assumed to be the same as wood waste, since the author did not receive detailed information from the nearby wood suppliers. The price of wood chips is £ 0.09 per kg delivered respectively (E4tech, 2010). As for the extra wood wastes that need to purchase, the price is £ 0.0825 per kg delivered derived from the price of wood chips per kg delivered subtracted from the price of chipping (£ 0.0075 per kg) (E4tech, 2010).

4.4.4 Biomass Boiler and CHP Specification

After specifying the wood fuel characteristics, many enquiries were sent to suitable biomass boiler and CHP suppliers in the UK to obtain prices and specifications. Four suppliers sent their prices and specifications, three of them supply biomass boilers, only one, however, supplied supply biomass CHP suitable with Solway Precast energy demand. However, only one boiler supplier provided enough boilers information to be used in this tool. There is also only one biomass CHP supplier that their wood fired CHP is not too big for Solway Precast thermal demand. Therefore, three biomass boilers and one biomass CHP will be used in the tool in this analysis.

<u>Biomass boiler and CHP specifications</u>

1. Supplier: FARM 2000 / TEISEN PRODUCTS LTD

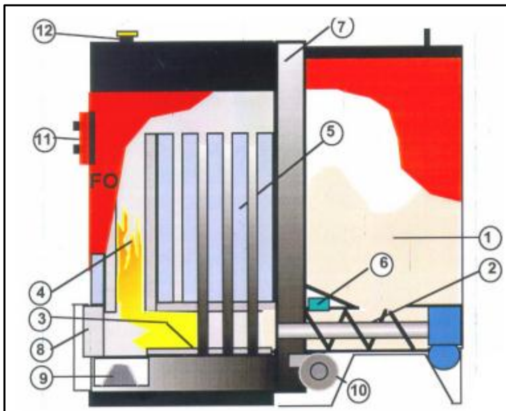
Supplier:	FARM 2000 / TEISEN PRODUCTS LTD
Manufacturer boiler model:	REFO 80
Conversion technology:	Combustion technology
Wood fuel type:	Woodchip, wood pellets, grain, rape mash, shredded timber, and sawdust
Thermal efficiency:	85-94% (claimed by the manufacturer)
Maximum thermal output:	75 kW_{th} (20%MC woodchip)
	70 kW_{th} (26%MC woodchip)
	40 kW_{th} (35-40%MC woodchip)
Woodchip size:	Wide range (can burn shredded pallets)
Suitable moisture content:	0-35%
Initial cost:	£ 22,350 (boiler, including auger and sluice valve)
	+ £ 6,670 (10 m^3 silo/feeder system)
	+ ≈ £ 7,500 (installation cost)
	+ ≈ £ 325 (delivery cost)
	+ ≈ £ 700 (chimney cost)
O&M cost:	≈ £ 750 per year

All values mentioned above are approximate values from the REFO 80 boiler specification and discussions with the supplier therefore they should be treated as guidelines. The values may be amended due to specific site characteristics, fuel types, user requirements and more detailed analysis of the particular projects.

REFO 80 boiler is an auto stoker boiler that has to be operated 24 hours per day, because it is designed to operate continuously in order to reach high efficiency and reliability. It cannot be turned on and off as often as oil and gas boilers. This model can modulate the thermal output from 10-100% of maximum output. Therefore it is not necessary to couple this boiler with thermal storage. However, it is better to operate at high thermal output due to the production of smoke and tar at low temperature combustion.

Figure 46: REFO 80 (Teisen Products Ltd, n.d.)

Figure 47: REFO 80 composition (Teisen Products Ltd, n.d.)



Pos.	Designation
1	Fuel bin
2	Feed auger
3	Stainless steel burner tube
4	Gas combustion tube
5	Convection tubes
6	Sprinkler
7	Exhaust outlet
8	Refractory material
9	Ash bin
10	Combustion blower
11	Microprocessor control
12	Sight glass

2. Supplier: FARM 2000 / TEISEN PRODUCTS LTD
   Manufacturer boiler model: HT 45
   Conversion technology: Combustion technology
   Wood fuel type: Solid pieces of wood and straw
   Thermal efficiency: 70% (claimed by the manufacturer)
   Maximum thermal output: 54 kW_{th} (20%MC woodchip)
   Initial cost: £ 4,650 (boiler)
   + ≈ £ 7,500 (installation cost)
   + ≈ £ 300 (delivery cost)
   + ≈ £ 700 (chimney cost)
   O&M cost: Can be neglected

3. Supplier: FARM 2000 / TEISEN PRODUCTS LTD
   Manufacturer boiler model: HT 50
   Conversion technology: Combustion technology
   Wood fuel type: Solid pieces of wood and straw
   Thermal efficiency: 70% (claimed by the manufacturer)
   Maximum thermal output: 85 kW_{th} (20%MC woodchip)
   Initial cost: £ 5,435 (boiler)
   + £ 6,670 (accumulator tank)
   + ≈ £ 7,500 (installation cost)
   + ≈ £ 300 (delivery cost)
   + ≈ £ 700 (chimney cost)
   O&M cost: Can be neglected

4. Supplier: FARM 2000 / TEISEN PRODUCTS LTD
   Manufacturer boiler model: HT 80
   Conversion technology: Combustion technology
   Wood fuel type: Solid pieces of wood and straw
   Thermal efficiency: 70% (claimed by the manufacturer)
   Maximum thermal output: 195 kW_{th} (20%MC woodchip)

Initial cost:	£ 8,950 (boiler)
	+ £ 6,670 (accumulator tank)
	+ ≈ £ 7,500 (installation cost)
	+ ≈ £ 300 (delivery cost)
	+ ≈ £ 700 (chimney cost)
O&M cost:	Can be neglected

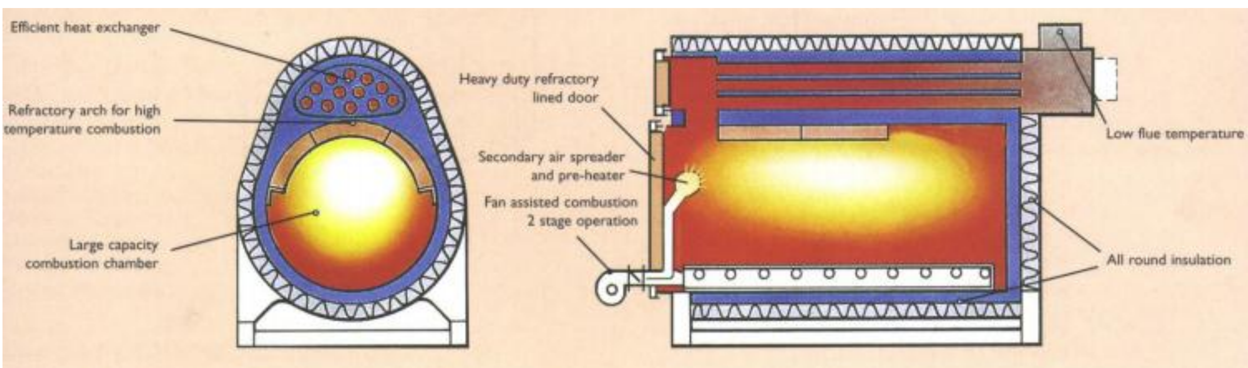
All values mentioned above are approximate values from the HT 45, 50, and 80 boiler specifications and discussions with the supplier therefore they should be treated as guidelines. The values may be amended due to specific site characteristics, fuel types, user requirements and more detailed analysis of the particular projects.

HT 45, 50, and 80 boilers are boilers that wood fuel has to be manually fed. These boilers are able to be turned on and off in a day. Manufacturer suggests installing the boiler that has a higher maximum thermal output than maximum thermal demand, so the accumulator tank will have enough thermal energy to supply the load when the boiler is turned off. Therefore the boilers usually operate at full potential and are coupled with the accumulator tank in the water circuit to supply the thermal energy demand. This way the boiler can operate at full potential resulting in complete combustion (less production of smoke and tar).

The reason for choosing HT 45, 50, and 80 boilers is the difference in combustion chamber size, and maximum thermal output. Combustion chamber size indicates the amount of wood fuel that can be fed into the boiler at one time which affects the stoking frequency of the boiler. Boilers that have a greater maximum thermal output can store more energy in the accumulator tank which also affects the stoking frequency of the boiler. This is the crucial parameter because there is thermal energy thermal demand during the night during weekdays all year, and at the weekend during the winter. Since wood fuels have to be manually fed to these boilers, a sufficient thermal energy supply at night and during the weekend is crucial as there will be no one available to feed the wood fuel into the boiler.

Figure 48: HT boiler with accumulator tank (Teisen Products Ltd, n.d.)

Figure 49: HT boiler composition (Teisen Products Ltd, n.d.)



5. Supplier: Talbott's Biomass Generators Ltd.

Manufacturer CHP model:	BG 25
Conversion technology:	Combustion technology
Power generation Technology:	Heat engine
Wood fuel type:	Woodchip, wood pellets, and crops
Thermal efficiency:	62% (claimed by the manufacturer)
Maximum thermal output:	80 kW_{th} (25%MC woodchip)
Maximum electrical output:	25 kW_e (25%MC woodchip)
Heat to power ratio (100% load)	3.2

Initial cost:	£ 165,000 (boiler)
	+ ≈ £ 10,000 (plumbing cost)
	+ ≈ £ 3,000 (grid connection)
	+≈ £ 7,500 (delivery, installation, and commissioning cost)
O&M cost:	≈ £ 6,010

All values mentioned above are approximate values from the BG 25 CHP specifications and discussions with the supplier and therefore should be treated as guidelines. The values may be amended due to specific site characteristics, fuel types, user requirements and more detailed analysis of the particular projects.

The principle of the BG 25 CHP operation is that the wood fuel is burnt and the hot gasses enter the air-to-air heat exchanger tubes on the shell side. The compressed air is heated and passed into a turbo-compound heat engine which drives the generator. This CHP is designed to operate at constant full power for 24 hours a day, 7 days per week. Modulation of thermal and power output can be done but it is not an economical use of the system since the loss of electrical output is much higher as the top temperature declines. Shutting down the CHP over the weekend or at night is also not recommended by the manufacturer due to thermal stresses induced in the CHP and the length of time required to build up temperature and electrical power.

Figure 50: BG 25 CHP (Talbott's Biomass Generators Ltd, n.d.)

Input

The previously mentioned biomass boiler and CHP specifications are entered in the biomass boiler and CHP specification section in the tool. Some of the following assumptions have to be made to be able to analyse and calculate the performance of each boiler and CHP.

- *REFO 80*

  The efficiency at different operation capacity will be 90% taken from the average of efficiency range given by the supplier. Since the thermal output of this boiler can be modulated, the boiler will operate following the thermal demand of two pre-stressed beds at the site.

- *HT 45*

  HT 45 will operate at full potential without thermal storage because the maximum thermal output is less than nominal thermal demand of two pre-stressed beds. HT 45 will be turned on during office times (Monday to Friday from 7:00am to 18:00pm). The thermal energy deficit will be supplied by the kerosene heaters. This method will be compared with HT 50 and HT 80 with an accumulator tank.

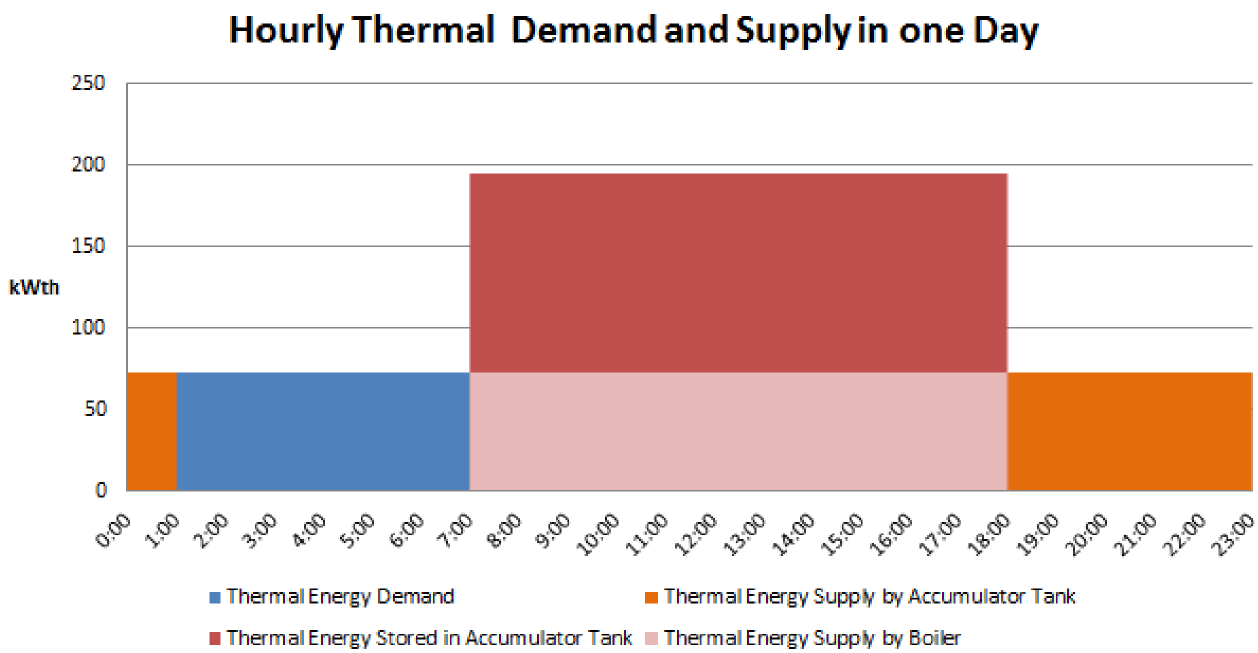
- *HT 50, HT 80 + Accumulator Tank (Thermal Storage)*

  As HT 50 and 80 boilers are the boilers that wood fuel has to be manually fed. They can only be operated when there are occupants at the site (until 18:00 pm). Two operation methods of these boilers will be analysed.

1st operation method

HT 50 and HT 80 boilers will be operated at full potential during office time (Monday to Friday from 7:00am to 18:00pm) and coupled with the accumulator tank. It is assumed that the kerosene heaters can be automatically turned on during unoccupied periods on site when the thermal supply from the boiler and accumulator tank is not enough. The kerosene heaters will supply the thermal demand when needed. The graph below shows the example of the 1st operation method for HT 50 and HT 80 boilers with an accumulator tank in one day.

Figure 51: Example day of 1st operation method for HT 50 and HT 80 boilers with accumulator tank

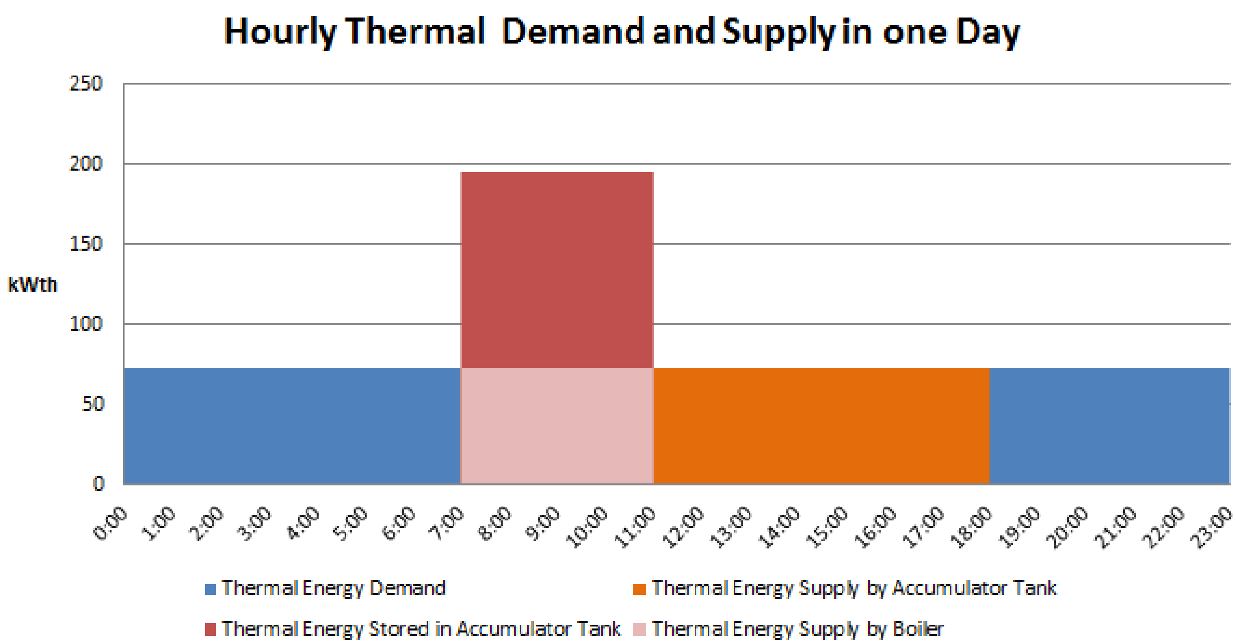


The kerosene heaters need to supply the thermal energy in the blue section of the above graph.

2nd operation method

HT 50 and HT 80 boilers will be operated at full potential for a few hours during the day from Monday to Friday and coupled with the accumulator tank. The number of hours of operation will only be enough to supply the thermal energy demand until around 18:00pm with the support of an accumulator tank. It is assumed that the kerosene heaters cannot be automatically turned on during unoccupied period on site when the thermal supply from the boiler and accumulator tank is not enough. Therefore, the kerosene heaters will supply the thermal demand during unoccupied periods of time starting from 18:00pm to 7:00am of the next day. The graph below shows the example of the 2nd operation method for HT 50 and HT 80 boilers with accumulator tanks in one day.

Figure 52: Example day of 2nd operation method for HT 50 and HT 80 boilers with accumulator tank



The kerosene heaters need to supply the thermal energy in the blue section of the above graph. This method needs to use more kerosene than the first method, but it uses less wood fuel with less stoking frequency, and provides less energy surplus.

The size of the accumulator tank is 15,000 litres which is the maximum size supplied by TEISEN PRODUCTS LTD. The maximum accumulator size is chosen to be able to minimise the stoking frequency, and have longer periods of supply without using the boiler.

Water is used as the working fluid in the thermal storage with a specific heat capacity of 0.0012 kWh per kg °C. The assumptions of minimum and maximum temperature of the thermal storage are 8.6 and 90°C. 8.6°C was the mean temperature at paisley climate station in 2010. 90°C is the set temperature of the boiler control thermostat. Also the temperature drop is assumed to be 0.1 °C per hour for 15,000 litres of thermal storage.

- *BG 25*

  BG 25 will operate 24 hours per day, every day in the year since it is designed to operate at constant full power. It will operate without thermal storage in this case study because the thermal output of the CHP will always exceed the thermal demand of two pre-stressed beds at the site. However, the accumulator tank should be installed in practice to balance other peak thermal demands at the site.

4.4.5 Financial Incentives and Parameters

Renewable Heat Incentives

Biomass boilers and CHP are eligible for the renewable heat incentive with the assumption that the wood fuels, biomass boiler and CHP comply with waste incineration and environmental permitting legislation. Since all the boilers and CHP installation capacities considered in this analysis are between 45kW$_{th}$ and 1 MW$_{th}$, they will receive 100 % of the biomass renewable heat incentive tariff.

The installation capacity for all the biomass boilers and CHP considered is less than 200 kW$_{th}$, therefore they fall under the double tiered tariff structure with the following parameters (Department of Energy and Climate Change, 2010).

Tier 1 tariff rate:	7.6	pence/kWh
Tier 1 tariff rate:	1.9	pence/kWh
Tariff duration:	20	years

Renewable Obligation Certificate

Biomass CHP is considered eligible for the support of renewable obligation certificate with the claim that the biomass CHP is accredited under the Combined Heat and Power Quality Assurance (CHPQA) programme by the supplier. Since the biomass CHP considered only consumes wood fuel, it is assumed that it will be cleaned and the metal materials will be removed from the wood waste.

Microgeneration stations (declared net capacity below 50 kW$_e$) and dedicated biomass CHPs will receive 2 ROCs/MWh. The length that ROCs can be issued for is twenty years, but not beyond 2037 (Office of Gas and Electricity Markets, 2011). Since the CHP only uses wood fuel, the qualifying percentage is 100 %. The average ROC sale price of £ 46.87 per ROC will be used in this analysis taken from the price on 28 July 2011 (Non-Fossil Purchasing Agency Limited, 2011).

Feed-in Tariff

Electricity generated from biomass is not eligible for the generation tariff and export tariff. However, it might be eligible for the feed-in tariffs in the future.

Grants and Loan

Grants and loans will be neglected in this analysis. Nevertheless, users can make use of this function provided by the tool.

Financial Parameters

Assume that all the long term inflation rates and long term discount rate are 4 %.

4.4.6 Results and Analysis

First of all, each case in the tool stated here will represent each boiler, CHP and their operation mode.

1st Case: HT 45 boiler operates at full potential during office times (Monday to Friday from 7:00am to 18:00pm) all year without the thermal storage.

2nd Case: HT 50 boiler operates at full potential during office times (Monday to Friday from 7:00am to 18:00pm) and coupled with the thermal storage (accumulator tank) all year.

3rd Case: HT 80 boiler operates at full potential during office times (Monday to Friday from 7:00am to 18:00pm) and coupled with the thermal storage (accumulator tank) all year.

4th Case: REFO 80 operates following the thermal demand of two pre-stressed beds at the site without thermal storage all year.

5th Case: BG 25 CHP operates at constant full potential without thermal storage all year.

6th Case: HT 50 boiler operates at full potential for a few hours during the day from Monday to Friday all year with thermal storage supplying thermal energy demands until around 18:00pm.

7th Case: HT 80 boiler operates at full potential for a few hours during the day from Monday to Friday all year with thermal storage supplying the thermal energy demands until around 18:00pm.

Thermal Energy Results and Analysis

After entering the required information into the tool, it calculates the thermal energy performance per year of each biomass boiler and CHP. The calculations are performed for the same hourly thermal energy demand profile for all cases. The table below shows the thermal energy supply demand matching results and their wood fuel consumption for one year.

Table 12: Thermal energy demand-supply matching results

Thermal Energy	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
Generated (kWh)	155,034	244,035	559,845	431,972	700,800	206,890	220,155
Delivered to Load (kWh)	155,034	226,579	391,415	431,972	431,972	196,203	207,078
Surplus (kWh)	0	0	138,890	0	268,828	0	0
Deficit (kWh)	276,938	205,393	40,556	0	0	235,769	224,894
Wood Fuel Consumption (kg)	59,636	93,871	215,350	129,238	251,599	79,582	84,685

The 1st case, which is HT 45 boiler, generates the lowest thermal energy per year (155,034 kWh) out of seven cases. As a result, it has the highest thermal energy deficit without any energy surplus. This is because HT 45 boiler can only operate during office hours, and it is not able to supply the total demand during its operation. The maximum thermal output (54 kW_{th}) of this boiler is even less than the minimum thermal demand of the two pre-stressed beds during summer (54.9 kW_{th}). In the winter, it can only supply about 75% of the thermal energy demand during its operation. Moreover, HT 45 boiler cannot operate out of office hours and during the weekend, because it needs to be manually fed wood fuel. Kerosene heaters still need to be used in this case to supplement the thermal energy supply to the two pre-stressed beds thermal demand. Besides, the boiler needs to be fed wood fuel many times in one day because it operates all day. This might cause an inconvenience in the usage of the boiler.

The 2nd case, which is HT 50 boiler with an accumulator tank, generates 155,034 kWh of thermal energy per year. It supplies half of the thermal energy demand to the load in one year due to the thermal energy stored in the accumulator tank being sufficient to supply during out of office hours or the weekends. It can only supply thermal energy for about 1 hour after the boiler is turned off in the winter, and 5 hours after the boiler is turned off in the summer. However, it can supply all the thermal demand needed during its operation. Kerosene heaters also need to be used in this case to supplement the thermal energy supply to the two pre-stressed beds thermal demand. This case also has a high stoking frequency of wood fuel.

The 3rd case, which is HT 80 boiler with an accumulator tank, generates the second highest thermal energy per year (559,845 kWh) out of seven cases, this is because it operates at its maximum output (195 kW_{th}) during office hours. However, it still has thermal energy deficit of 138,890 kWh per year. The energy stored in the accumulator tank is able to supply thermal energy all night after the boiler is turned off in the summer and the winter. However, it can only supply thermal energy for 17 hours during weekends after the boiler is turned off. Therefore the kerosene heaters are also needed in this case to supply thermal energy during the weekend. This case also has high stoking frequency of wood fuel. Extra wood fuel needs to be purchased, because the amount of wood fuel available at site is not sufficient for this case.

The 4th case, which is REFO 80 boiler, provides no thermal energy deficit and surplus. This boiler provides the best thermal energy performance out of seven cases. With the automatic wood fuel fed system, it can operate all year round. Moreover, this boiler can modulate its thermal output following thermal demand of two pre-stressed beds. Kerosene heaters are not needed in this case, because the boiler can supply all the thermal energy needed from two pre-stressed beds. Furthermore, it has very low stoking frequency. Because wood chips only need to be stored in the designated storage area once in a while, it depends on the size of the storage and it will be automatically fed into the boiler.

The 5th case, which is BG 25 CHP, generates the highest thermal energy per year (700,800 kWh) and consumes the highest amount of wood fuel out of seven cases. This is because BG 25 CHP operates at constant full potential all year round. As a result, it also has the highest thermal energy surplus. This thermal energy surplus needs to be dealt with by the heat dissipater or an alternative way of utilising this heat. Kerosene heaters are not needed in this case, because the boiler can supply all the thermal energy needed from two pre-stressed beds. Furthermore, it has a very low stoking frequency. Because wood chips only need to be stored in the 25 m^3 fuel bunker ,it will be automatically fed into the boiler. However, extra wood fuel needs to be purchased, because the amount of wood fuel available on site is not enough for this case.

The 6th case, which is the HT 50 boiler with an accumulator tank, generates 206,890 kWh of thermal energy per year. This boiler has to operate from 7:00am to 17:00pm to be able to have thermal energy stored in the accumulator tank in order to supply until 18:00pm during the winter. This case seems to be quite similar to the 2nd case due to the fact that the thermal energy stored in the accumulator tank can only supply thermal energy for about 1 hour after the boiler is turned off in the winter. However, it only needs to operate until 15:00pm during summer. Hence, this operation mode lowers the wood fuel consumption and stoking frequency compared to the 2nd case. However, it does increase the amount of kerosene needed to be used compared to the 2nd case during out of office hours and weekends.

The 7th case, which is the HT 80 boiler with an accumulator tank, generates 220,155 kWh of thermal energy per year. This boiler only needs to operate from 7:00am to 12:00pm in order to have thermal energy stored in the accumulator tank to supply until 18:00pm during the winter. Also it only needs to operate until around 10:00am during summer. This case consumes much less wood fuel than the 3rd case, because it operates for a few hours per day. Hence, this operation mode lowers the wood fuel consumption and stoking frequency compared to the 3rd case. However, it increases the amount of kerosene needed to be used compared to the 3rd case during out of office hours and weekends.

Electrical Energy Results and Analysis

After entering the required information to the tool, it calculates the electrical energy performance per year of each biomass boiler and CHP. The calculations are performed for the same hourly electrical energy demand profile for all cases. The table below shows the electrical energy supply demand matching results for one year.

Table 13: Electrical energy demand-supply matching results

Electrical Energy	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
Generated (kWh)	0	0	0	0	219,000	0	0
Delivered to Real Load (kWh)	0	0	0	0	143,761	0	0
Surplus (kWh)	0	0	0	0	13,919	0	0
Deficit (kWh)	523,398	523,398	523,398	552,973	379,637	523,398	523,398

There is only one CHP in this analysis. The 5th case, which is BG 25 CHP, is the only case that can generate electricity giving the lowest electrical energy deficit out of seven cases. This CHP generates 219,000 kWh of electrical energy per year. Since its electrical output is relatively low (25 kW_e) and the CHP consumes about 7 kW_e when it operates, the CHP can only supply about 27% of the electrical energy demand at the site. The electrical energy surplus is assumed to be exported to the grid. The 1st, 2nd, 3rd, 6th and 7th case consume the same amount of electrical energy as before, because the low electricity consumption of boilers can be neglected. The 4th case, which is REFO 80, consumes about 4.64 kW_e when it operates.

Energy Result Summary

In terms of matching thermal energy supply and demand, the 4th case, REFO 80 boiler, would be the most suitable boiler for this analysis because it can supply thermal energy with no thermal surplus and deficit. Therefore, there is no need to use kerosene heaters or to dissipate the extra heat. All other boilers except for BG 25 CHP have to be manually fed the wood fuel. Consequently REFO 80 and BG 25 are more convenient to be fed the wood fuel rather than other boilers. As for the BG 25 CHP, it can supply thermal energy to the load without any thermal energy deficit, but it produces a considerable amount of thermal energy surplus. Heat dissipaters or the methodology to utilise this extra heat will have to be considered.

In terms of matching electrical energy supply and demand, the 5th case, BG 25 CHP, is obviously the most suitable option. However, it is the only CHP in this analysis, and its capital cost is the highest cost compared to other boilers. For that reason, a financial analysis has to be put in place to determine the best option between biomass boilers and CHP.

Financial Results and Analysis

Economic performance is considerably important when choosing renewable technologies along with energy performance. The tool calculates financial results over 30 years. The following table shows the important financial parameters for seven cases.

Table 14: Financial results

Financial Parameters	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
Initial Cost (£)	13,150	20,605	24,120	37,545	185,500	20,605	24,120
Payback Time (Years)	1	1	1	1	4	1	1
Cumulative Cash Flow (£)	804,386	1,168,548	1,844,347	1,765,870	1,957,343	1,034,541	1,324,337
IRR	138%	131%	185%	107%	32%	118%	140%
NPV (£)	427,936	632,790	1,023,183	944,130	1,030,086	561,607	742,015
Profitability Index	33.54	31.71	43.42	26.15	6.55	28.26	31.76

As for economic factors, every case can provide positive cumulative profit over 30 years, and the period of payback times are within 4 years. The 3rd case has the highest profit with £ 1,957,343 with 4 years payback time. This is because it can provide the highest amount of thermal and electrical energy delivered to load, but it has the highest initial cost and operation and maintenance costs compared with the other boilers.

The other boilers have only 1 year payback time, but they give a smaller amount of profit over 30 years. The 3rd case and the 4th case, HT 80 with accumulator tank and REFO 80 respectively, give the second and third highest profit. This indicates that the technology that can deliver more energy to the load will have more economic benefits. However, one interesting point is noticeable between the 3rd case and the 4th case: the 4th case delivers more thermal energy to the load, but the 3rd case gives more profit over 30 years. This is mainly because the 3rd case has more RHI incomes per year due to the bigger installation capacity of the boiler. The double tiered tariff structure is more beneficial to the bigger size installed capacity of the boiler.

Nevertheless the capital costs of seven cases are different. So the profitability index (the amount of profit created per unit of capital cost) has to be taken into account. From the above table, it can be clearly seen that 3rd case has the highest profitability index. In other words, if the amount of investment money from the 5th case is taken and invested in the 3rd case, it will make more profit. In conclusion, the 5th case is the best option in terms of highest profit and NPV, but only if there is unlimited investment fund and it only has to be chosen from these seven cases. However, if there is limited investment funds, the 3rd case would be the best option in terms of profit per investment fund.

Environmental Impact Results and Analysis

The environmental impact of using biomass boilers and CHP in this analysis is the reduction of greenhouse gases. Greenhouse gases are released into the atmosphere by burning conventional fossil fuels, one of the main issues in climate change. The use of biomass will reduce the amount of greenhouse gases released into the atmosphere, since biomass is considered carbon neutral. However, it is not completely carbon neutral because biomass consumes some amount of energy to grow, store and transport biomass. This tool calculates the amount of equivalent CO_2 emissions produced by biomass, and the amount of equivalent CO_2 emissions produced by the kerosene or imported electricity for the same amount of energy produced by biomass. The amount of equivalent CO_2 emissions produced by increasing electrical demand is also considered. Finally, it calculates the amount of equivalent CO_2 emissions reduced by using biomass for seven cases. The table below shows the amount of CO_2 emissions produced by installing biomass boilers and CHP, and the amount of equivalent CO_2 emissions reduction for seven cases per year.

Table 15: Equivalent CO_2 emission results for one year

	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
Annual CO_2 emission from Biomass (kg CO_2)	4,614	7,263	16,962	7,936	20,425	6,158	6,552
Annual CO_2 emission reduction (kg CO_2)	62,098	90,236	151,468	160,388	250,806	78,270	82,555

The 5th case, BG 25 CHP, can reduce more CO_2 emissions (250,806 kgCO_2) than other cases, but it also produces large amounts of CO_2 emissions from biomass. This is because it has the highest biomass consumption out of the seven cases. In the meantime, it delivers not only more thermal energy than other boilers to the pre-stressed beds, but also electrical energy to the site. Therefore the large amount of energy produced from kerosene and imported electricity are replaced by wood fuel. The 3rd case and the 4th case, HT 80 with accumulator tank and REFO 80 respectively, give the second and third highest CO_2 emissions reduction because they also deliver large amounts of thermal energy to the load.

From the above table, it is indicated that the technologies that generate more energy will emit more equivalent CO_2 emissions. However, the technologies that deliver more energy to the load will reduce more equivalent CO_2 emissions. Because the more fossil fuel energy production is replaced by biomass, the less equivalent CO2 emissions will be released. The table below shows the equivalent CO_2 reduction over 30 year period.

Table 16: Table 15: Equivalent CO2 emission reduction results for 30 years

	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
Annual CO_2 emission reduction (kg CO_2)	1,862,962	2,707,090	4,544,069	4,811,611	7,524,186	2,348,121	2,476,665

4.5 Overall Results and Analysis

When considering energy, economic and environmental performance of biomass boilers and CHP, it can be concluded that the 3rd, 4th and 5th cases are more suitable for this case study than others. The 4th case, which is REFO 80 boiler, operates following the thermal load giving the best energy performance without thermal energy surplus and deficit, while the 3rd and 5th case, which are HT 80 boiler with the accumulator tank and BG 25 CHP, generate large amounts of thermal energy surplus that has to be dealt with. This thermal energy surplus can be used in other processes in the factory and space heating in the office, but the more accurate usage of gas heaters in the factory and space heating in the office have to be measured and investigated further. The BG 25 CHP in the 5th case can also generate electricity which will give the benefit from using and exporting its generated electricity. The energy deficit in the 3rd case can be supplemented by kerosene heaters, however, the HT 80 in the 3rd case needs to be manually fed the wood fuel which could be an inconvenience of using this boiler at the site.

The financial and environmental analysis also indicates that the 3rd, 4th and 5th cases are more suitable for this case study than the others. The BG 25 CHP in the 5th case gives the largest amount of profit and equivalent CO_2 reduction over 30 years, but the longest period of payback time. The 3rd and the 4th case gives lower profit and equivalent CO_2 reduction than the 5th case, but their payback periods are only one year.

The best boiler or CHP suitable for this case study is difficult to define. The 3rd, 4th and 5th cases have their advantages and disadvantages. The 3rd and 4th case, which is HT 80 boiler with accumulator tank and REFO 80 boiler respectively, would be the best suitable technologies for this case study, if the firm does not have the financial capacity to invest or want to wait for their investment to be paid off. However, the large amount of energy surplus and stoking problem has to be considered in the 3rd case. The 5th case, which is BG 25 CHP, would be the best suitable technology for this case study, if the firm has the financial capacity to invest and really want to commit to CO_2 emissions reduction. The installation of BG 25 CHP will give the highest profit over 30 years, but issue of the large amounts of energy surplus also has to be considered.

5. Conclusion

5.1 Conclusion

In line with the objectives mentioned this thesis has identified the precast concrete process and its energy usage, investigated the feasibility of biomass energy production technologies, evaluated the financial benefits and CO_2 emissions reduction of biomass energy production technologies, and created a scalable tool that can be adapted for other manufacturing processes.

The precast concrete process consumes both thermal and electrical energy. The amount of energy used in the precast concrete varies depending on the type of product, product ordered, and the technologies used. The majority of the thermal energy demand in this case study is from the curing process in pre-stressed beds. In practice, there are other methodologies of curing the concrete such as adding mineral admixture or chemical admixture. From the site visit, a rough hourly thermal energy demand profile has been made based on the two kerosene heaters usage for the two pre-stressed beds. Other thermal energy demand information has never been recorded nor has certain patterns of usage. Hence only the thermal energy demand from two pre-stressed beds was used in calculation of finding suitable a biomass boiler and CHP.

Wood waste at the Solway Precast site comes from the mould used in the process. There are around 150 tonnes of wood waste at the site and they are all different sizes and types of wood. Therefore the wood waste has to be cut or chipped into an appropriate size before using them in the some of the biomass boiler or CHP. It is also essential to make sure that the wood wastage is clean and does not contain any metal materials before being used in the biomass boiler or CHP.

The biomass boilers and CHP analysed in this tool are based on the manufacturer's specifications and discussions. This is done by sending an enquiry of suitable biomass boilers and CHPs to the suppliers. Then suppliers will send their quotation and specifications back. The boilers which are used in this case study can be manually fed or automatically fed the wood fuel. As for the CHP, the author could not find any supplier that could supply a suitable size of CHP for this thermal demand except for one. Therefore only biomass boilers and CHP specifications received from the supplier are analysed and calculated in the tool. The tool was created for the purpose of analysing the economic and environmental performance between selected wood waste boilers and CHPs at a particular site. It can be used in other manufacturing processes and different size of boilers or CHPs.

For this case study, proper biomass boilers or CHP and their operation methods can demonstrate economic and environmental benefits. One of the automatically fed wood fuel biomass boilers analysed in this thesis can easily supply the thermal energy demand from the two pre-stressed beds without thermal energy surplus or deficit. The manually fed wood fuel boiler can be used with the supplementary kerosene heaters. However, it still gives a certain amount of thermal energy surplus and deficit. The payback time for the boilers analysed in this tool is around 1 year. However, the boilers are not the best options in terms of long term profit.

Biomass CHP can give more long term profit than boilers in this analysis. Yet, it has a longer payback time, around 4 years. The quantity of CO_2 emission reduction from biomass CHP is also more than boilers in this analysis. However, the initial cost of the biomass CHP is much more expensive than boilers of the same size.

The best boiler or CHP suitable for this case study is not simple to define. It depends on the financial capacity of the firm. Investing in biomass CHP obviously has more risks than boilers due to the higher initial cost of the CHP. It also depends on the amount of commitment firms have to achieving a reduction in CO2 emissions.

This analysis is based on the thermal and electrical energy demands at the Solway Precast site. The energy efficiency and reduction at the site is not implemented in this analysis. If it were to be implemented at the site, it could reduce the size of the thermal and electrical demand, which in turn affects the size of the biomass boiler and CHP.

5.2 Further Investigation

Due to time constraints and limited information at the Solway Precast site, the results of this study should be treated as a guideline. The tool provided would gain more specific results if certain parameters had been clearly defined. Further investigation can be done on the Solway Precast site includes:

- Monitoring the use of kerosene and gas oil (propane) at the site to have a more accurate thermal demand profile
- Monitoring and recording the types of wood and the amount of wood wastage in more detail at the site in order to have a more accurate wood fuel characteristic
- Discussing in more detail specification and performance of the biomass boiler and CHP with the supplier, a site visit by the supplier could help them to be more accurate on specification and cost of their product
- Evaluating the wood storage methods and their costs
- Evaluating the price of wood chip and wood waste delivered to the site from nearby sawmills from whom, since the author did not received any replies
- Evaluating the utilisation of the thermal energy surplus on site, some of it could be used to dry the wood fuel
- Applying the energy efficiency scheme on site to decrease energy demand
- Assessment of all the inflation and discount rates in order to have more acceptable financial analysis

References

A National Statistics Publication, 2011. *Quaterly energy prices*. [Online] Available at: http://www.decc.gov.uk/assets/decc/11/stats/publications/qep/2074-qepjun11.pdf [Accessed 15 July 2011].

Action Renewables, n.d. *Utilising waste wood from the construction sector as an energy source*. [Online] Available at: http://www.actionrenewables.org/wp-content/uploads/Utilising-Waste-Wood-from-the-Construction-Sector-as-an-Energy-Source-_final-version_.pdf [Accessed 10 June 2011].

AEA Technology, 2006. *Scottish energy study*. s.l.: AEA Technology.

AEA Technology, 2011. *Guidelines to Defra / DECC's GHG conversion factors for company reporting*. s.l.: s.n.

Alakangas, E. & Flyktman, M., 2001. *Biomass CHP technologies*. JYVASKYLA: VTT Energy.

Al-Bazi, A.F., Dawood, N. & Dean, J.T., 2010. Improving performance and the reliability of off-site pre-cast concrete production operations using simulation optimisation. *Information Technology in Construction*.

American Concrete Pavement Association, 2003. Slag cement and concrete pavement. *R&T Update: Concrete Pavement Research & Technology*.

ASCENT, 2007. *Precast concrete achieves sustainability goals*. s.l.: s.n.

Austermann, S. & Whiting, K.J., 2007. *Advanced conversion technology (gasification) for biomass project*. [Online] Available at: http://gasifiers.bioenergylists.org/files/Renewables%20East%20-%20Gasification%20(Full%20Report).pdf [Accessed 18 July 2011].

Barr Ltd, n.d. *Solway Precast*. [Online] Available at: http://www.barr.co.uk/precast.html [Accessed 2011 June 15].

Biomass Energy Centre, 2003. *Carbon emissions of different fuels*. [Online] Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,163182&_dad=portal&_schema=PORTAL [Accessed 15 July 2011].

Biomass Energy Centre, 2009. *Information sheet no. 4 combined heat and power (CHP)*. [Online] Available at: http://www.biomassenergycentre.org.uk/pls/portal/docs/PAGE/RESOURCES/REF_LIB_RES/PUBLICATIONS/4.%20CHP%20V5.1%209-2009%20DRAFT.PDF [Accessed 10 July 2011].

Biomass Energy Centre, 200-. *Industrial waste and co-products*. [Online] Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17304&_dad=portal&_schema=PORTAL [Accessed 1 August 2011].

Biomass Energy Centre, 200-. *Typical calorific values of fuels*. [Online] Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal&_schema=PORTAL [Accessed 10 August 2011].

Biomass Energy Centre, 2011. *Fuel costs per kWh*. [Online] Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,59188&_dad=portal&_schema=PORTAL [Accessed 2011 July 15].

Biomass Energy Centre, n.d. *Chippers*. [Online] Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17880&_dad=portal&_schema=PORTAL [Accessed 1 August 2011].

Biomass Energy Centre, n.d. *The biomass storage facility*. [Online] Available at: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17730&_dad=portal&_schema=PORTAL [Accessed 11 August 2011].

BioRegional Development Group, 2006. *Wood chip production from tree surgery arisings in croydon*. s.l.: The Carbon Trust.

British Standards Institution, 2010. *BS EN 14961-1:2010 Solid biofuels. fuel specifications and classes. general requirements*. BSI.

Cement Concrete & Aggregates Australia, 2006. *Curing of concrete*. s.l.: s.n. Cement Concrete & Aggregates Australia.

CONSTRUCT, n.d. *National structural concrete specification for building construction*. Berkshire: s.n.

Deloitte, n.d. *Landfill tax: increase in rates*. [Online] Available at: http://www.ukbudget.com/UKBudget2010/indirect-tax/UKBudget2010-indirect-tax-landfill-tax-increase-in-rates.cfm [Accessed 27 July 2011].

Department for Environment, Food and Rural Affairs, 2008. *Waste wood as a biomass fuel*. London: Department for Environment, Food and Rural Affairs.

Department of Energy and Climate Change, 2010. *Renewable heat incentive*. London: s.n.

Department of the Environment Planning and Environmental Policy Group, 2007. *Directive 2000/76/EC on the incineration of waste*. Belfast: Department of the Environment in Northern Ireland.

Dong, L., Liu, H. & Riffat, S., 2009. Development of small-scale and micro-scale biomass-fuelled CHP systems. *Applied Thermal Engineering*, pp.2119-25.

E4tech, 2010. *Biomass prices in the heat and electricity sectors in the UK*. London: Department of Energy and Climate Change.

Eleotrowatt-ekono (UK) ltd, 2003. *Maximising the potential of wood use for energy generation in Ireland*. s.l.: COFORD.

Elhag, H.K., Glass, J. & Gibb, A., 2005. Towards sustainable business improvement in the precast concrete flooring industry. In *Corporate Social Responsibility & Environment Management Conference*. Leeds, 2005. University of Leeds.

Energy research Centre of the Netherlands (ECN), n.d. *Phyllis, select single material*. [Online] Available at: http://www.ecn.nl/phyllis [Accessed 3 August 2011].

Energy Solutions Center, 2004. *Microturbines*. [Online] Available at: http://www.poweronsite.org/AppGuide/Chapters/Chap4/4-2_Microturbines.htm [Accessed 16 August 2011].

Feed-In Tariffs Ltd, 2011. *Excluded installations*. [Online] Available at: http://www.fitariffs.co.uk/eligible/energies/excluded_installations/ [Accessed 17 July 2011].

Feed-In Tariffs Ltd, 2011. *Export tariffs*. [Online] Available at: http://www.fitariffs.co.uk/FITs/principles/export/ [Accessed 2011 August 15].

Food and Agriculture Organization of the United Nations, 1986. *Types of gasifiers*. [Online] Available at: http://www.fao.org/DOCREP/T0512E/T0512e0a.htm#2.3.2 downdraught or co current gasifiers [Accessed 22 July 2011].

Food and Agricutural Organization of the United Nations, 2004. *Unified bioenergy terminology - UBET*. [Online] Available at: http://www.fao.org/DOCREP/007/j4504E/j4504e08.htm#P1043_49499 [Accessed 5 August 2011].

Gasifier Experimenter's Kit, n.d. *Gasifier types*. [Online] Available at: http://gekgasifier.com/gasification-basics/gasifier-types/ [Accessed 25 August 2011].

Hu, H., 2006. A Study of resource planning for precast production. *Architectural Science Review*, 50(2), pp.106-14.

Kauriinoja, A., 2010. *Small scale biomass to energy solutions for nothern periphery area*. Oulu: University of Oulu.

Kellet, P., 1999. *Report on wood biomass combined heat and power for the Irish wood processing industry*. s.l.: Irish Energy Centre.

Kirjavainen, M. et al., 2004. *Small-scale biomass CHP technologies situation in Finland, Denmark and Sweden*. Espoo: VTT Processes.

Knoef, H., Quaak, P. & Stassen, H., 1999. *Energy from biomass: a review of combustion and gasification technologies*. Washington: The World Bank.

Kurkela, E., 2002. *Review of finish biomass gasification technologies*. Espoo: s.n.

Livingston, W.R., 2007. *Biomass ash characteristics and behaviour in combustion, gasification and pyrolysis systems*. s.l.: Doosan Babcock Energy Limited.

Macmillan, I., 2001. *Biomass Evaluation: Including a Case Study on Woodchip Utilisation at Ardverikie Estate, Kinlochlaggan*. Glasgow: University of Strathclyde.

Met Office, 2011. *Paisley station climate data*. [Online] Available at: http://www.metoffice.gov.uk/climate/uk/stationdata/paisleydata.txt [Accessed 1 August 2011].

Millar, M., 2006. *Research into the storage of woody biomass fuel for heating equipment*. s.l.: NIFES Consulting Group.

National Association of Forest Industries, 2006. *How is the value of wood waste determined?* Deakin: s.n.

Non-Fossil Purchasing Agency Limited, 2011. *e-ROC track record*. [Online] Available at: http://www.e-roc.co.uk/trackrecord.htm [Accessed 27 August 2011].

Nussbaumer, T., 2003. Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. *Energy & Fuels 2003*, 17(6), pp.1510-21.

Nussbaumer, T., 2008. *Biomass combustion in europe: overview on technologies and regulation*. New York: New York State Energy Research and Development Authority.

Obernberger, I., 1998. Decentralized biomass combustion: state of the art and future development. *Biomass and Bioenergy*, 14(1), pp.33-56.

Office of Gas and Electricity Markets, 2011. *Renewables obligation: guidance for generators*. London: Office of Gas and Electricity Markets.

Overend, R.P., 2004. *Thermochemical conversion of biomass*. Oxford: Eolss.

Penn State College of Agricultural Sciences, 2010. *Characteristics of biomass as a heating Fuel*. s.l.: s.n. Penn State College of Agricultural Sciences.

Sanderson, J. & Feltrin, M., n.d. *Small-scale biomass gasification in regional communities: possibilities, advantages, problems and impact*. Notting Hill: Gasification Australia.

Self Energy UK, 2009. *Cogeneration - CHP*. [Online] Available at: http://www.selfenergy.co.uk/decentralised-energy-generation/cogeneration_-_chp/ [Accessed 15 August 2011].

Sinjab, S., 2009. *An environmental and techno-economic assessment of energy recovery options for waste wood in the UK*. London: Imperial College London.

Spinelli, R. & Hartsough, B., 2000. A survey of Italian chipping operations. *Biomass and Bioenergy*, pp.434-44.

Talbott's Biomass Generators Ltd, n.d. *Talbott's biomass generator*. [Online] Available at: http://www.biomassgenerators.com/ [Accessed 15 August 2011].

Teisen Products Ltd, n.d. *FARM 2000*. [Online] Available at: http://www.farm2000.co.uk/REFO_Auto.html [Accessed 26 August 2011].

The Concrete Centre, 2009. *Precast concrete in civil engineering*. s.l.: s.n.

The Scottish Government, 2011. *2020 routemap for renewable energy in Scotland*. Edinburgh: APS Group Scotland.

The Waste & Resources Action Programme, 2005. *Review of wood waste arisings and management in the UK*. Oxon: The Waste & Resources Action Programme.

TRADA Technology & Enviros Consulting Ltd, 2005. *Options and risk assessment for treated wood waste*. Oxon: The Waste & Resources Action Programme.

Turkenburg, W.C., 2000. Renewable energy technologies. In Programme, U.N.D. *Energy and the challenge of sustainability*. New York: UNDP. p.223.

U. S. Environmental Protection Agency Combined Heat and Power Partnership, 2007. *Biomass combined heat and power catalog of technologies*. s.l.: s.n. Anon.

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

Vollenweider, B., 2004. Various methods of accelerated curing for precast Concrete applications, and their impact on short and long term compressive strength. *Concrete Technology*.

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

World Business Council for Sustainable Development, 2002. *The cement sustainability initiative*. The Cement Sustainability Initiative: World Business Council for Sustainable Development.

Appendix 1: Financial Results

1st Case: HT 45 boiler operates at full potential during office times (Monday to Friday from 7:00am to 18:00pm) all year without the thermal storage.

Table 17: 1st case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	13,150																	
1	0	0	0	0.08	150,000	59,636	0	0.00	10,631	10,631	62,099	0.0760	0.0190	155,034	6,990	0.10	0	0
2	0	0	0.00	0.08	240,364	59,636	0	0.00	11,056	11,056	62,099	0.08	0.02	155,034	7,270	0.10	0	0
3	0	0	0.00	0.09	330,729	59,636	0	0.00	11,498	11,498	62,099	0.08	0.02	155,034	7,561	0.11	0	0
4	0	0	0.00	0.09	421,093	59,636	0	0.00	11,958	11,958	62,099	0.09	0.02	155,034	7,863	0.11	0	0
5	0	0	0.00	0.09	511,458	59,636	0	0.00	12,437	12,437	62,099	0.09	0.02	155,034	8,177	0.12	0	0
6	0	0	0.00	0.10	601,822	59,636	0	0.00	12,934	12,934	62,099	0.09	0.02	155,034	8,505	0.12	0	0
7	0	0	0.00	0.10	692,187	59,636	0	0.00	13,451	13,451	62,099	0.10	0.02	155,034	8,845	0.13	0	0
8	0	0	0.00	0.11	782,551	59,636	0	0.00	13,990	13,990	62,099	0.10	0.03	155,034	9,199	0.13	0	0
9	0	0	0.00	0.11	872,916	59,636	0	0.00	14,549	14,549	62,099	0.10	0.03	155,034	9,566	0.14	0	0
10	0	0	0.00	0.11	963,280	59,636	0	0.00	15,131	15,131	62,099	0.11	0.03	155,034	9,949	0.14	0	0
11	0	0	0.00	0.12	1,053,645	59,636	0	0.00	15,736	15,736	62,099	0.11	0.03	155,034	10,347	0.15	0	0
12	0	0	0.00	0.12	1,144,009	59,636	0	0.00	16,366	16,366	62,099	0.12	0.03	155,034	10,761	0.15	0	0
13	0	0	0.00	0.13	1,234,374	59,636	0	0.00	17,020	17,020	62,099	0.12	0.03	155,034	11,191	0.16	0	0
14	0	0	0.00	0.13	1,324,738	59,636	0	0.00	17,701	17,701	62,099	0.13	0.03	155,034	11,639	0.17	0	0
15	0	0	0.00	0.14	1,415,103	59,636	0	0.00	18,409	18,409	62,099	0.13	0.03	155,034	12,105	0.17	0	0
16	0	0	0.00	0.14	1,505,467	59,636	0	0.00	19,146	19,146	62,099	0.14	0.03	155,034	12,589	0.18	0	0
17	0	0	0.00	0.15	1,595,832	59,636	0	0.00	19,911	19,911	62,099	0.14	0.04	155,034	13,092	0.19	0	0
18	0	0	0.00	0.16	1,686,196	59,636	0	0.00	20,708	20,708	62,099	0.15	0.04	155,034	13,616	0.19	0	0
19	0	0	0.00	0.16	1,776,561	59,636	0	0.00	21,536	21,536	62,099	0.15	0.04	155,034	14,161	0.20	0	0
20	0	0	0.00	0.17	1,866,925	59,636	0	0.00	22,398	22,398	62,099	0.16	0.04	155,034	14,727	0.21	0	0
21	0	0	0.00	0.18	1,957,290	59,636	0	0.00	23,294	23,294	62,099	0.00	0.00	155,034	0	0.22	0	0
22	0	0	0.00	0.18	2,047,654	59,636	0	0.00	24,225	24,225	62,099	0.00	0.00	155,034	0	0.23	0	0
23	0	0	0.00	0.19	2,138,019	59,636	0	0.00	25,194	25,194	62,099	0.00	0.00	155,034	0	0.24	0	0
24	0	0	0.00	0.20	2,228,383	59,636	0	0.00	26,202	26,202	62,099	0.00	0.00	155,034	0	0.25	0	0
25	0	0	0.00	0.21	2,318,748	59,636	0	0.00	27,250	27,250	62,099	0.00	0.00	155,034	0	0.26	0	0
26	0	0	0.00	0.21	2,409,112	59,636	0	0.00	28,340	28,340	62,099	0.00	0.00	155,034	0	0.27	0	0
27	0	0	0.00	0.22	2,499,477	59,636	0	0.00	29,474	29,474	62,099	0.00	0.00	155,034	0	0.28	0	0
28	0	0	0.00	0.23	2,589,841	59,636	0	0.00	30,653	30,653	62,099	0.00	0.00	155,034	0	0.29	0	0
29	0	0	0.00	0.24	2,680,206	59,636	0	0.00	31,879	31,879	62,099	0.00	0.00	155,034	0	0.30	0	0
30	0	0	0.00	0.25	2,770,570	59,636	0	0.00	33,154	33,154	62,099	0.00	0.00	155,034	0	0.31	0	0

1st Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-13,150	-13,150
0.00	0.00	0	0	0	0	17,621	17,621
0.00	0.00	0	0	0	0	18,326	35,947
0.00	0.00	0	0	0	0	19,059	55,006
0.00	0.00	0	0	0	0	19,821	74,827
0.00	0.00	0	0	0	0	20,614	95,441
0.00	0.00	0	0	0	0	21,439	116,880
0.00	0.00	0	0	0	0	22,296	139,176
0.00	0.00	0	0	0	0	23,188	162,364
0.00	0.00	0	0	0	0	24,116	186,480
0.00	0.00	0	0	0	0	25,080	211,560
0.00	0.00	0	0	0	0	26,083	237,644
0.00	0.00	0	0	0	0	27,127	264,770
0.00	0.00	0	0	0	0	28,212	292,982
0.00	0.00	0	0	0	0	29,340	322,323
0.00	0.00	0	0	0	0	30,514	352,836
0.00	0.00	0	0	0	0	31,734	384,571
0.00	0.00	0	0	0	0	33,004	417,575
0.00	0.00	0	0	0	0	34,324	451,899
0.00	0.00	0	0	0	0	35,697	487,596
0.00	0.00	0	0	0	0	37,125	524,721
0.00	0.00	0	0	0	0	23,294	548,014
0.00	0.00	0	0	0	0	24,225	572,240
0.00	0.00	0	0	0	0	25,194	597,434
0.00	0.00	0	0	0	0	26,202	623,636
0.00	0.00	0	0	0	0	27,250	650,886
0.00	0.00	0	0	0	0	28,340	679,227
0.00	0.00	0	0	0	0	29,474	708,701
0.00	0.00	0	0	0	0	30,653	739,353
0.00	0.00	0	0	0	0	31,879	771,232
0.00	0.00	0	0	0	0	33,154	804,386

2nd Case: HT 50 boiler operates at full potential during office times (Monday to Friday from 7:00am to 18:00pm) and coupled with the thermal storage (accumulator tank) all year.

Table 18: 2nd case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	20,605																	
1	0	0	0	0.08	150,000	93,871	0	0.00	15,537	15,537	90,236	0.0760	0.0190	226,579	10,671	0.10	0	0
2	0	0	0.00	0.08	206,129	93,871	0	0.00	16,158	16,158	90,236	0.08	0.02	226,579	11,098	0.10	0	0
3	0	0	0.00	0.09	262,259	93,871	0	0.00	16,805	16,805	90,236	0.08	0.02	226,579	11,542	0.11	0	0
4	0	0	0.00	0.09	318,388	93,871	0	0.00	17,477	17,477	90,236	0.09	0.02	226,579	12,004	0.11	0	0
5	0	0	0.00	0.09	374,517	93,871	0	0.00	18,176	18,176	90,236	0.09	0.02	226,579	12,484	0.12	0	0
6	0	0	0.00	0.10	430,647	93,871	0	0.00	18,903	18,903	90,236	0.09	0.02	226,579	12,983	0.12	0	0
7	0	0	0.00	0.10	486,776	93,871	0	0.00	19,659	19,659	90,236	0.10	0.02	226,579	13,503	0.13	0	0
8	0	0	0.00	0.11	542,905	93,871	0	0.00	20,445	20,445	90,236	0.10	0.03	226,579	14,043	0.13	0	0
9	0	0	0.00	0.11	599,034	93,871	0	0.00	21,263	21,263	90,236	0.10	0.03	226,579	14,604	0.14	0	0
10	0	0	0.00	0.11	655,164	93,871	0	0.00	22,114	22,114	90,236	0.11	0.03	226,579	15,189	0.14	0	0
11	0	0	0.00	0.12	711,293	93,871	0	0.00	22,998	22,998	90,236	0.11	0.03	226,579	15,796	0.15	0	0
12	0	0	0.00	0.12	767,422	93,871	0	0.00	23,918	23,918	90,236	0.12	0.03	226,579	16,428	0.15	0	0
13	0	0	0.00	0.13	823,552	93,871	0	0.00	24,875	24,875	90,236	0.12	0.03	226,579	17,085	0.16	0	0
14	0	0	0.00	0.13	879,681	93,871	0	0.00	25,870	25,870	90,236	0.13	0.03	226,579	17,769	0.17	0	0
15	0	0	0.00	0.14	935,810	93,871	0	0.00	26,905	26,905	90,236	0.13	0.03	226,579	18,479	0.17	0	0
16	0	0	0.00	0.14	991,940	93,871	0	0.00	27,981	27,981	90,236	0.14	0.03	226,579	19,218	0.18	0	0
17	0	0	0.00	0.15	1,048,069	93,871	0	0.00	29,100	29,100	90,236	0.14	0.04	226,579	19,987	0.19	0	0
18	0	0	0.00	0.16	1,104,198	93,871	0	0.00	30,264	30,264	90,236	0.15	0.04	226,579	20,787	0.19	0	0
19	0	0	0.00	0.16	1,160,327	93,871	0	0.00	31,475	31,475	90,236	0.15	0.04	226,579	21,618	0.20	0	0
20	0	0	0.00	0.17	1,216,457	93,871	0	0.00	32,734	32,734	90,236	0.16	0.04	226,579	22,483	0.21	0	0
21	0	0	0.00	0.18	1,272,586	93,871	0	0.00	34,043	34,043	90,236	0.00	0.00	226,579	0	0.22	0	0
22	0	0	0.00	0.18	1,328,715	93,871	0	0.00	35,405	35,405	90,236	0.00	0.00	226,579	0	0.23	0	0
23	0	0	0.00	0.19	1,384,845	93,871	0	0.00	36,821	36,821	90,236	0.00	0.00	226,579	0	0.24	0	0
24	0	0	0.00	0.20	1,440,974	93,871	0	0.00	38,294	38,294	90,236	0.00	0.00	226,579	0	0.25	0	0
25	0	0	0.00	0.21	1,497,103	93,871	0	0.00	39,826	39,826	90,236	0.00	0.00	226,579	0	0.26	0	0
26	0	0	0.00	0.21	1,553,233	93,871	0	0.00	41,419	41,419	90,236	0.00	0.00	226,579	0	0.27	0	0
27	0	0	0.00	0.22	1,609,362	93,871	0	0.00	43,075	43,075	90,236	0.00	0.00	226,579	0	0.28	0	0
28	0	0	0.00	0.23	1,665,491	93,871	0	0.00	44,798	44,798	90,236	0.00	0.00	226,579	0	0.29	0	0
29	0	0	0.00	0.24	1,721,620	93,871	0	0.00	46,590	46,590	90,236	0.00	0.00	226,579	0	0.30	0	0
30	0	0	0.00	0.25	1,777,750	93,871	0	0.00	48,454	48,454	90,236	0.00	0.00	226,579	0	0.31	0	0

2nd Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-20,605	-20,605
0.00	0.00	0	0	0	0	26,208	5,603
0.00	0.00	0	0	0	0	27,256	32,860
0.00	0.00	0	0	0	0	28,347	61,206
0.00	0.00	0	0	0	0	29,481	90,687
0.00	0.00	0	0	0	0	30,660	121,347
0.00	0.00	0	0	0	0	31,886	153,233
0.00	0.00	0	0	0	0	33,162	186,395
0.00	0.00	0	0	0	0	34,488	220,883
0.00	0.00	0	0	0	0	35,868	256,750
0.00	0.00	0	0	0	0	37,302	294,053
0.00	0.00	0	0	0	0	38,794	332,847
0.00	0.00	0	0	0	0	40,346	373,194
0.00	0.00	0	0	0	0	41,960	415,154
0.00	0.00	0	0	0	0	43,638	458,792
0.00	0.00	0	0	0	0	45,384	504,176
0.00	0.00	0	0	0	0	47,199	551,376
0.00	0.00	0	0	0	0	49,087	600,463
0.00	0.00	0	0	0	0	51,051	651,514
0.00	0.00	0	0	0	0	53,093	704,607
0.00	0.00	0	0	0	0	55,217	759,823
0.00	0.00	0	0	0	0	34,043	793,866
0.00	0.00	0	0	0	0	35,405	829,271
0.00	0.00	0	0	0	0	36,821	866,092
0.00	0.00	0	0	0	0	38,294	904,386
0.00	0.00	0	0	0	0	39,826	944,212
0.00	0.00	0	0	0	0	41,419	985,630
0.00	0.00	0	0	0	0	43,075	1,028,706
0.00	0.00	0	0	0	0	44,798	1,073,504
0.00	0.00	0	0	0	0	46,590	1,120,094
0.00	0.00	0	0	0	0	48,454	1,168,548

3rd Case: HT 80 boiler operates at full potential during office times (Monday to Friday from 7:00am to 18:00pm) and coupled with the thermal storage (accumulator tank) all year.

Table 19: 3rd case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	24,120																	
1	0	0	0	0.08	150,000	150,000	65,350	5,228.03	26,840	21,612	151,469	0.0760	0.0190	391,415	22,042	0.10	0	0
2	0	0	0.00	0.08	150,000	150,000	65,350	5,437.16	27,913	22,476	151,469	0.08	0.02	391,415	22,924	0.10	0	0
3	0	0	0.00	0.09	150,000	150,000	65,350	5,654.64	29,030	23,375	151,469	0.08	0.02	391,415	23,841	0.11	0	0
4	0	0	0.00	0.09	150,000	150,000	65,350	5,880.83	30,191	24,310	151,469	0.09	0.02	391,415	24,794	0.11	0	0
5	0	0	0.00	0.09	150,000	150,000	65,350	6,116.06	31,399	25,283	151,469	0.09	0.02	391,415	25,786	0.12	0	0
6	0	0	0.00	0.10	150,000	150,000	65,350	6,360.70	32,655	26,294	151,469	0.09	0.02	391,415	26,817	0.12	0	0
7	0	0	0.00	0.10	150,000	150,000	65,350	6,615.13	33,961	27,346	151,469	0.10	0.02	391,415	27,890	0.13	0	0
8	0	0	0.00	0.11	150,000	150,000	65,350	6,879.74	35,319	28,440	151,469	0.10	0.03	391,415	29,006	0.13	0	0
9	0	0	0.00	0.11	150,000	150,000	65,350	7,154.93	36,732	29,577	151,469	0.10	0.03	391,415	30,166	0.14	0	0
10	0	0	0.00	0.11	150,000	150,000	65,350	7,441.12	38,202	30,760	151,469	0.11	0.03	391,415	31,373	0.14	0	0
11	0	0	0.00	0.12	150,000	150,000	65,350	7,738.77	39,730	31,991	151,469	0.11	0.03	391,415	32,628	0.15	0	0
12	0	0	0.00	0.12	150,000	150,000	65,350	8,048.32	41,319	33,270	151,469	0.12	0.03	391,415	33,933	0.15	0	0
13	0	0	0.00	0.13	150,000	150,000	65,350	8,370.25	42,972	34,601	151,469	0.12	0.03	391,415	35,290	0.16	0	0
14	0	0	0.00	0.13	150,000	150,000	65,350	8,705.06	44,690	35,985	151,469	0.13	0.03	391,415	36,702	0.17	0	0
15	0	0	0.00	0.14	150,000	150,000	65,350	9,053.26	46,478	37,425	151,469	0.13	0.03	391,415	38,170	0.17	0	0
16	0	0	0.00	0.14	150,000	150,000	65,350	9,415.39	48,337	38,922	151,469	0.14	0.03	391,415	39,696	0.18	0	0
17	0	0	0.00	0.15	150,000	150,000	65,350	9,792.01	50,271	40,479	151,469	0.14	0.04	391,415	41,284	0.19	0	0
18	0	0	0.00	0.16	150,000	150,000	65,350	10,183.69	52,281	42,098	151,469	0.15	0.04	391,415	42,936	0.19	0	0
19	0	0	0.00	0.16	150,000	150,000	65,350	10,591.04	54,373	43,782	151,469	0.15	0.04	391,415	44,653	0.20	0	0
20	0	0	0.00	0.17	150,000	150,000	65,350	11,014.68	56,548	45,533	151,469	0.16	0.04	391,415	46,439	0.21	0	0
21	0	0	0.00	0.18	150,000	150,000	65,350	11,455.27	58,810	47,354	151,469	0.00	0.00	391,415	0	0.22	0	0
22	0	0	0.00	0.18	150,000	150,000	65,350	11,913.48	61,162	49,248	151,469	0.00	0.00	391,415	0	0.23	0	0
23	0	0	0.00	0.19	150,000	150,000	65,350	12,390.02	63,608	51,218	151,469	0.00	0.00	391,415	0	0.24	0	0
24	0	0	0.00	0.20	150,000	150,000	65,350	12,885.62	66,153	53,267	151,469	0.00	0.00	391,415	0	0.25	0	0
25	0	0	0.00	0.21	150,000	150,000	65,350	13,401.04	68,799	55,398	151,469	0.00	0.00	391,415	0	0.26	0	0
26	0	0	0.00	0.21	150,000	150,000	65,350	13,937.08	71,551	57,614	151,469	0.00	0.00	391,415	0	0.27	0	0
27	0	0	0.00	0.22	150,000	150,000	65,350	14,494.57	74,413	59,918	151,469	0.00	0.00	391,415	0	0.28	0	0
28	0	0	0.00	0.23	150,000	150,000	65,350	15,074.35	77,389	62,315	151,469	0.00	0.00	391,415	0	0.29	0	0
29	0	0	0.00	0.24	150,000	150,000	65,350	15,677.32	80,485	64,808	151,469	0.00	0.00	391,415	0	0.30	0	0
30	0	0	0.00	0.25	150,000	150,000	65,350	16,304.42	83,704	67,400	151,469	0.00	0.00	391,415	0	0.31	0	0

3^rd^ Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-24,120	-24,120
0.00	0.00	0	0	0	0	43,654	19,534
0.00	0.00	0	0	0	0	45,400	64,934
0.00	0.00	0	0	0	0	47,216	112,150
0.00	0.00	0	0	0	0	49,105	161,255
0.00	0.00	0	0	0	0	51,069	212,323
0.00	0.00	0	0	0	0	53,112	265,435
0.00	0.00	0	0	0	0	55,236	320,671
0.00	0.00	0	0	0	0	57,445	378,116
0.00	0.00	0	0	0	0	59,743	437,860
0.00	0.00	0	0	0	0	62,133	499,993
0.00	0.00	0	0	0	0	64,618	564,611
0.00	0.00	0	0	0	0	67,203	631,814
0.00	0.00	0	0	0	0	69,891	701,706
0.00	0.00	0	0	0	0	72,687	774,392
0.00	0.00	0	0	0	0	75,594	849,987
0.00	0.00	0	0	0	0	78,618	928,605
0.00	0.00	0	0	0	0	81,763	1,010,368
0.00	0.00	0	0	0	0	85,033	1,095,401
0.00	0.00	0	0	0	0	88,435	1,183,836
0.00	0.00	0	0	0	0	91,972	1,275,808
0.00	0.00	0	0	0	0	47,354	1,323,162
0.00	0.00	0	0	0	0	49,248	1,372,410
0.00	0.00	0	0	0	0	51,218	1,423,629
0.00	0.00	0	0	0	0	53,267	1,476,896
0.00	0.00	0	0	0	0	55,398	1,532,294
0.00	0.00	0	0	0	0	57,614	1,589,907
0.00	0.00	0	0	0	0	59,918	1,649,826
0.00	0.00	0	0	0	0	62,315	1,712,140
0.00	0.00	0	0	0	0	64,808	1,776,948
0.00	0.00	0	0	0	0	67,400	1,844,348

4th Case: REFO 80 operates following the thermal demand of two pre-stressed beds at the site without thermal storage all year.

Table 20: 4th case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	37,545																	
1	0	750	0.0085	0.09	150,000	129,238	0	1,098.52	29,621	28,522	160,389	0.0760	0.0190	431,972	13,825	0.10	-29,575	-2,958
2	0	780	0.01	0.09	170,762	129,238	0	1,142.46	30,806	29,663	160,389	0.08	0.02	431,972	14,378	0.10	-29,575	-3,076
3	0	811	0.01	0.10	191,525	129,238	0	1,188.16	32,038	30,850	160,389	0.08	0.02	431,972	14,953	0.11	-29,575	-3,199
4	0	844	0.01	0.10	212,287	129,238	0	1,235.68	33,319	32,084	160,389	0.09	0.02	431,972	15,551	0.11	-29,575	-3,327
5	0	877	0.01	0.11	233,050	129,238	0	1,285.11	34,652	33,367	160,389	0.09	0.02	431,972	16,173	0.12	-29,575	-3,460
6	0	912	0.01	0.11	253,812	129,238	0	1,336.52	36,038	34,702	160,389	0.09	0.02	431,972	16,820	0.12	-29,575	-3,598
7	0	949	0.01	0.11	274,575	129,238	0	1,389.98	37,480	36,090	160,389	0.10	0.02	431,972	17,493	0.13	-29,575	-3,742
8	0	987	0.01	0.12	295,337	129,238	0	1,445.58	38,979	37,534	160,389	0.10	0.03	431,972	18,193	0.13	-29,575	-3,892
9	0	1,026	0.01	0.12	316,100	129,238	0	1,503.40	40,538	39,035	160,389	0.10	0.03	431,972	18,920	0.14	-29,575	-4,048
10	0	1,067	0.01	0.13	336,862	129,238	0	1,563.53	42,160	40,596	160,389	0.11	0.03	431,972	19,677	0.14	-29,575	-4,209
11	0	1,110	0.01	0.13	357,625	129,238	0	1,626.08	43,846	42,220	160,389	0.11	0.03	431,972	20,464	0.15	-29,575	-4,378
12	0	1,155	0.01	0.14	378,387	129,238	0	1,691.12	45,600	43,909	160,389	0.12	0.03	431,972	21,283	0.15	-29,575	-4,553
13	0	1,201	0.01	0.14	399,150	129,238	0	1,758.76	47,424	45,665	160,389	0.12	0.03	431,972	22,134	0.16	-29,575	-4,735
14	0	1,249	0.01	0.15	419,912	129,238	0	1,829.11	49,321	47,492	160,389	0.13	0.03	431,972	23,019	0.17	-29,575	-4,925
15	0	1,299	0.01	0.16	440,675	129,238	0	1,902.28	51,294	49,392	160,389	0.13	0.03	431,972	23,940	0.17	-29,575	-5,121
16	0	1,351	0.02	0.16	461,437	129,238	0	1,978.37	53,346	51,367	160,389	0.14	0.03	431,972	24,898	0.18	-29,575	-5,326
17	0	1,405	0.02	0.17	482,200	129,238	0	2,057.51	55,479	53,422	160,389	0.14	0.04	431,972	25,894	0.19	-29,575	-5,539
18	0	1,461	0.02	0.18	502,962	129,238	0	2,139.81	57,699	55,559	160,389	0.15	0.04	431,972	26,929	0.19	-29,575	-5,761
19	0	1,519	0.02	0.18	523,725	129,238	0	2,225.40	60,007	57,781	160,389	0.15	0.04	431,972	28,007	0.20	-29,575	-5,991
20	0	1,580	0.02	0.19	544,487	129,238	0	2,314.41	62,407	60,092	160,389	0.16	0.04	431,972	29,127	0.21	-29,575	-6,231
21	0	1,643	0.02	0.20	565,250	129,238	0	2,406.99	64,903	62,496	160,389	0.00	0.00	431,972	0	0.22	-29,575	-6,480
22	0	1,709	0.02	0.21	586,012	129,238	0	2,503.27	67,499	64,996	160,389	0.00	0.00	431,972	0	0.23	-29,575	-6,740
23	0	1,777	0.02	0.21	606,775	129,238	0	2,603.40	70,199	67,596	160,389	0.00	0.00	431,972	0	0.24	-29,575	-7,009
24	0	1,849	0.02	0.22	627,537	129,238	0	2,707.54	73,007	70,300	160,389	0.00	0.00	431,972	0	0.25	-29,575	-7,289
25	0	1,922	0.02	0.23	648,300	129,238	0	2,815.84	75,927	73,112	160,389	0.00	0.00	431,972	0	0.26	-29,575	-7,581
26	0	1,999	0.02	0.24	669,062	129,238	0	2,928.47	78,964	76,036	160,389	0.00	0.00	431,972	0	0.27	-29,575	-7,884
27	0	2,079	0.02	0.25	689,825	129,238	0	3,045.61	82,123	79,077	160,389	0.00	0.00	431,972	0	0.28	-29,575	-8,200
28	0	2,163	0.02	0.26	710,587	129,238	0	3,167.43	85,408	82,241	160,389	0.00	0.00	431,972	0	0.29	-29,575	-8,528
29	0	2,249	0.03	0.27	731,350	129,238	0	3,294.13	88,824	85,530	160,389	0.00	0.00	431,972	0	0.30	-29,575	-8,869
30	0	2,339	0.03	0.28	752,112	129,238	0	3,425.90	92,377	88,951	160,389	0.00	0.00	431,972	0	0.31	-29,575	-9,224

4th Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-37,545	-37,545
0.00	0.00	0	0	0	0	38,640	1,095
0.00	0.00	0	0	0	0	40,185	41,280
0.00	0.00	0	0	0	0	41,793	83,073
0.00	0.00	0	0	0	0	43,464	126,537
0.00	0.00	0	0	0	0	45,203	171,740
0.00	0.00	0	0	0	0	47,011	218,751
0.00	0.00	0	0	0	0	48,891	267,642
0.00	0.00	0	0	0	0	50,847	318,490
0.00	0.00	0	0	0	0	52,881	371,371
0.00	0.00	0	0	0	0	54,996	426,367
0.00	0.00	0	0	0	0	57,196	483,563
0.00	0.00	0	0	0	0	59,484	543,047
0.00	0.00	0	0	0	0	61,863	604,910
0.00	0.00	0	0	0	0	64,338	669,248
0.00	0.00	0	0	0	0	66,911	736,160
0.00	0.00	0	0	0	0	69,588	805,747
0.00	0.00	0	0	0	0	72,371	878,119
0.00	0.00	0	0	0	0	75,266	953,385
0.00	0.00	0	0	0	0	78,277	1,031,662
0.00	0.00	0	0	0	0	81,408	1,113,070
0.00	0.00	0	0	0	0	54,372	1,167,442
0.00	0.00	0	0	0	0	56,547	1,223,989
0.00	0.00	0	0	0	0	58,809	1,282,799
0.00	0.00	0	0	0	0	61,162	1,343,960
0.00	0.00	0	0	0	0	63,608	1,407,568
0.00	0.00	0	0	0	0	66,152	1,473,720
0.00	0.00	0	0	0	0	68,798	1,542,519
0.00	0.00	0	0	0	0	71,550	1,614,069
0.00	0.00	0	0	0	0	74,412	1,688,482
0.00	0.00	0	0	0	0	77,389	1,765,870

5th Case: BG 25 CHP operates at constant full potential without thermal storage all year.

Table 21: 5th case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	185,500																	
1	0	6,010	0.0085	0.09	150,000	150,000	154,354	15,166.82	29,621	14,454	250,806	0.0760	0.0190	431,972	14,199	0.10	143,761	14,376
2	0	6,250	0.01	0.09	150,000	150,000	154,354	15,773.49	30,806	15,032	250,806	0.08	0.02	431,972	14,767	0.10	143,761	14,951
3	0	6,500	0.01	0.10	150,000	150,000	154,354	16,404.43	32,038	15,634	250,806	0.08	0.02	431,972	15,358	0.11	143,761	15,549
4	0	6,760	0.01	0.10	150,000	150,000	154,354	17,060.61	33,319	16,259	250,806	0.09	0.02	431,972	15,972	0.11	143,761	16,171
5	0	7,031	0.01	0.11	150,000	150,000	154,354	17,743.03	34,652	16,909	250,806	0.09	0.02	431,972	16,611	0.12	143,761	16,818
6	0	7,312	0.01	0.11	150,000	150,000	154,354	18,452.75	36,038	17,586	250,806	0.09	0.02	431,972	17,276	0.12	143,761	17,491
7	0	7,605	0.01	0.11	150,000	150,000	154,354	19,190.86	37,480	18,289	250,806	0.10	0.02	431,972	17,967	0.13	143,761	18,190
8	0	7,909	0.01	0.12	150,000	150,000	154,354	19,958.50	38,979	19,021	250,806	0.10	0.03	431,972	18,685	0.13	143,761	18,918
9	0	8,225	0.01	0.12	150,000	150,000	154,354	20,756.84	40,538	19,781	250,806	0.10	0.03	431,972	19,433	0.14	143,761	19,675
10	0	8,554	0.01	0.13	150,000	150,000	154,354	21,587.11	42,160	20,573	250,806	0.11	0.03	431,972	20,210	0.14	143,761	20,462
11	0	8,896	0.01	0.13	150,000	150,000	154,354	22,450.60	43,846	21,396	250,806	0.11	0.03	431,972	21,018	0.15	143,761	21,280
12	0	9,252	0.01	0.14	150,000	150,000	154,354	23,348.62	45,600	22,251	250,806	0.12	0.03	431,972	21,859	0.15	143,761	22,131
13	0	9,622	0.01	0.14	150,000	150,000	154,354	24,282.57	47,424	23,141	250,806	0.12	0.03	431,972	22,734	0.16	143,761	23,017
14	0	10,007	0.01	0.15	150,000	150,000	154,354	25,253.87	49,321	24,067	250,806	0.13	0.03	431,972	23,643	0.17	143,761	23,937
15	0	10,407	0.01	0.16	150,000	150,000	154,354	26,264.02	51,294	25,030	250,806	0.13	0.03	431,972	24,589	0.17	143,761	24,895
16	0	10,824	0.02	0.16	150,000	150,000	154,354	27,314.58	53,346	26,031	250,806	0.14	0.03	431,972	25,572	0.18	143,761	25,891
17	0	11,257	0.02	0.17	150,000	150,000	154,354	28,407.17	55,479	27,072	250,806	0.14	0.04	431,972	26,595	0.19	143,761	26,926
18	0	11,707	0.02	0.18	150,000	150,000	154,354	29,543.45	57,699	28,155	250,806	0.15	0.04	431,972	27,659	0.19	143,761	28,003
19	0	12,175	0.02	0.18	150,000	150,000	154,354	30,725.19	60,007	29,281	250,806	0.15	0.04	431,972	28,765	0.20	143,761	29,123
20	0	12,662	0.02	0.19	150,000	150,000	154,354	31,954.20	62,407	30,453	250,806	0.16	0.04	431,972	29,916	0.21	143,761	30,288
21	0	13,169	0.02	0.20	150,000	150,000	154,354	33,232.37	64,903	31,671	250,806	0.00	0.00	431,972	0	0.22	143,761	31,500
22	0	13,695	0.02	0.21	150,000	150,000	154,354	34,561.66	67,499	32,938	250,806	0.00	0.00	431,972	0	0.23	143,761	32,760
23	0	14,243	0.02	0.21	150,000	150,000	154,354	35,944.13	70,199	34,255	250,806	0.00	0.00	431,972	0	0.24	143,761	34,070
24	0	14,813	0.02	0.22	150,000	150,000	154,354	37,381.90	73,007	35,625	250,806	0.00	0.00	431,972	0	0.25	143,761	35,433
25	0	15,405	0.02	0.23	150,000	150,000	154,354	38,877.17	75,927	37,050	250,806	0.00	0.00	431,972	0	0.26	143,761	36,850
26	0	16,022	0.02	0.24	150,000	150,000	154,354	40,432.26	78,964	38,532	250,806	0.00	0.00	431,972	0	0.27	143,761	38,324
27	0	16,663	0.02	0.25	150,000	150,000	154,354	42,049.55	82,123	40,074	250,806	0.00	0.00	431,972	0	0.28	143,761	39,857
28	0	17,329	0.02	0.26	150,000	150,000	154,354	43,731.53	85,408	41,676	250,806	0.00	0.00	431,972	0	0.29	143,761	41,452
29	0	18,022	0.03	0.27	150,000	150,000	154,354	45,480.79	88,824	43,344	250,806	0.00	0.00	431,972	0	0.30	143,761	43,110
30	0	18,743	0.03	0.28	150,000	150,000	154,354	47,300.02	92,377	45,077	250,806	0.00	0.00	431,972	0	0.31	143,761	44,834

5th Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-185,500	-185,500
0.00	0.00	219,000	13,919	0	14,781	51,800	-133,700
0.00	0.00	219,000	13,919	0	15,372	53,872	-79,827
0.00	0.00	219,000	13,919	0	15,987	56,027	-23,800
0.00	0.00	219,000	13,919	0	16,627	58,268	34,469
0.00	0.00	219,000	13,919	0	17,292	60,599	95,068
0.00	0.00	219,000	13,919	0	17,983	63,023	158,091
0.00	0.00	219,000	13,919	0	18,703	65,544	223,635
0.00	0.00	219,000	13,919	0	19,451	68,166	291,801
0.00	0.00	219,000	13,919	0	20,229	70,892	362,693
0.00	0.00	219,000	13,919	0	21,038	73,728	436,421
0.00	0.00	219,000	13,919	0	21,879	76,677	513,098
0.00	0.00	219,000	13,919	0	22,755	79,744	592,843
0.00	0.00	219,000	13,919	0	23,665	82,934	675,777
0.00	0.00	219,000	13,919	0	24,611	86,251	762,028
0.00	0.00	219,000	13,919	0	25,596	89,702	851,730
0.00	0.00	219,000	13,919	0	26,620	93,290	945,020
0.00	0.00	219,000	13,919	0	27,684	97,021	1,042,041
0.00	0.00	219,000	13,919	0	28,792	100,902	1,142,943
0.00	0.00	219,000	13,919	0	29,943	104,938	1,247,881
0.00	0.00	219,000	13,919	0	31,141	109,136	1,357,017
0.00	0.00	219,000	13,919	0	0	50,002	1,407,018
0.00	0.00	219,000	13,919	0	0	52,002	1,459,020
0.00	0.00	219,000	13,919	0	0	54,082	1,513,102
0.00	0.00	219,000	13,919	0	0	56,245	1,569,348
0.00	0.00	219,000	13,919	0	0	58,495	1,627,843
0.00	0.00	219,000	13,919	0	0	60,835	1,688,677
0.00	0.00	219,000	13,919	0	0	63,268	1,751,946
0.00	0.00	219,000	13,919	0	0	65,799	1,817,745
0.00	0.00	219,000	13,919	0	0	68,431	1,886,176
0.00	0.00	219,000	13,919	0	0	71,168	1,957,344

6th Case: HT 50 boiler operates at full potential for a few hours during the day from Monday to Friday all year with thermal storage supplying thermal energy demands until around 18:00pm.

Table 22: 6th case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	20,605																	
1	0	0	0	0.08	150,000	79,582	0	0.00	13,454	13,454	78,271	0.0760	0.0190	196,203	10,094	0.10	0	0
2	0	0	0.00	0.08	220,418	79,582	0	0.00	13,992	13,992	78,271	0.08	0.02	196,203	10,498	0.10	0	0
3	0	0	0.00	0.09	290,835	79,582	0	0.00	14,552	14,552	78,271	0.08	0.02	196,203	10,918	0.11	0	0
4	0	0	0.00	0.09	361,253	79,582	0	0.00	15,134	15,134	78,271	0.09	0.02	196,203	11,355	0.11	0	0
5	0	0	0.00	0.09	431,670	79,582	0	0.00	15,739	15,739	78,271	0.09	0.02	196,203	11,809	0.12	0	0
6	0	0	0.00	0.10	502,088	79,582	0	0.00	16,369	16,369	78,271	0.09	0.02	196,203	12,281	0.12	0	0
7	0	0	0.00	0.10	572,505	79,582	0	0.00	17,023	17,023	78,271	0.10	0.02	196,203	12,772	0.13	0	0
8	0	0	0.00	0.11	642,923	79,582	0	0.00	17,704	17,704	78,271	0.10	0.03	196,203	13,283	0.13	0	0
9	0	0	0.00	0.11	713,340	79,582	0	0.00	18,413	18,413	78,271	0.10	0.03	196,203	13,815	0.14	0	0
10	0	0	0.00	0.11	783,758	79,582	0	0.00	19,149	19,149	78,271	0.11	0.03	196,203	14,367	0.14	0	0
11	0	0	0.00	0.12	854,175	79,582	0	0.00	19,915	19,915	78,271	0.11	0.03	196,203	14,942	0.15	0	0
12	0	0	0.00	0.12	924,593	79,582	0	0.00	20,712	20,712	78,271	0.12	0.03	196,203	15,540	0.15	0	0
13	0	0	0.00	0.13	995,010	79,582	0	0.00	21,540	21,540	78,271	0.12	0.03	196,203	16,161	0.16	0	0
14	0	0	0.00	0.13	1,065,428	79,582	0	0.00	22,402	22,402	78,271	0.13	0.03	196,203	16,808	0.17	0	0
15	0	0	0.00	0.14	1,135,845	79,582	0	0.00	23,298	23,298	78,271	0.13	0.03	196,203	17,480	0.17	0	0
16	0	0	0.00	0.14	1,206,263	79,582	0	0.00	24,230	24,230	78,271	0.14	0.03	196,203	18,179	0.18	0	0
17	0	0	0.00	0.15	1,276,680	79,582	0	0.00	25,199	25,199	78,271	0.14	0.04	196,203	18,906	0.19	0	0
18	0	0	0.00	0.16	1,347,098	79,582	0	0.00	26,207	26,207	78,271	0.15	0.04	196,203	19,662	0.19	0	0
19	0	0	0.00	0.16	1,417,516	79,582	0	0.00	27,255	27,255	78,271	0.15	0.04	196,203	20,449	0.20	0	0
20	0	0	0.00	0.17	1,487,933	79,582	0	0.00	28,345	28,345	78,271	0.16	0.04	196,203	21,267	0.21	0	0
21	0	0	0.00	0.18	1,558,351	79,582	0	0.00	29,479	29,479	78,271	0.00	0.00	196,203	0	0.22	0	0
22	0	0	0.00	0.18	1,628,768	79,582	0	0.00	30,658	30,658	78,271	0.00	0.00	196,203	0	0.23	0	0
23	0	0	0.00	0.19	1,699,186	79,582	0	0.00	31,885	31,885	78,271	0.00	0.00	196,203	0	0.24	0	0
24	0	0	0.00	0.20	1,769,603	79,582	0	0.00	33,160	33,160	78,271	0.00	0.00	196,203	0	0.25	0	0
25	0	0	0.00	0.21	1,840,021	79,582	0	0.00	34,486	34,486	78,271	0.00	0.00	196,203	0	0.26	0	0
26	0	0	0.00	0.21	1,910,438	79,582	0	0.00	35,866	35,866	78,271	0.00	0.00	196,203	0	0.27	0	0
27	0	0	0.00	0.22	1,980,856	79,582	0	0.00	37,301	37,301	78,271	0.00	0.00	196,203	0	0.28	0	0
28	0	0	0.00	0.23	2,051,273	79,582	0	0.00	38,793	38,793	78,271	0.00	0.00	196,203	0	0.29	0	0
29	0	0	0.00	0.24	2,121,691	79,582	0	0.00	40,344	40,344	78,271	0.00	0.00	196,203	0	0.30	0	0
30	0	0	0.00	0.25	2,192,108	79,582	0	0.00	41,958	41,958	78,271	0.00	0.00	196,203	0	0.31	0	0

6^{th} Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-20,605	-20,605
0.00	0.00	0	0	0	0	23,548	2,943
0.00	0.00	0	0	0	0	24,490	27,433
0.00	0.00	0	0	0	0	25,470	52,903
0.00	0.00	0	0	0	0	26,488	79,391
0.00	0.00	0	0	0	0	27,548	106,939
0.00	0.00	0	0	0	0	28,650	135,589
0.00	0.00	0	0	0	0	29,796	165,385
0.00	0.00	0	0	0	0	30,988	196,372
0.00	0.00	0	0	0	0	32,227	228,600
0.00	0.00	0	0	0	0	33,516	262,116
0.00	0.00	0	0	0	0	34,857	296,973
0.00	0.00	0	0	0	0	36,251	333,224
0.00	0.00	0	0	0	0	37,701	370,925
0.00	0.00	0	0	0	0	39,209	410,134
0.00	0.00	0	0	0	0	40,778	450,912
0.00	0.00	0	0	0	0	42,409	493,321
0.00	0.00	0	0	0	0	44,105	537,426
0.00	0.00	0	0	0	0	45,869	583,295
0.00	0.00	0	0	0	0	47,704	630,999
0.00	0.00	0	0	0	0	49,612	680,612
0.00	0.00	0	0	0	0	29,479	710,091
0.00	0.00	0	0	0	0	30,658	740,749
0.00	0.00	0	0	0	0	31,885	772,634
0.00	0.00	0	0	0	0	33,160	805,794
0.00	0.00	0	0	0	0	34,486	840,280
0.00	0.00	0	0	0	0	35,866	876,146
0.00	0.00	0	0	0	0	37,301	913,447
0.00	0.00	0	0	0	0	38,793	952,239
0.00	0.00	0	0	0	0	40,344	992,583
0.00	0.00	0	0	0	0	41,958	1,034,541

7th Case: HT 80 boiler operates at full potential for a few hours during the day from Monday to Friday all year with thermal storage supplying the thermal energy demands until around 18:00pm.

Table 23: 7th case financial result

Year	Initial costs	O&M Costs	Biomass Fuel Price (£ / kg)		Biomass Available at Site (kg)	Biomass Fuel Consumption(kg)		Biomass Fuel Cost	Conventional Fuel Cost	Fuel Saving	CO_2 Reduction	RHI (£ / kWh)		Useful Heat Produced	RHI Tariff	Electricity Price Rate	Electricity Reduction (+) or Extra(-)	Electrical Saving or Cost
	£	£	At Site	Purchase		At Site	Purchase	£	£	£	kg CO_2	Tier 1	Tier2	kWh	£	£ / kWh	kWh	£
0	24,120																	
1	0	0	0	0.08	150,000	84,685	0	0.00	14,200	14,200	82,556	0.0760	0.0190	207,078	18,540	0.10	0	0
2	0	0	0.00	0.08	215,315	84,685	0	0.00	14,768	14,768	82,556	0.08	0.02	207,078	19,281	0.10	0	0
3	0	0	0.00	0.09	280,630	84,685	0	0.00	15,358	15,358	82,556	0.08	0.02	207,078	20,052	0.11	0	0
4	0	0	0.00	0.09	345,945	84,685	0	0.00	15,973	15,973	82,556	0.09	0.02	207,078	20,855	0.11	0	0
5	0	0	0.00	0.09	411,260	84,685	0	0.00	16,612	16,612	82,556	0.09	0.02	207,078	21,689	0.12	0	0
6	0	0	0.00	0.10	476,575	84,685	0	0.00	17,276	17,276	82,556	0.09	0.02	207,078	22,556	0.12	0	0
7	0	0	0.00	0.10	541,890	84,685	0	0.00	17,967	17,967	82,556	0.10	0.02	207,078	23,458	0.13	0	0
8	0	0	0.00	0.11	607,205	84,685	0	0.00	18,686	18,686	82,556	0.10	0.03	207,078	24,397	0.13	0	0
9	0	0	0.00	0.11	672,520	84,685	0	0.00	19,433	19,433	82,556	0.10	0.03	207,078	25,373	0.14	0	0
10	0	0	0.00	0.11	737,835	84,685	0	0.00	20,210	20,210	82,556	0.11	0.03	207,078	26,388	0.14	0	0
11	0	0	0.00	0.12	803,150	84,685	0	0.00	21,019	21,019	82,556	0.11	0.03	207,078	27,443	0.15	0	0
12	0	0	0.00	0.12	868,465	84,685	0	0.00	21,860	21,860	82,556	0.12	0.03	207,078	28,541	0.15	0	0
13	0	0	0.00	0.13	933,780	84,685	0	0.00	22,734	22,734	82,556	0.12	0.03	207,078	29,682	0.16	0	0
14	0	0	0.00	0.13	999,095	84,685	0	0.00	23,643	23,643	82,556	0.13	0.03	207,078	30,870	0.17	0	0
15	0	0	0.00	0.14	1,064,410	84,685	0	0.00	24,589	24,589	82,556	0.13	0.03	207,078	32,105	0.17	0	0
16	0	0	0.00	0.14	1,129,725	84,685	0	0.00	25,573	25,573	82,556	0.14	0.03	207,078	33,389	0.18	0	0
17	0	0	0.00	0.15	1,195,040	84,685	0	0.00	26,596	26,596	82,556	0.14	0.04	207,078	34,724	0.19	0	0
18	0	0	0.00	0.16	1,260,355	84,685	0	0.00	27,659	27,659	82,556	0.15	0.04	207,078	36,113	0.19	0	0
19	0	0	0.00	0.16	1,325,670	84,685	0	0.00	28,766	28,766	82,556	0.15	0.04	207,078	37,558	0.20	0	0
20	0	0	0.00	0.17	1,390,985	84,685	0	0.00	29,916	29,916	82,556	0.16	0.04	207,078	39,060	0.21	0	0
21	0	0	0.00	0.18	1,456,300	84,685	0	0.00	31,113	31,113	82,556	0.00	0.00	207,078	0	0.22	0	0
22	0	0	0.00	0.18	1,521,615	84,685	0	0.00	32,358	32,358	82,556	0.00	0.00	207,078	0	0.23	0	0
23	0	0	0.00	0.19	1,586,930	84,685	0	0.00	33,652	33,652	82,556	0.00	0.00	207,078	0	0.24	0	0
24	0	0	0.00	0.20	1,652,245	84,685	0	0.00	34,998	34,998	82,556	0.00	0.00	207,078	0	0.25	0	0
25	0	0	0.00	0.21	1,717,560	84,685	0	0.00	36,398	36,398	82,556	0.00	0.00	207,078	0	0.26	0	0
26	0	0	0.00	0.21	1,782,875	84,685	0	0.00	37,854	37,854	82,556	0.00	0.00	207,078	0	0.27	0	0
27	0	0	0.00	0.22	1,848,190	84,685	0	0.00	39,368	39,368	82,556	0.00	0.00	207,078	0	0.28	0	0
28	0	0	0.00	0.23	1,913,505	84,685	0	0.00	40,943	40,943	82,556	0.00	0.00	207,078	0	0.29	0	0
29	0	0	0.00	0.24	1,978,820	84,685	0	0.00	42,580	42,580	82,556	0.00	0.00	207,078	0	0.30	0	0
30	0	0	0.00	0.25	2,044,135	84,685	0	0.00	44,284	44,284	82,556	0.00	0.00	207,078	0	0.31	0	0

7th Case (continue)

FIT for generate	Fit for export	Electricity Generated	Electricity Exported	Feed-In Tariff Incomes	ROC Incomes	Pre-Tax Cash Flow	Cumulative Cash Flow
£ / kWh	£ / kWh	kWh	kWh	£	£	£	£
						-24,120	-24,120
0.00	0.00	0	0	0	0	32,739	8,619
0.00	0.00	0	0	0	0	34,049	42,668
0.00	0.00	0	0	0	0	35,411	78,079
0.00	0.00	0	0	0	0	36,827	114,906
0.00	0.00	0	0	0	0	38,300	153,206
0.00	0.00	0	0	0	0	39,832	193,038
0.00	0.00	0	0	0	0	41,426	234,464
0.00	0.00	0	0	0	0	43,083	277,546
0.00	0.00	0	0	0	0	44,806	322,352
0.00	0.00	0	0	0	0	46,598	368,950
0.00	0.00	0	0	0	0	48,462	417,412
0.00	0.00	0	0	0	0	50,400	467,813
0.00	0.00	0	0	0	0	52,417	520,229
0.00	0.00	0	0	0	0	54,513	574,742
0.00	0.00	0	0	0	0	56,694	631,436
0.00	0.00	0	0	0	0	58,961	690,398
0.00	0.00	0	0	0	0	61,320	751,717
0.00	0.00	0	0	0	0	63,773	815,490
0.00	0.00	0	0	0	0	66,324	881,814
0.00	0.00	0	0	0	0	68,977	950,790
0.00	0.00	0	0	0	0	31,113	981,903
0.00	0.00	0	0	0	0	32,358	1,014,261
0.00	0.00	0	0	0	0	33,652	1,047,913
0.00	0.00	0	0	0	0	34,998	1,082,911
0.00	0.00	0	0	0	0	36,398	1,119,309
0.00	0.00	0	0	0	0	37,854	1,157,163
0.00	0.00	0	0	0	0	39,368	1,196,531
0.00	0.00	0	0	0	0	40,943	1,237,473
0.00	0.00	0	0	0	0	42,580	1,280,054
0.00	0.00	0	0	0	0	44,284	1,324,337

Appendix 2: Monthly Biomass Consumption

Table 24: Monthly biomass consumption in kg

Month	Monthly Fuel Consumption (kg)						
	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
January	4,798.26	7,552.81	17,327.05	16,293.62	25,849.21	6,866.20	7,875.93
February	4,569.77	7,193.16	16,501.95	14,716.81	23,347.67	6,539.23	7,500.89
March	5,255.24	8,272.13	18,977.24	10,796.71	25,849.21	7,520.12	8,626.02
April	5,026.75	7,912.47	18,152.14	10,293.01	25,015.36	7,193.16	8,250.97
May	4,798.26	7,552.81	17,327.05	9,745.51	25,849.21	6,866.20	7,875.93
June	5,026.75	7,912.47	18,152.14	7,818.31	25,015.36	5,754.53	4,950.58
July	5,026.75	7,912.47	18,152.14	7,719.76	21,849.21	5,754.53	4,950.58
August	5,026.75	7,912.47	18,152.14	7,703.33	21,849.21	5,754.53	4,950.58
September	5,026.75	7,912.47	18,152.14	7,818.31	25,015.36	5,754.53	4,950.58
October	4,798.26	7,552.81	17,327.05	9,767.41	25,849.21	6,866.20	7,875.93
November	5,026.75	7,912.47	18,152.14	10,271.11	25,015.36	7,193.16	8,250.97
December	5,255.24	8,272.13	18,977.24	16,293.62	25,849.21	7,520.12	8,626.02

Table 25: Monthly biomass consumption in m^3

Month	Monthly Fuel Consumption (m^3)						
	1st Case	2nd Case	3rd Case	4th Case	5th Case	6th Case	7th Case
January	7.03	11.06	25.37	62.67	99.42	10.05	11.53
February	6.69	10.53	24.16	56.60	89.80	9.58	10.98
March	7.70	12.11	27.79	41.53	99.42	11.01	12.63
April	7.36	11.59	26.58	39.59	96.21	10.53	12.08
May	7.03	11.06	25.37	37.48	99.42	10.05	11.53
June	7.36	11.59	26.58	30.07	96.21	8.43	7.25
July	7.36	11.59	26.58	29.69	99.42	8.43	7.25
August	7.36	11.59	26.58	29.63	99.42	8.43	7.25
September	7.36	11.59	26.58	30.07	96.21	8.43	7.25
October	7.03	11.06	25.37	37.57	99.42	10.05	11.53
November	7.36	11.59	26.58	39.50	96.21	10.53	12.08
December	7.70	12.11	27.79	62.67	99.42	11.01	12.63