Techno-economic performance analysis and environmental impact assessment of energy production from biomass at different scales

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I, Chandni Patel, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

"Judge each day not by the harvest you reap but by the seeds you plant"

Robert Louis Stevenson

I would like to dedicate this thesis to my loving parents and brother.

Abstract

Burning fossil fuels contributes largely to the release of CO_2 emissions, which CO_2 accounted for 84% of the total UK greenhouse emissions in 2009. Energy production can affect climate change because it is currently produced using non- renewable fuels. As a result the UK Government has set a target of 15% renewable energy use by 2020. Renewable energy is the production of energy using fuels that are produced and sourced sustainably. Maximising renewable energy by using alternative fuels to produce our heat and electricity can help decrease our emissions and reach Government targets.

The main objective of this work is to investigate the techno-economic assessment and life cycle assessment of energy from different types of biomass in the UK context. Energy use in the UK and climate change is discussed to present a case for sustainable energy. An extensive review of the thermal treatment options, as well as the different types of biomass available in the UK has been presented. Issues related to energy from biomass such as food vs.. fuel and land vs.. fuel are also discussed.

In this thesis two second generation types of biomass are individually investigated - solid recovered fuel (SRF) and forestry waste wood chips (FWWC). A techno-economic assessment was performed on small to medium scale combustion plants using SRF (50 ktpa and 100 ktpa) or FWWC (50 ktpa, 80 ktpa and 160 ktpa). These are waste forms of biomass one of which is a mixed waste source (SRF) and the other a single waste source (FWWC), of which we have a great untapped resource in the UK. Discounted cash flow analysis, internal rate of return and levelised cost for the plants are calculated. The techno-economic assessment for the SRF plants were done previously by Yassin et al., (2008) and updated in this study using new cost data, such as landfill disposal costs and the new banded ROC’s scheme. The techno-economic performance of the FWWC was devised in the same way as for the SRF plant to ensure consistency.

The results showed that the small and medium scale SRF plants were technically and economically viable, whilst only the largest scale FWWC plant

was economically viable. A sensitivity analysis on the economic assessment was also performed, to investigate changes in levelised cost when seven different parameters were changed by 10% and 30%.

As a result of these investigations a life cycle assessment (LCA) was performed on the large scale plants to investigate environmental aspects of sustainability. Hot-spot analysis was conducted for both plants and landfill reference systems were investigated for the SRF plant, whilst the FWWC plant investigated the emissions associated with leaving wood in the forest. In addition, the plants were compared against fossil fuel alternatives at the same production scale. The results of the LCA showed that both types of biomass are more environmentally friendly than fossil fuel alternatives. The SRF hot-spot analysis showed that the Fairport Process releases the most CO_2. The FWWC hot-spot analysis showed harvesting released most CO_2.

The work was developed further by investigating a first generation liquid form of biomass rapeseed oil (RSO) for the production of energy using internal combustion engines. RSO is grown in increasing amounts in the UK for bio-diesel production but can also be used crude to produce energy. A techno-economic assessment of energy from RSO was conducted at small (27 ktpa) to medium (40 ktpa) scale plants, using the identical methodology as above. The results found only the medium scale plant to be economically viable. A sensitivity analysis on the economic assessment was also performed using the same percentage changes as above.

An LCA was performed for the 40 ktpa RSO plant. A base case was investigated and compared to the plant. A hot-spot analysis was investigated, which showed the harvesting and cultivating units released the most CO_2. The effects of growing rapeseed oil and how we use our land is investigated. The results showed the plant releases least emissions when the rapeseed is grown on rotation, using reduced tillage methodology.

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Contents

Abstract **3**
Acknowledgements... **5**
Contents **6**
List of Tables **10**
List of Figures... **12**
1 General Introduction **14**
Summary 14

1.1. Sustainable Development 14

1.2. Life Cycle Assessment 16

1.3. The UK Energy System and Climate Change 19

1.4. Electricity Demand and Supply in the UK 24

1.5. Energy and the Economy 26

1.6. Research Objectives 30

2. Renewable Energy: the Role of Biomass... **32**
Summary 32

2.1. Renewable energy and policies 32

2.2. Biomass 37

2.2.1. Food vs. Fuel 38

2.2.2. Land vs. Fuel 41

2.3. Types of Biomass 43

2.3.1. Solid Biomass 45

2.3.2. Liquid Biomass 46

2.4. UK Biomass Strategy 2007 47

2.5. Rapeseed Oil 48

2.6. Forestry waste wood chips 51

2.7. Municipal Solid Waste 52

2.8. Solid Recovered Fuel (SRF) 53

2.9. Thermal Treatment Technologies and Reciprocating Engines 65

Summary 65

2.9.1. Pyrolysis 65

2.9.2. Pyrolysis Limitations... 68

2.10. Gasification 68

2.10.1. Gasification Limitations 71

2.11. Combustion 73

2.11.1. Fixed bed combustion 74

2.11.2. Fluidised bed combustion... 75

2.12. Reciprocating Engines... 79

2.13. Conclusions 80

3. Techno-economic assessment of solid recovered fuel and forest waste wood chips combustion plants 82

Summary 82

3.1. Methodology 83

3.1.1. Biomass characteristics and system layout 83

3.1.2. Technical Analysis - Overall system efficiency calculations............. 84

3.1.3. Developing the economic analysis.. 85

3.1.3.1. Capital Costs 85

3.1.3.2. Operating costs... 86

3.1.3.3. Working capital 87

3.1.3.4. Corporation Tax 87

3.1.3.5. Projected revenues... 88

3.1.3.6. Net Present Value and Levelised Cost 89

3.1.3.7. Depreciation 89

3.1.3.8. Operating Profit... 90

3.2. Results and Discussion... 90

3.2.1. Technical analysis 90

3.2.2. Economic Assessment 91

3.3. Economic Sensitivity Analysis 94

3.3.1. Changes in biomass calorific value 96

3.3.2. Changes in steam turbine efficiency and engine efficiency 97

3.3.3. Capital and Operating Costs 97

3.3.4. Changes in plant lifetime 99

3.3.5. Changes in Biomass Feed Rate 99

3.3.6. Changes in Discount rate 100

3.4. Changes in electricity selling price and ROCs selling price 100

3.5. Conclusions 103

4. Case study: Life cycle assessment of energy from SRF and FWWC 105

Summary 105

4.1. Goal and Scope Analysis 105

4.2. Inventory Analysis 129

4.3. Impact Assessment 131

4.4. Conclusions 138

5. Techno-economic and environmental impact assessment of energy from RSO using internal combustion engine technology 140

Summary 140

5.1. Biomass characteristics and system layout 141

5.2. Technical Analysis - Overall system efficiency calculations 143

5.3. Results and Discussion 144

5.3.1. Technical analysis 144

5.3.2. Economic Assessment 144

5.4. Economic Sensitivity Analysis 148

5.4.1. Changes in Biomass Calorific Value 149

5.4.2. Changes in steam turbine efficiency and engine efficiency 149

5.4.3. Capital and Operating Costs 149

5.4.4. Changes in plant lifetime 152

5.4.5. Changes in Biomass Feed Rate 152

5.4.6. Changes in Discount rate 153

5.4.7. Changes in electricity selling price and ROCs selling price 153

5.5. Conclusions 156

5.6. Case study: Life cycle assessment of energy from RSO at medium scale 158

5.6.1. Goal and Scope Analysis 158

5.6.2. Inventory Analysis 160

5.6.3. Impact Assessment 165

5.7. Conclusion 170

6. Results and main conclusions 171

6.1. Results 173

6.2. Main Conclusions 182

6.2.1. Small Scale Energy Production 183

6.2.2. Transport 184

6.2.3. Plant Location 184

6.2.4. The Role of Legislation 184

6.3. Future work 185

Nomenclature 188

Abbreviations 188

References 191

Appendix 1. LCA for FWWC plant 201

Appendix 2. LCA for SRF plant 202

Appendix 3. LCA for RSO plant 203

Publications 204

List of Tables

Table 1.1 Examples of projected impacts by sector due to extreme precipitation-related weather and climate change 23
Table 1.2 Absolute share of net electricity supplied by fuel for 2008 and 2009 . 25
Table 2.1 First three carbon budgets 34
Table 2.2 Financial incentives for bio-energy in the UK 36
Table 2.3 Biomass supply and conversion chain 44
Table 2.4 Solid biomass types according to origins 45
Table 2.5 Liquid biomass types according to origin 46
Table 2.6 Suitability of methods of disposal for grades of waste wood 51
Table 2.7 Mechanical Waste Preparation Technologies 54
Table 2.8 Mechanical waste separation technologies 55
Table 2.9 Different methods of pyrolysis and the resulting constituents in percentage 66
Table 2.10 current advance thermal treatment plants 72
Table 2.11 design parameters for BFB and CFB combustors 76
Table 2.12 Overview of fluidised bed combustion technologies 77
Table 2.13 MSW incineration plants in UK 78
Table 2.14 Examples of established power plants 80
Table 3.1 Proximate and ultimate analysis of the biomass investigated 84
Table 3.2 Overall electrical and power results of each plant 91
Table 3.3 Economic performance of the biomass plants 92
Table 3.4 capital and operating cost comparison of a coal combustion plant producing 18 MW of electricity in the UK and Europe 99
Table 3.5 Sensitivity analysis results of percentage changes in electricity price for the 160 ktpa forest waste wood chip plant 100
Table 3.6 Sensitivity analysis results of percentage changes in the electricity price of the 100 ktpa SRF plant 101
Table 3.7 Sensitivity analysis results of percentage changes in ROC price 102
Table 3.8 ROC buy out prices per year from 2002 to 2013 103
Table 4.1. Radiative efficiency of the three main GHGs 113
Table 4.2 Energy used and conversion factors used for each box in the FWWC plant 115
Table 4.3 Conversion factors for CO_2 and CH_4 E_{GWP} of non-renewable plants 119
Table 4.4 Emissions associated with energy production from the base case, the electricity mix plant and the energy from FWWC plant 121
Table 4.5 Energy used for the SRF plant 131
Table 4.6 Emission values used to calculate the overall E_{GWP} including displacement of energy from SRF combustion compared with the MSW

landfill base case 135
Table 5.1 Proximate and ultimate analysis of the biomass 143
Table 5.2 Overall electrical efficiencies and heat and power results of the plants 144
Table 5.3 Economic performance of the biomass plants 146
Table 5.4 Sensitivity analysis results of percentage changes in electricity........ 154
Table 5.5 sensitivity analysis results of percentage changes in ROC price 155
Table 5.6 ROC buy out prices per year from 2002 to 2013............................... 156
Table 5.7 Characterisation factors for carbon storage on GWP......................... 161
Table 5.8 Energy used for boxes in the RSO plant.. 165

List of Figures

Figure 1.1 Sustainability diagram 15
Figure 1.2 Life cycle stages and system boundaries 17
Figure 1.3 UK energy consumption and distribution in 2009 21
Figure 1.4 Total carbon dioxide emissions by sector 22
Figure 1.5 Electricity demand by sector 24
Figure 1.6 share of net electricity supplied by fuel for 2008 and 2009 25
Figure 1.7 Electricity supply system in Great Britain in 2003 29
Figure 2.1 Potential Scenario to meet 15% renewable energy by 2020 33
Figure 2.2 waste Management Hierarchy 53
Figure 2.3 An illustration of the potential Mechanical Biological Treatment options 56
Figure 2.4 Mechanical Heat Treatment 59
Figure 2.5 Schematic of the Fairport Process 63
Figure 2.6 Application of bio-oil 67
Figure 2.7 Application of Syngas 70
Figure 2.8 Diagram illustrating a typical energy flow of a biomass combustion process 74
Figure 3.1 Process diagram of energy recovery from combustion of FWWC or SRF coupled with steam turbine technology 84
Figure 3.2 Sensitivity analysis of the 160 ktpa FWWC fluidised bed combustion plant 95
Figure 3.3 Sensitivity analysis of 100 ktpa SRF fluidised bed combustion plant 96
Figure 3.4 Sensitivity analysis of changes in capital cost ±30% for the FWWC and SRF plants 98
Figure 3.5 changes in electricity price per year from 1979 to 2011 102
Figure 4.1 System boundary and sub-systems of the FWWC plant 109
Figure 4.2 Fraction of a GHG emission pulse remaining in the atmosphere throughout the subsequent 1000 years, calculated according to IPCC's parameterized decay function. 113
Figure 4.3. The Moura-Costa approach calculated for a 100-year time horizon. Sequestering and storing one tonne of CO_2 during 48 years (red area) is equivalent to the impact of a 1-tonne CO_2 pulse-emission integrated over 100 years (blue area). 114
Figure 4.4 Global warming potential of base cases compared to energy from FWWC 117
Figure 4.5 E_{GWP} of the FWWC plant compared with electricity mix at the same scale. 119

Figure 4.6 E_{GWP} of the FWWC compared with energy from electricity mix including emission displacement 120
Figure 4.7 The forest waste wood base case compared with the energy from electricity mix plant and the energy from FWWC plant including displacement..121
Figure 4.8 Hot-spot analysis of FWWC plant..122
Figure 4.9 Changes in carbon emission with increased transport distance........123
Figure 4.10 Effect on the overall E_{GWP} of energy from FWWC when increasing transport distance 124
Figure 4.11 E_{GWP} of the FWWC plant compared with coal at the same scale...125
Figure 4.12 E_{GWP} of electricity from FWWC compared with electricity from coal including emission displacement 126
Figure 4.13 System boundary of the SRF fluidised bed combustion plant........128
Figure 4.14 Landfill Base Case for the energy from SRF study........................133
Figure 4.15 Global warming potential comparison between energy from SRF combustion and MSW landfill base case including displacement............134
Figure 4.16 E_{GWP} from the SRF plant compared with energy from the electricity mix plant of the same scale...135
Figure 4.17 E_{GWP} of the SRF plant compared with energy from the electricity mix plant of the same scale including emission displacement..........................136
Figure 4.18 Hot-spot analysis for the SRF plant...137
Figure 5.1 Energy recovery from RSO utilised in internal combustion engines with heat recovery using ORCE technology...142
Figure 5.2 Sensitivity analysis on the levelised costs 148
Figure 5.3 Sensitivity analysis percentage change in levelised costs by changing the capital costs by± 30%..150
Figure 5.4 CHP capital and operating cost against plant scale in the UK 152
Figure 5.5 Changes in electricity price per year from 1979 to 2011.................154
Figure 5.6 System boundary and sub-systems for the RSO plant......................160
Figure 5.7 System boundary for growing RSO on set aside land and the base case option on leaving the land as set aside 163
Figure 5.8 Base case versus Energy from RSO 164
Figure 5.9 E_{GWP} of RSO compared with coal and natural gas 166
Figure 5.10 E_{GWP} of RSO compared with coal or natural gas plants of similar scales including emissions displacement 167
Figure 5.11 Hot-spot analysis for the RSO plant 168

1 General Introduction

Summary

In this chapter, the concept of sustainability of a business or process is discussed and LCA is introduced as a tool to quantify sustainable behaviour. An overview is provided of the link between climate change, sustainability, human consumption and energy demand on the basis of economics and behaviour. The goal of this project is then presented and the chapter concludes with an outline of the thesis.

1.1. Sustainable Development

Sustainable development has become one of the most important topics on political agendas. In 1987, the Brundtland report defined sustainable development as "development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs". The UN, EU and many other countries, particularly Switzerland, have incorporated sustainable development as a policy principle (Heijungs et al, 2010). Sustainable development is also continuously being incorporated in business companies and industrial processes. To be sustainable, a business or service must consider the interactions of economic, social and environmental aspects. Figure 1.1 illustrates the aspects of sustainability that should be considered by a business or industrial process.

In 1998 the Boston based non-profit organisation Ceres started a Global Reporting Initiative (GRI) division which has developed a reporting framework. Sustainability reports based on the GRI Framework can be used to demonstrate organisational commitment to sustainable development, to compare organisational performance over time and, to measure organisational performance with respect to laws, norms, standards and voluntary initiatives. Although GRI would seem to be an ideal reporting tool for all companies, there still seems to be some negative aspects on the boundary setting. According to the guidance book "The Sustainability Report", boundary should include the entities over which the reporting organisation exercises control or have significant influence both in and through its relationship with various entities upstream (e.g. supply chain) and downstream (e.g. distribution and customers) however this is not a necessity and a company can avoid entities that may have negative results on overall sustainability (GRI, 2006).

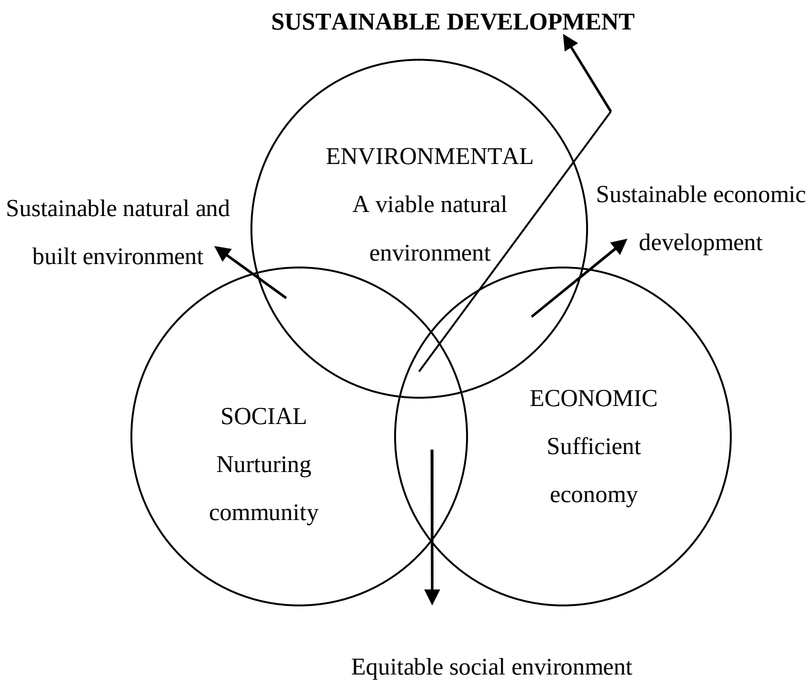


Figure 1.1 Sustainability diagram

(Adapted from Institute for Sustainability, 2011)

Businesses are being pressurised to become sustainable and a prime target area for a business or process is the global supply chain. Larger businesses are now in the habit of having supply chains around the world, especially at the production stage. This reduces costs for the business due to cheaper labour, low land costs and machinery. Although the business would benefit economically, it would suffer environmentally and socially because more energy would be spent in transport and less jobs would be created for the residents in the country that the business supplies to (Lanner, 2011). In order to assess the sustainability of a company supply chain, it is necessary to ensure that sustainability assessments are carried out constantly.

A range of quantitative and qualitative tools exist for sustainability assessment. These range from tools and frameworks developed by international or national governmental bodies, to tools and frameworks developed for specific industries, businesses and engineering processes. Ness et al. (2007) developed a holistic framework for sustainability assessment tools. The tools considered are divided into three categories (De Feo, 2009):

1. Indicators and indices. This category is divided into three sub-categories: non-integrated, integrated and regional flow indicators.
2. Product related assessment. This category includes tools such as life cycle assessment, life cycle costing, product material flow analysis and product energy analysis.
3. Integrated assessment. This category comprises conceptual modelling and system dynamics, multi-criteria decision analysis, risk and uncertainty analysis and various types of impact assessment.

This study investigates the product related assessment category using life cycle assessment (LCA).

1.2. Life Cycle Assessment

Life cycle assessment is a tool used to help identify and quantify the impacts of human interactions on the environment. The official ISO-definition states that LCA is “the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO, 2006). LCA is used in various studies concerning energy from waste because it provides environmental impact analysis which in turn can be used to provide evidence and information for policy makers and for decisions made concerning municipal solid waste (MSW) management options (Chaya et al, 2007). Khoo (2009) used LCA to determine the environmental impact of energy from MSW and found that energy from waste is a better waste management option than landfill, in industrialised and highly populated cities with limited land area such as Singapore. In his comparative analysis of selected reviewed papers, Cleary (2009) emphasized that LCA is a popular tool used for the analysis of MSW management systems. This illustrates the substantial number of LCA models addressing MSW management.

Initially, the scope of the study must be determined. Defining the system boundary is based on a subjective choice made during the scoping phase when boundaries are initially set. The system boundary can specify several dimensions, such as boundaries between the technological system and the environment, boundaries between production and production of capital goods and boundaries between the life cycle of the product studied and related life cycles of other products. Within the system boundary lies a detailed system characterisation where a number of interlinked sub-systems are shown; these are represented by flow diagrams. The sub-systems can represent a unit operation or a group of units (Papageorgiou et al., 2009). The LCA can investigate the ‘cradle to grave’ cycle from extraction of raw materials (“cradle”) to final disposal (“grave”), or from extraction of raw material “cradle” to product at the factory “gate”. Alternatively, it can represent the optimisation boundary of a process engineering cycle from “gate” to “gate” (see Figure 1.2).

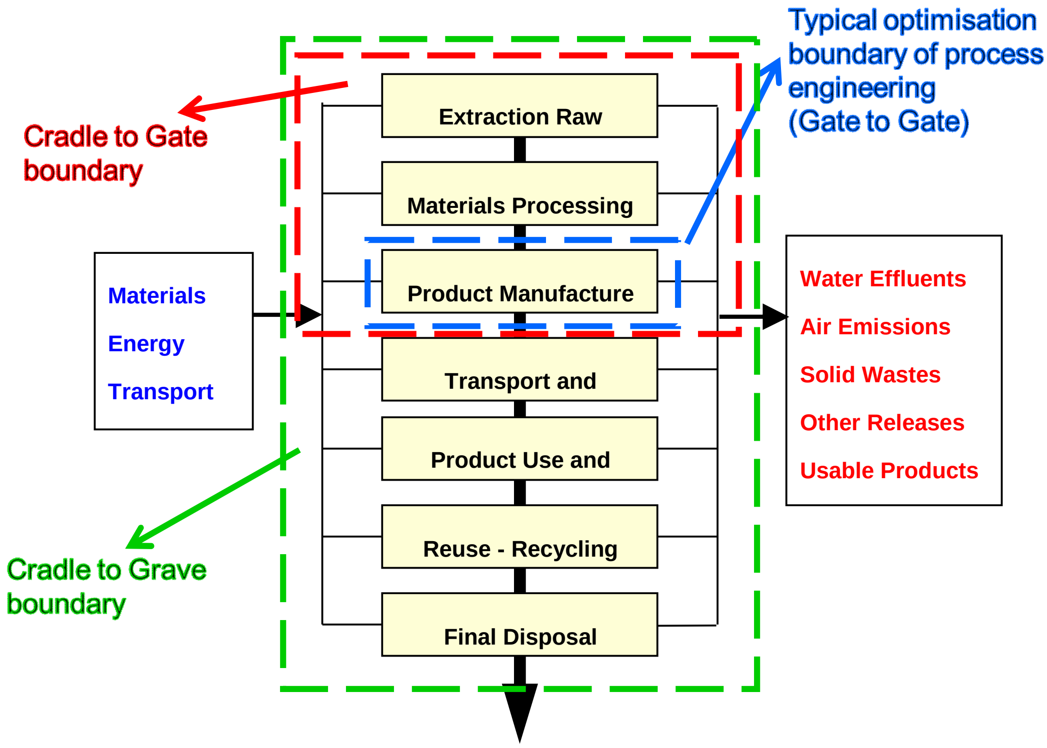


Figure 1.2 Life cycle stages and system boundaries

(Taken from Lettieri, 2011)

A functional unit (FU) is a fundamental element in an LCA study, because it represents a quantitative measure of the output of products or services which the system delivers. LCA enables various types of analytical investigation. For instance, a company may wish to find ‘hot-spots’ in the process system. This is used to define areas within a process plant that contribute to high emissions. This information can be used internally by the company to reduce the environmental impacts from specific unit operations. Additionally, the results from an LCA study can be used by a company to perform comparative studies (Azapagic et al, 2004).

One example is the early LCA study conducted in 1969 by the Midwest Research Institute (and later Franklin Associates) of the Coca-Cola Company, to determine which type of beverage container (glass or plastic) had the lowest emission release to the environment and made the fewest demands for raw materials, transportation and energy transportation used. An example of a comparative LCA study is the Tetra Pak packaging synthesis carried out for France. A cradle to grave approach was used here to develop environmentally friendly packaging. Four types of Tetra Pak packaging were investigated and compared to the impacts of their competitors. The results found Tetra Pak packaging generally has a lower environmental impact than its competitors (Tetra Pak, 2007).

An LCA study must be conducted with complete transparency to ensure that the study can be repeated and the results interpreted correctly by the reader. An LCA study undergoes 4 well identified stages:

1. Goal and scope analysis: indicates the purpose of the study and its intended use, the system and system boundaries, the functional unit, the data quality and the assumptions and limitations of the study.
2. Inventory analysis: gives a detailed definition of the system under study, data collection, and allocation and quantification of environmental burdens in multiple function systems.
3. Impact assessment: involves classification of environmental burdens into a smaller number of environmental impact categories, to indicate their potential on human and ecological health, hot-spot analysis and landfill reference analysis.

4. Interpretation/conclusions: identify major burdens and impacts, hot-spots in the life cycle and evaluate LCA findings and final recommendations.

It is argued, that LCA is usually restricted to environmental aspects; therefore it is necessary to widen the scope of LCA by adding economic and social dimensions. This means that the LCA results can be presented and discussed in a different form to incorporate economic and social aspects.

This work applies the LCA approach to investigate the sustainable production of energy from biomass in the UK. Prior to this, we discuss the energy system in the UK and its connection with climate change and the economy.

1.3. The UK Energy System and Climate Change

Throughout history, the energy sector has changed. Between 1970 and 2001 energy consumption fluctuated, with peaks in 1973 and 1979 and dips in 1975 and 1982. However energy consumption increased by 13 per cent in 2001 compared with 1970 and there has been an 11 per cent increase since 1990. Many factors influence our energy usage, ranging from the weather to a country's economic system. In a cold year, more energy is consumed to maintain a consistent internal house temperature than during a warmer year (DTI, 2001). In 2001, the UK was at its highest consumption level, equating 161 million tonnes of oil equivalent (mtoe) compared to any other year over the last thirty years. From 2001 to 2010 we saw a change in our energy consumption habits as energy security and climate change became popular topics of concern. In addition, 2007 saw the beginning of the economic down turn (MacLeay et al, 2010) with consequences for energy demand and CO_2 emissions.

The energy industry in the UK plays a central role in the economy by producing, transforming and supplying energy in its various forms to all sectors. Indigenous production had been falling each year since 1999. In 2009, the UK primary supply of fuel had decreased by 6.3 per cent (to 220 mtoe) from 2008's figures, with aggregate primary fuel consumption not being met by indigenous production. This has been a continuing trend since 2004, when the UK became a net importer of fuel. In 2009, the UK imported more coal, manufactured fuels, crude oil, electricity and gas than it exported; however, it remains a net exporter of petroleum products. Due to the decrease in demand for electricity, in 2009 generation of electricity decreased by 17% from coal-fired and by 6% from gas-fired plants, whilst nuclear increased by 32%, as plants came back online from repair and maintenance. Energy generation from wind increased sharply that year by 31% compared to 2008. The switch from coal fired electricity generation to nuclear contributed to a fall in CO_2 emissions from 483 $MtCO_2$ to 431 $MtCO_2$ between 2008 and 2009. Additional factors contributing to the fall include lower fossil fuel consumption by industry and road transport, as a consequence of the economic crisis. Generation efficiency and fuel mix drive the release of emissions from power stations. In 2009, a decrease in fossil fuels such as coal and an increase in nuclear power led to a decrease in generation of 5% and a decrease in emissions of 13% (DECC[c], 2010).

Demand for energy has declined for the past four years with the drop in 2009 being far greater than that of the previous three years, reflecting the impact of the recession. Figure 1.3 shows the energy distribution of consumption in 2009 (MacLeay et al, 2010).

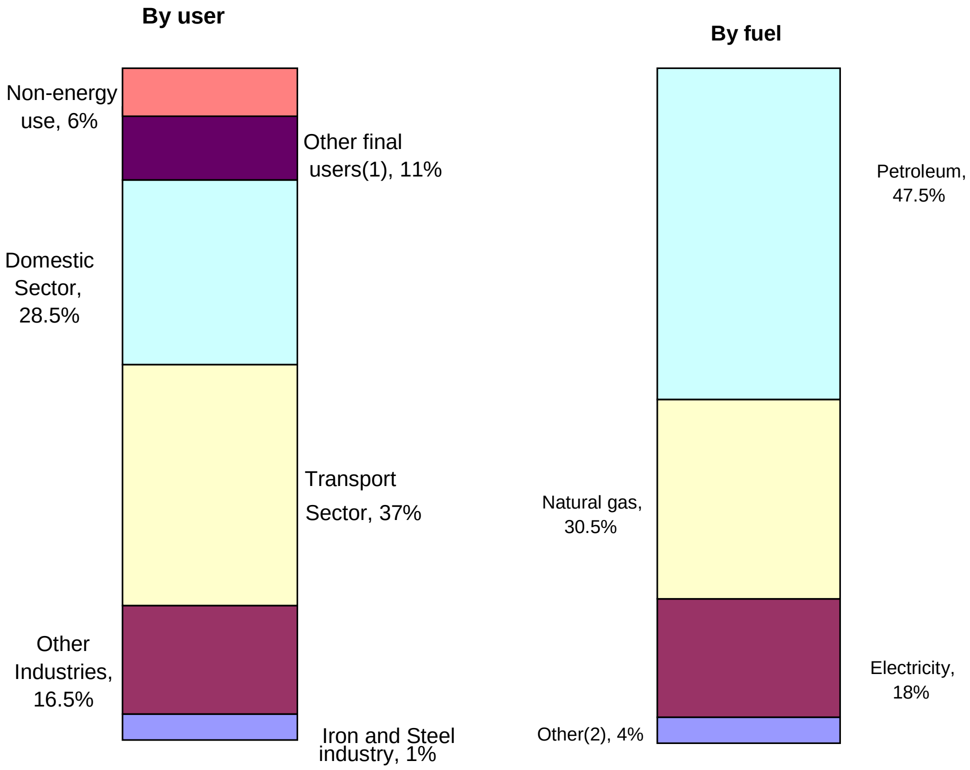


Figure 1.3 UK energy consumption and distribution in 2009
(Adapted from MacLeay et al, 2010)

Final demand for energy in 2009 was 154 mtoe; an 11 mtoe reduction from 2008. As shown in Figure 1.3 the two main users of energy were transport (37%) and domestic (28.5%). The main fuels used by consumers were petroleum (47.5%) and natural gas (30.5%) (MacLeay et al., 2010).

Burning fossil fuels contributes largely to the release of CO_2 emissions, which accounted for 84% of the total UK greenhouse emissions in 2009. Methane and nitrous oxide made up most of the remaining greenhouse emissions (DECC[c], 2010). Excluding purchases via the emissions trading scheme, emissions provisionally fell by 26% between 1999 and 2009 and in 2009, energy consumption and production emissions fell by 10%. Of the estimated 483 $MtCO_2$ emitted during 2009, power stations are the largest single contributor (151 $MtCO_2$) (see Figure 1.4).

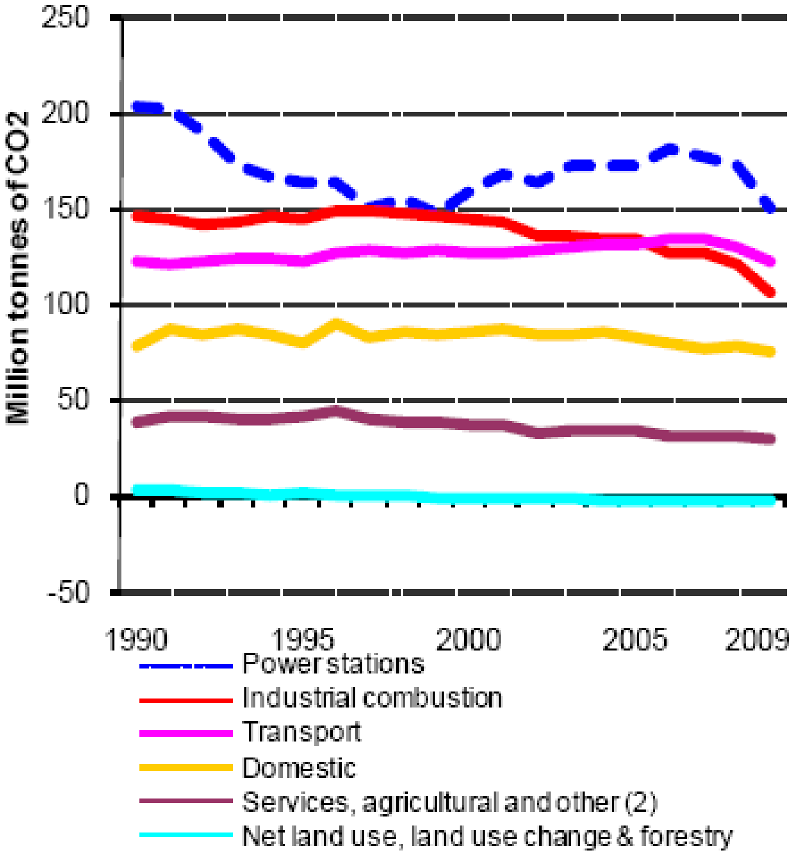


Figure 1.4 Total carbon dioxide emissions by sector

(Taken from DECC[c], 2010)

Climate change is directly linked to energy production supply and demand, because the more non-renewable energy we use and produce the more emissions we release. It is vital to formulate a plan to meet the stringent targets set by the government to reduce climate change, or the global consequences for energy, water, ecosystems, food supply, coastal regions and public health will become severe. Table 1.1 provides examples of major projected impacts by sector due to changes in extreme precipitation-related weather and climate events. These predictions are based on projections to the mid-to late 21st century (IPCC, 2008).

Table 1.1 Examples of projected impacts by sector due to extreme precipitation-related weather and climate change

Phenomenon	Examples of major projected impacts by sector			
	Agriculture, forestry and ecosystems	**Water resources**	**Human health**	**Industry, settlements and society**
Heavy precipitation events: frequency increases over most areas	Damage to crops; soil erosion; inability to cultivate land due to waterlogging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases	Land degradation, lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water and food borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potential; potential for population migration
Intense tropical cyclone activity increases	Damage to crops; wind throw (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water and food borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers; potential for population migration; loss of property

Production of electricity and heat contribute to most of the CO_2 emissions (DECC[c], 2010) and it is therefore vital to find alternative means via renewable energy sources. Maximising renewable energy by using alternative fuels to produce our heat and energy can help decrease our emissions and reach government targets.

1.4. Electricity Demand and Supply in the UK

Supply is driven by demand and the impact of the recession has been a major contributor in the decrease in supply of electricity since 2009 (MacLeay et al., 2010). The domestic sector predominates in electricity demand as seen in Figure 1.5.

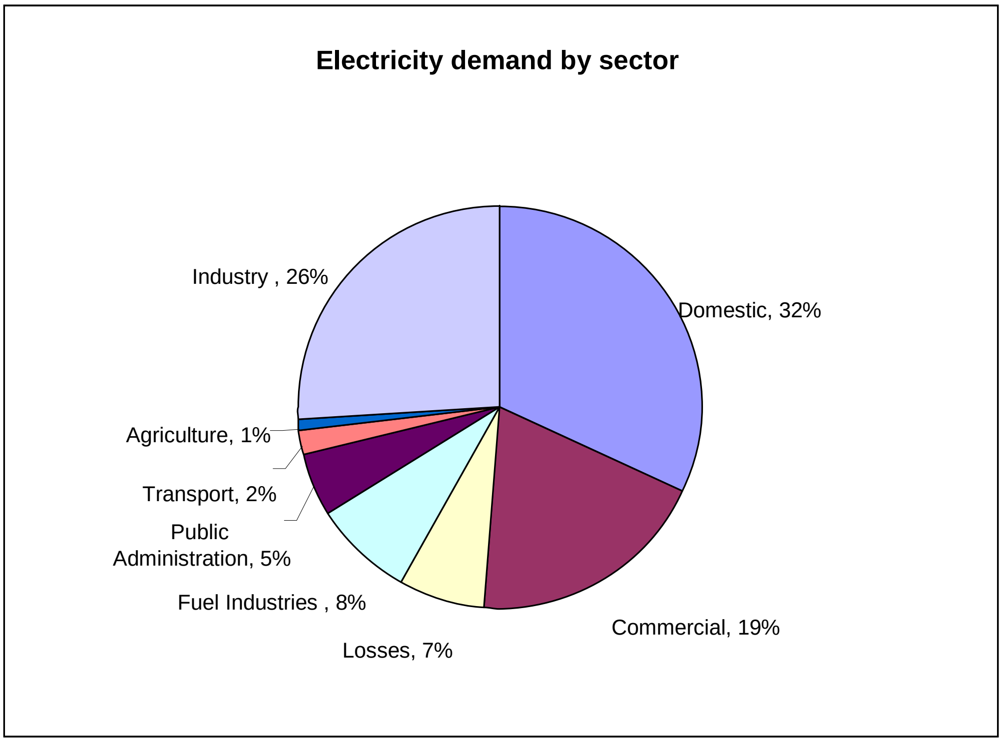


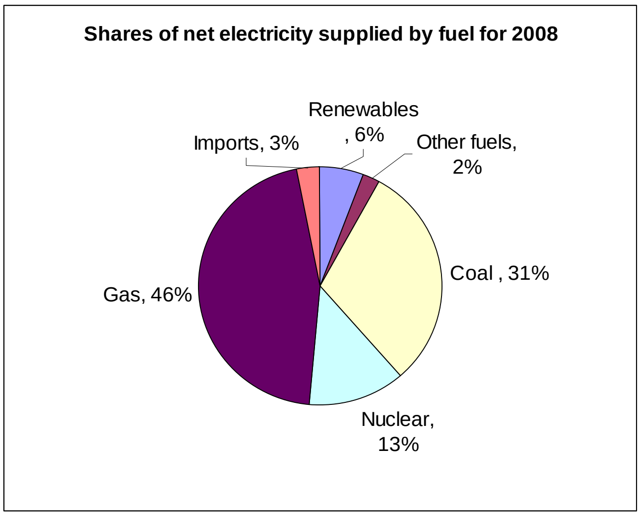
Figure 1.5 Electricity demand by sector
(Adapted from MacLeay et al., 2010)

Total electricity produced in the UK in 2009 was 376 TWh. The fuel share of electricity supplied in 2009 compared with 2008 is shown in Figure 1.6. The absolute values for the figures shown in Figure 1.6 are presented in Table 1.2.

Table 1.2 Absolute share of net electricity supplied by fuel for 2008 and 2009

	2008 (GWh)	2009 (GWh)
Total supply for year	384,579	371,978
Imports	121,294	6,609
Renewable	21,512	25,348
Other	5,907	5,333
Coal	120,299	100,108
Nuclear	21,486	69,098
Gas	174,078	371,978

(Adapted from MacLeay et al., 2010)



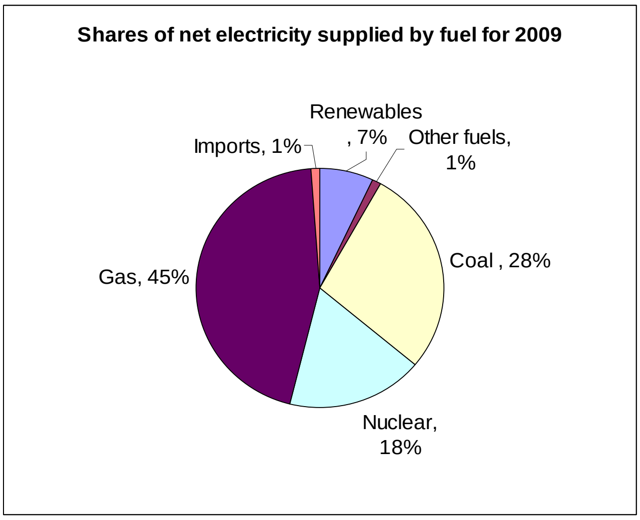


Figure 1.6 share of net electricity supplied by fuel for 2008 and 2009

(Adapted from MacLeay et al., 2010)

Although electricity production from coal and gas has reduced and renewable electricity has increased by 1% from 2008 to 2009, this change in balance will have to increase further in order to achieve emission targets.

Great Britain houses various types of energy generating plants as detailed in Figure 1.7. At present, coal fired plants and nuclear plants predominate, combined cycle gas turbine plants are also plentiful, whilst biomass plants are the lowest in number. The UK energy mix also consists of 19 operating reactors at ten nuclear power stations, which supply 18% of the electricity generated (DECC[b],2010). In 2009, the UK coal supply was 48 Mt, with 38 Mt being transformed into electricity (DUKES[a], 2010). Oil and gas also remain vital parts of the UK energy mix to produce electricity. In 2009, the UK supply of primary oil was 75 Mt (DUKES[b], 2009) and natural gas was 1,000,000 GWh with 350,000 GWh being transformed into electricity (DUKES[c], 2010). For the near future fossil fuels will remain a necessary source of UK energy. However, an increase in renewable energy is required to meet our UK emissions target and help reduce climate change and accelerate a move towards low-carbon energy security (DECC[a], 2010)

1.5. Energy and the Economy

Climate change is an issue which encompasses the finance and economic ministries as well as those for energy and the environment (CERA, 2008). There are two primary areas of discussion regarding economy and climate change. Firstly, how climate change affects the economy and secondly how the price of fossil fuels and the economy effect climate change and the role of renewable energy. The most certain effect of climate change is a rise in sea level, which will effect low lying islands and deltaic regions in countries such as Bangladesh and Egypt (The Economic Affairs Committee, 2005). Preparation can mitigate rising sea levels; for example plans to extend and enhance the flood defences of London have already taken place. However, this planning is a luxury that many poor countries cannot afford and as a result, international assistance will be needed to finance such countries. Additionally, costs may be incurred through accompanying changes in the local ecology, which can result in animal habitat changes. Farmers will incur costs as climate change will affect agriculture and land and therefore food security.

To reduce climate change our greenhouse gas emissions should be minimised (The Economic Affairs Committee, 2005). In 2001, the IPCC estimated the cost of achieving 550 parts per million (ppm) atmospheric concentration of CO_2 would cost anything from £1.2 trillion to £11 trillion (Watson et al, 2001). However, many economists believe costs will be lower than anticipated because emitters will invest in renewable technologies and cheaper ways to overcome compliance problems such as new climate regulations. The Department of Trade and Industry in 2001 predicted costs between £10 billion and £42 billion for the UK to achieve their 60% reduction in CO_2 emissions by 2050 target (The Economic Affairs Committee, 2005).

The price of oil is directly related to the economy and the volatile oil prices between 2002 and 2008 were directly related to the worldwide economy. Rising prices between 2003 and 2007 reflected the best global economic growth in a generation which in turn led to overleveraging on a global scale and the breakdown and financial crisis which began in summer 2007. The increased oil prices were not only driven by supply and demand, but also a weakening dollar and an emphasis on oil and other commodities as an asset class and storehouse of value. High oil prices played a role in triggering the economic downturn by undermining consumer spending and confidence, burdening businesses and by impacting industries such as automobiles and airlines (CERA, 2008). Other events triggered the increases in oil price, such as supply disruptions in Venezuela and Nigeria in the run up to the Iraq war. Additionally, as a result of higher economic growth, an increase in demand in 2004 added further pressure. Investment setups were delayed due to scepticism about the durability of high and rising oil prices, changes in terms of which resources could be accessed and increases in tax.

As the world is in recession now, the price of oil has dropped by two thirds. A decade ago, a drop in oil prices and hence an economic down turn would have made renewable energy less competitive with fossil fuels. In the present economic climate however, the government is enforcing the need to reduce fossil fuel use by encouraging renewable energy through incentives and carbon credits, in order to reduce climate change (CERA, 2008). The economy plays an important role in the implementation of renewable energy. Incentives, targets and policy are vital to encourage people to invest in renewable energy, especially when oil prices are competitive.

Figure 1.7 Electricity supply system in Great Britain in 2003

(Taken from DECC[d], 2010)

1.6. Research Objectives

The main objective of this research is to investigate the use of different types of biomass for energy production in the UK and the suitability of different types of biomass for energy production at different scales using a sustainable approach. The chosen types of biomass are all available in the UK. Fluidised bed combustion and internal combustion engines being established technologies, they were chosen for solid and liquid biomass types respectively. The most appropriate scales for each of these approaches in relation to system efficiencies and economics were evaluated, so that an evidence-based judgement could be made as to whether biomass should be used for energy production in this context. Additionally, the social implications of using biomass for energy production are discussed. Therefore, the main objectives of this work can be summarised as follows:

- A comprehensive assessment of combustion technology and operational process conditions. Report of the present and future status of other thermal treatment technologies such as gasification and pyrolysis. Research different types of biomass used for energy production, their current status in the UK in terms of supply and demand and the arguments of food and land vs. fuel. Review the UK government's strategy towards ensuring a sustainable and economical market for biomass.
- Investigate the energy from clean biomass and energy from mixed waste stream industrial plants, through a collaboration study with Germanà & Partners Consulting Engineers in Rome (Italy). The aim of this aspect of the PhD was to gain knowledge and understanding of engineering principles and develop energy and efficiency calculations of the plants investigated.
- Evaluate the technical and economic analysis of small to medium scale forestry waste wood chip (FWWC) biomass combustion plants at three different scale scenarios of 50 ktpa, 80 ktpa and 160 ktpa. Solid recovered fuel (SRF) combustion at 50 ktpa and 100 ktpa. Rapeseed oil (RSO), a first generation biomass utilised in internal combustion engines at 27 ktpa and 40 ktpa is investigated separately. The aim was to highlight

the implications of different scales of the technologies on system efficiency and economic viability in the UK.

- A sensitivity analysis of the economic assessment is performed on the economically viable plants to test the model. Energy generation and overall system efficiency are calculated and the energy calculations are performed for each individual unit (see Appendices) within the energy from biomass plants.
- Assess the environmental benefits associated with energy from biomass through LCA. The LCA is developed from scratch, where conversion factors alone are sourced from $BEAT_V2$ (2010). The LCA also compares non-renewable plants of the same capacity. Hot-spot analysis is conducted and base cases are compared to proposed systems for each plant.

The overall objectives of this research are to evaluate the economic viability and environmental impact of the plants listed above, using specific types of waste and newly grown biomass for energy production, in order to help tackle climate change.

2. Renewable Energy: the Role of Biomass

Summary

Biomass is a potential feed source for renewable energy production. This chapter introduces different types of biomass and their use in the UK; the UK Biomass Strategy 2007 and the UK Biomass Availability are discussed. Three forms of biomass, SRF, FWWC and RSO are considered as a feed for energy production.

2.1. Renewable energy and policies

When the EU decided in 2008 to cut its greenhouse gas emissions, it showed its commitment to tackling the climate change threat and to lead the world in demonstrating how this could be done. The agreed cut of 20% from 1990 levels by 2020, together with a 20% renewables target, was a crucial step for the EU's sustainable development and a clear signal to the rest of the world that the EU was ready to take the action required. As a result June 2009 brought forward The UK Renewable Energy Strategy, which aims to describe how to meet the target of 15% production of renewable energy by 2020. The strategy focuses on renewable energy, nuclear power, carbon capture and storage and introduces policies such as the EU Emissions Trading System and energy saving measures. Due to growth in global demand and the depletion of our North Sea oil and gas resources, a new approach to sourcing and using energy must be sought. Renewable energy sources will aid the UK to recover self-sufficiency, whilst assuring that more of our imported energy comes from reliable sources (UK Renewable Energy Strategy, 2009). Additionally, a new low-carbon future will provide employment opportunities, helping to maximise the economy. Figure 2.1 shows the breakdown of the final share of different energy sectors based on new policies the government intends on putting in place to meet the 15% target for renewable energy by 2020.

The Government (DECC[h], 2011) will continue to provide financial incentives to overcome issues of greater financial support, swifter delivery in the planning system, supply chain grid connections and sustainable bio-energy, coupled with a stronger push on new technologies and resources to help reduce the cost of meeting our 2020 targets. These incentives will also address the short term impact of the global financial crisis. In order to achieve this, the Government will expand the renewable obligation incentive scheme to ensure that it can deliver 30% renewable electricity by 2020. Additionally, it will deal with immediate pressures resulting from the global financial crisis by facilitating up to £4 billion of lending from the European Investment Bank, for renewable energy and enabling secure financial loans for deployment (DECC[h], 2011).

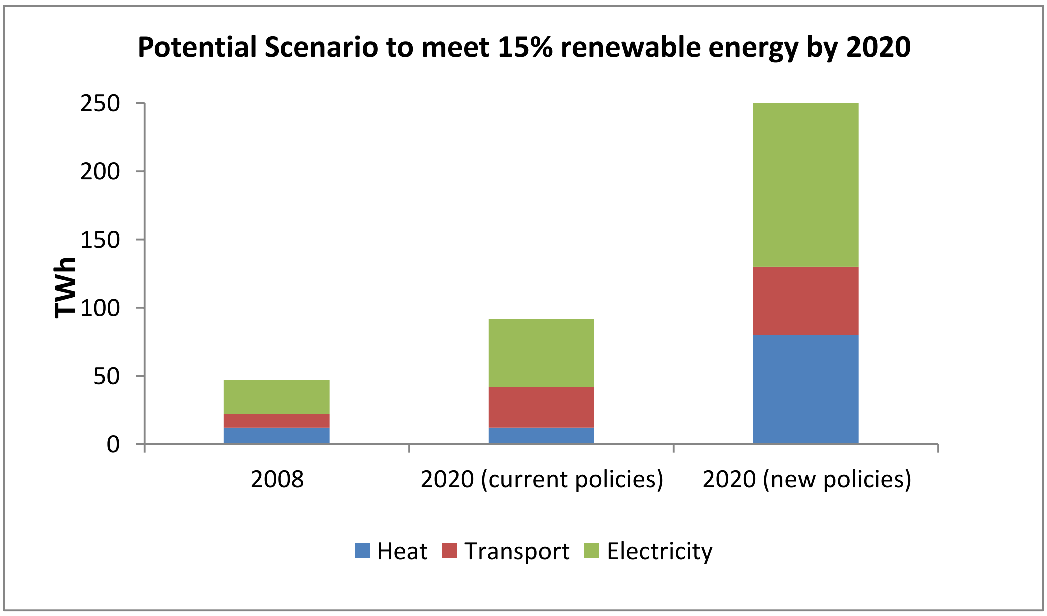


Figure 2.1 Potential Scenario to meet 15% renewable energy by 2020
(Adapted from UK Renewable Energy Strategy, 2009)

The strategy introduces a more efficient use of energy across all sectors to reduce emissions, which implies changing the mix of fuels used for energy production.

At an international level, the UK plays a crucial role in tackling climate change through the EU, G8 and UN Framework Convention on Climate Change. In order to reach a target of 80% reduction in greenhouse gas emissions (compared to 1990 levels) by 2050, the Government is required to set carbon budgets for five year intervals, which place binding limits on greenhouse gas emissions and define the trajectory towards the 2050 target. In this regard, on

22nd April 2009 the Government announced the first three carbon budgets (see Table 2.1).

Table 2.1 First three carbon budgets

	Budget 1 (2008-12)	**Budget 2 (2013-17)**	**Budget 3 (2018-22)**
Carbon Budget ($MtCO_2$)	3018	2782	2544
Percentage reduction below 1990 levels (%)	22	28	34

(Adapted from: DECC[e], 2009)

Achieving the 15% renewable energy target by 2020 across the energy spectrum of electricity, heat and transport will imply:

- Around 30% of our electricity supply is from renewable sources
- 12% of our heat supply is renewable
- 10% of our transport supply is renewable

The lead scenario suggests an increase up to 30% of our electricity supply be from a sustainable renewable source (up from the current 5.5%). The majority of this growth is expected to come from the wind sector and a considerable 22% from bio-energy. An increase to 12% of heat supply from renewable sources (from the current 1%) is envisaged to come from combined heat and power. These targets need to be reached quickly and on a large scale. To this end, the government are attempting to think of ways to source funding and incentives to encourage investment in renewable energy. The Renewable Obligation (RO) aside (Ofgem, 2007), another possible incentive is the "contract for difference" scheme in which:

- In any chosen period of time (for instance yearly) when the wholesale value of renewable electricity exceeds a set level, generators would be required to make a corresponding payment into a fund.
- In any period where the value fell below a set level, generators would receive a corresponding payment from the fund.
- The cash flow from the above payments would be spread across electricity suppliers.

The strategy aims to push energy suppliers to increase renewable energy production sustainably to reach the 2020 target.

To reach two key goals of addressing climate change and ensure energy security, the UK set the energy targets mentioned in the previous sections. As of 2009, the primary tools to meet these goals are two renewable fuel obligations currently in effect in the UK - the renewable obligations (RO) for electricity generation and the Renewable Transport Fuel Obligation (RTFO) for road transport fuel sales (Anandarajah et al., 2010). The UK Renewable Energy Strategy introduced the Renewable Heat Programme (RHP), which requires renewable final energy consumption for heat at 12% in commercial, public and residential buildings (DECC[g], 2009) (see CERT and CESP at the end of this section). The RO legislation has so far proven to be a success. In 2008, ROCs legible generation was 4.4% compared with 2% in 2001; raising the electricity RO was one of the measures to meet the 15% renewable share energy supply by 2020 (Anandarajah et al, 2010). In spring 2009, the Government also introduced differentiated support levels (banding) to replace the previous 1 ROC MW generated. The banding system promotes the deployment of technologies which require greater support for development, whilst avoiding over-subsidy of cheaper technologies, like landfill gas (Slade et al., 2009).

The RTFO programme was launched in April 2008; its purpose was to reduce GHG emissions from UK road transport. It places an obligation on fuel suppliers to ensure that a certain percentage of their aggregate sales is made up of bio-fuels. This was put in place to achieve the 5% target of all UK fuel sold on UK forecourts to come from a renewable source by 2010. It also aimed to reduce CO_2 emissions from the road transport sector by 2.6 - 3.0 $MtCO_2$ per annum. In the Renewable Energy Strategy, the RTFO has been increased to 10% (from 2020) (Anandarajah et al., 2010).

In addition to the RO and RTFO, other incentives exist for renewable energy and bio-energy. The initiatives are a reflection of the priority given to bio-energy and the delivery organisations are active participants in the process of policy formation. Sixteen incentive schemes benefiting the UK bio-energy sector were identified by the end of 2005. See Table 2.2 (Slade et al., 2009).

Table 2.2 Financial incentives for bio-energy in the UK

Delivery mechanism	**Funding initiative**					
	Renewable energy/low carbon technology			**Bio-energy only**		
	Programme	**Approx. value**	**Units**	**Programme**	**Approx. value**	**Units**
Grant	Clear Skies	3	£m.yr^{-1}	Woodlands grant scheme	20	£m.yr^{-1}
	Community Energy Programme	5	£m.yr^{-1}	Energy crop scheme	3	£m.yr^{-1}
	Carbon Trust R&D	4	£m.yr^{-1}	Farm woodland scheme	2	£m.yr^{-1}
	DTI technology programme	80	£m.yr^{-1}	Farm woodland premium scheme	8	£m.yr^{-1}
				English woodland grant scheme	10	£m
				Bio-energy infrastructure scheme	3.5	£m
				Bio-energy capital grants scheme	66	£m
				Common Agricultural Policy – energy crops	45	£.ha^{-1}
Information/ facilitation market mechanisms	Community renewable initiative	0.5	£m.yr^{-1}			
	Renewable Obligation Certificates (ROCs)	33.3	£.MWh^{-1}			
	Emissions Trading Scheme (EU)	16	£tcarbon^{-1}			
	Climate change levy exemption certificate	4.41	£.MWh^{-1}			

(Data adapted from: Slade et al., 2009)

Additionally there are several schemes set up by DECC and administed by Ofgem to push energy companies to help reduce carbon footprints. Obligated parties are to reduce carbon emissions through incentiving and installing different measures in the home. These schemes are called carbon emission reduction target (CERT) and community energy saving programme (CESP). These schemes are of particular interest in this work because they incentivise energy companies to install district heating and promote different technologies such as CHP, combustion, gasification and solar combined with communal boilers. This is an attempt to help communities in fuel poverty and push for more district heating. The plant discribed in Chapter 5 produces heat and electricity at a small scale which can be used to supply communities, just like those in the CERT and CESP programmes.

The EU will meet its Kyoto Protocol target and has a strong track record in climate change. It has always been clear that actions by the EU alone will not be enough to combat climate change and also that a 20% cut by the EU is not the end of the story. EU action alone is not enough to deliver the goal of keeping global temperature increase below 2°C compared to pre-industrial levels. All countries will need to make an additional effor, including cuts of 80-95% by 2050 by developed countries. An EU traget of 20% by 2020 is just a first step to put emissions onto this path. That is why the EU matched its 20% unilateral commitement with a commitment to move to 30%, as part of a genuine global effort. This remains EU policy today.

2.2. Biomass

Biomass is plant or animal based material. In the context of biomass for energy production, this is often used to mean plant-based material and animal derived material. Biomass is carbon based and is composed of a mixture of organic molecules such as hydrogen with additional oxygen molecules, often nitrogen and, depending on the type of biomass, alkali, alkaline earth and heavy metals. The biomass is constructed from carbon absorbed from the atmosphere as CO_2 by plant life, using energy from the sun. These plants may subsequently be eaten by animals and converted into animal biomass (Biomass Energy Centre 2010). Biomass can be categorised as first generation such as food crops, where the biomass is grown and subsequently used for energy production, or second generation biomass such as MSW, forestry residue and non-food energy crops (Biomass Energy Centre, 2010). The media generally portray biomass as being first generation bio-alternatives and, in particular food crops (most popular of which are sugar cane, corn and wheat). However, upon reviewing the life cycle process from "cradle to grave" for this type of biomass production, criticism in relation to emissions and other arguments related to "food vs. fuel" and "land vs. fuel" were highlighted (Defra[a], 2008).

2.2.1. Food vs. Fuel

From 1983, food crops have been used for ethanol production. Research has shown that, over the next few decades, bio-fuels will be very disruptive to global agricultural commodity prices (Zhang et al., 2003). The food vs. fuel argument emerged on a global scale because of the 2007-2008 world agricultural commodity price crises. The price spikes were due to a number of mutually reinforced factors in global agricultural markets, such as a sharp increase in bio-fuel demand, rapid economic growth, droughts in key grain-producing areas, high oil prices, a weak US dollar, speculation and export restrictions. Research suggests that it is impossible to truly determine the impacts of bio-fuels on agricultural commodity prices, without analysing data and distinguishing between the short-run versus the long-run impacts (Zhang et al., 2003).

Koizumi (2003) used time-series prices on fuels (ethanol, gasoline and oil) and agricultural commodities (corn, rice, soybeans, sugar and wheat) to investigate the influence of fuel prices on agricultural commodities. The long-run, co-integration of these prices is investigated along with their short-run interactions. Results indicate that there is no direct long-run price relationship between fuel and agricultural commodity prices and limited, if any, direct short-run relationships. With regards to short-run price movements, sugar prices are influencing all agricultural commodity prices except rice. As sugar is mostly utilised in ethanol production, results indicate that increased ethanol production is potentially influencing short-run agricultural commodity prices through its impact on sugar prices (Koizumi, 2003). Zhang et al. (2003) however suggested that sugar prices are a leading indicator of economic growth and serve as a growth surrogate. Sugar production contributes 20% of Gross Domestic Product (GDP) and employs 30% of the workforce in African, Caribbean and the Pacific Group of States (FAO, 2003). Therefore economic growth, in general, is the driver for short-run agricultural commodity price fluctuations (Zhang et al., 2003). These relationships are established exogenously based on economic theory and expert opinions with assumptions and parameter specifications. There then remains the model determining the magnitude of long-run agricultural commodity price impacts of fuel-price shocks. If these are included in the analysis they take into account interactions with other markets. It is therefore vital when considering such research that the assumptions and interactions are defined within the model and refer to other markets, otherwise the magnitude of long-run agricultural commodity price impact of fuel-price shocks will be determined incorrectly. Zhang et al., (2003) did not consider other markets in their study.

The major feedstock's used for bio-fuel production are corn, wheat, barley, sugarcane, rapeseed oil, soybean and sunflower, which are also directly or indirectly used for food production. Bioethanol production is based on wheat in the EU, whilst biodiesel is based on RSO. Ajanovic (2010) studied the fundamental relationship between bio-fuels and the biomass feed based on quantities produced, costs of production and resulting market prices and a review of literature on "food vs. fuel" was investigated. The work concluded that bio-fuels do have a natural influence on feedstock prices. This conclusion is based on a hypothesis that rising bio-fuel prices would cause a shift in agricultural commodities from food towards fuel production, which would then drive up agricultural commodity prices (Ajanovic, 2010). However, time-series results do not support this hypothesis. Rising fuel prices are not directly causing inflated agricultural commodity prices. In fact, rising sugar prices appear to be the leading cause of price inflation (Zhang et al., 2010). As bio-fuel production continues to increase price shift have and will cause a redistribution of acreage towards fuel production. In my opinion, the computable general equilibrium model for food vs. fuel scenarios should consider data inputs from producing bio-fuel from non-edible sources. If these modes of renewable energy are able to supplant food-crop energy and fuel, then links between fuel and food prices could possibly be severed, or at least reduce the impact of the link between fuel and increasing food prices.

Many agree that bio-fuels have a part to play in food price volatility, however many other aspects also play key roles. For instance, increased global bio-fuel demand during 2000 – 2007 accounted for 30% of the increase in weighted average grain price. Developing countries such as India could face similar situations in food prices with the growing demand for bio-fuel targets set by their Government. However, if planned appropriately with regulation and policy, the bulk of bio-diesel can be produced from non-edible Jatropha grown on wastelands (Ravindranath et al, 2010).

According to recently published research bio-fuels are related to volatility in food prices, but not as significantly as portrayed by the media. The true impact of price increases on food using first generation biomass for energy production is not clear enough to make a sound conclusion. There are clearly many other influencing factors such as speculation, oil price changes and troubled land areas for farming which contribute to food price increases. Additionally, the models used to determine the food prices from increases in bio fuel and bio energy production, are based on models which include assumptions and that do not consider the developments in bio energy from non-food crops, such as wood chips, paper waste, non-food crops and crop residues. In my opinion there are many contributing factors to rising food prices, with bio-fuel production being only a small contributor. However, without considering the impact of bio fuel production from non-edible biomass sources, I believe a sound projection of future food prices cannot be made. Therefore economic models must consider new developments and bio-fuel production and bio-energy production from non-edible sources.

Chapters 4 and 5 show that the cost of edible biomass such as rapeseed oil (RSO), compared to non-edible biomass such as solid recovered fuel (SRF) or forestry waste wood chips (FWWC) used for energy production, is much higher. However, the reason why crops such as Rapeseed (RS) are used for energy production is due to their higher calorific value and ability to produce more energy resulting in an economical plant to run at certain scales.

2.2.2. Land vs. Fuel

Land vs. fuel is an argument affecting energy from biomass which poses direct competition between land and fuel. The argument includes both first and second generation biomass but does not include waste biomass. Arguments that land used to grow biomass competes with land that could be used to grow food or urbanising forests, is one that became popular with an increase in use of bio-energy. Evans et al. (2010) provide evidence of second generation biomass helping to rehabilitate degraded or marginal soil, for example in Australia, where Mallee plantations are helping to resolve salinity problems where other plant life could not survive. The tree itself will be used for electricity production at a nearby pilot plant. Although this study found Mallee biomass achieves a higher energy ratio than other biomass crops such as rapeseed and demonstrating a strong energy gain, the study did not consider optimising the harvest and transport logistics, especially as almost 80% of energy consumption was from harvesting and transport. It is obviously important the most efficient harvesting process is used to minimise the release of carbon emissions.

By examining the change in land use over time, Rathmann et al. (2010) concluded that historical patterns of land use have changed in the face of a new production dynamic derived from the introduction of energy produced from agricultural biomass. With an increase in demand for energy from biomass, the way land is managed and used have altered, resulting in a shift from areas traditionally allocated for food production to bio-fuel production. Nevertheless this change cannot yet be called significant, as research by Rathmann et al. (2010) claims, bio-fuel production is not the sole factor determining land use changes, nor will this trend last over a long period of time; other factors add to this effect, such as China’s strong economic growth. This economic change has increased demand on land through increased consumption of durable and non-durable goods. In the United States however, modelling on agro-energy production demonstrates that farmers are shifting lands from growing wheat to corn and are converting forests and pastures to agricultural production. I believe that crops should only be grown for bio energy production if they are produced sustainably and do not result in an increase in emissions. Conversion of land areas in the short term results in long-term effects such as changes in farmers expectations of price trends of their crops and a new movement for production of renewable energy, which also influences farmer's decisions and the dynamic of food and energy prices (Searchinger, 2008). The majority of research on the impact of land vs. fuel comes from work conducted in the United States and Brazil, because since the 1970s both these countries have been producing ethanol from corn and sugarcane respectively. The trends seen in the United States and Brazil are now becoming evident in the UK, Germany and France, with increased production of rapeseed for bio-diesel production. The conclusion that land will be used for energy production rather than food production comes from the assumption that farmers will allocate resources and production factors to the activity that provides the greatest return. Following this logic, the greater attractiveness of energy from agriculture will mean lower food output, resulting in price changes in the short run for products related to agricultural commodities.

These conclusions are based on assumptions that do not consider the production of energy from other forms of biomass, such as agricultural wastes. In either case, if we are to assume that the influencing factor for changes in land use is the drive for profit by farmers, it would be possible, over a longer time horizon to minimize these impacts through legislation and policy. Government and commissions should work together to ensure energy is produced from sustainable sources of biomass as there is no environmental gain in producing renewable energy if the overall impact on the environment is a negative one. For example, this could be due to increases in emissions from replacing land used for food or forestry, which would then need to be planted elsewhere and as a result releases carbon stocks. Activities in The Land Use, Land-Use Change and Forestry (LULUCF) sector can provide a relatively cost-effective way of counting avoided direct and indirect emissions, either by increasing the removals of greenhouse gases from the atmosphere (e.g. by planting trees or managing forests), or by reducing emissions (e.g. by curbing deforestation). However there are drawbacks as it may often be difficult to estimate greenhouse gas removals and emissions resulting from activities of LULUCF. In addition, greenhouse gases may be unintentionally released into the atmosphere if a sink is damaged or destroyed through a forest fire or disease. Under Article 3.3 of the Kyoto Protocol, Parties decided that greenhouse gas removals and emissions through certain activities – namely, afforestation and reforestation since 1990 – are accounted for in meeting the Kyoto Protocol emission targets. Conversely, emissions from deforestation activities will be subtracted from the amount of emissions that a Party may emit over its commitment period. LULUCF activities were not included in the 2008 climate and energy package, but have potential for additional emission reductions. Also maintaining and restoring natural carbon sinks is necessary to avoid further emission increases. Today, uncertainties in calculation and volatility make short term predictability of LULUCF activities and their contribution to EU targets difficult to assess. However, as the work continues to establish effective rules to govern these activities, they could over time provide a growing contribution to the mitigation effort through improved cultivation methods and forestry management. The Common Agriculture Policy could incentivise farmers and foresters to move towards more sustainable practise and make a greater contribution to emission reductions over time.

I believe that competition for land can be minimised with National Governments. Legislation of sustainable bio-fuel production and farming can allow co-existence of bio-energy and land for food. Chapter 5 investigates the production of energy from rapeseed oil where a life cycle assessment is presented, taking into consideration changes in land use and the effect of growing rapeseed on different types of land.

2.3. Types of Biomass

First and second generation biomass are used to produce transport fuel and energy respectively. Waste biomass includes waste wood chips and non-edible biomass such as straw, husks and municipal solid waste (MSW). Table 2.3 illustrates waste forms of biomass, the key elements in the supply system and the processes used to convert biomass into fuel or energy. The specific supply system and conversion process will vary according to the type of biomass involved and the nature of its end use.

Table 2.3 Biomass supply and conversion chain

Biomass Resources	Supply Systems	Conversion	End Use
Conventional forestry	Harvesting	Biochemical	Transportation fuels
Short rotation forestry	Collection	Thermo chemical	Heat
Sawmill conversion products	Handling	Physical/Chemical processes	Electricity
Agricultural residues	Delivery	Deoxygenation	Solid fuels
Oil-bearing plants	Storage	Depolymerisation	Renewable construction materials
Animal products		Pyrolysis	Plant based pharmaceuticals
Municipal solid waste		Gasification	Renewable chemicals including polymers
Industrial waste		Hydrolysis	
		Fermentation	

Data adapted from UK Biomass Strategy, (2007)

The carbon emissions from the use of bio-energy are an avoided burden by the carbon captured during its growth. However, this carbon balance is sensitive to the carbon intensity used in the production, supply and transport. With due regard to sustainability and carbon savings, it can result in a reduction in overall carbon emissions and can help tackle climate change. Biomass is very flexible as it can be used as a feed across the energy spectrum for heat, electricity and transport fuel. The use of biomass in place of fossil fuels offers the prospect of a diverse energy mix.

Different countries suit growth and sourcing of different forms of biomass. Brazil and the USA for example, utilise sugar cane and wheat for bio-ethanol production on a large scale. Sugar cane is not a viable option for the UK and wheat is a staple food source, however RS is a viable form of grown biomass. Agriculture and forestry have an important role to play in the way that biomass is used to tackle climate change. Changes to our current land use practices will have to be addressed, as biomass becomes used in increasing amounts. For example, on 20th November 2008, an agreement was reached at the Agriculture Council on the Common Agricultural Policy Health Check – a scheduled review and adjustment of the mechanisms of the EU's Common Agricultural Policy. This was intended to improve, reinforce and build on previous Common Agricultural Policy reforms (Defra[b], 2008).

2.3.1. Solid Biomass

There are many types of biomass, which can be organised into two categories, solid biomass and liquid biomass. Solid biomass also known as dry biomass can be classified according to origin. The various solid biomass types are summarised in Table 2.4.

Table 2.4 Solid biomass types according to origins

Category	**Solid Biomass Type**
Agriculture	Rice husk, Rice straw, Wheat straw, Vegetable residue
Livestock	Animal waste, Butchery waste
Forestry	Forest residue, Thinned wood, Processing waste, Sawdust, Wood chips
Industry	Organic processing waste
Household	Municipal solid waste
Continental Area	Grain, Plant, Vegetables

(Data adapted from Bio fuels Technology Platform, 2008)

Solid biomass resources can all be used as a feed in thermal conversion systems such as combustion, gasification or pyrolysis, to produce alternative energies such as electricity, heat, or transport fuel.

2.3.2. Liquid Biomass

Liquid biomass, also known as wet biomass, can be used to produce electricity, heat, or transport fuel. Transesterification technology converts waste oil into bio-diesel, which in turn is combusted or gasified to produce electricity or heat. Alternatively, the bio-diesel can be used as a transportation fuel. The liquid biomass types can be categorised according to origin and are presented in Table 2.5.

Table 2.5 Liquid biomass types according to origin

Category	**Liquid Biomass Type**
Industry	Sewage sludge
Continental Area	Fats and oils
Water Area	Algae and photosynthetic bacteria

Data adapted from Bio fuels Technology Platform[a], (2008)

This thesis is focused on vegetable oil, more specifically rapeseed oil (RSO). Vegetable oils are lipid materials derived from plants. Various types of vegetable oils are available such as canola, sunflower, safflower, peanut, rapeseed, soybean, palm and olive oil. In the UK, RSO is being produced in increasing amounts and is purified for use in vehicles as bio-diesel. Alternatively, crude RSO can be used for the production of electricity in internal combustion engines. The UK has appropriate climatic conditions for the production of RS in preference to other vegetable oils and it plays an advantageous role as a breaking crop (UK Agriculture, 2009). RS has a useful soil improving role which aids in the growth of cereal crops in particular wheat. Despite RS’s usefulness as a breaking crop, it cannot be grown too regularly in the same field because of a risk of disease build up. Therefore RS is grown as a rotation crop and is rarely returned to the same field more than once in six years. RS was grown on 642,000 hectares of UK land in 2010, producing 2230 kilo tonnes in volume of RSO, at a yield of 3.5 tonnes per hectare (UK Agriculture, 2012).

2.4. UK Biomass Strategy 2007

The UK Biomass Strategy was established in 2007, its intentions are to fulfil the following (UK Biomass Strategy, 2007):

- Realise a major expansion in the supply and use of biomass
- Facilitate the development of a competitive, sustainable market and supply chain
- Promote innovation and low-carbon technology development, so biomass can deliver relatively higher energy yields
- Contribute to overall environmental benefits and the health of ecosystems through the achievement of multiple benefits from land use
- Facilitate a shift towards a bio-economy, through sustainable growth and development of the use of biomass
- Maximise the potential of biomass to contribute to the delivery of our climate change and energy policy goals: to reduce CO_2 and other greenhouse emissions and achieve a secure, competitive and affordable supply of fuel

In order to achieve these objectives, the strategy focuses on the use of biomass from a variety of energy sources and sectors, to ensure that the biomass used is maximised in the following contexts (UK Biomass Strategy, 2007):

- Where biomass can most cost effectively contribute to decarbonising energy supply
- How biomass can best be used to help meet the UK's renewable energy targets
- How biomass can be used to develop renewable materials and products e.g. plant based pharmaceuticals, renewable construction materials and renewable chemicals
- How biomass can help deliver low carbon transport

In an ideal world, expansion of biomass quantity followed by a transition from fossil fuel to biomass. The strategy suggests that there is significant potential to expand the UK supply of biomass without any detrimental effect on food supplies or on land if a sustainable approach to management is applied. Harnessing currently unmanaged woodland and increasing the recovery of wood for energy from managed woodland can source an additional 1 million dry tonnes of wood per annum. By the year 2020, an additional 350,000 hectares across the UK can be used to produce perennial energy crops, bringing the total land availability for bio-fuel and energy crops to 17% of total UK arable land. Finally, increasing the energy supply from high calorific value organic waste materials such as slurries manures, certain organic wastes source separated waste biomass and waste derived SRF can also be used for energy production.

In the future, biomass supply in the UK will be approximately 8.3 million tonnes of oil equivalent (Mtoe) (UK Biomass Strategy, 2007). This compares with a 143 Mtoe of energy consumption in the UK in 2009 (DECC[f], 2010). Although energy consumption seems to be much higher than the potential increase in biomass production, other renewable technologies such as wind hydro and solar will also play a role in achieving renewable energy targets. Biomass will contribute to the bio-economy if managed sustainably. Imports will play a large role in the UK for bio-energy production; the exact figure is unknown as the costs of imports will play a crucial role. Assessments of transport costs and overall LCA’s would need to be conducted and clarification of whether the imports will be biomass or energy in its finished form. Presently however, the UK has the potential to supply a variety of biomass such as first generation biomass RSO, FWWC and SRF from MSW.

This thesis focuses on the production of electricity using FWWC, SRF and the production of heat and electricity from RSO. This is in line with the government target of achieving 15% renewable energy by the year 2020 (which is aimed to increase to 30%), the majority of which is to come from the electricity and heat sectors (Figure 2.1).

2.5. Rapeseed Oil

RS is a first generation biomass because it is grown and subsequently used to produce oil. RSO is used for human consumption and is always grown as part of a farm rotation. In this thesis, RSO has been chosen as a viable feed because production of RS in the UK over the last decade has been growing steadily. Additionally RSO has the benefit of a high calorific value when compared to waste forms of biomass such as SRF and FWWC, resulting in a higher electricity output.

RSO can be used in its crude form unlike refined RSO being used in bio-diesel production. Crude RSO can be used directly in an internal combustion engine when coupled with Organic Rankin Cycle (ORC) technology which has the benefit of producing heat as well as electricity, which can then be sold for a profit. A full techno-economic and life cycle assessment of energy from RSO is presented in Chapter 5. When considering RSO as a potential feed for energy production, social aspects of the sustainability triangle have to be taken into consideration. RSO must be grown on land and there is a threshold above which bio-fuel cannot be produced without threatening food supplies and biodiversity. Because of the "food and land vs. fuel" debate (See section 2.2.1 and 2.2.2), RSO may have a negative image in the eyes of the general public. As a result, the analysis in Chapter 5 also considers a land use reference system which investigates the emissions released when rapeseed is grown on different types of land.

The method of cultivation and harvesting in the UK entails minimum tillage of soils. Minimum tillage (also known as reduced tillage) is a method of cultivation which passes at a shallow depth when compared to normal ploughing. Minimum tillage is used extensively in Europe to reduce costs and take advantage of benefits such as: (1) stabilising soil nutrients, which leads to a higher quality soil; (2) the structure of the soil is improved by the activities of earthworms; and (3) there is a reduction in the use of diesel fuel needed to run cultivation machinery. (Defra[h], 2004). In this study reduced tillage as well as normal tillage is considered when investigating the emissions associated with growing rapeseed. Different methods of farming depend on the method of tillage used (Chapter 5).

The most common harvesting technique used in the UK is to directly cut the rapeseed plant ~150 mm from the ground followed by thrashing in a combined harvester to remove the seeds from the pods. Subsequently, the seeds are separated from the rest of the plant. The remaining rape straw, consisting of stalks, pods and leaves, is generally ploughed back into the soil, providing additional nutrients. (Stephenson et al, 2008). In the UK, industrial crushing plants, crush the seeds and use solvent extraction to remove as much oil as possible from the rapeseed, leaving the rape meal with ~2 wt.% oil. The process involves seed cleaning, cooking and flaking, before the seed is in an appropriate state for mechanical pressing to remove a portion of the oil.

After mechanical pressing, the rape meal still contains around 20 wt.% of oil. Solvent extraction is performed on the meal with hexane to reduce the oil content to 2 wt.%. 1 kg hexane/ton of rapeseed is required to replenish the losses of solvent extraction; the hexane is removed using a desolventiser toaster. The meal is then dried and cooled. The solution of oil and hexane is distilled to separate them. Water is then added to remove water-soluble, unwanted hydrophilic phospholipids, the aqueous phase being separated from the oil by a continuous centrifuge. Electricity is provided by the National Grid, at 158 MJ/ton rapeseed (Stephenson et al, 2008).

In 20010, the UK produced 2230 kilo tonnes of RSO, which demonstrates, the potential for energy production. RSO is known to be utilised in the bio-diesel production industry on a large scale (Bayer, 2010) and is generally used to produce bio-diesel for use in vehicles using esterification technology. However RSO can also be used in energy production for our ever increasing need to heat and light buildings. Wartsila (see section 2.12.1) produce stationary plants utilising internal combustion engines for energy production using vegetable oils such as RSO (Wartsila, 2010). With a high calorific value and higher engine efficiency, crude RSO is an attractive form of biomass for energy production especially when renewable heat and electricity targets are ever increasingly higher than those for transport fuel. By 2020, 10% of transport demand is to be sourced from renewable sources compared with 30% of electricity demand. An economic evaluation and the environmental burden of the production of RSO and subsequently energy generation must be determined, to assess the feasibility of energy production from RSO. This is one of the objectives tackled in this thesis.

2.6. Forestry waste wood chips

In 2008, Defra released the "Waste Wood as a Biomass Fuel" report highlighting the fact that waste wood is underutilised in the UK. It is estimated that energy recovery from 2 Mt of waste wood could generate 2600 GWh electricity and 1.15 $MtCO_2equ$ emissions, with greater benefits available by recovering heat as well as power. Waste wood is obtained from a variety of sources, in varying quantities and levels of purity. Waste wood arises from construction and demolition, MSW and commercial and industrial sectors. Unfortunately, waste wood from construction and demolition and MSW is unpredictable in terms of tonnage and wood materials are often mixed with other types of waste. Waste wood disposal is influenced by its grade and the hierarchy triangle, with the most desirable option being to recycle followed by energy recovery and lastly landfill. The wood is graded as follows (Defra[c], 2008):

- Grade A- clean wood, relatively homogeneous (hardwood/softwood)
- Mixed grade-hard wood and softwood mix, including some contaminants such as paint and screws but as a relatively low proportion
- Low grade- processed wood containing contaminants such as panel board and melamine

The different grades of wood are suitable for different methods of disposal as shown in Table 2.6.

Table 2.6 Suitability of methods of disposal for grades of waste wood

Grade	Landfill	Energy recovery	Recycling
Grade A	High	High	High
Mixed grade	High	Medium	Medium
Low grade	High	Medium	Low

Data adapted from Defra[c], (2008)

Although landfill is suitable for disposal of all grades, it is the least desirable option. Landfill used to be relatively cheap and benefited from low processing costs, as all grades apart from hazardous could go to landfill.

However, landfills are becoming scarce resulting in an increase in gate fees. Additionally, landfill tax is continuously rising. Landfill tax was £ 24 in 2007/08 and will increase each year by £ 8 until 2011. As the wood waste is mixed with contaminants, it must be cleaned to abide by the waste incineration directive standards before being processed for energy recovery. This study examines forestry waste wood as a possible renewable source for energy production. This form of waste wood is chosen because forestry thinning is generally left in the forest on the land and not used. This biomass can be combusted to produce energy. A techno-economic and life cycle assessment of energy from FWWC is presented in Chapters 3 and 4 respectively.

2.7. Municipal Solid Waste

Municipal solid waste (MSW) is composed of household waste and waste from industrial sources, both collected by local authorities.

In 2009/10, 26.2 million tonnes of MSW was collected, compared to 28.7 million tonnes in 2005/06, resulting in a 1.4% increase of waste produced (Defra[f], 2011). In 2010, 23.5 million tonnes of MSW was collected in England, 89% of which was from households (Defra[f], 2011). Household waste comprises food waste, waste packaging and waste paper. The population as a whole is continuing to grow and so we would expect our waste production to increase, resulting in growing problems for the local authorities, due to restrictions being placed on the amount of MSW that can be sent to landfills.

Sustainable waste management is an extremely important area. Waste management produces carbon dioxide and methane which are both GHG’s. When we manage the treatment and disposal of our wastes, we are also managing the method by which the carbon will be released back into the environment. This is because waste is broken down by organisms either in the presence of air to make carbon dioxide or without air to produce methane, which occurs in landfills. At present, over 70% of waste in the UK is sent to landfill, resulting in a serious problem with the management and control of the subsequent methane emissions (Defra News, 2007). The waste management hierarchy shows the most desirable and sustainable option being waste reduction and the least desirable and unsustainable option being landfill. (See Figure 2.2)

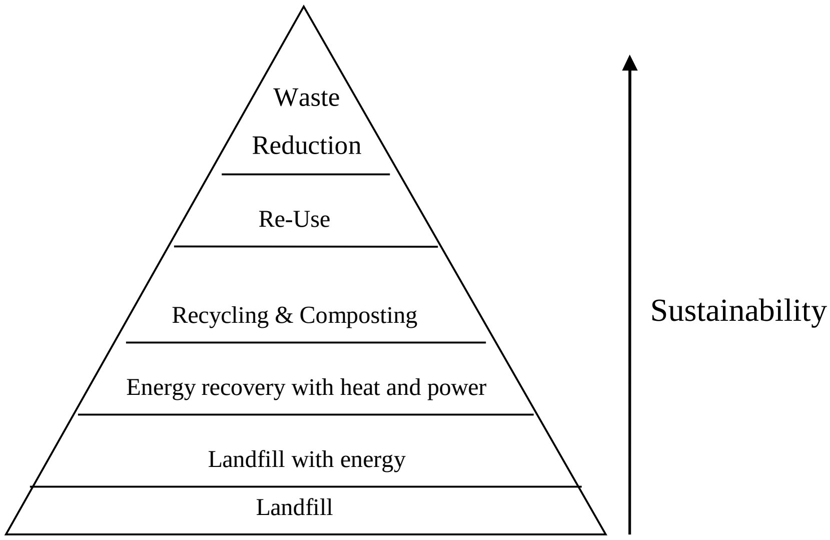


Figure 2.2 waste Management Hierarchy

Image adapted from Climate Change and Waste Management: The Link, (2005)

2.8. Solid Recovered Fuel (SRF)

Turning MSW into SRF is one of the options available for waste treatment. It reduces the volume of waste being sent to landfill, whilst simultaneously recovering embodied energy from the material. MSW can be pre-treated by mechanical biological or mechanical heat treatments (MBT/MHT) to produce SRF. Generally an MBT (See section 2.8.1) and MHT (See section 2.8.2) facility will convert 50% of black bag/residual waste to SRF. The typical net calorific value of SRF is 15 MJ/kg (Arias-Garcia, 2009). MBT plants mechanically sort mixed waste into different fractions. A summary of waste preparation technologies and waste separation technologies are presented in Tables 2.7 and 2.8 respectively (Defra[d], 2005).

Table 2.7 Mechanical Waste Preparation Technologies

Technology	Principle	Key Concerns
Hammer Mill	Material significantly reduced in size by swinging steel hammers	Wear on hammers; pulverising and 'loss' of glass/aggregates; exclusion of pressurised containers
Shredder	Rotating knives or hooks rotate at a slow speed with high torque. The shearing action tears or cuts most materials	Large, strong objects can physically damage; exclusion of pressurised containers
Rotating Drum	Material is lifted up the sides of a rotating drum and then dropped back into the centre. Uses gravity to tumble, mix and homogenize the wastes. Dense, abrasive items such as glass or metal will help break down the softer materials, resulting in considerable size reduction of paper and other biodegradable materials	Gentle action- high moisture of feedstock can be a problem
Ball Mill	Rotating drum using heavy balls to break up or pulverise the waste	Wear on balls; pulverising and 'loss' of glass/aggregates
Wet rotating Drum with Knives	Waste is wetted, forming heavy lumps which break against the knives when tumbled in the drum	Relatively low size reduction potential for damage from large items
Bag Splitter	A more gentle shredder used to split plastic bags whilst leaving the majority of the waste intact	No size reduction, may be damaged by large strong objects

Data adapted from: Defra[d] , (2005)

Table 2.8 Mechanical waste separation technologies

Technology	Separation Property	Materials Targeted	Key Concerns
Trammels and Screens	Size and density	Oversize – paper, plastic Small – organics, glass, fines	Air containment and cleaning
Manual separation	Visual examination	Plastics, contaminants, oversize, not usually for MSW	Ethics of role, Health & Safety issues
Magnetic separation	Magnetic properties	Ferrous metals	-
Eddy current separation	Electrical conductivity	Non-ferrous metals	-
Wet separation technology	Differential densities	Floats – plastics, organics Sinks – stones, glass	Produces wet waste streams
Air classification	Weight	Light – plastics, paper Heavy – stones, glass	Air cleaning
Ballistic separation	Density and Elasticity	Light – plastics, paper Heavy – stones, glass	-
Optical separation	Optical properties	Specific plastic polymers	Rates of throughput

Data adapted from: Defra[d] , (2005)

There are a variety of alternative waste management options and strategies available for dealing with MSW, to limit the residual amount left for disposal to landfill. MBT and MHT are pre-treatment technologies, which contribute to the diversion of MSW from landfill when operated as part of a wider integrated approach involving additional treatment stages. The generic purpose of these processes is to separate a mixed waste stream into several component parts, to give further options for recycling and recovery. These are discussed in more detail in the following sections.

2.8.1. Mechanical Biological Treatment

MBT plants sort mixed waste into different fractions using mechanical means. The exact mix of technologies employed in an MBT facility will depend on the additional objectives of the plant. These objectives would typically be one or more of the following (Defra[d], 2005):

- Part stabilise the waste prior to landfilling;
- Biologically process a segregated 'organic rich' component of the waste (for example, to form a low grade soil conditioner); and
- Produce a segregated high calorific value waste to feed an appropriate thermal process to utilise its energy potential.

The biological element of an MBT process may either take place prior to or after mechanical sorting as described in Figure 2.3 (Defra[d], 2005).

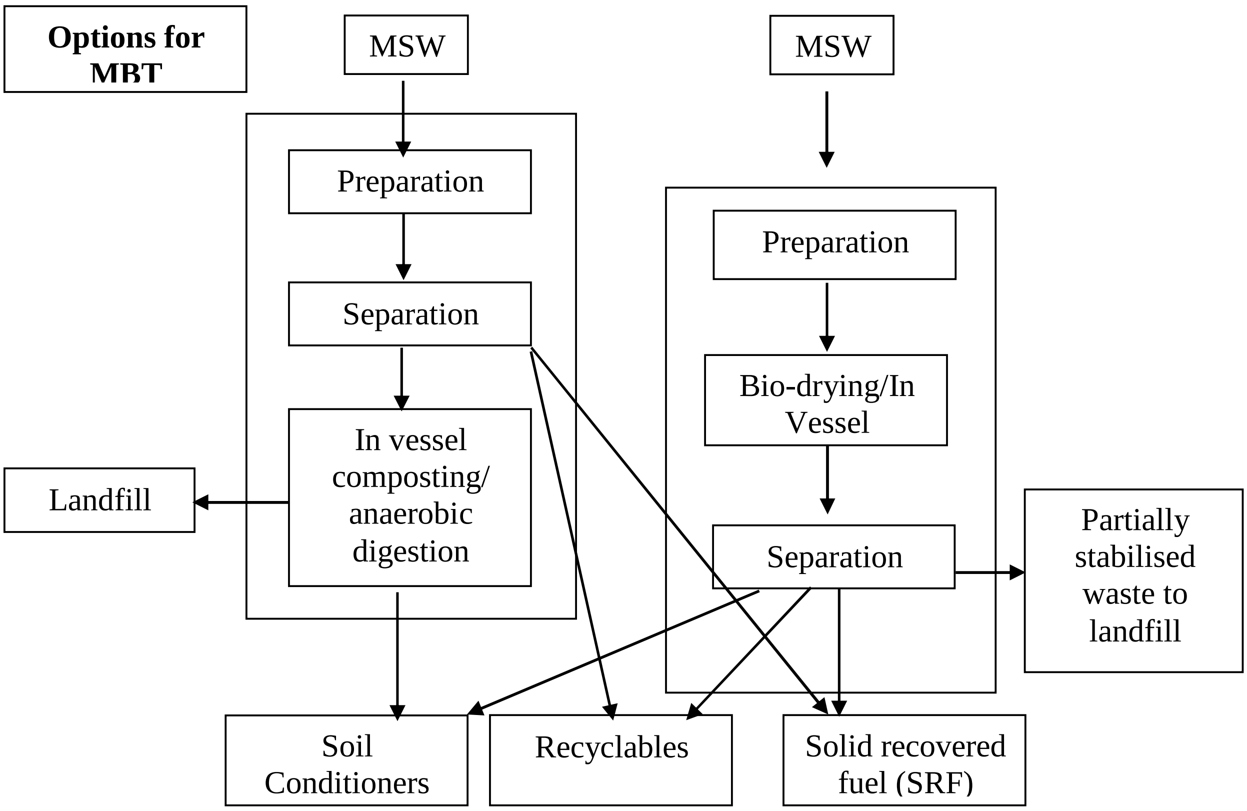


Figure 2.3 An illustration of the potential Mechanical Biological Treatment options

There are several MBT processes but two such processes are the Arrow Bio Process and the Ecodeco Process. These are described in more detail in Section 2.8.1.1.

2.8.1.1. The Arrow Bio Process and the Ecodeco Process

The Arrow Bio Process is an MBT process which includes: MSW reception, bag splitting, a wet separator (where the biodegradable material is separated from the ferrous and non-ferrous metals and other heavy material), the “Hydrocrusher” (which separates the fibres in the biodegradable material), followed by a two stage anaerobic digestion. The gas from the digesters is burnt in an engine-powered generator. The Ecodeco Process is where the waste is shredded to around 200mm followed by forced aeration composting to give bio drying and finally, the material is separated in a Materials Recovery Facility (MRF). In the composting stage, air is drawn through the waste which has been heaped in a hall. The bio-decomposition generates heat, which in turn dries the material to the stage where further composting cannot proceed. Air from the hall is cleaned via a bio-filter prior to release. In the MRF, metals are removed and recycled and during this process the dense and light fractions are separated. The dense fraction usually goes to landfill, the lighter organic and plastic fraction requires a market. It can be further separated or processed to a specification needed for a particular application, such as land remediation and use as a fuel. A limitation to MBT is that often clean materials are not achieved. Recyclables derived from the various MBT processes are typically of a lower quality than those derived from a separate household recyclate collection system and therefore have a lower potential for high value markets (Defra[d], 2005).

An alternative to MBT is MHT (See section 2.8.2) which can be configured to meet various objectives with regard to the waste outputs from the process (Figure 2.4). The alternatives may be one or more of the following (Defra[d], 2005):

- Separate an ‘organic rich’ component of the waste for subsequent biological processing (for example to form a low grade soil conditioner)

- Produce a segregated high calorific value waste (SRF) to be applied in an appropriate process to utilise its energy potential
- Extract materials for recycling (typically glass and metals, potentially plastics and the 'fibrous' organic and paper fraction)

Glass and metals derived from MHT processes have the potential to be significantly cleaner than those from MBT processes, due to the action of steam cleaning which removes glues and labels. Other recyclables such as plastics may also be extracted from some systems; however certain plastic materials may be deformed by the heat of the process potentially making them more or less difficult to recycle. The types of materials recovered from MBT and MHT processes almost always include metals (ferrous and non-ferrous) and for many systems this is the only recyclate extracted. However these plants can help enhance overall recycling levels and enable recovery of certain constituent items that would not otherwise be collected in household systems (e.g. steel coat hangers, paper lips etc.). Textiles, paper and plastics, if extracted, are unlikely to receive a significant income as a recyclate and in some instances may not yield a positive value. Paper is unlikely to be segregated in isolation from some textiles, plastic film, etc. unless hand-picked. The plastics separated from these processes will almost always be mixed plastics. Whilst the technology is available to separate individual plastic types, it is expensive and unlikely to be applied to most MBT and MHT processes (Defra[d], 2005). MHT processes are described in more detail in the following section.

2.8.2. Mechanical Heat Treatment

MHT (Figure 2.4) is used to describe configurations of mechanical and thermal (including steam), based technologies. Two MHT processes are discussed in this Chapter, The Estech Process and The Fairport Process. Section 2.8.2.1 discusses The Estech Process whilst Section 2.8.2.2 discusses the Fairport Process.

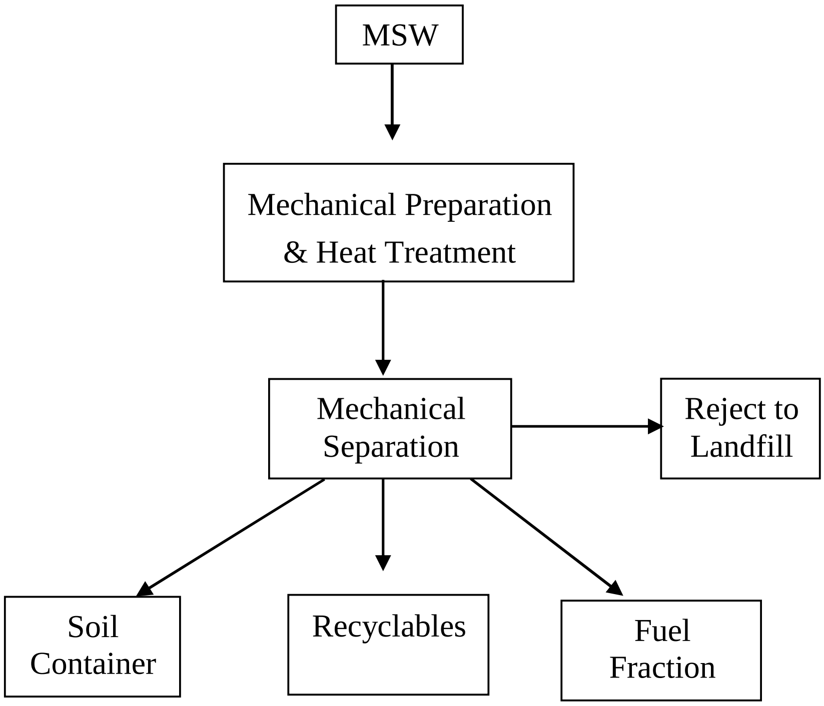


Figure 2.4 Mechanical Heat Treatment

2.8.2.1. The Estech Process

The Estech Process is an MHT process which uses wet steam under pressure (autoclave) to clean materials into a fibre. Following the autoclaving process the materials can be easily and effectively separated in a MRF. The key process stages include waste reception and storage, waste feeding, autoclaving, materials separation and recyclates recovery.

The autoclave stage is central to the process and operates as a batch operation. The primary product is a fibre which could constitute a refuse derived fuel. The secondary streams comprise of mixed plastics, a glass and aggregate stream and separate ferrous and non-ferrous metals. Having been steam cleaned, all these streams are exceptionally pure. Often these MHT systems utilise two autoclave vessels which are run in parallel, the sterilised material that emerges from the autoclave may then be fed through a separation process to extract recyclables and fibre, or the recyclables can be extracted prior to autoclaving.

The Fairport Process differs to autoclave processes in being a non-pressurised system (Defra[d], 2005). This work focuses on the Fairport Process, which is described in the following section and considered later in Chapter 4 in the energy from SRF LCA.

2.8.2.2. The Fairport Process

The Fairport Process begins in a reception area where waste is unloaded (Figure 2.5). Waste is then transported by a 360° grab crane to a trommel, in which it is separated by size at around 150mm. Plastic bags containing smaller waste are opened within the trommel. The size of the holes for the trommel must satisfy the ability to separate textiles. Oversized materials separated by the trommel pass through a shredder to reduce the material to <150mm this is then reunited with the undersize materials from the trommel and transported to the homogeneous stockpile. Waste from the stockpile is transferred to a pair of wet preparation drums, in which the material is thoroughly mixed and moisture added if necessary. The wet preparation hoppers feed a pair of large rotating non-pressurised thermal processors, which break down the putrescible material and clean and sanitise other materials. A gas burner in the process drum blows hot air along the drum. While waste progresses through the thermal processor it is turned, lifted and progressively dried through contact with the hot air. At the same time, organic material is broken down, steel and aluminium cans are de-labelled and cleaned and dense plastics are softened and deformed.

Controlling the moisture content of the waste is key to producing steam and therefore controlling the temperature in the main thermal processor drum. Moisture in the waste produces steam in the main processor drums to sanitise the recyclables and fuel products. The high moisture content also suppresses dust formation during thermal treatment. Drying is controlled to optimise the moisture content of the final processed fuel products and aid pelletisation (Stringfellow et al., 2010).

After the thermal processor, treated waste is transported via a belt conveyor to the materials classification area where a sizing screen divides the material into two categories, normally >50mm and <50mm. Material in the >50mm category arrives at the ballistic classifier where it is divided into three streams: light, heavy and fine. Light, buoyant materials such as plastics, textiles and paper are conveyed up the classifier while heavier, less aerodynamic materials such as tins, bottles and cans fall off the bottom end. Fine material passes through the holes in the classifier decks where it re-joins the <50mm material (Stringfellow et al., 2010).

The light fraction (paper, plastics and textiles) is suitable for fuel production. It is sent through a granulator and then combined with other light fraction particle sizes that come from the Biomass Density Separator. An overband magnet is used to trap metals to protect the granulator and to reduce the metal content of the fuel products (Stringfellow et al., 2010).

The heavy fraction, which consists of large items such as tins, bottles, cans, lumps of wood and stone, is conveyed beneath and an overband magnet is used to separate ferrous metals which are then conveyed to a skip for collection. The remaining material in the heavy stream is transported by belt to an eddy current separator, where any residual ferrous metals are removed to the skip and non-ferrous metals are separated onto a conveyor, leading on to the non-ferrous metal skip for collection. The rest of the stream is passed through an optical separator which separates plastics using an infrared detector and a compressed air deflector. The deflected plastics can be sent to a plastic baler or passed through a granulator and sent to a mixed plastic blending bin for inclusion in high calorific value fuel products. The remaining unsorted material is compacted into a container and sent to landfill (Stringfellow et al., 2010).

Fine material from the ballistic classifier is mixed with the <50mm waste stream from the sizing screen. Ferrous and non-ferrous metals are separated from this stream using an overband magnet and eddy current separator. The remaining stream is diverted to a twin deck screen, which splits the remaining material into three size fractions: >16 to <50mm, <6 to <16mm and <6mm. From the twin deck screen, the various materials are further refined as follows (Stringfellow et al., 2010):

- >16 to <50mm materials are sent to an air separator where dense particles (heavies) which are used as aggregates (mainly glass), are sorted from less dense particles (lights), which are used as fuel and sent to storage hopper 2

- >6 to <16mm materials are sent to the Biomass Density Separator which has two stages of refining. In the first stage, less dense fuel materials are separated from heavy materials such as glass and rubble; they may be sent either to storage hopper 4 or through a second stage of refinement to remove light plastics to produce a fuel with a high biomass content which is sent to hopper 3. The removed light plastics are sent to hopper 1
- <6mm materials pass through one stage of refining where lightweight fuel materials are sent to storage hopper 5. Any remaining heavy materials are stored and then sent to the glass skip aggregate
- Dust extraction points are fitted to various pieces of equipment in the separation area. The dust is collected and added to hopper 5

By the end of the separation process, the light organic and plastic material has been separated into the following storage hoppers (Stringfellow et al., 2010):

1- Granulated plastics, textiles and paper from the ballistic classifier

2- Light material from the air classifier

3- Material from the >6 to <16mm Biomass Density Separator (from two stage separation of >6 to <16mm material)

4- Light material from >6 to <16mm Biomass Density Separator (from single-stage separation of >6 to <16mm material)

5- Light material from the <6mm Biomass Density Separator and dust

6- Granulated material (predominantly plastic) from the Optical Sorter

Materials from the six blending bins may be blended to form SRF which will then go on to be made into pellets see section 2.8.3 (Stringfellow et al., 2010).

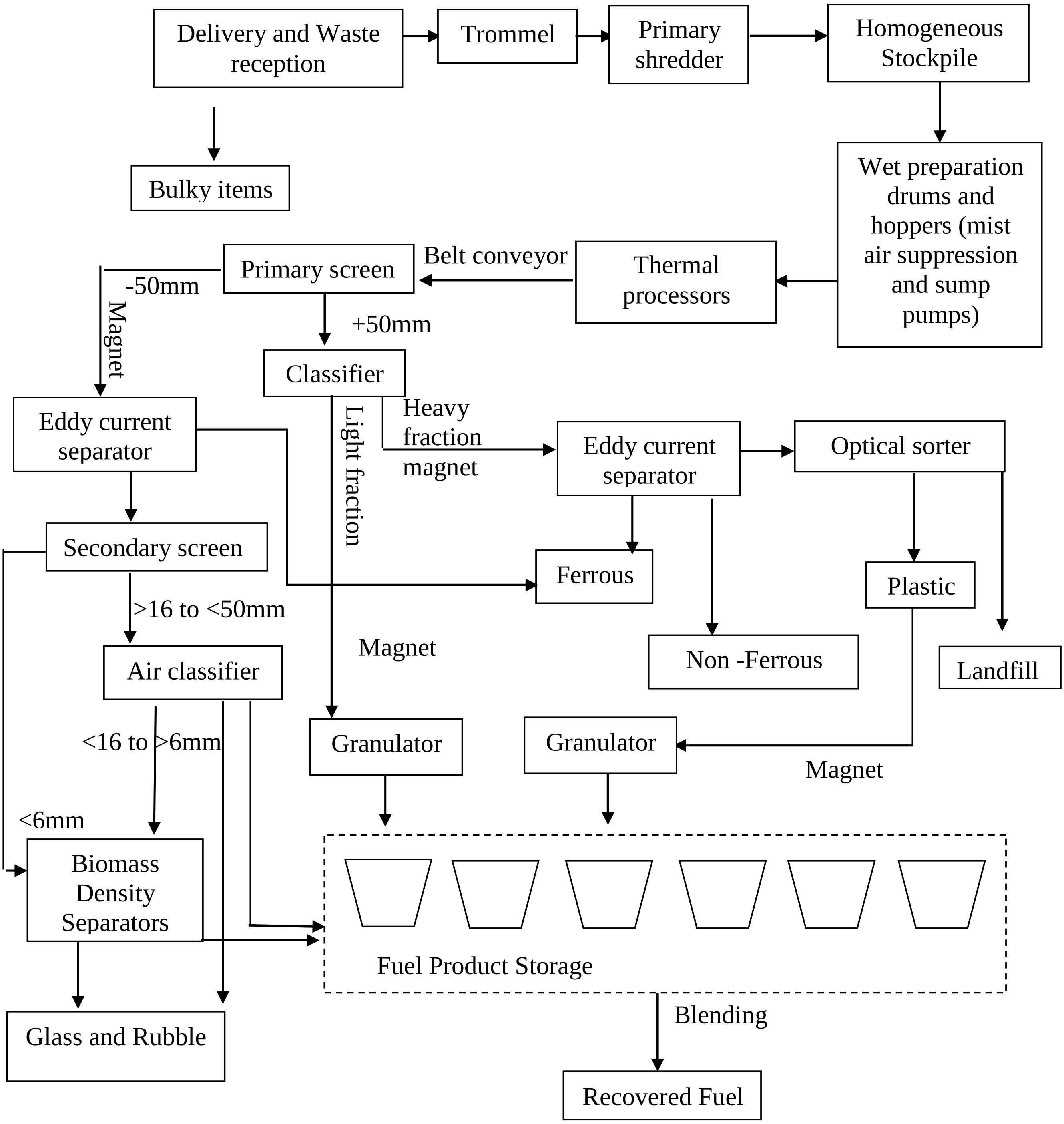


Figure 2.5 Schematic of the Fairport Process

This work focuses on the Fairport Process because it is an MHT process which produces cleaner products than the MBT processes, it is a well-established process and has a successful plant built and tested in Lancashire (Stringfellow et al., 2010). The technology has been proven to be most appropriate for processing above 70,000 t/yr of MSW in the UK. This research focuses on energy production from small scale combustion plants which can supply electricity to cities and towns. The Fairport Process can be used to treat MSW produced by a town or city to produce SRF which can then be fed into a combustion plant such as the one investigated in Chapter 3. The Fairport Process is also considered to be a reliable technology for this work because reliable data is extracted from BEATV2 for the life cycle assessment developed in Chapter 4. This program reports data from the Fairport Process for the production of SRF and is considered a reliable and accurate source of data because it has been derived from the Lancashire Fairport Process plant by the experts who developed the BEATV2 tool. AEAT, Defra and the Environmental Agency developed this tool as an aid to understanding of impacts of energy from a variety of energy generating plants. In this study, the tool is used to extract data from the database for certain processes in the life cycle assessments (Chapters 3 and 5) which had to be sourced from literature. The process and equipment shown in Figure 2.5 will be used to calculate the environmental burden of using The Fairport Process in the LCA presented in Chapter 4.

2.8.3. Pelletisation

The manufacture of pellets involves the following processes (Keys et al., 2001):

- Breaking the raw material down to a small and uniform size. This stage is normally referred to as hogging, grinding or milling
- Drying, the material is dried to a moisture level of 8 to 10%
- Pelletising, the dry material is extruded into pellets using piston or roller presses and a perforated die. Dry steam is sometimes used to condition the pellet. No additives are normally used
- The pellets are then transported to the customer

The environmental burden of the pelletisation stage is explored in the LCA in Chapter 4, where the energy used by this process is taken from the BEATv2 tool.

The biomass mentioned in this chapter can all be used to produce energy. In the UK, we have underutilised waste forms for biomass such as MSW and

FWWC and we are producing RSO on a large scale. Chapter 3 investigates the techno-economic assessment of SRF and FWWC combustion for energy production, whilst Chapter 4 investigates the techno-economic assessment of electricity and heat from RSO. The type of combustion technology employed in Chapters 3 and 4 are discussed in section 2.9.

2.9. Thermal Treatment Technologies and Reciprocating Engines

Summary

In this section, a review of thermal treatment technologies including combustion, gasification and pyrolysis is presented. Gasification and pyrolysis are known as advanced thermal treatments. Combustion is a mature and established technology, but only recently has pyrolysis and gasification have been applied commercially to the treatment of biomass. Whereas pyrolysis and gasification are still in their infancy in the UK, large scale plants are already operational in Europe, North America and Japan (Defra[e], 2007).

2.9.1. Pyrolysis

Pyrolysis is the thermal degradation of a substance in the absence of oxygen. An external heat source is required to maintain temperatures between 300°C to 800ºC. The products of pyrolysis are a liquid fuel, a solid residue and a synthetic gas (syngas) (Defra[e], 2007). The liquid fuel or bio-oil can be used directly as a substitute for fuel oil in heat and power applications, or to produce a wide range of speciality and commodity chemicals (Bridgewater, 2003). The solid residue (also known as char) consists of non-combustible materials and carbon. The syngas is a mixture of gases specifically carbon monoxide, hydrogen, methane and a broad range of other volatile organic compounds (Defra[e], 2007). The composition of the pyrolysis products depends on the heating rate, residence time and temperature, as well as on the composition of the fuel. Pyrolysis is the first step in combustion and gasification processes, followed by partial or total oxidation of the primary product. Lower temperature and longer vapour residence times favour the production of charcoal. High temperature and longer residence time increase biomass conversion to gas whilst moderate temperature and short vapour residence time are optimum for producing liquids as summarised in Table 2.9 (Bridgewater, 2003),

Table 2.9 Different methods of pyrolysis and the resulting constituents in percentage

Method	**Conditions**	**Liquid (%)**	**Char (%)**	**Gas (%)**
Fast pyrolysis	Moderate temperature, short residence time particularly vapour	75	12	13
Carbonisation	Low temperature, very long residence time	30	35	35
Gasification	High temperature, long residence times	5	10	85

Data adapted from Bridgewater, (2003)

Pyrolysis generates valuable gases which can be useful for other applications, such as chemical synthesis and high efficiency combustion systems (such as fuel cells) but before secondary processing they must be cleaned to remove the tar. Temperature is an important variable in the thermal decomposition of biomass. Pyrolysis is an endothermic process and the use of low temperatures decreases the input energy for a system but also results in higher liquid yields and lower gas yields (García, et al., 2000). Recently, fast pyrolysis to produce liquid is of particular interest as it can utilise any form of biomass. Although most work has been conducted on wood because of its consistency and comparability, nearly 100 different biomass types have been tested in laboratories including olive pits, nut shells, miscanthus, sorghum, sewage sludge and leather wastes.

The process occurs in a few seconds or less; the main objective is to bring the reacting biomass particle to the optimum process temperature and to minimise its exposure to the lower temperatures that favour charcoal formation. This can be achieved by using small particles or by transferring heat very fast only to the particle surface that contacts the heat source. The liquid that is produced is an intermediate product of flash degradation of hemicellulose, cellulose and lignin but with a higher calorific value (HHV) of 16 – 19 MJ/kg, compared to 42 – 44 MJ/kg for conventional fuel. The resulting bio-oil is incompatible with conventional fuels as it contains solids, has a high viscosity and is chemically unstable; therefore, the oil is generally upgraded using hot gas filtration to reduce the ash content. As shown in Figure 2.6, the oil can be used as a substitute for fuel oil or diesel in many static applications including boilers, furnaces, engines and turbines for electricity generation (Bridgewater, 2003).

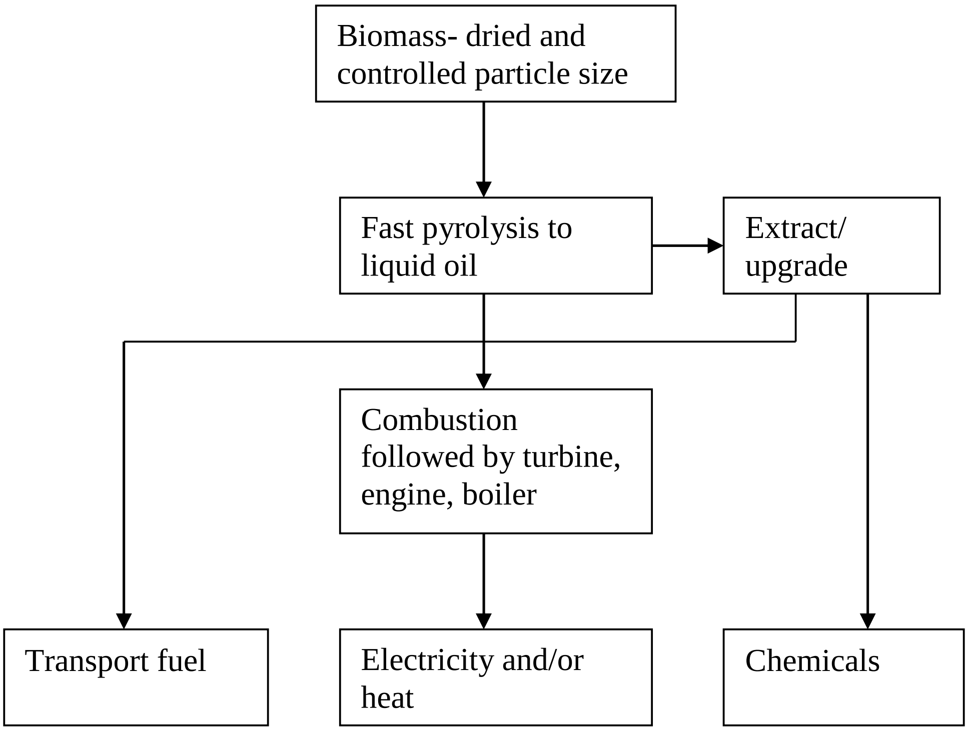


Figure 2.6 Application of bio-oil

(Image adapted from Bridgewater, 2003)

Limited uses and difficulty in downstream processing of bio oil have restricted the wide application of biomass pyrolysis technology especially in the UK (Wang et al, 2008). Pyrolysis produces a bottom ash (BA) residue which contains vast amounts of carbon. As a result this must be disposed of in a landfill or further processed to reduce the carbon content using gasification or combustion. If treated, the final bottom ash residue can be recycled as a secondary aggregate (Defra[e], 2007).

2.9.2. Pyrolysis Limitations

Pyrolysis generates liquid bio-oil which has the benefit of being storable and transportable as well as having the potential to supply a number of valuable chemicals. However, there are certain limitations to the technology, product and application.

- The cost of bio-oil ranges from 10% to 100% more than fossil fuels,
- There are limited supplies for testing the bio-oil
- There is a lack of standards for use and distribution of bio-oil
- Inconsistent quality inhibits its use for wider applications, resulting in a considerable need for standardisation and characterisation
- It is incompatible with conventional fuels making mixing impossible.

As a result, dedicated fuel handling systems would be needed.

In 2008, a small scale pyrolysis plant was commissioned in the UK. As of yet no large scale applications are operational in the UK, which deters new investors. Another issue that needs to be addressed during handling, transport and usage, is environmental health and safety (Bridgewater, 2003).

2.10. Gasification

Gasification is the partial oxidation of a substance and the temperatures employed are typically above 750 ºC. A syngas is produced, containing carbon monoxide, hydrogen and methane, with a typical net calorific value of 4 – 10 MJ/Nm^3. Gasification also produces a solid residue of non-combustible materials (bottom ash) containing a relatively low level of carbon, which can then be recycled as a secondary aggregate (Defra[e], 2007). Gasification takes place in a number of sequential steps:

- Drying to evaporate moisture
- Pyrolysis to produce gas, vaporised tars or oils and a solid char

residue

- Gasification of the solid char, pyrolysis tars and pyrolysis gases

In gasification, pyrolysis proceeds at a faster rate than gasification, resulting in the latter being the rate controlling step. The gas, liquid and solid products of the pyrolysis steps then react with the oxidising agent (air, pure oxygen, steam or a mixture of these gases) to give permanent gases.

Air-based gasifiers typically produce a product gas containing a relatively high concentration of nitrogen with a low heating value (Bridgewater, 2003). Oxygen and steam-based gasifiers produce a product gas containing a relatively high concentration of hydrogen and carbon monoxide, with a higher heating value. Although oxygen produces a syngas with a high heating value, it will result in an increase in operating costs due to oxygen production. Alternatively, partial combustion of biomass with air or oxygen can supply heat to dry the biomass, increasing the biomass temperature and driving the endothermic gasification reactions. Using CO_2 as the gasifying agent has an advantage because of its existing presence in the syngas. CO_2, with a catalyst such as Ni/Al can convert char, tar and CH_4 into H_2 and or CO, thus increasing valuable H_2 and CO. However pure steam or CO_2 would require an indirect or external heat supply for the endothermic gasification reactions (Wang et al., 2008).

Three main types of gasifiers exist:

- Fixed bed
- Moving bed
- Fluidised bed

Fixed bed and moving bed gasifiers produce syngas with large quantities of either tar and/or char, because of low and non-uniform heat and mass transfer between solid biomass and the gasifying agent. However, they benefit by being simple, reliable designs and can be used to gasify biomass with high moisture content on an economically small scale. Fluidised beds have been used widely in biomass gasification, they contain a large percentage of hot inert bed material such as sand and 1 – 3% biomass. Fluidised bed gasification can achieve a high heating rate, uniform heating and high productivity (Wang et al., 2008). The syngas can replace fossil fuels in high efficiency power generation, heat, CHP applications and in the production of liquid fuels and chemicals via syngas. Syngas is combusted and used with conventional steam turbines or utilised in dedicated gas engines and turbines following gas clean up, to produce electricity heat and chemicals as shown in Figure 2.7. Gas engines and gas turbines benefit from higher electrical conversion efficiencies compared with steam turbines, ranging from 35% for gas engines and up to 40% for combined cycle gas turbine (CCGT) (Baratieri et al., 2009).

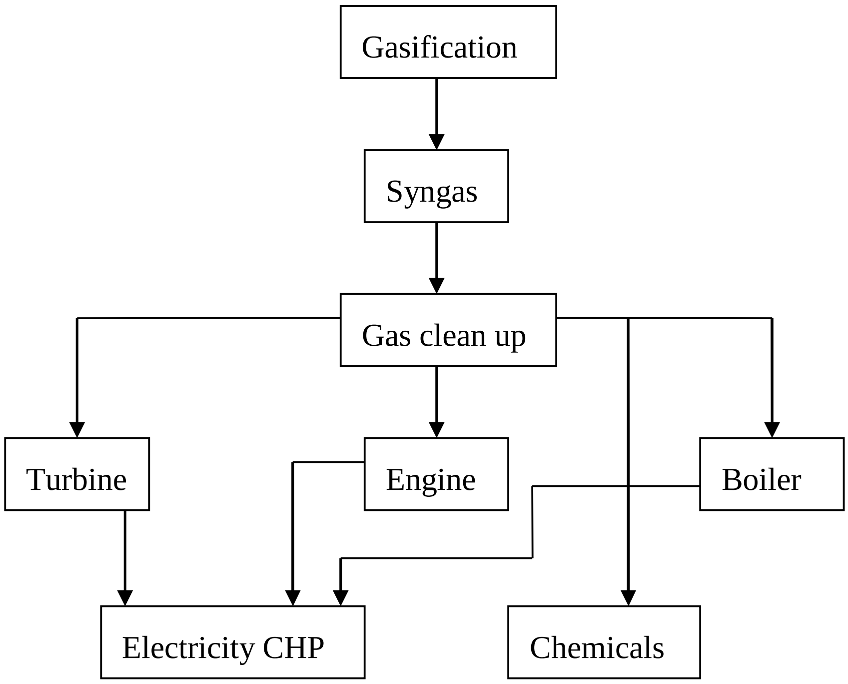


Figure 2.7 Application of Syngas
Image adapted from Bridgewater (2003)

Due to physical or geometrical limitations of the reactor and the chemical limitations of the reactions involved, some liquid products from the pyrolysis stage are not converted, producing contaminant tars in the final products. Due to the higher temperatures involved in gasification, these tars tend to stay stable and are difficult to remove by thermal, catalytic or physical processes. Turbines in particular, have high gas quality standards and tar remains a particular technical barrier. Tars are destroyed using two basic methods:

- By catalytic cracking using, for example, dolomite or nickel
- By thermal cracking, for example by partial oxidation or direct contact

Storing or transporting the gas is expensive and so they must be utilised immediately. Hot-gas efficiencies for the gasifier can reach 97% for close-coupled turbine and boiler applications and up to 85% for cold gas efficiencies.

2.10.1. Gasification Limitations

Ash related issues include sintering, agglomeration, deposition, erosion and corrosion are the main obstacles to economically viable application of biomass gasification. Fluidised bed gasification performs better than fixed bed gasification in this respect, because fluidised bed temperature can be kept uniform and below the ash slagging temperature. Low temperature in a fluidised bed can also reduce the volatilization of ash elements such as sodium and potassium into the syngas. Even fluidised bed biomass gasification results in char and tar in the syngas which is used in internal combustion engines, gas turbines and fuel cells for heat and power generation and as a feedstock for the synthesis of liquid fuels and chemicals, requires removal of dust and condensable tar (Wang et al, 2008). There is little information on costs, emissions, efficiencies and actual operational experience especially in the UK, making it difficult to convince investors, however in recent years, several advanced thermal treatment plants have been commissioned and are running at a small scale as shown in Table 2.10.

Table 2.10 current advance thermal treatment plants

Manufacturer	Primary technology	Country	Operational	Capacity (tpa)	Feed type
Compact power	Tube pyrolysis	UK-Avonmouth	2001	8,000	Clinical waste
Energos	Grate gasification	Isle of White	2008	30,000	MSW
Energos	Grate gasification	Norway	1997	10,000	Industrial and paper waste
Energos	Grate gasification	Norway	2000	34,000	MSW
Energos	Grate gasification	Norway	2001	36,000	MSW & industrial waste
Energos	Grate gasification	Norway	2002	70,000	MSW & industrial waste
Energos	Grate gasification	Norway	2002	37,000	MSW
Energos	Grate gasification	Germany	2002	37,000	MSW & industrial waste
Energos	Grate gasification	Germany	2005	80,000	MSW, commercial, industrial waste
Energos	Grate gasification	Sweden	2005	80,000	MSW & industrial waste
Enerkem/Novera	Fluidised bed gasification	Spain	2002	25,000	Plastics
FERCO	Fluidised bed gasification	USA	1997	165,000	Biomass
Foster Wheeler	Fast (ablative) pyrolysis	Finland	1998	80,000	Mixed waste
Mitsui Babcock	Rotary kiln pyrolysis	Japan	2000	80,000	MSW
Mitsui Babcock	Rotary kiln pyrolysis	Japan	2002	150,000	MSW
Mitsui Babcock	Rotary kiln pyrolysis	Japan	2002	50,000	MSW
Mitsui Babcock	Rotary kiln pyrolysis	Japan	2003	95,000	MSW

Mitsui Babcock	Rotary kiln pyrolysis	Japan	2003	75,000	MSW
Mitsui Babcock	Rotary kiln pyrolysis	Japan	2003	60,000	MSW
Novera Energy	Gasification	UK-Havering, Essex	2006	70,000-90,000	RDF
Thermoselect	Tube pyrolysis	Germany	1999	225,000	Domestic & industrial wastes
Thermoselect	Tube pyrolysis	Japan	1999	100,000	Domestic & industrial wastes
Thermoselect	Tube pyrolysis	Japan	2003	50,000	Industrial waste
Techtrade/Wastegen	Rotary kiln pyrolysis	Germany	1984	35,000	RDF
Techtrade/Wastegen	Rotary kiln pyrolysis	Germany	2002	100,000	Domestic & industrial waste
Yorwaste	Pyrolysis	UK-Seamer Carr, North Yorkshire	2008	12,000	RDF

Data adapted from Defra[e], (2007)

2.11. Combustion

Combustion a proven technology used to convert biomass energy into heat, mechanical power or electricity. It is understood, relatively straightforward and commercially available. Compared to gasification and pyrolysis it is the simplest and most developed thermal technology and biomass combustion systems can be easily integrated within existing infrastructure. Combustion is the total oxidation of organic matter at temperatures in excess of 850ºC to produce heat, water vapour, carbon dioxide and non-combustible material or bottom ash. The emissions and residues from the combustion process are described in more detail in Section 2.13. Although the actual process design and plant layout may differ from one facility to another, Figure 2.8 illustrates a typical energy flow from biomass combustion plant.

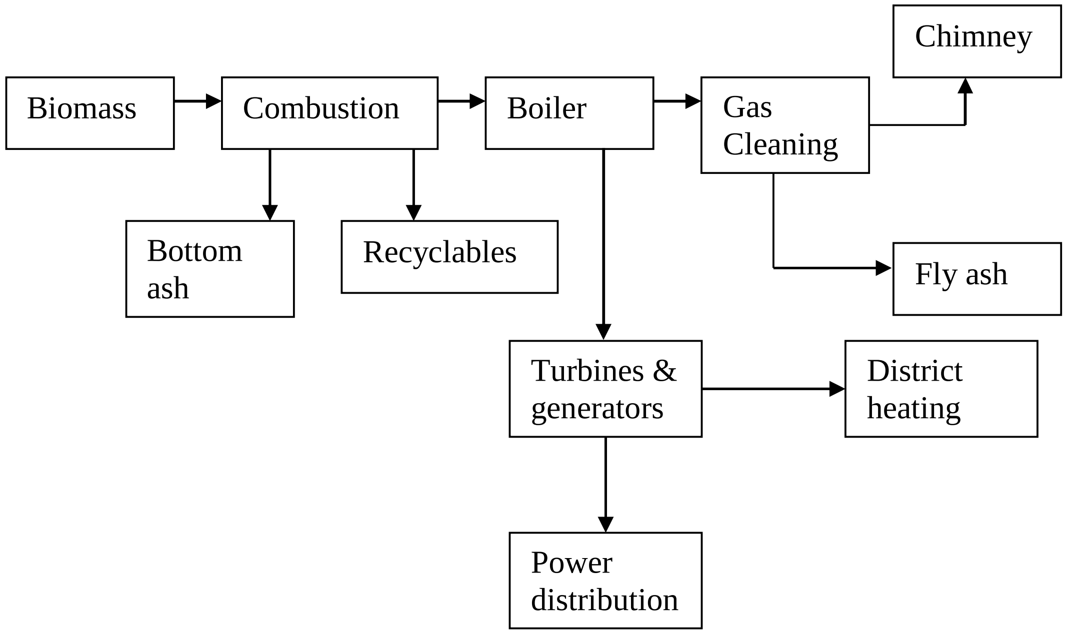


Figure 2.8 Diagram illustrating a typical energy flow of a biomass combustion process
Adapted from Yassin et al. (2008)

Combustion units can be distinguished by one of the following (Bridgewater, 2003):

- Fixed bed combustion
- Fluidised bed combustion

2.11.1. Fixed bed combustion

Fixed bed combustion is one of the oldest and most common methods of coal use. In the last three decades fixed beds have lost part of their traditional market to fluidised bed technology. There are two prominent types of fixed bed combustion, underfeed stokers and grate firings.

Air is primarily supplied through the grate from below and initial combustion (with some gasification) takes place on the grate. This allows for secondary combustion in another chamber above the first, where secondary air is supplied. Underfeed stokers are a relatively cheap and safe option for biomass combustion, but they are generally more suitable for small scale systems. They have the advantage of being easier to control than other technologies, since load changes can be achieved quickly and with relative simplicity, due to the fuel feed method. Fuel is fed into the furnace from below by a screw conveyor and then forced upwards onto the grate where combustion begins. Underfeed stokers are limited in terms of fuel type to low ash content fuels such as wood chips. Due to ash removal problems it is not feasible to burn ash rich biomass as this can affect the air flow into the chamber and cause combustion conditions to become unstable (Basu, 2006).

The other type of fixed bed combustion is grate fired, there are several types of grate firing, with both fixed and moving grates. They benefit from being able to accommodate fuels with high moisture and ash content as well as with varying fuel sizes. It is very important that fuel is spread out evenly over the grate surface. This ensures that air is distributed uniformly throughout the fuel and thus combustion is kept homogenous and stable. There are various types of grate fired combustors including fixed grates, moving grates, rotating grates and travelling grates (Hobbs et al., 1993).

2.11.2. Fluidised bed combustion

Fluidised bed technology requires high pressure air to be blown through the feed. The particles become trapped in the air and form a floating or fluidised bed, behaving like a fluid in which the constituent particles move and collide with one another. Fluidised beds can burn a variety of fuels such as biomass, petro-coke, coal and wastes (however MSW must be pre-sorted into SRF). This bed contains around 5% of fuel, whilst the rest of the bed is primarily an inert material such as sand.

Fluidised bed temperatures are around 800 – 900°C. The low temperature helps minimise the production of NO_x and with the addition of sorbent into the bed (limestone), much of the SO_2 formed can be captured. Other advantages of fluidised bed combustion are compactness, ability to burn low calorific valued fuels (as low as 1800 kcal/kg) and production of less erosive ash.

There are essentially two types of fluidised beds, bubbling (BFB) and circulating (CFB). The main differences are summarised in Table 2.11. Other advantages of fluidised beds include a higher combustion efficiency that is comparable to pulverised fuel-fired combustors, reduction in boiler size, low corrosion and erosion with easier ash removal and simple operation with fast response to load fluctuations (Basu, 2006).

Table 2.11 design parameters for BFB and CFB combustors

Design parameter	**BFB**	**CFB**
Combustion temperature (°C)	760-870	800-900
Fuel particle size (mm)	0-50	0-25
Fluidisation velocity (m/s)	1-3	3-10
Solid circulation	No	Yes

Data adapted from Koornneef et al. (2007)

Since the introduction of fluidised bed combustion, there has been a series of mergers and acquisitions resulting in four major market players; Alstom, Foster Wheeler, Lurgi and Kvaerner Pulping, as shown in Table 2.12. Alstom and Foster Wheeler are the largest producers of CFB technology, while Kvaerner is the market leader for BFB technology. Bharat Heavy Electricals and Energy Product of Idaho (EPI) are only active in their own regions in India and North America, respectively (Koornneef et al., 2007).

Table 2.12 Overview of fluidised bed combustion technologies

Manufacturer	Technology	Capacity (MWe)		No. of installations	Start-up
		Min	Max		
Alstom	BFB	17	142	7	1988-1999
	CFB	2	520	51	1986-2005
Babcock and Wilcox	CFB	3	76	22	1982-2002
Babcock Borsig	BFB	0	35	5	1982-2000
	CFB	9	120	10	1989-1999
Bharat Heavy Electricals	BFB	5	50	18	1987-1998
EPI	BFB	10	45	9	1981-1993
Foster Wheeler	BFB	0	117	51	1976-2002
	CFB	0	460	161	1981-2006
Kvaerner Pulping	BFB	6	117	56	1985-2005
	CFB	0	240	32	1984-2002
Lurgi	CFB	9	225	35	1982-2004

Data adapted from Koornneef et al. (2007)

The majority of UK energy comes from combustion plants utilising non-renewable fuels; there are 19 waste incineration plants in operation in the UK Table 2.13.

Table 2.13 MSW incineration plants in UK

Incinerator Plant	Scale (tpa)	Energy recovery (MW)	Establishment
Alington, Kent	500,000	Electricity 40	2008
Edmonton	500,000	Electricity 32	1975
SELCHP	420,000	Electricity 32	1994
Tysesley Birmingham	350,000	Electricity 25	1996
Cleveland	245,000	Electricity 20	1998
Coventry	240,000	Electricity 17.7 & Heat	1975
Stoke	200,000	Electricity 12.5	1997
Marchwood	165,000	Electricity 14	2004
Portsmouth	165,000	Electricity 14	2005
Nottingham	150,000	Electricity & Heat (max 20 heat)	1973
Sheffield	225,000	Electricity 19 (max) & 39 Heat (max)	2006
Dundee	120,000	Electricity 8.3	2000
Wolverhampton	105,000	Electricity 7	1998
Dudley	90,000	Electricity 7	1998
Chineham	90,000	Electricity 7	2003
Kirklees	136,000	Electricity 9	2002
Douglas (Isle of Man)	60,000	Electricity 6	2004
North East Lincolnshire	56,000	Electricity 3 & Heat 3	2004
Shetland	23,000	Heat	2000
Isles of Scilly	3,700	No energy recovery	1987

Data adapted from Defra[g], (2007)

In addition to the operational facilities presented in Table 2.13, further incineration plants are being considered or are in the process of being commissioned for the UK. Examples of incinerators which are being built or have recently received planning permission include:

- Belvedere, Bexley (585,000 tpa), received a further planning permission in 2007 but is still undergoing problems from public opposition; the plant is proposed to produce around 66 MW of electricity
- Colnbrook, Slough (400,000 tpa) was due for completion and commissioning in 2008 but has been delayed. This plant will have an electricity output of 32 MW (Defra[g], 2007)

Combustion plants are well established for energy production making funding easier for them compared to the newer gasification and pyrolysis plants. Combustion plants benefit from better operation and compatibility in terms of technology at medium to large scale, when utilising biomass and at present, UK energy production is saturated with large scale combustion plants (see Table 2.13 and Figure 1.7). This work investigates the technical and economic possibility of energy generation from biomass combustion on a small scale, to provide energy to small cities and towns. Specifically it will consider electricity from underutilised FWWC (see section 2.6) from SRF (see section 2.7 and Chapters 3 and 4), as well as electricity and heat from RSO (see section 2.5 and Chapter 5). If proved technically, economically and environmentally viable, this could be a novel method of energy production in the UK.

2.12. Reciprocating Engines

In the nineteenth century, steam engines were used in almost all industries. The engines were developed considerably resulting in an elaboration of other heat engines such as the internal combustion engine and improved steam engines. These heat engines had higher efficiency, smaller size and better meet the requirements of industry and transport.

An internal combustion engine is a heat engine in which fuel is burned directly in the working cylinder. Upon combustion of fuel in the cylinder, the pressure rises and is transmitted to the piston. As a result, its reciprocating motion is converted into rotary motion of the crankshaft with the aid of an epicyclic gear. The great advantage of these engines is that they are operated without a boiler and other auxiliary devices and they are of compact design. Fuels for internal combustion engines are usually combustible gases such as generator, natural and blast furnace gases and oil products such as gasoline, kerosene, solar oil and diesel oil. Internal combustion engines have found a wide use in stationary, marine and transport applications (Shvets et al., 1975).

In addition to general requirements of strength, reliable construction, simplicity and accessibility of various units and parts and small fuel consumption, every type of engine has to meet special requirements relating to size and weight, direction of crankshaft rotation, steady running, engine horsepower, speed and type of fuel utilised (Shvets et al., 1975).

Internal combustion engine plants are produced on a large scale around the world. One of the worldwide leading producers of these plants is Wartsila Corporation (Table 2.14).

Table 2.14 Examples of established power plants

Destination	**Type of Customer**	**Engine Type**	**Total Output (MW)**	**Type of Fuel**
Corinth Pipework, Greece	Industry	6 x Wartsila 12V200	12	Light Fuel Oil
City of Kennett, USA	Utility	2 x Wartsila 18V34SG	11	Natural Gas
Haripur, Bangladesh	IPP	8 x Wartsila 18V46	120	Heavy Fuel Oil
Petrolina, Brazil	IPP	8 x Wartsila 18V38	128	Heavy Fuel Oil
Kipevu, Kenya	Utility	7 x Wartsila 18V38	74	Heavy Fuel Oil
Yue Yuen, China	Industry	6 x Wartsila 18V32	38	Heavy Fuel Oil

2.13. Conclusions

Our current energy demand and use is 220 mtoe, lower than in previous years. Nonetheless the UK government targets for emission control are yet to be met and these must be met to reduce climate change. The method by which we produce our electricity can help to reach this target of 80% reduction in CO_2 emissions by 2050 is to use renewable forms of input feeds such as biomass to help reduce emissions and ensure a secure energy supply for future generations.

There are various forms of biomass, both clean and mixed which can subsequently be placed into categories of liquid or solid forms. In this study, MSW, a solid mixed form of biomass, FWWC, a solid clean form of biomass and RSO, a liquid clean form of biomass are considered for energy production using combustion technology. The biomass types are chosen because we have a good supply of each in the UK.

MSW is generally sent to landfill, however with growing taxation on landfill and a need to reduce emissions, this waste biomass can be turned into SRF, a higher calorific value fuel used in fluidised bed combustion to produce energy. Similarly FWWC, a clean form from forestry thinning is also sent to landfill. Using SRF and FWWC in fluidised bed combustion to produce energy will tackle the social aspect of sustainability because the SRF and FWWC waste will be better managed according to the waste management hierarchy. Finally RS is being grown at an increasing scale in the UK and mainly used for bio diesel production for use in transportation but is also used for human consumption. RSO can be used in stationary internal combustion engine plants to produce electricity and heat to help meet our renewable energy targets.

Combustion technology is chosen to process the biomass because it is a proven and well established technology which can process the chosen biomass feeds. Internal combustions engines have the benefit of recuperating heat and being able to sell this heat for revenue. Analysis on the RSO plant was also performed to investigate the combustion of a liquid form of biomass. Although combustion of non-renewable fuels is very successful, it is vital to ensure combustion of biomass is technically and economically viable. This will help source investors and place confidence in the production of energy from biomass to reduce our emissions. Chapter 3 focuses on the techno-economic analysis of small to medium scale plants of SRF fluidised bed combustion using steam turbine technology and FWWC fluidised bed combustion using steam turbine technology.

3. Techno-economic assessment of solid recovered fuel and forest waste wood chips combustion plants

Summary

As part of this research I took a three month placement programme at Germanà & Partners, Consultant Engineers in Rome, Italy. The main aim of the collaboration was to gain an in-depth understanding of design methodologies and engineering principles as applied in the detailed design of an actual industrial energy recovery plant. Germanà & Partners have a long established track record in the process design of energy from biomass facilities and it is one of the few engineering consultancies in Italy that can provide the full range of design skills (including process, mechanical, electrical and civil engineering expertise) necessary to take a concept through to full design.

This thesis compares the results of a techno-economic performance analysis of two combustion plants for the recovery of energy from two waste forms of biomass, SRF and FWWC. Small and medium scale plants have been investigated; 50 kilo tonnes per annum (ktpa), 80 ktpa and 160 ktpa combustion plants, with steam turbine technology utilising FWWC. Initially a combustion plant of 160 ktpa was investigated, but this plant was scaled down to 50 ktpa, which is the same as the SRF plant previously investigated by Yassin et al., 2008. The SRF plants investigated previously by Yassin et al. were of 50 ktpa and 100 ktpa. The 100 ktpa SRF plant was a case study in Italy and this plant was then scaled down to 50 ktpa to investigate its economic viability. All cost data and assumptions based on current legislation have been updated in this study. The technical assessment includes calculations for electricity generation and overall system efficiency and the economic viability of the different plants is investigated through discounted cash flow analysis. The levelised cost is used to calculate the cost of production of one unit of electricity.

The effect of changing model input parameters on economic performance is evaluated. Six different system variables have been chosen - changes in calorific value, steam turbine efficiency, discount rate, plant lifetime, operating costs and biomass feed rate and the effect of a 10% and 30% change on the

levelised cost has been examined. Additionally changes in purchase price of biomass, ROC selling price and electricity price are investigated to establish break even points for each variable.

Parts of this chapter have been published in:

Patel, C., L., Lettieri, P., Simons, S.J.R., Germanà, A. (2011). Techno-economic performance analysis of energy production from biomass at different scales in the UK context. Chemical Engineering Journal, Issue 171, pages 986-996.

3.1. Methodology

3.1.1. Biomass characteristics and system layout

The large scale plants investigated correspond to real plants under construction in Italy. These plants were then scaled down to investigate whether they would be technically and economically viable at a smaller scale. The FWWC and SRF plants were scaled down to 50 kpta, which was chosen because of previous work conducted by Yassin et al., (2008). The FWWC plant was also scaled to 80 ktpa, to investigate the techno-economic assessment.

A flow chart for the fluidised bed combustion plants is shown in Figure 3.1. The proximate and ultimate analysis is shown in Table 3.1. The proximate analysis gives the moisture content, combustibles, the ash mineral content (inerts) and the lower heating value (LHV) (kJ/kg). The ultimate analysis gives the composition of the biomass in dry%wt. of carbon, hydrogen, oxygen and nitrogen (the major components) as well as chlorine and sulphur.

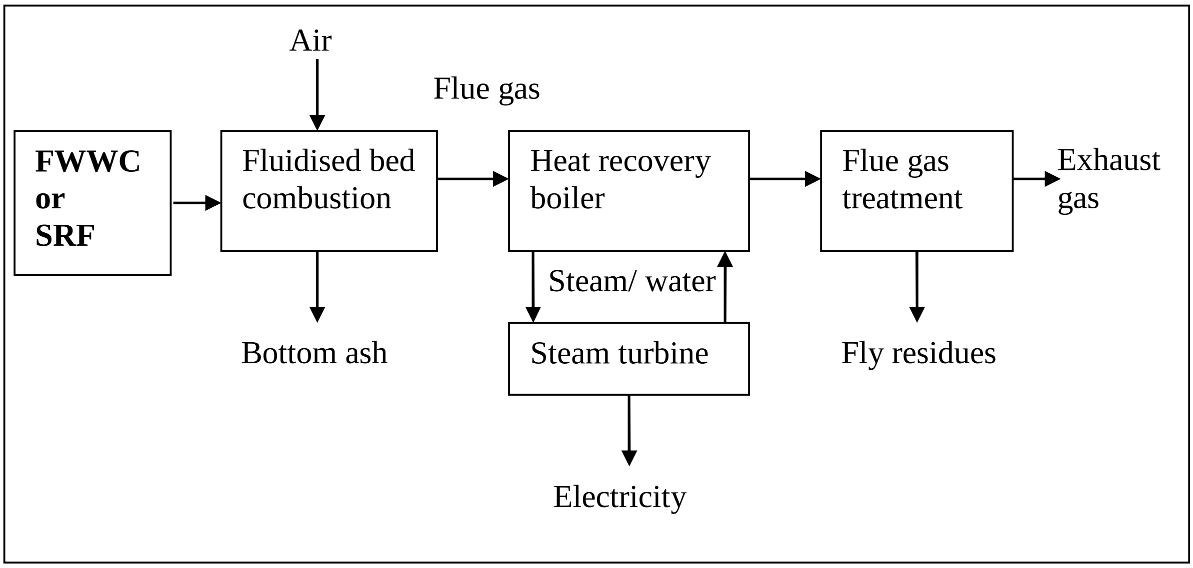


Figure 3.1 Process diagram of energy recovery from combustion of FWWC or SRF coupled with steam turbine technology

Table 3.1 Proximate and ultimate analysis of the biomass investigated

Biomass type	**Proximate analysis (%)**				**Ultimate analysis (%)**					
	Moisture (wt.%)	**Combustibles**	**Inerts**	**LHV (kJ/kg) (wt.%)**	**C**	**H**	**O**	**N**	**S**	**Cl**
FWWC	30.00	62.50	7.50	10819	50.2	8.73	40.8	0.15	0.07	0.05
SRF	15.80	64.20	20.00	16701	49.8	6.85	41.2	0.66	0.62	0.87

3.1.2. Technical Analysis - Overall system efficiency calculations

Performing energy calculations enables the assessment of the technical performance of the two different technologies and the impact of the biomass feeds by determining their overall system efficiencies. These are defined as the ratio of the net generated electricity to the energy input to the system, see Eq.(1):

$$\text{Overall efficiency } = \frac{Net\,Power\,output\left[MW\right]}{Energy\ input\ to\ the\ system\left[MW\right]} \times 100 \qquad \textbf{(1)}$$

For the fluidised bed combustion plants, the energy input to the system is given by the thermal capacity of the biomass, E_{th}, see Eq. (2):

$$E_{th}\ [MWth] = LHV\left[kJ/kg\right] \times m\left[kg/h\right] \qquad \textbf{(2)}$$

where LHV is the calorific value of the biomass and m is the biomass feed rate.

The net power output is the net electricity generated $E_{electricity,\ net}$ which is given by:

$$E_{electricity,net}\left[MWe\right] = E_{electricity,gross} - E_{auxiliary} \tag{3}$$

Gross electricity generated = $E_{electricity,gross}\left[MWe\right] = \eta_{steam\ turbine} \times E_{th}$ **(4)**

Where the Gross electrical generation efficiency of the steam turbine $\eta_{steam\ turbine}$ is 30% and the auxiliary consumption $E_{auxiliary}$ is fixed at 1 MWe. These are standard values used in industrial scale plants of this type (Germanà' & Partners, 2010).

3.1.3. Developing the economic analysis

The economic viability is calculated using a discounted cash flow analysis. This relates the values of costs and revenues that occur over the economic life of the project in terms of their present value, i.e. the amount that a future sum of money is worth today given a specified rate of return. Standardised financial tools, such as the net present value (NPV) and internal rate of return (IRR), were employed to assess the profitability of the different options. The costs and revenues resulting from the economic evaluation are indicative. Such costs and revenues will depend on suppliers, plant scale, technology used and type of energy recovery system employed, as well as local area factors.

3.1.3.1. Capital Costs

The capital needed to supply the necessary manufacturing and plant facilities is known as the fixed capital investment or capital costs (Rice, 2008). The capital costs for the biomass plants are shown in Table 3.3, where detailed costs for the FWWC are provided (Yassin et al., 2008). All cost data are updated and reported in sterling (£).

The capital costs reported in this study represent the total plant costs (TPC), which cover main equipment costs (EC), direct plant costs (DPC) and indirect plant costs (IPC). The main equipment costs cover waste and residue storage and transport systems, combustion/internal combustion engine system with heat exchanger network, the gas cleaning system and the energy generation system.

Direct costs include costing for piping, auxiliary systems and services, electrical, instrumentation control and civil work, indirect costs constitute engineering and supervision, contingency and contractor fees. The model excludes grid connection costs, waste collection costs and revenues from material recycling prior to thermal treatment.

The main equipment and direct costs are obtained from previous working experiences and contracts by Germanà & Partners (2007), whereas the indirect costs are obtained by factorial estimation using cost factors published by Gerrard (2000) and Peters & Timmerhaus (2003) and are summarised in Table 3.3. Where the cost data are unavailable, Eq. (5) is used, which gives the general relationship between costs and scale.

$$\frac{C}{Cr} = \left(\frac{S}{Sr}\right)^{n} \qquad \textbf{(5)}$$

Where *C* is the cost of the proposed plant at scale *S*, which is in terms of the amount of biomass treated; *Cr* is the cost of the reference plant at scale *Sr* and *n* is the scale exponent. The scale exponent, *n*, is derived from historical data for similar plants and is usually in the range of 0.4 – 0.8, typically 0.65 (Gerrard, 2000) as used in this study.

3.1.3.2. Operating costs

The operating costs to run the plant include raw materials, labour, electrical energy consumed, maintenance, materials consumed (chemicals etc.), consultant services, general insurance, expenses, local tax, unforeseen expenses and ash disposal. These costs are calculated by taking a percentage of the fixed capital cost. Operating costs for the four biomass plants are shown in Table 3.3, where detailed costs for the SRF plant were obtained by Yassin et al., (2008) and those for the FWWC plant were calculated on the basis of the larger scale values given by Germanà & Partners (2010).

Local tax is applied as a percentage of the fixed capital investment. In this study, 4% of the fixed capital investment was considered for general insurance, expenses and local tax. Additionally a 28% corporation tax is paid on profits.

3.1.3.3. Working capital

Working capital is capital immobilized in the first year of work and returned at the end of the operation. The working capital consists of raw materials and suppliers carried in stock, finished products in stock and semi-finished products in the process of being manufactured, accounts receivable, cash kept on hand for monthly payment of operating expenses such as salaries wages and raw material purchases and accounts payable (see Table 3.3).

3.1.3.4. Corporation Tax

Corporation tax is applied to the taxable profits of a company. These include:

- Profits from taxable income such as trading profits and investment profits
- Capital gains known as chargeable gains for Corporation Tax purposes.

In order to calculate the amount of Corporation Tax to be paid; all taxable profits must first be calculated, meaning that there should be no depreciation deductions from profits. Instead, tax allowances known as capital allowances can be claimed, which are deducted from the profit to arrive at the taxable profits. Calculation of the tax is given by Eq (6):

$$CT[£] = ((Ptp[£] + Dpn[£]) - Ca[£]) * TR[\%] \quad \textbf{(6)}$$

Where *CT* is the Corporation Tax, *Ptp* is the Pre-tax operating profit, *Dpn* is the Annual straight line depreciation charge, *Ca* is the Capital allowance (this takes the place of the depreciation charge). The amounts of capital allowance that can be claimed are an Annual Investment Allowance (AIA) of up to £100,000 and a Writing Down Allowance (WDA), which is 20% (per annum) of the remaining costs after AIA. Finally *TR* is the tax rate (taken at 28% for 2011) (HM Revenues & Customs, 2011).

3.1.3.5. Projected revenues

Revenues for the SRF plant include sales of electricity, Levy Exemption Certificates (LECs) sales of secondary aggregates and Gate fees; these were taken from Yassin et al., (2008) for 50 ktpa and 100 ktpa and are presented in Table 3.3.

Revenues for the FWWC biomass plant include the sales of electricity, Renewable Obligation Certificates (ROCs), Levy Exemption Certificates (LECs) and sales of secondary aggregates. The different revenues considered are described as follows:

- Sales of electricity – a price of 105 £/MWh is used according to Department of Energy and Climate change statistics for 2010 (DECC[a], 2010)
- Renewable Obligation Certificates (ROCs) – a value of £36.99 was used according to Ofgem (2010/11). Renewable Obligation is the primary support scheme for renewable electricity projects in the UK. Certificates are issued to an accredited generator for eligible, renewable, electricity generated within the UK and supplied to customers within the UK. These certificates can then be traded to suppliers. The price of the certificates can change much like on the Stock Exchange (Ofgem, 2010)
- Levy Exemption Certificates (LECs) –represents the value of being exempt from the climate change levy on electricity. The current rate for the 2010 period is £4.70 (Defra[e], 2007)
- Sales of secondary aggregates – the price value for bottom ash as a secondary aggregate range from 7 £/t to 11 £/t according to WRAP, (2006). A value of £9/t was used in this study

- The revenues for the FWWC biomass plant are presented in Table

3.3

- Gate fee – this is a charge levied upon a given quantity of waste received at a waste processing facility

3.1.3.6. Net Present Value and Levelised Cost

Net Present Value (NPV) refers to the difference between the present and future value of all costs and associated revenues, it is determined as follows:

$$NPV = \sum_{n=1}^{20} \frac{CFn}{(1+i)^n} - TPC \qquad \textbf{(7)}$$

Where i is the discount rate, CFn is the annual cash flow (revenues – operating costs) at the n^{th} year and TPC is the total plant cost.

Another way to perform comparisons between different technologies with different capital investment, operation and power output, is to calculate their levelised cost of the biomass treatment; this is generally the accepted method for the economic comparison of different power generation plants. It quantifies the unitary cost of electricity produced during the plant life-time and is reported in £/MWh. In this thesis, the levelised cost was calculated as the ratio of the total plant lifetime expenses against total expected outputs, expressed in terms of present worth (NEA & IEA, 2005).

3.1.3.7. Depreciation

The plants need to account for the consumption of investments over time in a way that reflects their reducing value; the term given to this consumption is depreciation. A depreciation calculation gives the total amount to be depreciated between each accounting period of the assets useful economic life. Depreciation is calculated in this study using Eq (8):

$$Dpn = (C - R)/N \qquad \textbf{(8)}$$

Where Dpn is the annual straight line depreciation charge (£), C is the investment cost (£), R is the residual value of the asset (in this study it is taken equal to 10% of the investment cost), N is the useful economic life of the investment in years.

3.1.3.8. Operating Profit

Operating profit is the amount of profit released from a business's operations after taking out operating expenses such as costs of goods sold and depreciation. Operating profits are calculated using Eq (9):

$$Ptp = Rv - Dpn \qquad \textbf{(9)}$$

Where *Ptp* is the operating profit (£), *Rv* is the revenues (£) and *Dpn* is the annual straight line depreciation charge (£).

3.2. Results and Discussion

3.2.1. Technical analysis

The electricity produced by the fluidised bed combustion plants at all scales are shown in Table 3.2, along with the overall system efficiency. The 100 ktpa SRF plant generates 62% more power than the 50 ktpa, whilst the 160 ktpa FWWC plant generates 71% more power than the 50 ktpa plant and 53% more power than the 80 ktpa plant. At 100 ktpa and 160 ktpa scales the SRF and FWWC plants both have an overall system efficiency of 28%. The amount of energy produced by the plants depends on the feed characteristics if the LHV of the SRF plant or the FWWC changes. This will also affect the amount of electricity produced and hence the economics of the plant (as discussed in more details in the sensitivity analysis in section 3.3).

Table 3.2 Overall electrical and power results of each plant

Plant scale (ktpa)	SRF 50 Steam turbine	SRF 100 Steam turbine	FWWC 50 Steam turbine	FWWC 80 Steam turbine	FWWC 160 Steam turbine
Electricity produced (MWe)	5	13	5	8	17
Steam Turbine electrical efficiency (%)	30	30	30	30	30
Overall system efficiency (%)	26	28	26	27	28

3.2.2. Economic Assessment

The economic evaluation model consists of capital costs, operating costs and working capital, projected annual revenues, depreciation and corporation tax. The indicative costs and revenues resulting from the economic model can be used to compare the different scales of plan, since a consistent methodology has been adopted for this analysis. However, costs and revenues are contract values and can depend on suppliers, plant scale, technology used and type of energy recovery system employed, as well as local area factors.

The results for the various SRF and FWWC plants are presented in Table 3.3 (The discount rate used in the NPV analysis is 6% and the corporation tax rate is 28%). It is assumed that prices for the recycled material and power costs are constant. A discount rate of 6% is used in this analysis to take into consideration public sector borrowing; the effect of inflation is excluded as it is assumed that it influences all cash flows to the same degree. Standardised financial tools such as the NPV and IRR, are employed to assess the profitability of the different options. An investment is economically viable when the IRR is greater than the rate of return that could be earned from an alternative investment. The IRR is calculated as the discount rate that makes the NPV equal to zero (Sutherland, 2007). The levelised costs are also shown in Table 3.3.

Table 3.3 Economic performance of the biomass plants

Plant scale (ktpa)	**SRF 50**	**SRF 100**	**FWWC 50**	**FWWC 80**	**FWWC 160**
Plant lifetime (years)	**20**	**20**	**20**	**20**	**20**
Fixed capital cost (£m) (sum of total direct plant costs and working capital)	**39**	**51**	**35**	**38**	**50**
Total direct plant costs (£m) (sum a.)	**29**	**46**	**29**	**33**	**45**
• Equipment and machinery	-	26	-	-	25
• Purchased equipment and installation	-	8	-	-	8
• Piping and valve	-	3	-	-	3
• Electrical installation	-	2	-	-	2
• Instrument and control installation	-	2	-	-	2
• Civil work	-	3	-	-	3
• Land purchased		2	-	-	2
Working capital (£m) (sum b.)	**-**	**5**	**-**	**-**	**5**
• Engineering and supervision	-	1	-	-	1
• Construction expenses	-	1	-	-	1
• Contingency (accounts payable, accounts receivable, cash kept on hand for monthly payments)	**-**	3	-	-	3
Operating costs (£m)	**2**	**5**	**4**	**6**	**17**
Biomass	-	-	-	-	9
Workers	-	0.5	-	-	0.6
Electrical energy consumed	-	0.5	-	-	0.6

Maintenance	-	0.8	-	-	1.2
Chemicals	-	0.8	-	-	0.7
Specialist and consultant fees	-	0.06	-	-	0.06
General insurance, taxes and expenses	-	1	-	-	3
Unforeseen expenses	-	1	-	-	2
Revenues (£m)	**8**	**19**	**7**	**10**	**22**
Electrical energy sold (£m)	4	10	3	4	12
Green certificates (ROCs) (£m)	-	-	4	6	9
Levy exemption certificats (LECs) (£m)	0.3	0.6	0.2	0.3	1
Bottom ash sold (£m)	0.02	0.05	0.01	0.02	0.5
Gate Fee (£m)	4	9	-	-	-
Annual depreciation on capital investment (not including land) (£m)	**1.5**	**1.8**	**1**	**1**	**1.8**
Operating profit (£m) (revenue - operating costs - depreciation)	**4.5**	**12.2**	**2**	**3**	**3.2**
Corporation Tax (£m)	**1.3**	**3**	**0.6**	**0.8**	**1**
NPV (£m)	**13**	**25**	**-123**	**-76**	**118**
IRR (%)	**10**	**10**	**-5**	**-3**	**17**
Levelised cost (£/MW)	**90**	**55**	**377**	**246**	**123**

The results indicate that the SRF combustion plant is economically viable at both scales, due to the revenue obtained through the gate fees when compared with the biomass purchase cost incurred for the FWWC plants. However the SRF plant does have higher costs for chemicals used in the cleaning process. This is mainly due to SRF being a mixed waste source, needing more investment for the gas neutralisation stage. The FWWC has significantly higher operating costs which at smaller scales cannot be avoided because of the amount of energy produced and the low level of revenues generated. The lower operating costs for the SRF plant are further evidence of the revenue obtained through the gate fee. Operating costs are difficult to predict, vary from one country to another and from technology to technology. The FWWC plant is only economically viable at 160 ktpa, where a 17% IRR is obtained. For 80 ktpa a -3% IRR is obtained, whilst at a 50 ktpa scale a -5% IRR is reported. The sensitivity analysis shows how variable are the economics of the plant.

The levelised cost shows the unitary cost of electricity produced during the plant lifetime. Table 3.3 shows that the levelised cost decreases as the scale of the plant increases, due to the trade-off between the amount of electricity produced and the costs of production. The levelised cost for the FWWC biomass plant at 80 ktpa and 50 ktpa are significantly higher quantified at 377 £/MW and 246 £/MW respectively than for the 160 ktpa. This is quantified at 123 £/MW because at 50 ktpa and 80 ktpa the plant makes much less energy whilst still having high costs. When comparing different feeds, the levelised cost shows the lowest cost of production of energy. In this study, SRF does not include a cost for purchasing the feed; instead a gate fee is paid to the processing facility, resulting in the lower levelised cost. In the future, this may change and a purchase fee may be introduced, in which case the levelised cost would increase. Alternatively, the purchase cost of forestry waste wood may decrease resulting in a corresponding decrease in levelised cost.

3.3. Economic Sensitivity Analysis

In this section, the effect on the economic performance of changing the model input parameters is evaluated. Sensitivity analysis is a useful procedure in evaluating the model input parameters. It can direct us to where the uncertainties lay, identifying the most influential parameters and testing the robustness of the assumptions made in the model. Six different system variables have been chosen and the effect of a 10% and 30% change in these variables on the levelised cost has been examined. These variables were chosen as having a significant effect on either the amount of energy produced or the cost of production. Operating costs can be uncertain and so these were considered to be an important variable to consider in the sensitivity analysis, which was performed on the larger scale plants, as these were all economically viable. Figures 3.2 and 3.3 show the results of the sensitivity analysis for the 160 kpta FWWC plant and the 100 ktpa SRF plant respectively. Changes in capital cost for each plant up to 30% are shown in Figure 3.4.

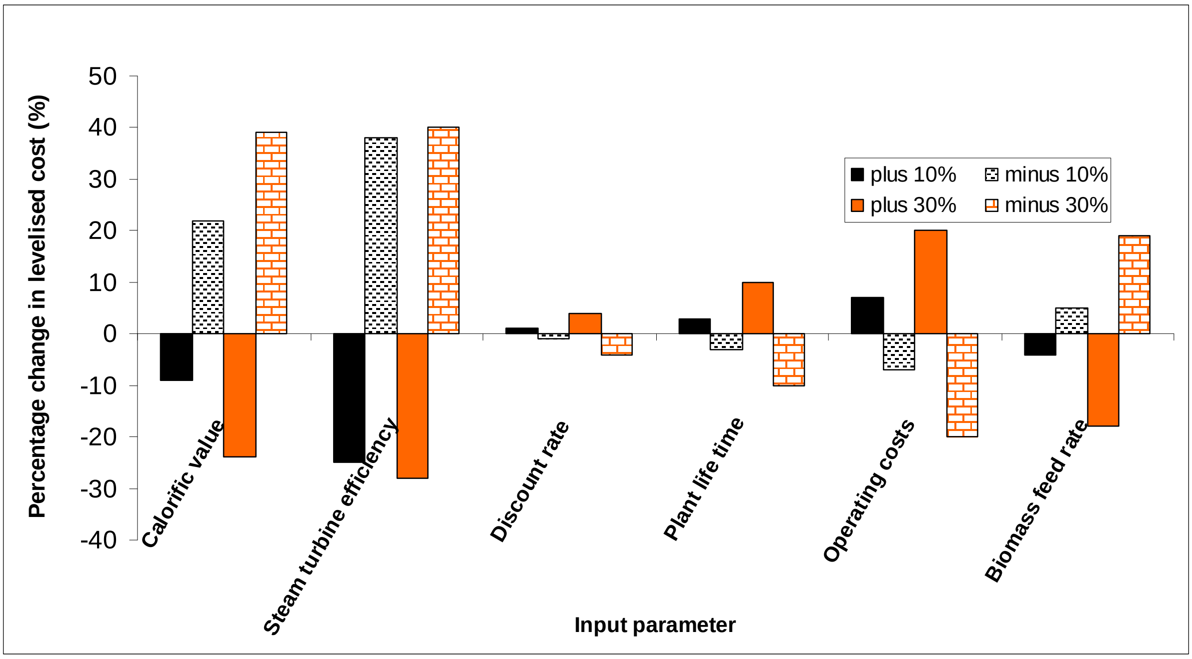


Figure 3.2 Sensitivity analysis of the 160 ktpa FWWC fluidised bed combustion plant

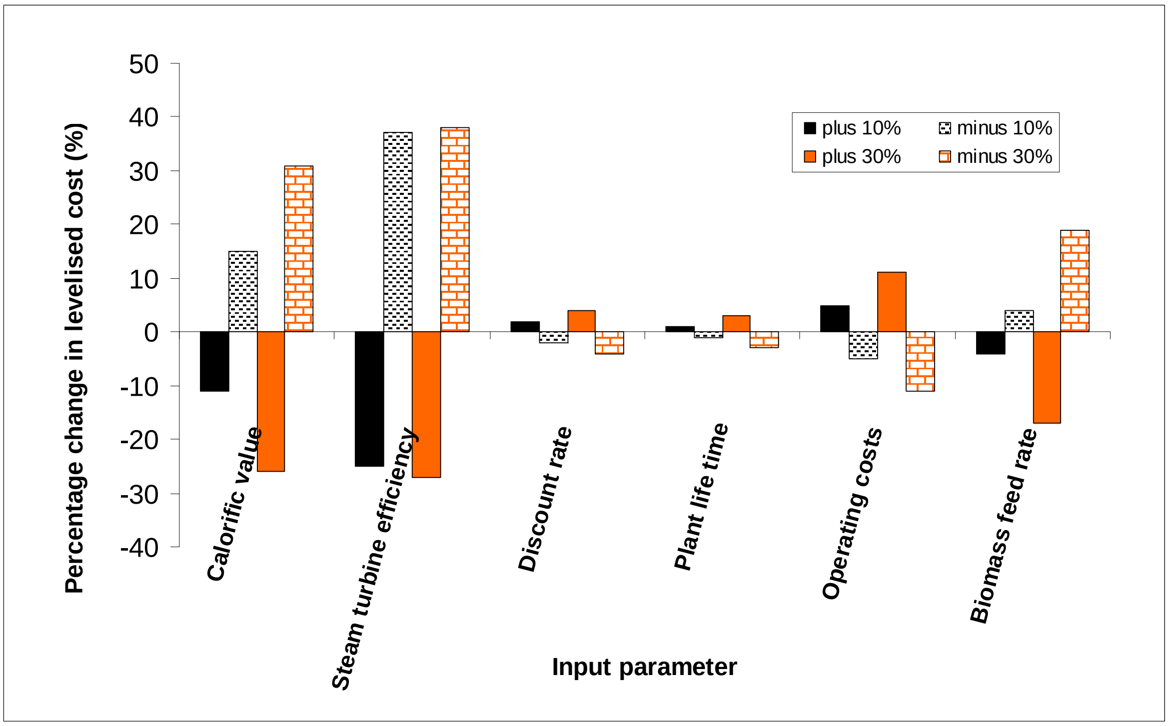


Figure 3.3 Sensitivity analysis of 100 ktpa SRF fluidised bed combustion plant

3.3.1. Changes in biomass calorific value

The calorific value of the biomass is an important parameter for the evaluation of the levelised costs. LHV is used to calculate the amount of electricity generated; if the LHV is high then the amount of energy produced is also high. When calculating the levelised cost per MW produced, the higher the amount of the energy produced, the lower is the levelised cost. The change in levelised cost is significant for both biomass types when the calorific value is changed. SRF shows 11 – 15% change in levelised cost when a 10% change is applied and a 26 – 31% change in levelised cost when a 30% change is applied. FWWC biomass shows a 9 – 22% and 24 – 39% change in the same scenario. The FWWC plant is most susceptible to changes in levelised cost because the revenues barely offset the costs of the plant. To put this into context, decreasing the calorific value by 10% results in a negative IRR. It is vital therefore that the wood obtained from forestry thinning does not change significantly in terms of calorific value, which is difficult if the wood is sourced from various forests because moisture content can vary significantly.

The SRF plant also shows significant changes in levelised cost when the calorific value of the feed is changed. When SRF is produced it has a pre-defined calorific value, as a result, it is unlikely to change significantly. However, if in the future the plant needs to change its feed to MSW due to price increases in SRF, the calorific value of the feed would be a very important factor. MSW can vary significantly between locations, time of year and even society as the calorific value of MSW depends on human characteristics and habits. We change the way we live and products we use, resulting in a change in our waste production, businesses are becoming more environmentally friendly and sustainable resulting in a change in the waste they produce. All of these issues will affect the calorific value of MSW, but at present, changes in calorific value of SRF is unlikely because it is predefined.

3.3.2. Changes in steam turbine efficiency and engine efficiency

The efficiency of the turbine and the efficiency of the engine are involved in the calculation of the amount of electricity produced. A change of efficiency can be seen at a 10% increase or decrease, which results in 25 – 38% change whereas a 30% increase or decrease results in a 28 – 40% change for both SRF and FWWC plants. A decrease of 10% in efficiency renders both plants uneconomical and a change in the efficiency of the steam turbine results in a significant change in the levelised cost. However, steam turbines are used extensively in industry and the efficiency level chosen in this study (30%) is recognised as a reasonable value (Rice, 2008). To avoid any disruption to the turbine blades and hence the turbine efficiency we must ensure efficient cleaning of the gas and steam because deposits can accumulate on turbine blades in a very short time when steam purity is poor. Unless more efficient steam turbines are developed, the levelised cost in terms of efficiency is unlikely to fluctuate significantly.

3.3.3. Capital and Operating Costs

The capital and operating costs are very difficult to predict for economic performance, as they rely on external factors such as feed costs, labour, chemical costs, equipment costs, suppliers, plant scale, technology used and type of energy recovery system employed, in addition to local area variables. The operating costs of the FWWC plant are £17 m/year and those of the SRF plant are £4 m/year. Changing the capital cost by 10% results in a high percentage of changes in levelised cost, quantified at 20% and 22% for FWWC and SRF plants respectively. This cost has been seen to change quite dramatically from country to country and with time. As a result a 30% change in capital cost seemed reasonable to be investigated in the sensitivity analysis (Figure 3.4). A 10% change in the operating cost has a higher influence on the levelised cost for the FWWC plants (quantified at 7%), whereas in the SRF plant it results in a 5% change in levelised cost. A 30% change in operating cost result in a 20% change for the FWWC and an 11% change for the SRF plant.

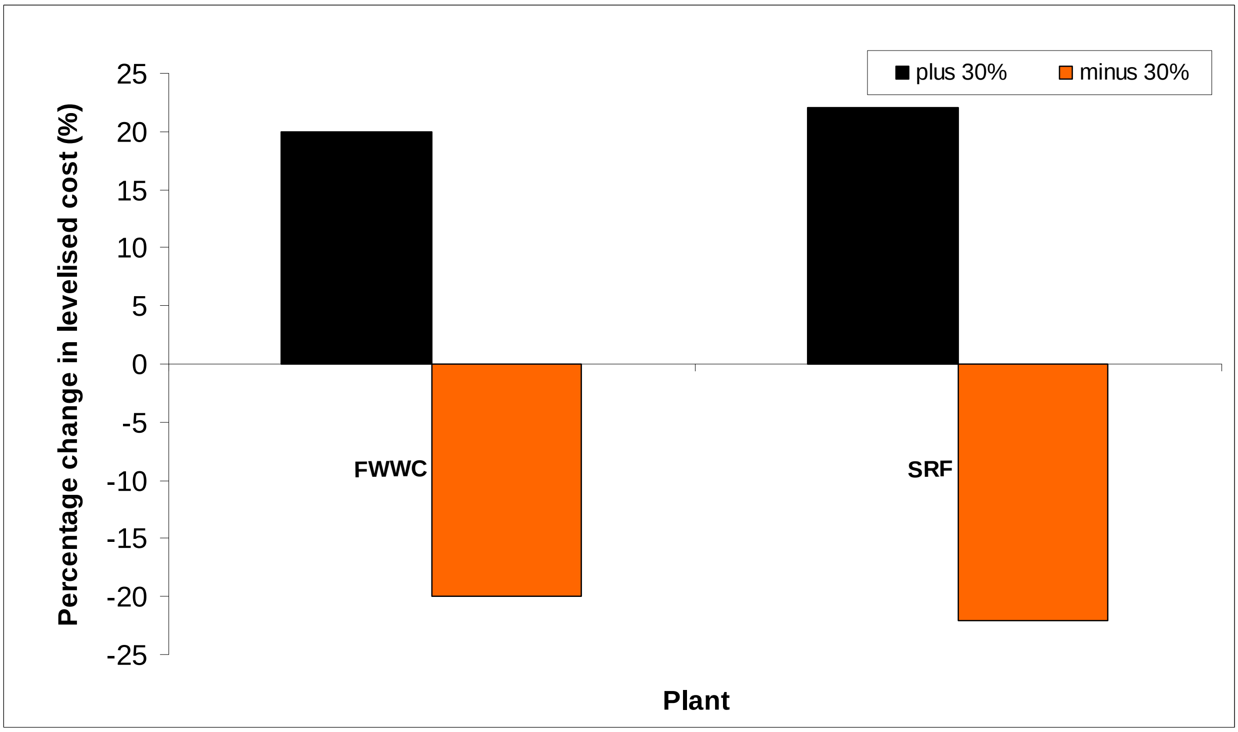


Figure 3.4 Sensitivity analysis of changes in capital cost ±30% for the FWWC and SRF plants

In the UK capital and operating costs are known to be high. This is demonstrated in Table 3.4, where a comparison of average capital costs and operating costs for a traditional coal combustion plant in the UK is compared to one in Europe (Bauen et. al, 2003).

Table 3.4 capital and operating cost comparison of a coal combustion plant producing 18 MW of electricity in the UK and Europe

Europe		UK	
Capital cost (€)	**Operating cost (€)**	**Capital cost (£)**	**Operating cost (£)**
30m	16m	50m	20m

Due to these high costs in order for plants in the UK to be economically viable, they are generally of a large scale (>50 MW). However, with incentives for the use of biomass, despite high capital and operating costs in the UK, small scale (160 ktpa FWWC, 50 kpta SRF or 100 kpta SRF) plants are economically viable (Table 3.3).

3.3.4. Changes in plant lifetime

In this work, both plants are considered operational for 20 years. The changes in levelised cost for the plant lifetime are small, with only 1% change for the case of SRF and 3% change for the FWWC plant. Changing the plant lifetime by ±30% results in 3% change in levelised cost for the SRF plant and 10% change in levelised cost for the FWWC plant. A 30% decrease in plant lifetime would make the FWWC plant uneconomical, because the plant would not be able to make sufficient revenue to pay for its capital investment. The plants are very unlikely to increase in operation time, because the machinery generally would need to be replaced after 20 years.

3.3.5. Changes in Biomass Feed Rate

The plants considered in this study all operate at full capacity. The biomass feed rate affects the amount of electricity produced and therefore the revenues generated. The biomass feed rate must be used on full scale production if the best value for levelised cost is to be achieved. The results show that if the biomass feed rate is decreased by 10% and 30%, the cost of production increases by 4% for the SRF and 19% for the FWWC plant. This is expected, as the plant is not being utilised to its full potential, resulting in a decrease in the amount of electricity produced but with no change in the costs for both plants.

3.3.6. Changes in Discount rate

The discount rate is generally fixed and should not change. However if the lending rate does change or a different rate is obtained, the levelised cost does not differ significantly for either plant and even with a 30% increase would still result in an economically viable plant. The change in levelised cost for the FWWC plant with a 10% change in discount rate results in 1% and a 30% change results in a 4% difference in levelised cost. The change in levelised cost for the SRF plant with a ±10% and ±30% change in discount rate results in 2% and 4% difference in levelised cost respectively.

3.4. Changes in electricity selling price and ROCs selling price

The price of electricity and ROCs are subject to changes and in the model, a change in electricity price from 10% up to 70% is performed to analyse its effect on the IRR. Separately, a change in ROCs price from 10% up to 50% is also analysed for the FWWC plant (at 160 ktpa). Tables 3.5 and 3.6 show the resulting IRR (%) changes for the FWWC plant and SRF plant.

Table 3.5 Sensitivity analysis results of percentage changes in electricity price for the 160 ktpa forest waste wood chip plant

Electricity Price for FWWC plant	Percentage change in IRR (%)	Resulting IRR (%)
Plus 10%	+11	19
Minus 10%	-11	15
Plus 20%	+22	21
Minus 20%	-22	13
Plus 30%	+39	24
Minus 30%	-39	10
Plus 40%	+45	25
Minus 40%	-45	9
Plus 50%	+60	27
Minus 50%	-60	7
Plus 60%	+83	31
Minus 60%	-83	3
Plus 70%	111	36
Minus 70%	-111	-2

Table 3.6 Sensitivity analysis results of percentage changes in the electricity price of the 100 ktpa SRF plant

Electricity Price for SRF plant	**Percentage change in IRR (%)**	**Resulting IRR (%)**
Plus 10%	+17	12
Minus 10%	-17	8
Plus 20%	+22	12
Minus 20%	-22	8
Plus 30%	+39	14
Minus 30%	-39	6
Plus 40%	+45	15
Minus 40%	-45	6
Plus 50%	+61	16
Minus 50%	-61	4
Plus 60%	+84	18
Minus 60%	-84	2
Plus 70%	113	21
Minus 70%	-113	1

The results in Table 3.5 show the price of electricity would need to drop by 70% before the plant becomes uneconomical. The price of electricity would need to reach £32 /MW based on a current value of £105 /MW, whilst for the SRF plant, the price of electricity would need to drop by 70% before the plant becomes uneconomical. The price of electricity has not reached £32 since 2001 to 2004 and it has been increasing since 2005 (Figure 3.5). However in 2010 there was a decrease in electricity price from £83 to £75. The price of electricity is not expected to drop drastically to £32 from current prices.

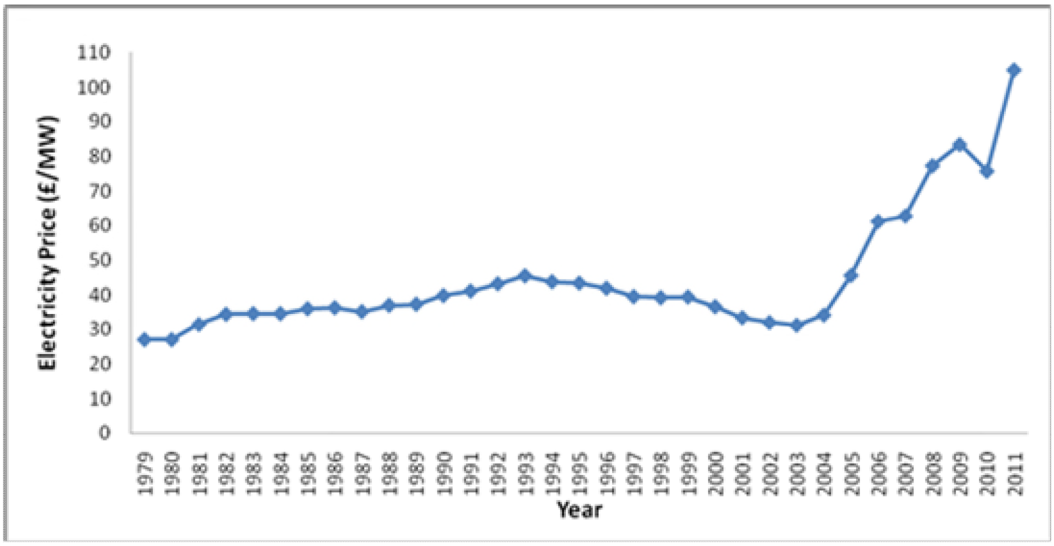


Figure 3.5 changes in electricity price per year from 1979 to 2011

The results in Table 3.7 show the ROC price would need to decrease by 50% before the plant would be uneconomical, reaching £18.46 /MW, based on the 2011 value of £36.99.

Table 3.7 Sensitivity analysis results of percentage changes in ROC price

ROC price	Percentage change in IRR	Resulting IRR (%)
plus 10%	24	21
minus 10%	-24	13
plus 20%	48	25
minus 20%	-48	9
plus 30%	60	27
minus 30%	-60	7
plus 40%	72	29
minus 40%	-72	5
plus 50%	100	34
minus 50%	-100	0

The ROC came into action in 2002 and has never dropped below £30 /MW (Table 3.8). The ROC buy out price depends on the year's retail price index. If the index decreases, then the ROC buy out price will decrease, depending on the price of a ROC for the previous year. Table 5.6 shows that ROC prices are increasing year on year, except for 2011 when it had decreased by 20p. As a result, unless the retail price index decreases drastically, ROC prices will remain stable or increase.

Table 3.8 ROC buy out prices per year from 2002 to 2013

Obligation period (1st April – 31st March)	Buy-out Price (£)
2002-2003	30.00
2003-2004	30.51
2004-2005	31.39
2005-2006	32.33
2006-2007	33.24
2007-2008	34.30
2008-2009	35.76
2009-2010	37.19
2010-2011	36.99
2011-2012	38.69
2012-2013	40.71

3.5. Conclusions

Biomass shows great promise as an alternative fuel for the production of energy. SRF and FWWC can be utilised for lowering our fossil carbon emissions into the atmosphere, avoiding the use of landfill (the lowest viable option in the waste management hierarchy) and utilising an untapped source to help meet our energy requirements and targets. SRF can be utilised to produce energy and it has a high calorific value. The utilisation of FWWC if increased and monitored can be developed into an industry in its own right, which will in turn reduce the cost of processing the feed, as competition from suppliers begins to take effect.

A techno-economic analysis of SRF and FWWC combustion plants was undertaken at Germanà & Partners Consultant Engineers in Rome, Italy. This study investigated the application of 50 ktpa and 100 ktpa SRF plant with an overall efficiency of 26% and 28% respectively and 50 ktpa, 80 ktpa and 160 ktpa FWWC plants with an overall efficiency of 26%, 27% and 28% respectively. The SRF plants are economically viable at both scales in light of the low operating costs, with a positive 10% IRR for both cases. The FWWC biomass plant is economically viable only at the larger scales, with a 17% IRR. These results suggest that the SRF plant is the most economically flexible in terms of scale, predominately due to its low operating costs.

The results of the sensitivity analysis indicate that the main parameter affecting the levelised cost for the SRF plant is the turbine efficiency. A change of 10% or 30% in turbine efficiency causes a variation in levelised cost of 25% or 40%. The variable most affecting the FWWC biomass plant is the calorific value of the fuel, with a 9% to 40% change in the levelised costs when altering the calorific value by ±10% or ±30%. A change in the operating costs causes a variation in levelised cost of between 7% to 20%. The operating cost varies more for the FWWC plant when compared to the SRF plant because of the high purchase cost of FWWC. In the future, costs for feeds may change depending on how the markets develop. SRF may no longer have a gate fee and charge for its use instead. Alternatively, FWWC prices may decrease as competition from suppliers take place. Additionally, the sensitivity analysis demonstrates that if the ROCs selling price and electricity selling price decreases below 10%, the plants will no longer be economically viable. This shows that government incentives (ROCs and LECs) are key to rendering such renewable energy plants economically viable.

This work forms the basis for the subsequent analysis investigating the environmental impact assessment using LCA of energy from SRF at 100 ktpa and energy from FWWC at 160 ktpa.

4. Case study: Life cycle assessment of energy from SRF and FWWC

Summary

This chapter investigates the life cycle assessment (LCA) of the economically viable energy from SRF and FWWC plants. The LCA will highlight the greenhouse gas emissions savings that can be achieved and quantify how environmentally competitive is the energy from SRF and FWWC plants, compared to traditional fossil fuels such as coal and gas in the electricity mix. The economic evaluation showed that the viability of renewable energy plants may be dependent on the plant scale, tax and subsidies, in order to be cost competitive. A cradle to gate LCA is investigated; reasons for the chosen methodology are explained. The system boundary, functional unit, type of data used in the LCA and allocation procedure are explained.

Parts of this chapter have been published in:

Patel, C., L., Lettieri, P., Germanà, A. (2012). Techno-economic performance analysis and environmental impact assessment of small to medium scale SRF combustion plants for energy production in the UK. Process Safety and Environmental Protection. May, 2012.

4.1. Goal and Scope Analysis

LCA is performed to fully assess the environmental impact of energy from SRF and FWWC using combustion technology and to understand the social aspects, in terms of better waste management options for using these forms of biomass for energy production. Hot-spot analysis is used to define the unit operations within the process that contribute to high emissions. When choosing the system boundary several issues arise. for example, treating MSW may result in several products that are collectively treated in the waste management process and as a result, the LCA must consider recycling and landfill. This problem is called the “allocation problem”.

There are two methods of resolving the allocation problem, one is "partitioning", where the resource consumption and emissions associated with the multiple process and the processes up-stream are divided between the products. The other method is "system expansion", where an industrial system is credited with the environmental load from the energy production that is avoided when produced by the alternative process. Generally system expansion is only used with consequential LCA (CLCA), however this is not a rule that is set in stone and in my opinion system expansion can be used with attributional LCA to compare current practice with the proposed practice, using average data. The allocation problem is addressed in this study through system expansion for the FWWC plant because an attributional LCA is considered and the primary goal is to focus on the emissions associated with the production of energy from FWWC, system expansion is used to compare GWP of energy from FWWC and energy from the electricity mix.

This study uses system expansion as a comparative analysis because it considers that an alternative way of producing the energy exists; however when applying system expansion an uncertainty is introduced concerning exactly how to model the additional process. To address this uncertainty I will answer the following question, what alternative fuel would be replaced, if the industrial process delivered the set amount of energy? Therefore system expansion is investigated by calculating the environmental load that would have occurred had the same amount of energy been produced from electricity mix using average data. The LCA's of energy from FWWC provide information about the impacts of the processes used to produce, consume and dispose of electricity, but do not consider indirect effects arising from changes in the output of the electricity. As a result these are attributional LCAs (ALCA) with system expansion. Further on in this chapter an LCA of the SRF plant is investigated using an ALCA and system expansion. ALCA provides information on the average unit of product and use average data. The source of the data used in this study is reliable and accurate because it is sourced from an actual plant that is currently under construction in Rome (Italy) and the background conversion factors are sourced from a reliable model called BEAT$_{V}$2. This model was constructed by Defra and members of Automic Energy Authority Technology (AEAT).

4.1.1. Goal and Scope of FWWC fluidised bed combustion

The goals of the LCA are to:

- Compare emissions of producing energy from FWWC as opposed to keeping forestry thinning in the forest.
- Compare the environmental impact of energy from an alternative fuel producing the same amount of energy to energy from FWWC?
- Determine what is the overall environmental burden of energy production from FWWC using fluidised bed combustion technology?
- Determine which activities in the life cycle contribute most to the environmental impact of energy from FWWC using fluidised bed combustion technology?

The functional unit for this study is 1MJ of electricity. The FWWC system boundary is chosen to include transport, storage, processing of the FWWC for energy production and disposal of any waste streams produced during energy generation. This would make up the foreground system i.e. those processes on which measures may be taken concerning their selection or mode of operation as a result of decisions based on the study. Production of energy from an alternative fuel - harvesting and establishment of the forest thinning and chipping - form the background system i.e. all other modelled processes which are influenced by measures taken in the foreground system. The following process and system boundary is investigated:

Fluidised bed combustion utilising 160 ktpa of FWWC with steam turbine technology. The system boundary includes power production, harvesting and establishment of the forest thinning, chipping, transportation of the FWWC to the power producing facility, storage of the FWWC, storage of the bottom ash, transportation of the bottom ash to be used as a secondary aggregate and transportation of FA to a specialist landfill site (see Figure 4.1).

A detailed system diagram and base case scenario is available in Appendix 1 where the data used for the energy production from FWWC using fluidised bed combustion technology is from an actual combustion plant in the construction stage in Italy (Germanà & Partners, 2007). For transport calculations, it was assumed that the combustion plants were situated 20 kilometres away from the biomass production sites. A distance of 20 km is also assumed for the disposal of FA and bottom ash for each of the plants. Data from BEAT$_V$2 is used for the FWWC chipping stage, whilst data from Whittaker et al., (2010) was used for harvesting and establishment of the forest thinning.

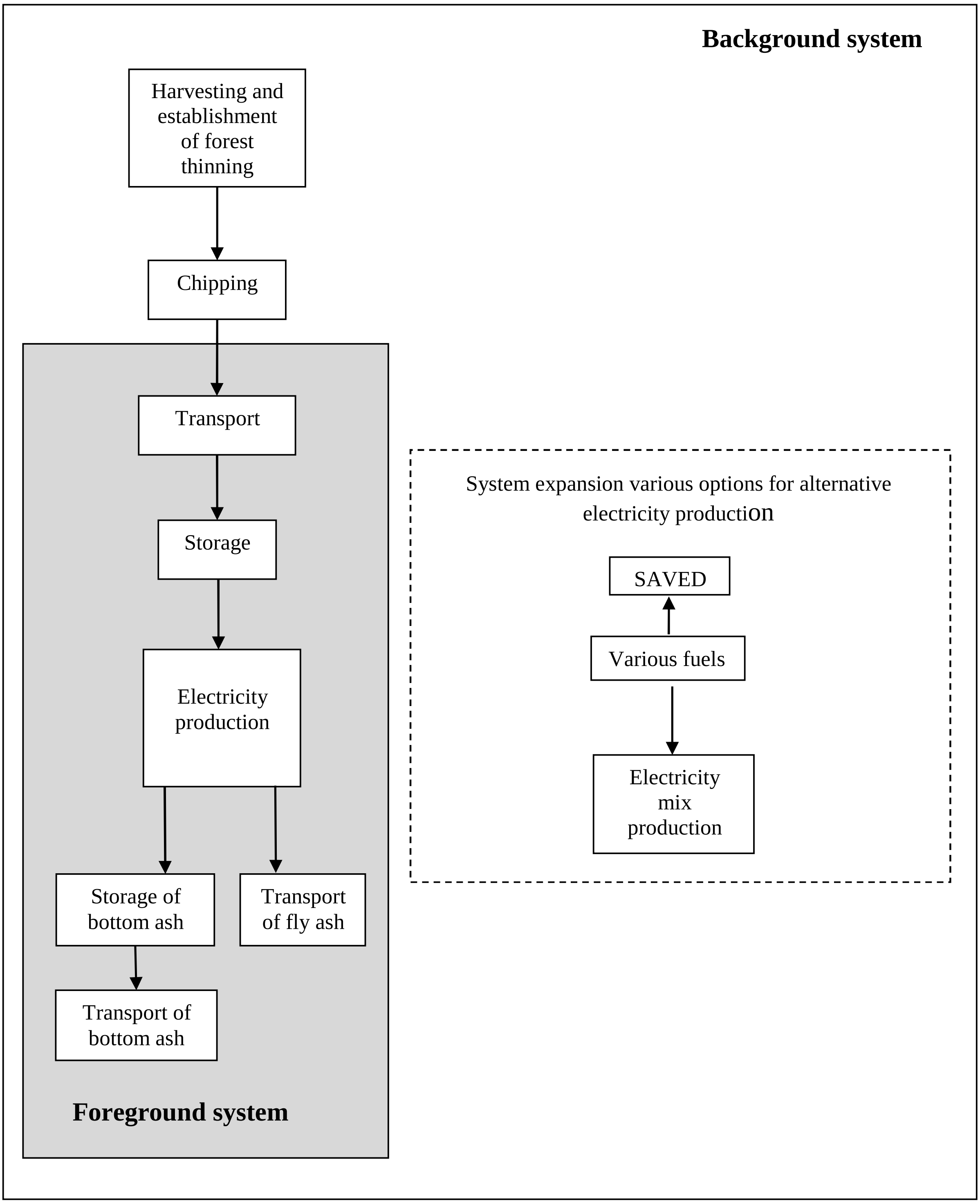


Figure 4.1 System boundary and sub-systems of the FWWC plant

The system boundary represents an attributional LCA and is defined to include activities contributing to the environmental impact of introducing electricity from

FWWC. Attributional LCA uses average data representing the effects of a change in the output of goods (i.e. the net environmental impact from average changes in production and consumption). Average changes are determined in this study by predicting the amount of carbon that can be saved by producing electricity from FWWC and as a result, avoiding electricity production from electricity mix. System expansion is used to compare the production of energy using FWWC with the same amount of energy produced from the electricity mix. This comparison includes avoided burdens and uses conversion factors for average data.

4.1.1.1. Inventory Analysis for FWWC fluidised bed combustion

The foundation of the LCA resides in energy calculations for the combustion plant. In this thesis, the LCA calculations are developed from scratch and in a transparent way as described below. The Biomass Environmental Assessment Tool Version 2 ($BEAT_V2$) was used to provide conversion factors (CF) expressed in terms of CO_2 and CH_4 (BEATv2, 2009). $BEAT_V2$ is a model devised by AEAT, DEFRA and The Environment Agency, The Biomass Energy Centre, North Energy and Drax. The data used in the model is taken from various field trials across the UK; the field trial most relevant to this work is forestry data from the Forestry Commission and an SRF production plant in Merseyside (see SRF plant in section 4.1.2). The plant is still in operation today, and data was collected for a year to be fed into the $BEAT_V2$ model, by collecting data over a one year period, the creators of $BEAT_V2$ were able to factor in any start up issues and document the different types of waste that they came across throughout the year. Forestry data was collected from the Forestry Commission and fed into the databases of the model. Information on the amount of diesel fuel used in machinery was calculated during trials of farming practice ($BEAT_V2$, 2009). These are reported in Table 4.2. The following section explains how the amount of CO_2 and CH_4 released was calculated in all of the boxes shown in Appendix 1:

<u>Transport</u>

$BEAT_V2$ energy figures (MJ/ t-km) were used to calculate the amount of energy used during transportation. The vehicle would use a different amount of fuel when travelling empty and when travelling at full capacity; this is defined in Eq (10):

$$L_{fl}[MJ] + L_e[MJ] = L_u[MJ] \qquad \textbf{(10)}$$

Where L_{fl} is the MJ used when travelling fully loaded. L_e is the MJ used when travelling empty and L_u is the MJ used for the complete trip.

<u>Storage</u>

A value from the forestry commission of the attributed energy requirement of a building was used to account for the CO_2 and CH_4 released during storage (Mann and Spath, 2001), this is labelled $E_{total,store}$ and is defined in Eq. (11):

$$E_{total,store} = Q[MJ] = ER_{build}[MJ] * t_{store}[yr] * B_{harvest}[tonnes] \qquad \textbf{(11)}$$

where Q is the energy cost of storing a given quantity of feed in a barn with the barn's storage capacity being fully utilised. ER_{build} is the attributed energy requirement of the building (with a life span of 20 years holding 100 tonnes of biomass, a typical value of 104 MJ odt^{-1}yr^{-1} was used in this study). t_{store} is the time for which a unit mass of biomass is stored in the barn (a life span of 20 years was used) and $B_{harvest}$ is the quantity of biomass to be stored.

<u>Chipping of FWWC</u>

The quantity of fuel required by a machine in carrying out work and the horse power of the machine was taken from the Forestry Commission and used to account for CO_2 released during chipping of the FWWC (Mann and Spath, 2001), this is indicated as L and is defined in Eq. (12):

$$L[l] = FR_{engine}[l, hp^{-1}hr^{-1}] * hp[hp] * T_{machine}[hr] \qquad \textbf{(12)}$$

where L is the amount of diesel utilised to chip the thinning, FR_{engine} is the quantity of fuel required by the machine in order to carry out a unit of work (0.3 is used in this study) and hp is the power the machine has to generate in order to carry out the treatment (250 is used in this study) (Mann and Spath, 2001). $T_{machine}$ is the time taken by the machine to chip the thinning (3 hours).

Once the amount of litres used is established, this is converted to gallons using Eq (13) and subsequently to MJ using Eq (14):

$$UK\ Gallon = L[l] * 0.22 \quad \textbf{(13)}$$

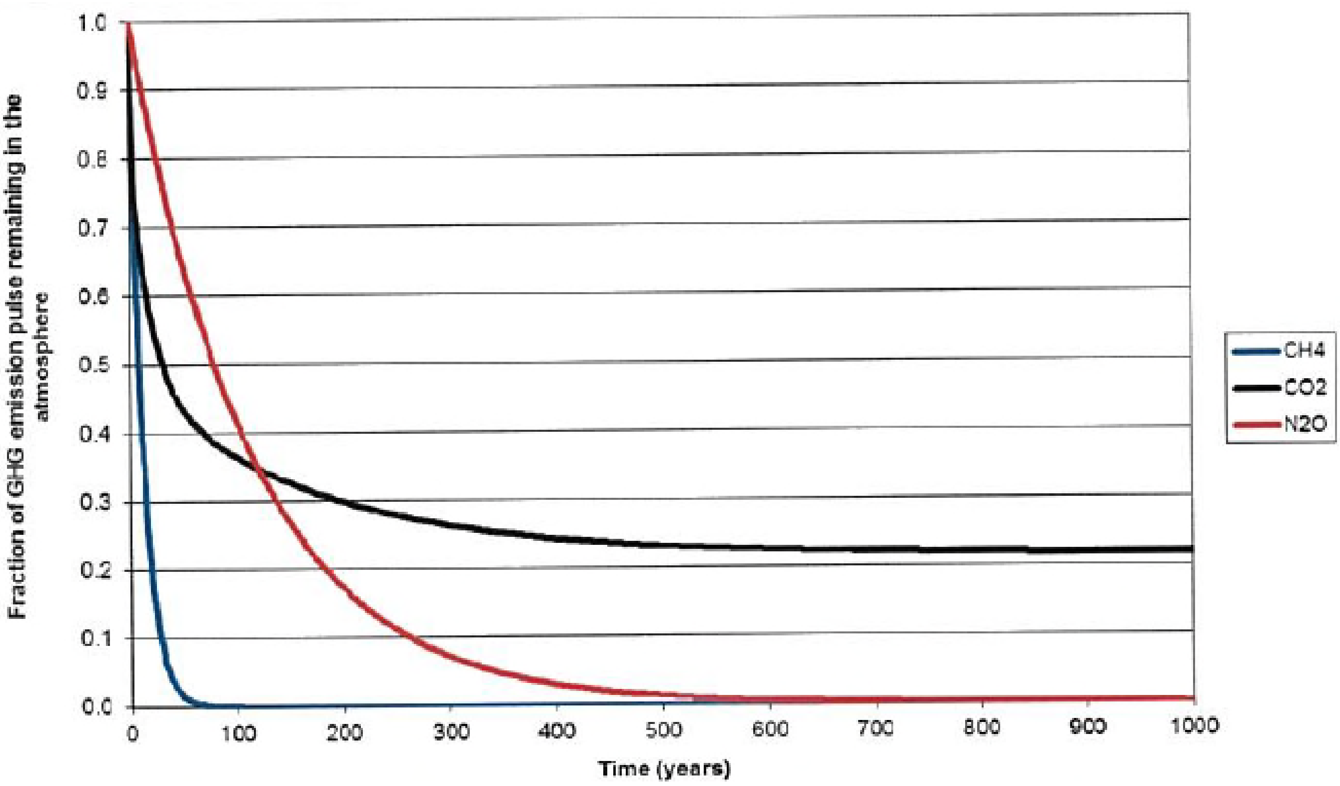
$$Q[MJ] = UK\ Gallon * 176 \quad \textbf{(14)}$$

Harvesting FWWC

The energy utilised when harvesting forestry waste wood chips is calculated using an experimental value from Whittaker et al., (2010), 668 MJ of energy is used per tonne of FWWC during harvesting. The base case shown in Appendix 1 considers carbon sequestration of forest thinning over a 20 year lifetime. As a result if these types (three base case examples) of wood were to be thinned and left in the forest (common practice) then the CO_2 in the debris boxes in Appendix 1 would be sequestered.

This study uses the Moura-Costa and Wilson (2000) method of accounting for carbon sequestration and storage on a kg CO_2-eq per year basis. The Moura-Costa approach uses the value of 48 tonne-years of CO_2 to calculate an equivalence factor between radiative forcing, carbon sequestration and temporary storage. Radiative forcing is a measure of the influence that a climate forcing factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system. The atmospheric residence of GHG's and radiative efficiency determines GWPs. Figure 4.2 shows that the different main GHGs have varying residence times in the atmosphere. Carbon dioxide, in particular, is very long-lived and, hence, excluding its radiative forcing after a finite number of years will underestimate the relative importance of CO_2 relative to other GHGs. When assessing the impacts on climate change, the radiative forcing potencies per molecule or kg also vary. The cumulative radiative forcing of a GHG is termed Absolute Global Warming Potential (AGWP) and depends on the atmospheric residence time of that GHG and its radiative efficiency. Methane and nitrous oxide are shorter-lived than carbon dioxide (see Figure 4.2) but have a much greater radiative efficiency (see Table 4.1) (Brandão, 2010).

Figure 4.2 Fraction of a GHG emission pulse remaining in the atmosphere throughout the subsequent 1000 years, calculated according to IPCC's parameterized decay function.



(Taken from Brandão, 2010)

	Radiative efficiency (Wm^{-2} $ppbv^{-1}$)
Carbon Dioxide	1.4×10^{-5}
Methane	3.7×10^{-4}
Nitrous Oxide	3.03×10^{-3}

Table 4.1 Radiative efficiency of the three main GHGs

(Taken from Brandão, 2010)

A characterisation factor for each gas is therefore used, allowing the total contribution from all GHGs to be expressed as a single value in units termed CO_2-equivalents (CO_2equ). Moura-Costa and Wilson (2000) developed a method for accounting for carbon sequestration and storage by deriving an equivalence factor between t CO_2equ and t CO_2-year. By calculating the integral of the decay fraction then available, they showed that 1 t CO_2equ emitted has an integrated effect of 48 tCO_2-yr (the blue area in Figure 4.2 is equal to the red area). This means that the integral of the decay curve of 1 tonne of atmospheric CO_2 over

100 years is equivalent to the sequestration and storage of 0.48 tonne of CO_2 for 100 years. The Moura-Costa approach uses the value of 48 tonne-years of CO_2 to calculate an equivalence factor between radiative forcing and carbon sequestration and temporary storage. In this approach, sequestering from the atmosphere and storing in the biosphere (plant biomass and soil) 0.48 tonne of biogenic CO_2 for 100 years (or 1 t of CO_2 during 48 years, or 48 t CO_2 during 1 year, i.e. and area similar to the red and blue areas in Figure 4.2) is equivalent to avoiding the radiative forcing of a pulse-emission of one tonne of CO_2 integrated over 100 years (blue area in Figure 4.3). Therefore, biogenic carbon sequestration and temporary storage can compensate for the impact of fossil-carbon emissions to the atmosphere in a way consistent with the GWP_{100} logic (Brandão, 2010).

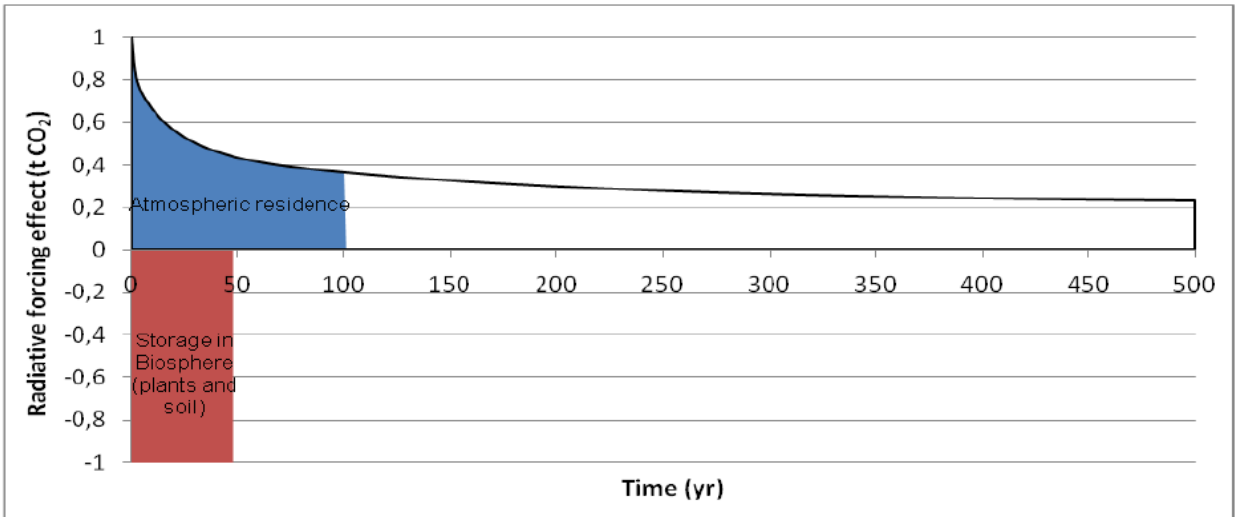


Figure 4.3. The Moura-Costa approach calculated for a 100-year time horizon. Sequestering and storing one tonne of CO_2 during 48 years (red area) is equivalent to the impact of a 1-tonne CO_2 pulse-emission integrated over 100 years (blue area).

(Taken from Brandão, 2010)

Throughout the thesis this method is used because, in my opinion, in the future, if carbon sinks are discovered and the way we account for carbon sequestration develops, the Moura-Costa and Wilson (2000) method allows for the calculation of the amount of carbon sequestered to be re-calculated and reassessed as early as possible. By adopting a delayed methodology of accounting for carbon sequestration, such as the Lashof method would result in a completely different result and would assume the sequestered carbon dioxide and storing its carbon for a given number of years is equivalent to delaying a CO_2 emission until the end of the storage period. In my opinion, CO_2 should be accounted for each year and can be adapted in the future as progress in this area is made.

Table 4.2 shows the amount of energy utilised for the boxes illustrated in Appendix 1. Conversion factors were used to calculate the emissions released in each box presented in Appendix 1. The conversion factors were taken from $BEAT_V2$, (2009) and are also given in Table 4.2. The emissions released in each unit are calculated using Eq (18) to (20).

Table 4.2 Energy used and conversion factors used for each box in the FWWC plant

Boxes in Appendix 1	(MJ/FU)	kgCO_2/MJ	kgCH_4/MJ
Harvesting and Establishment of forest thinning (diesel)	13360	0.07	0.00004
Chipping (diesel)	6456	0.08	0.0001
Transport of FWWC (diesel)	336	0.08	0.0001
Storage of woodchips (coal)	6	0.0004	0.0004
Combustion (coal)	106	0.05	0.0001
Transport of bottom ash (diesel)	528	0.08	0.0001
Extraction pump (coal)	0.5	0.05	0.0001
Storage of bottom ash (coal)	1	0.0004	0.0004
Pump to boiler (coal)	0.2	0.05	0.0001
Boiler (coal)	68	0.05	0.0001
Transport of fly ash (diesel)	66	0.08	0.0001

4.1.1.1.1. Impact assessment for FWWC fluidised bed combustion

The global warming potential (E_{GWP}) is now calculated for the energy utilised in each box. E_{GWP} is equal to the sum of emissions of the greenhouse gases (CO_2 and CH_4), where these are multiplied by their respective global warming potential (GWP) classification factors (Azapagic et al., 2004), $ec_{2,j,}$:

$$E_{GWP} = \sum_{j-1}^{j} ec_2,_j \; B_j \qquad \textbf{(15)}$$

B_j represents the emission of greenhouse gas $_{j.}$ The E_{GWP} classification factors, $ec_{2,j}$ for different greenhouse gases are expressed relative to the GWP of CO_2, which is therefore defined to be unity. The time horizon chosen is 100 years. The classification factors for CO_2, CH_4, and N_2O are 1, 25 and 298 respectively (PAS2050, 2011).

Emission calculations

The global warming emissions (PAS2050, 2011) are calculated as defined in Eq (16) to Eq (19):

$$GWP_{CO_2}[kg_{CO_2}equ / FU] = \left(Q[MJ] * CF_{CO_2}\right) * 1 \qquad \textbf{(16)}$$

$$GWP_{CH_4}[kg_{CO_2}equ / FU] = \left(Q[MJ] * CF_{CH_4}\right) * 25 \qquad \textbf{(17)}$$

$$GWP_{N_2O}[kg_{CO_2}equ / FU] = \left(Q[MJ] * CF_{N_2O}\right) * 298 \qquad \textbf{(18)}$$

$$E_{GWP}[kg_{CO_2}equ / FU] = GWP_{CO_2} + GWP_{CH_4} + GWP_{N_2O} \qquad \textbf{(19)}$$

Where *Q[MJ]* is the energy produced, *CF* is the conversion factor for the respective emission (BEATV2, 2009) and E_{GWP} is the total emissions for the production of energy.

The E_{GWP} for the energy from FWWC is compared to a base case scenario where the forest wood is thinned and left in the forest to decompose along with other debris. This is a common practice and helps sequester carbon, increase other soil nutrients and also improves the habitat of the forest.

Figure 4.4 shows the E_{GWP} of energy from wood compared to the E_{GWP} of the base cases shown in Appendix 1.

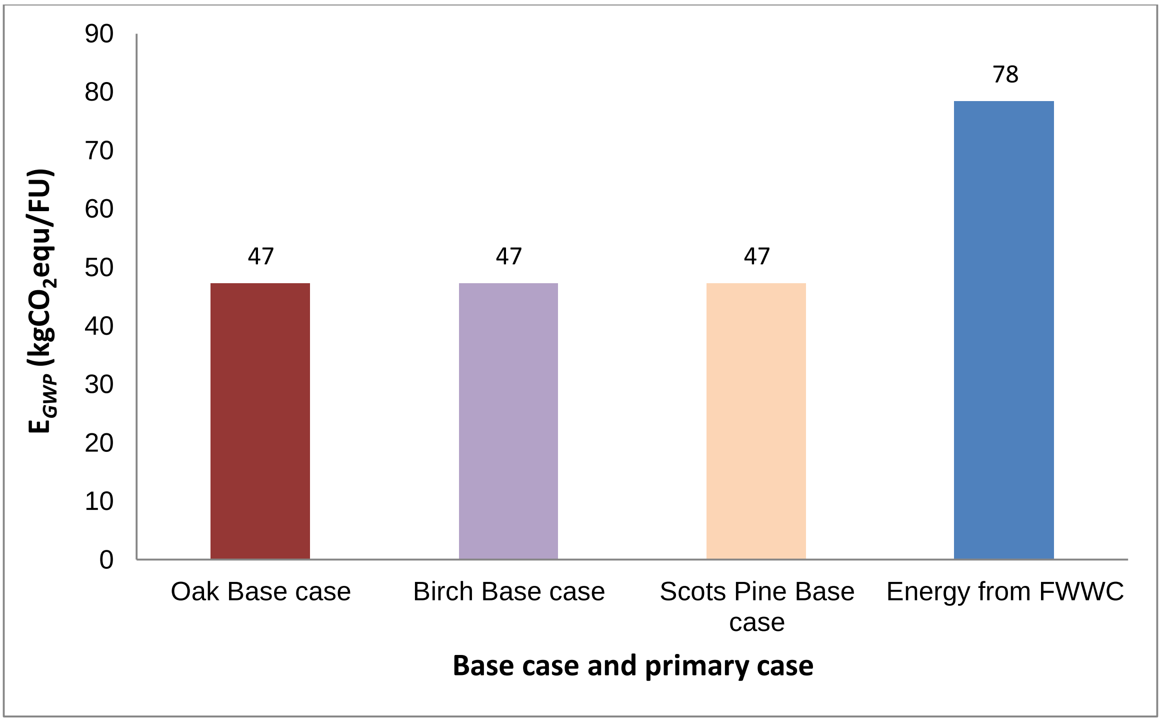


Figure 4.4 Global warming potential of base cases compared to energy from FWWC

The results in Figure 4.4 show that production of energy from FWWC results in a significantly higher global warming potential compared to the base case scenarios. Three types of wood were chosen as base cases and the results show that the three types of chosen wood have the same global warming potential. The values used to represent kgCO_2equ/FU of wood type, has been calculated by the Forestry Commission (Randel et. al, 2011). After investigating how these figures are calculated, it is highly unlikely that each type of wood would have the same value of sequestration. The values were generated from a linked series of models which have been developed by members of the Forest Measurement Modelling and Forecasting research group, within the Forestry Commission's Forest Research Agency. Estimates of carbon stocks were produced for all major UK forest species. Forest carbon accounting models refer to yield tables for basic growth and yield predictions. The yield tables present growth and yield estimates based on the GB averages for each of the many combinations of tree species, initial planting spacing, growth rate and management regime modelled. These tables were used to predict the sequestration values. The yields of different species vary considerably, depending on the location in the UK. As a result it is highly unlikely that the sequestration values for each of the species shown in Figure 4.4 are all the same. The Forestry Commission do however state that “although the look up tables will usually provide reliable estimates of carbon stocks it is nevertheless recommended that, once a carbon project has been established, the estimates of carbon stocks originally derived from the lookup tables are followed up with a direct assessment using the most appropriate field method documented in Jenkins et al. (2011) (Randel et. al, 2011).” Therefore I believe the values presented by the Forestry Commission would need to be followed up once such a plant is established. It is most likely that one of the species will match the value shown in Figure 4.4 whilst the other two will deviate (possibly smaller). However without doing a GB sized field test with accurate yield values, it would be very difficult to establish the exact values at this stage.

The E_{GWP} calculated for the FWWC plant were then compared to those obtained for a non-renewable electricity mix plant of a similar scale (system expansion as shown in Figure 4.1). The results are presented in Figure 4.5. The conversion factors for the non-renewable plant was taken from the Department for Environment, Food and Rural Affairs (Defra) annual conversion factors for company reporting (Defra[i], 2009). Defra releases conversion factors of E_{GWP}/kW produced for non-renewable energy plants. These conversion factors can be used directly to calculate the E_{GWP} for an equivalent scale non-renewable energy plant. The conversion factors for the non-renewable energy plants are reported in Table 4.3. These conversion factors refer to generators that provide spinning reserve. This is in line with all of the conversion factors used throughout the LCA analysis in this thesis.

Table 4.3 Conversion factors for CO_2 and CH_4 E_{GWP} of non-renewable plants

	Coal	Natural Gas	Electricity Mix
E_{GWP}(CO_2equ/FU)	0.33	0.18	0.51

Data taken from Defra[i], (2012)

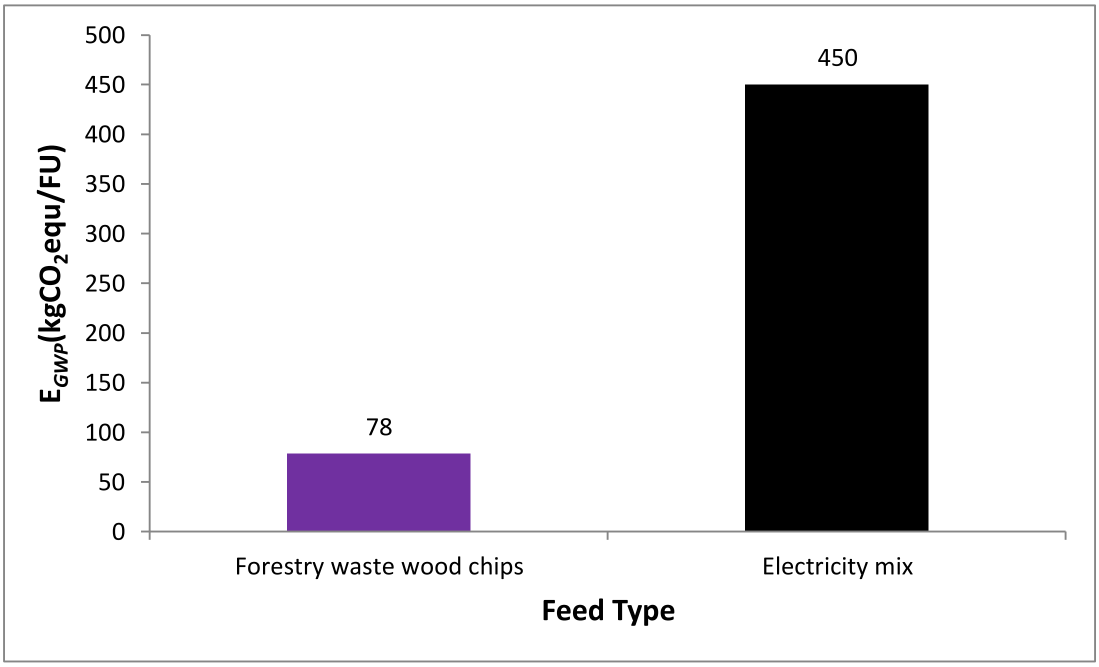


Figure 4.5 E_{GWP} of the FWWC plant compared with electricity mix at the same scale.

Figures 4.5 shows that the E_{GWP} obtained for the FWWC plant is less than that for the electricity mix alternative option. From a sustainability perspective, the results show that the renewable plants are both economically and environmentally viable.

The comparison in Figure 4.5 is developed further in Figure 4.6, where the results take into consideration energy displacement, i.e. the emissions generated from the electricity mix energy plant has been displaced by instead operating the FWWC plants under investigation.

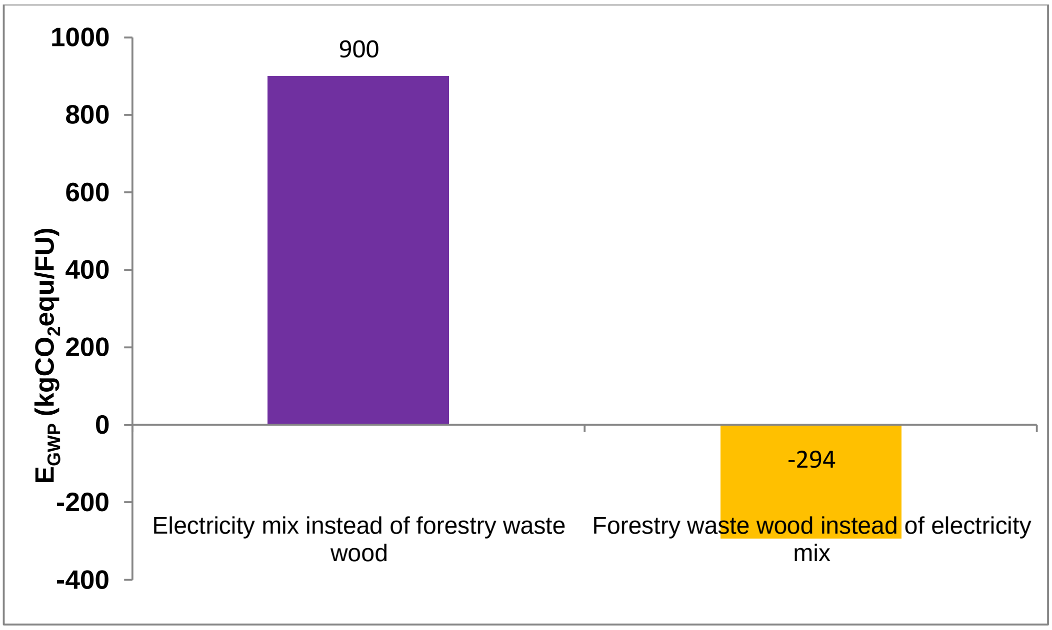


Figure 4.6 E_{GWP} of the FWWC compared with energy from electricity mix including emission displacement

Figure 4.6 shows the FWWC plant results in significantly lower E_{GWP} when compared to an electricity mix plant, when considering emissions displacement.

The three different types of forest wood are very similar in E_{GWP} when considered per functional unit (1 MJ of electricity production). As a result, only Oak is compared with the electricity mix alternative. The results of this analysis is shown in Figure 4.7. If the emissions associated to the base cases scenario shown in Appendix 1 is analysed further then this scenario would also have to include the emissions from producing energy from electricity mix, because the forestry waste wood is not being used to produce energy, but is left in the forest. Therefore the E_{GWP}, including energy displacement, associated with leaving the wood in the forest is 450 E_{GWP} ($kgCO_2equ/FU$). The emissions associated with energy from electricity mix would also need to consider the addition of emissions associated with producing the energy that is not being produced from wood. In this case it is assumed this energy would be produced from the electricity mix. Therefore the emission associated with energy from electricity mix is doubled. However the FWWC is left in the forest to sequester carbon. Therefore the emissions associated with producing energy from the electricity mix results in a subtraction of the sequestered carbon from the FWWC. Finally the emissions associated with energy from FWWC includes an addition of the emissions of the sequestered carbon from leaving wood in the forest and a subtraction of the emissions associated from the production of energy from the electricity mix because this energy would no longer need to be produced. The emissions used to calculate the results presented in Figure 4.7 are presented in Table 4.4.

Table 4.4 Emissions associated with energy production from the base case, the electricity mix plant and the energy from FWWC plant

Description	Emission (kgCO$_2$eq per FU)
Harvesting wood	47
Sequestered carbon from leaving wood in the forest	47
Electricity mix emissions	450
Energy from FWWC emissions	78

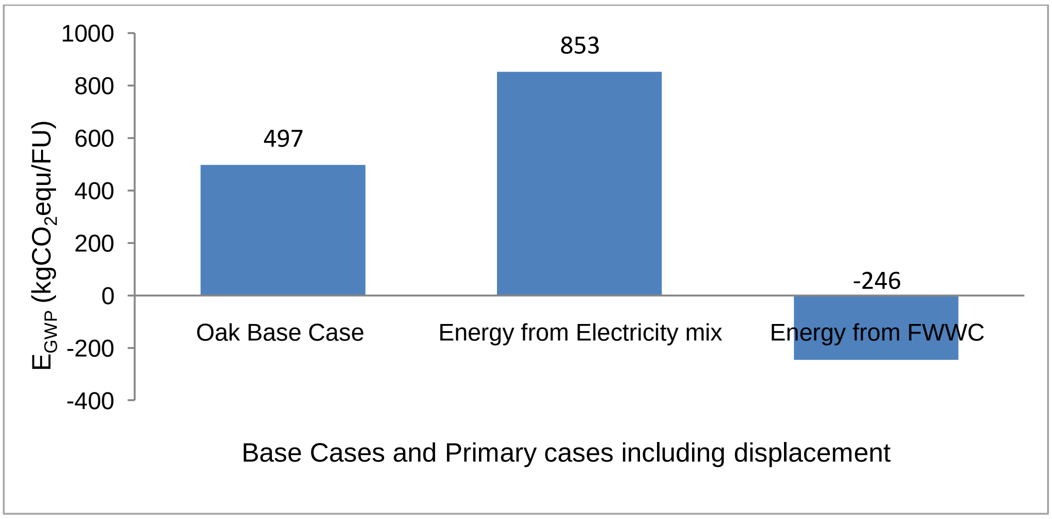


Figure 4.7 The forest waste wood base case compared with the energy from electricity mix plant and the energy from FWWC plant including displacement

The results in Figure 4.7 show energy from FWWC is environmentally favourable compared to the base case and energy from electricity mix when displacement is included.

Hot-spot analysis was also conducted to quantify the CO_2 emissions released from each box presented in Appendix 1. This information can be used to identify the unit operations causing the most critical environmental impact. Hot-spot analysis can also be used as a selling point if the plant benefits from low emissions. The hot-spot analysis for the FWWC plant is shown in Figures 4.8. The conversion factors were sourced from $BEAT_V2$ and are shown in Table 4.1.

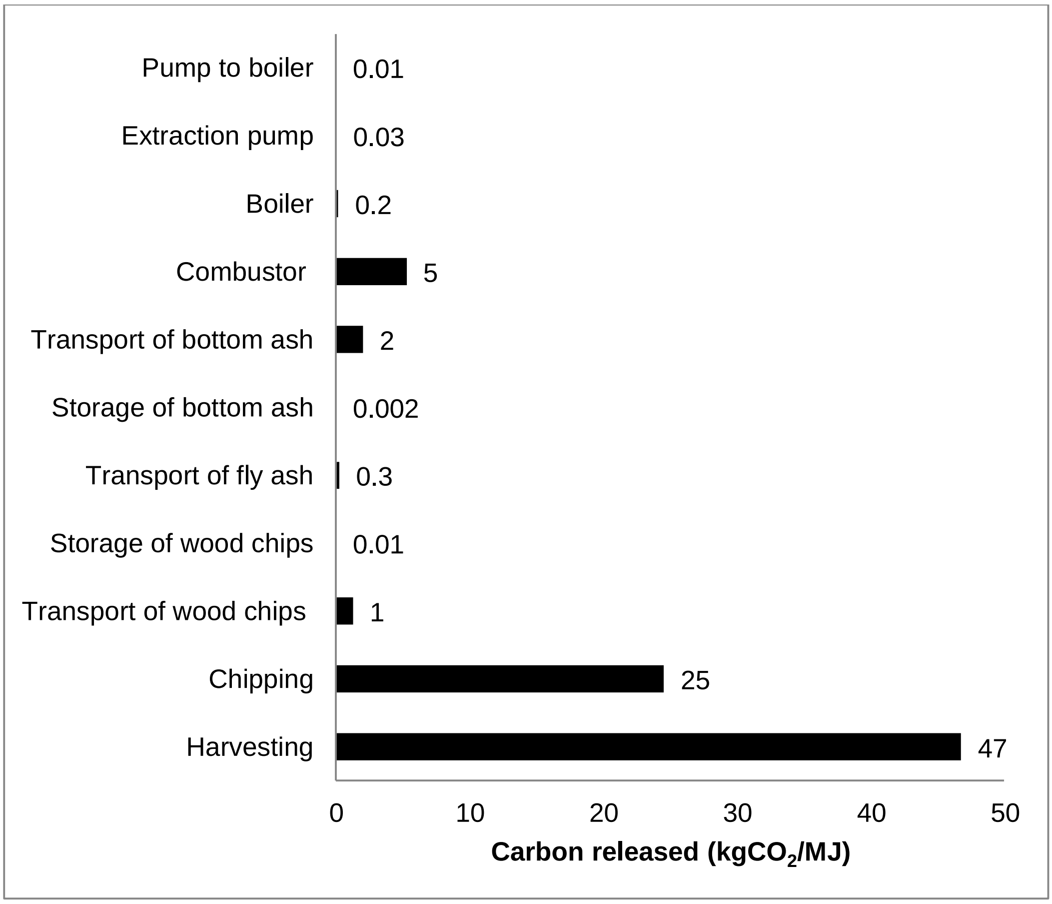


Figure 4.8 Hot-spot analysis of FWWC plant

The most polluting unit for the FWWC plant is the harvesting stage quantified at 47 $kgCO_2/MJ$. Unless a new method or machinery which utilises less diesel is produced, this unit will remain the most carbon intensive in this hot-spot analysis.

The emissions for transport are very low because these plants are designed to be installed close to the biomass feed source as well as to residents receiving the electricity, resulting in lower emissions released at the transport stage. In the UK, plants are generally large scale (>50MW) due to economic viability and are situated far away from residents, making the possibility of district heating connections unlikely. Although this system does not include heat production, it is a small plant designed to be situated close to small towns and cities to provide electricity. In addition most energy plants in the UK have to transport the feed for the plant over long distances and often from abroad. As the plants are very large, they must import most of the feed because the capacity of the plant is too large to be met by an indigenous feed (Forth Energy, 2010). Promoting small scale plants as shown in this study will ensure that appropriate scaling is performed for the town or city in question and that this demand is met by indigenous feeds. The benefit of this work is that the plants utilise indigenous feed sourced close to it (less than 20 km away), minimising transport costs and transport emissions. As a result transport distances must be limited to avoid the high emissions demonstrated in Figure 4.9, which quantify the increase in carbon emissions ($kgCO_2$) when increasing the transport distance for wood chips to the plant.

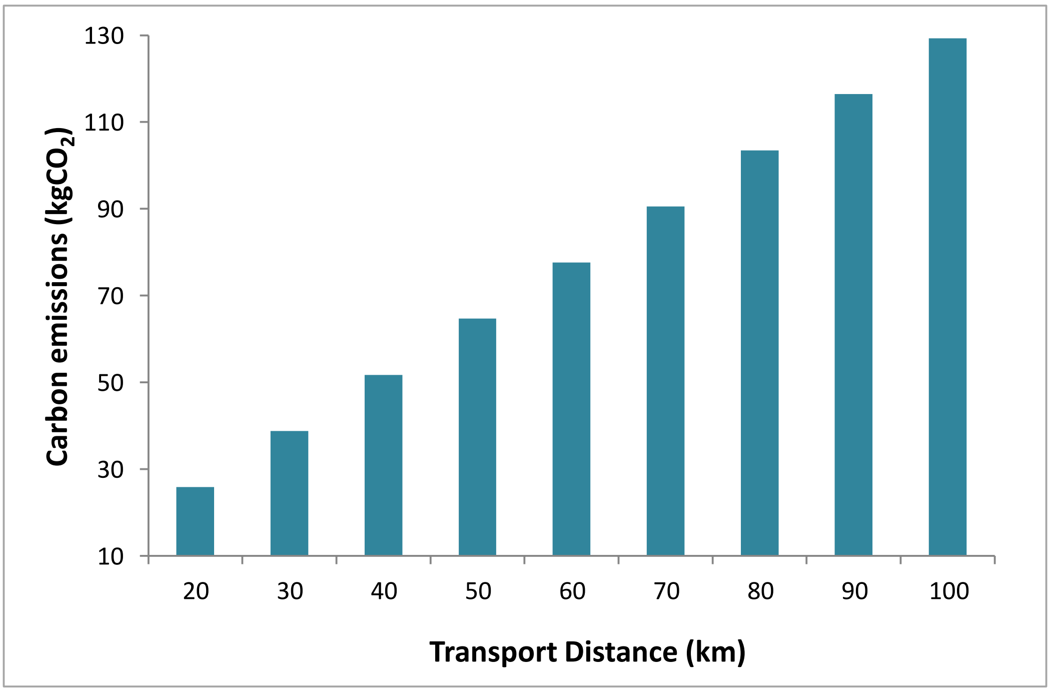


Figure 4.9 Changes in carbon emission with increased transport distance

To develop this work further and investigate the effects transport has in this LCA study, the effect of longer transport distances on the overall E_{GWP} was investigated. The transport distances were increased to two further distances, 50 km and 100 km. The result of this analysis is shown in Figure 4.10.

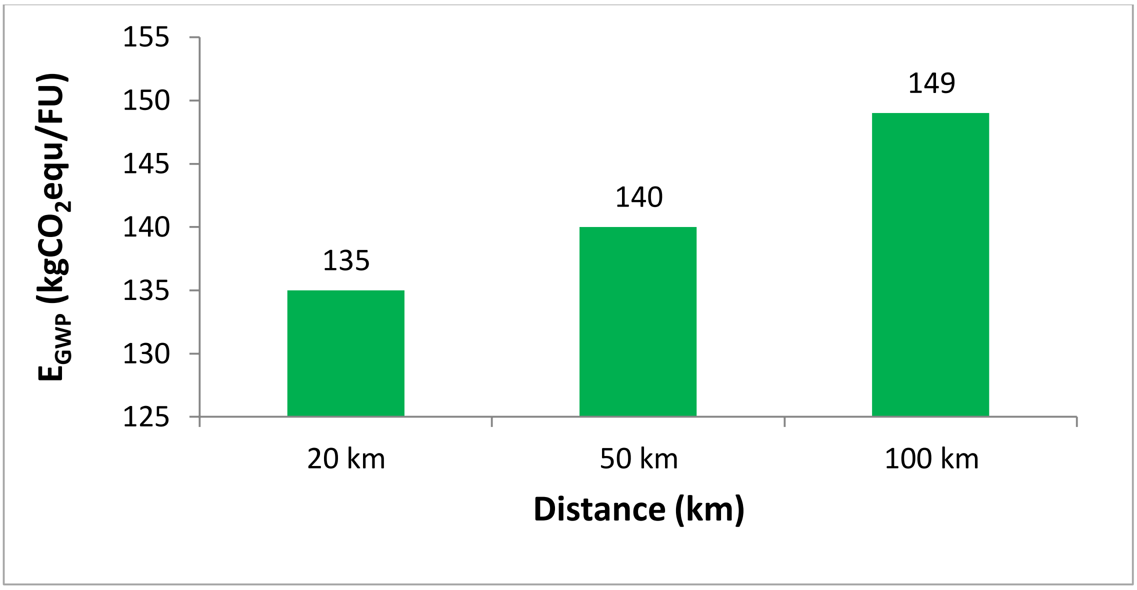


Figure 4.10 Effect on the overall E_{GWP} of energy from FWWC when increasing transport distance

The results show that increasing the distance of transport in the analysis to 50 km and 100 km results in an increase in E_{GWP} of 4 % and 6 % respectively. The results conclude it is important to ensure the transport distance is minimised to avoid increased emissions. Although the results show a small increase in emissions and the increase in E_{GWP} still results in a better E_{GWP} compared to non-renewable alternatives, it is important to ensure the transport distance is controlled. If the transport distance was not controlled then the E_{GWP} could increase significantly in particular for example if the biomass had to be sourced from abroad.

Further on in the thesis the production of energy using RSO is investigated (see Chapter 5) and this analysis also shows that small scale energy from RSO situated close to the RSO production site is beneficial in avoiding emissions from increased distances. However generally large scale energy production is not only situated far away from the biomass site, but also requires more biomass feed which may need to be transported over long distances. Therefore this analysis further evidences the benefits and need for economically viable small scale energy from RSO production.

This case study is an attributional LCA and therefore used average data. System expansion was used purely as a separate comparative analysis still using average data; generally system expansion is used in consequential LCAs. To develop this work further, the same system boundary was used to develop an LCA using marginal data. The average data was replaced with marginal data from the $BEAT_v2$ model to assess when using average or marginal data, if there is any variation in E_{GWP} and if so to what degree? Marginal data used assumed coal was the primary fuel supply that was used by the energy plant to convert the FWWC into electricity. The result of the E_{GWP} of energy from FWWC and energy from coal is shown in Figure 4.11.

Figure 4.11 E_{GWP} of the FWWC plant compared with coal at the same scale

The results presented in Figure 4.11 show as would be expected, the E_{GWP} is lowest for electricity from FWWC compared with electricity from coal, also the carbon intensity of coal compared to average electricity from the grid is evident in the E_{GWP} because the E_{GWP} for electricity from FWWC using average data is 78 E_{GWP} kgCO_2equ/FU (Figure 4.3), whilst the E_{GWP} of electricity from FWWC using marginal data is 95 E_{GWP} kgCO_2equ/FU. The result shows that the use of average or marginal data is vital because the E_{GWP} in this scenario changed by 16 %. The study was investigated further by calculating the E_{GWP} of electricity from FWWC with displacement using marginal data. The result of this assessment is shown in Figure 4.12.

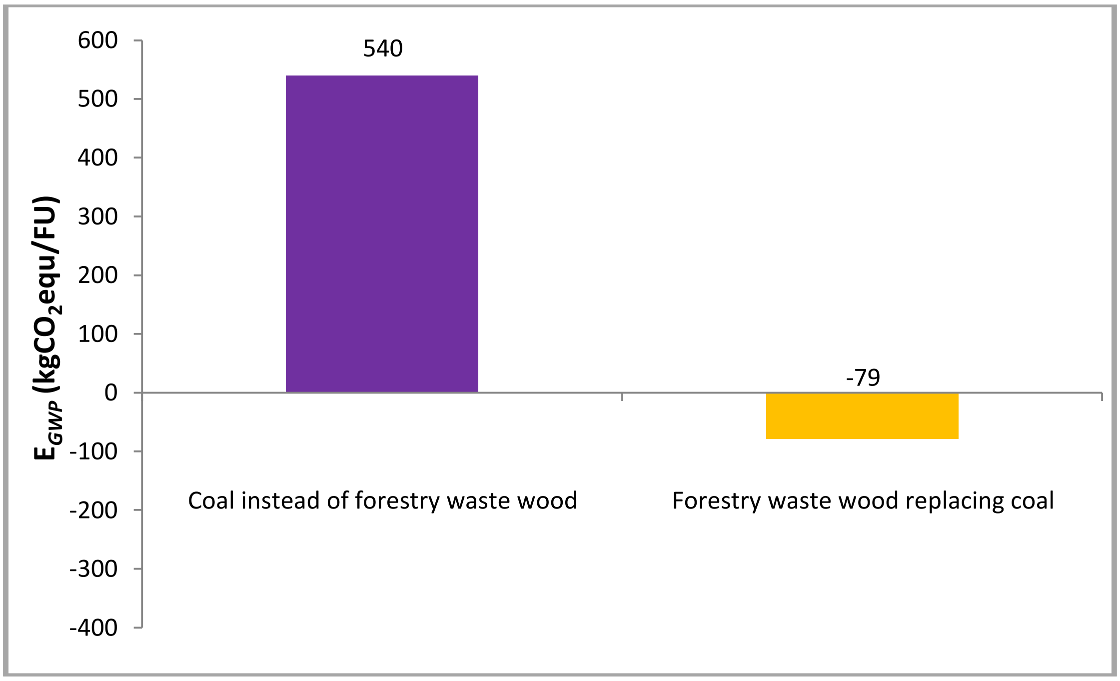


Figure 4.12 E_{GWP} of electricity from FWWC compared with electricity from coal including emission displacement

The result in Figure 4.12 and Figure 4.6 show that identifying the type of data used (average or marginal data) is vital because there is a significant (over 50 %) difference in the overall E_{GWP} when considering displacement. Therefore it is necessary that the type of data used, either marginal or average, should be explained when the system boundary is being decided, and if possible the type of data used must be kept consistent.

4.1.2. Goal and Scope of SRF fluidised bed combustion

The goals of the LCA are to:

- Determine what is the overall environmental burden of energy production of SRF using fluidised bed combustion technology?
- Identify which are the activities in the chosen life cycle that contribute the most to the environmental impact associated with energy from SRF using fluidised bed combustion technology?
- Compare the environmental impact of energy from alternative fuel producing the same amount of energy to the chosen system boundary.

The functional unit for this study is 1 MJ of electricity.

In this thesis the system boundary for the energy from the SRF plant includes SRF production, transport, storage, processing of the SRF for energy production and disposal of any waste streams produced during energy generation. This would make up the foreground system i.e. those processes on which measures may be taken concerning their selection or mode of operation as a result of decisions based on the study. The production of energy from an alternative fuel and MSW collection form the background system i.e. all other modelled processes which are influenced by measures taken in the foreground system. The following process and system boundary is investigated:

Fluidised bed combustion utilising 100 ktpa of SRF with steam turbine technology. The system boundary includes collection of the MSW, pre-treatment of the MSW, Fairport Process for SRF production, landfill of part of the MSW, recycling, pelletisation, transportation of the SRF to the power generating facility, storage of the SRF, power production, storage of BA, transportation of BA to be used as secondary aggregate, transportation of FA to specialised landfill site and system expansion of energy from an alternative mix plant.

A detailed system diagram is available in Appendix 2 where the data used for the energy production from SRF using fluidised bed combustion technology is from a combustion plant in the construction stage in Italy (Germanà & Partners, 2007). For transport calculations, it was assumed that the combustion plants were situated 20 km away from the biomass production sites. A distance of 20 km is also assumed for the disposal of FA and BA for each of the plants. Data from BEAT$_{V}$2 is used for the SRF production stages, pre-treatment and Fairport Process,(A detailed explanation of the Fairport Process given in section 2.8.2.2) pelletisation, recycling and re-use. Data for landfill is based on a model constructed by Mann and Spath (2001).

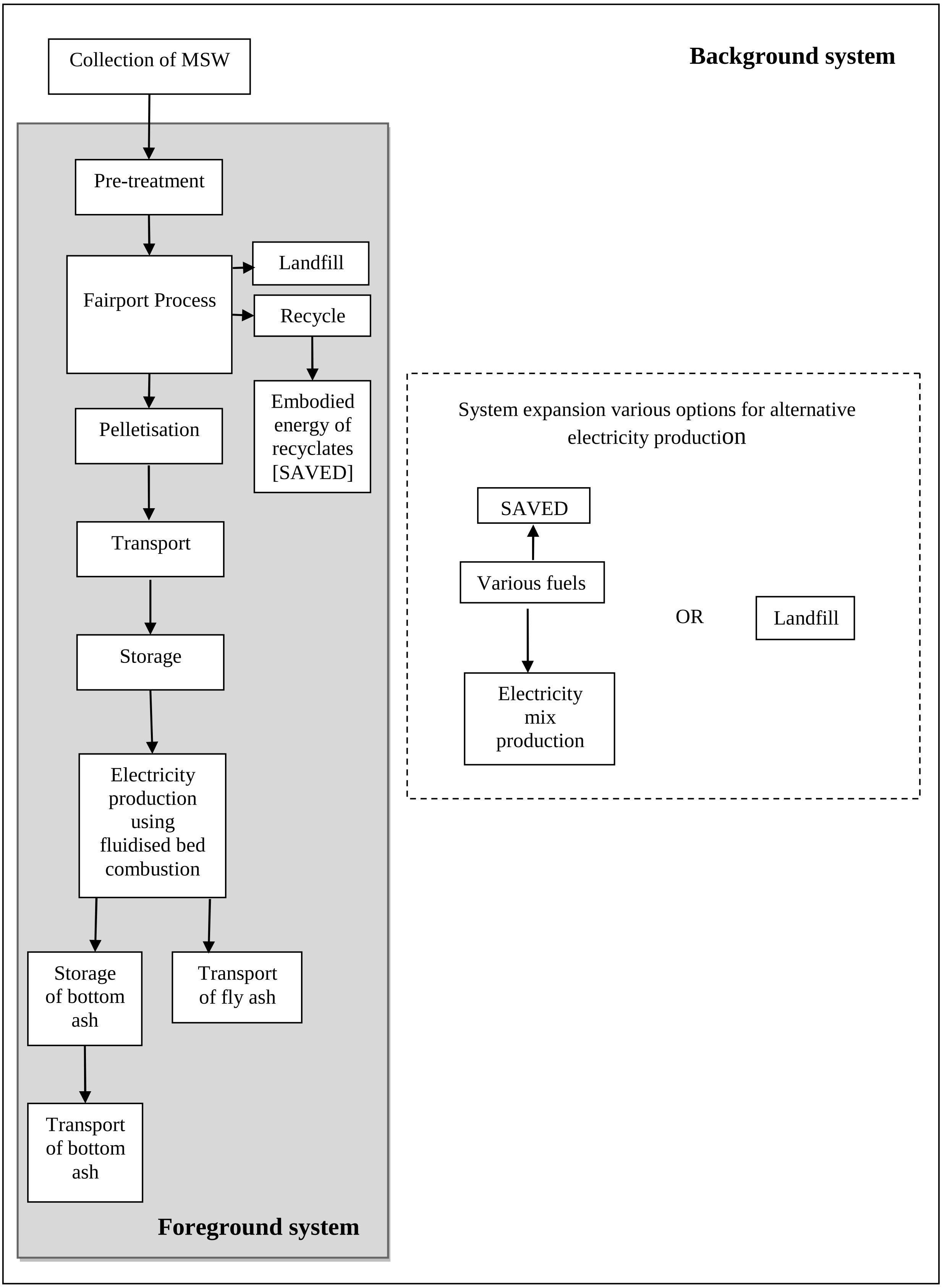


Figure 4.13 System boundary of the SRF fluidised bed combustion plant

The system boundary chosen in this study represents an attributional LCA (Figure 4.13). The system boundary is defined to include activities contributing to the environmental impact of introducing electricity from SRF and those from sorting MSW (i.e. disposal at a landfill facility and recycle streams) using the Fairport Process. The subsequent LCA uses average data to represent the effects of a small change in the output of goods (i.e. the net environmental impact from average changes in production and consumption). Average changes are determined in this study by predicting the amount of carbon that can be saved by producing electricity from SRF and as a result, avoiding electricity production from electricity mix. System expansion is used to compare the production of energy using SRF with the same amount of energy produced from the electricity mix. This comparison includes indirect avoided burdens and uses conversion factors for average data.

4.2. Inventory Analysis

Production of SRF

MSW is pre-treated to produce SRF, this process requires the following pieces of equipment and amounts of energy (MJ/t msw) to pre-treat the MSW ($BEAT_V2$, 2009):

- Trommel – 430 MJ/t msw
- Shredder – 832 MJ/t msw
- Compressor – 115 MJ/t msw
- Mist Air Suppression – 31 MJ/t msw
- Sump Pumps – 9 MJ/t msw

The Fairport Process includes the following equipment and amounts of energy (MJ/t msw) to produce the SRF:

- Thermal processors – 2081 MJ/t msw
- Gas burners in the thermal processors – 10329 MJ/t msw
- Gas scrubber – 913 MJ/t msw
- Gas Vaporiser – 499 MJ/t msw
- Trommel – 497 MJ/t msw

- Screen/Conveyors – 134 MJ/t msw
- Density separator – 2047 MJ/t msw
- The pelleting stage requiring 294 MJ/t SRF

Storage of SRF

The calculation methodology used for SRF storage is the same as that shown in section 4.1.1.1

Energy production boxes

The calculation methodology used for the energy production boxes in Appendix 2 is the same that used for the FWWC plant as shown in section 4.1.1.1

Transport

The calculation methodology used for the transport boxes in Appendix 2 is the same that used for the FWWC plant as shown in section 4.1.1.1

Table 4.5 show the energy required (MJ) for the LCA of energy from SRF. Conversion factors were used to calculate the emissions released in each box and were taken from BEAT$_{V}$2, (2009) for the boxes presented in Appendix 2 and Table 4.5. The emissions released in each box are calculated using Eq (18) to (20).

Table 4.5 Energy used for the SRF plant

Boxes in Appendix 2	(MJ/FU)	$kgCO_2/MJ$	$kgCH_4/MJ$
Collection of MSW (diesel)	1015	0.08	0.0001
Pre-treatment (coal)	1417	0.2	0.0004
Fairport Process (coal)	16501	0.2	0.0004
Pelletisation (coal)	3675	0.2	0.0004
Transport of SRF (diesel)	806	0.08	0.0001
Storage of SRF (coal)	4	0.0004	0.00003
Combustion (coal)	98	0.05	0.0001
Transport of bottom ash (diesel)	882	0.08	0.0001
Extraction pump (coal)	0.3	0.05	0.0001
Storage of bottom ash (coal)	1	0.0004	0.00003
Pump to boiler (coal)	0.2	0.05	0.0001
Boiler (coal)	65	0.05	0.0001
Transport of fly ash (diesel)	5	0.08	0.0001

4.3. Impact Assessment

The E_{GWP} is now calculated for the energy utilised in each box in Appendix 2. E_{GWP} are equal to the sum of emissions of the greenhouse gases CO_2 and CH_4, where these are multiplied by their respective GWP classification factors (Azapagic et al., 2004), as expressed in Eq (19). Total global warming emissions are then calculated using Eq (18) to Eq (20).

The E_{GWP} for energy from SRF is compared to a base case scenario, where the original MSW is collected and disposed of immediately into a landfill, as would be usual. Landfill is a common base case used in LCA studies. In this study, a landfill model based on the work conducted by Mann and Spath (2001) and Whittaker et al., (2009) has been used. The model takes into account potential carbon sequestration and energy production from the landfill gas.

The emissions and carbon balance of the landfill base case depend on a number of factors. The most significant emissions from landfill are methane emissions. Sequestered carbon is considered as a carbon sink, as it is not emitted to the atmosphere. The model also includes energy recovery from landfill sites, which is assumed to displace conventional grid electricity generation. Landfill sites are generally mechanically compressed and then sealed with a clay cap to restrict both oxygen availability and methane emissions (Whittaker et al., 2009). Anaerobic decomposition of organic matter results in the formation of a gas containing 50% methane, carbon dioxide and traces of other gases including hydrogen sulphide. The total emissions from the system are determined by two key variables: the rate of breakdown of landfill material and the percentage of methane emitted from landfill sites

The model used in this study assumes that the MSW contains 57% carbon, of which 65% is degraded in landfill and the remaining 35% is sequestered (Mann and Spath, 2001).

Once formed, methane will migrate through the layers of the landfill site until it either escapes into the atmosphere or it is captured. Efficiency of capturing landfill gas depends on the landfill cap technology used and how intact the cap layer is maintained. Captured gas can be used to generate electricity and under the EU 2002 Landfill Directive, it is required that all new landfills are to practice methane capture technology with energy recovery. Capping with energy recovery consists of a network of pipes and fans that provide a favourable route for the methane to migrate through to where it can be captured. Landfill gas capture efficiency is 72 – 75%. Therefore in the landfill reference system, it is assumed that 75% of the methane is captured and oxidised to carbon dioxide and of this, 90% is utilised for energy recovery (Mann and Spath, 2001). The model is based on landfilling 25 tonnes of MSW that would otherwise have been collected for SRF production. The landfill model for the MSW is presented in Figure 4.14.

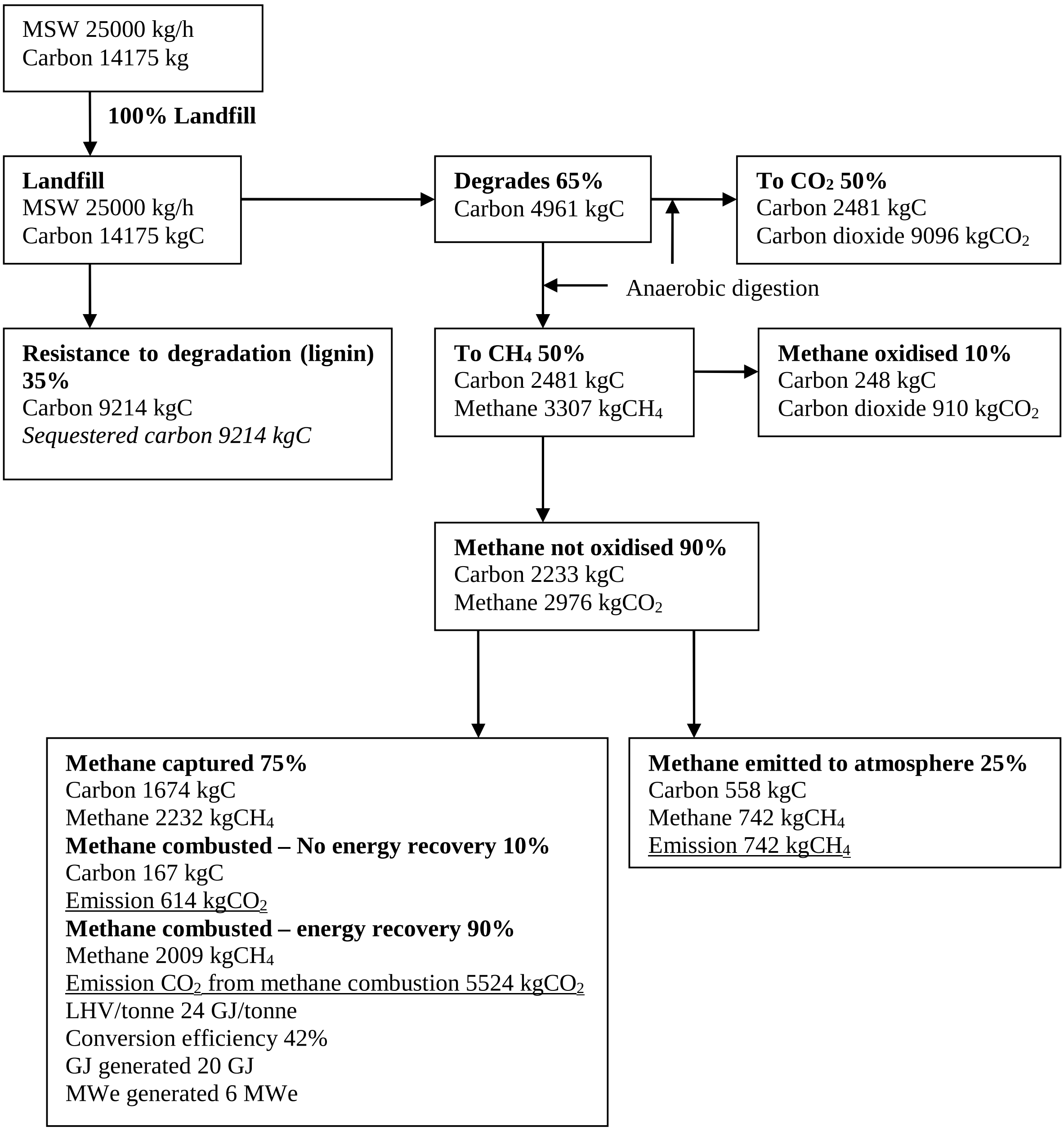


Figure 4.14 Landfill Base Case for the energy from SRF study

(Based on Mann and Spath. 2001)

The result of the landfill base case was compared to the life cycle assessment of the SRF combustion plant and is shown in Figure 4.15.

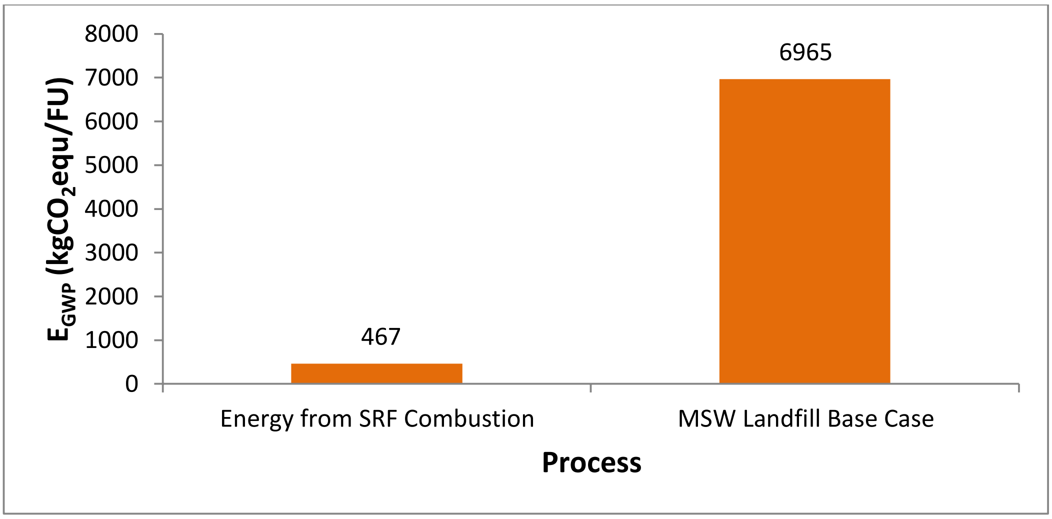


Figure 4.15 Global warming potential comparison between energy from SRF combustion and MSW landfill base case including displacement

The comparison takes into account energy displacement. The emission generated of energy from SRF takes into consideration the displacement of emission generated from energy produced at the base case landfill and sequestered carbon at the base case landfill. Therefore a subtraction of emissions of the energy production at the base case landfill from the energy from SRF combustion plant is carried out, followed by an addition of emission that would no longer be sequestered by the base case landfill scenario. The emission of the energy from SRF plant considers landfill of the non SRF fraction of the MSW. Therefore only a fraction of the sequestered emission of the base case landfill is added to the energy from SRF combustion scenario. The E_{GWP} used to calculate the overall E_{GWP} values in Figure 4.15 are presented in Table 4.6

Table 4.6 Emission values used to calculate the overall E_{GWP} including displacement of energy from SRF combustion compared with the MSW landfill base case

Description	**Emissions ($kgCO_2eq$ per FU)**
Emission of energy from SRF combustion	214 E_{GWP} ($kgCO_2/FU$)
Emission of energy generated at base case landfill	315 E_{GWP} ($kgCO_2/FU$)
Emission of sequestered carbon at landfill base case	568 E_{GWP} ($kgCO_2/FU$)

The E_{GWP} calculated for the SRF plant was then compared to the E_{GWP} obtained for electricity mix plant of similar scale. The results are presented in Figure 4.16, this result does not consider energy displacement.

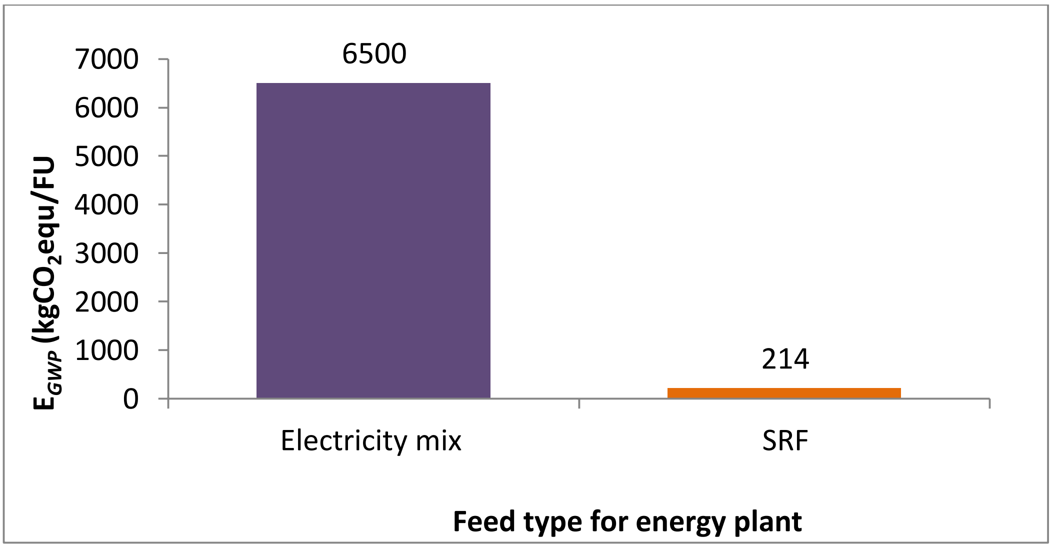


Figure 4.16 E_{GWP} from the SRF plant compared with energy from the electricity mix plant of the same scale

The results show that energy from SRF has a lower E_{GWP} compared to electricity mix alternative. The comparison in Figure 4.16 was developed further to include energy displacement, i.e. the emissions generated from the non-renewable energy plant that have been displaced as a consequence of operating the SRF plant. The results are shown in Figure 4.17.

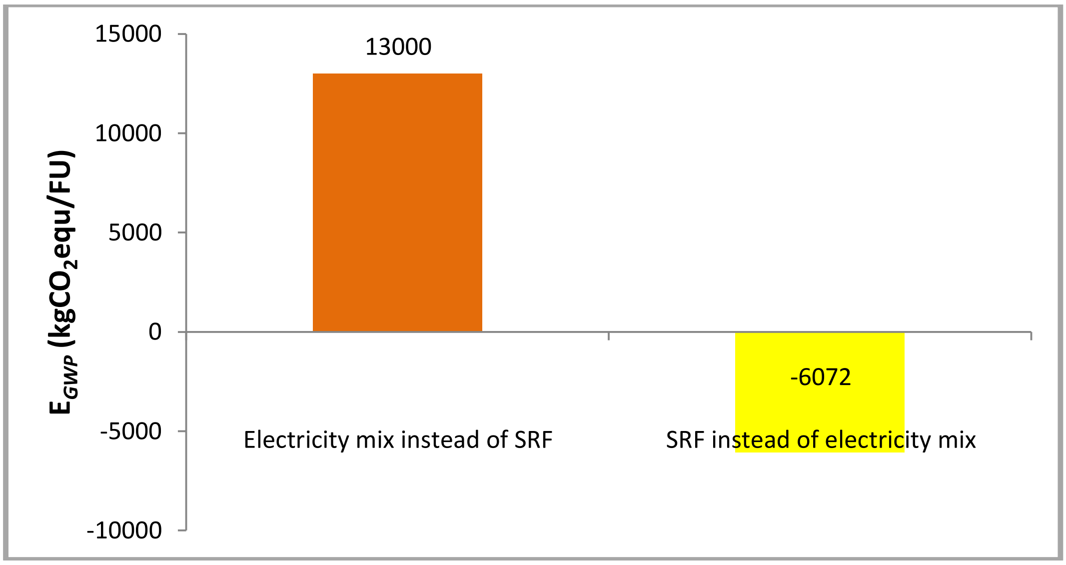


Figure 4.17 E_{GWP} of the SRF plant compared with energy from the electricity mix plant of the same scale including emission displacement

The results in Figure 4.17 show that energy from SRF has a significantly lower E_{GWP} compared with non-renewable alternatives when considering emission displacement and as a result it is favoured environmentally compared to any of the other non-renewable options investigated.

Hot-spot analysis was also conducted to quantify the CO_2 emissions released from each box presented in Appendix 2. This information can be used to identify the unit operations causing the most critical environmental impact. Hot-spot analysis can also be used as a selling point if the plant benefits from low emissions. The hot-spot analysis for the SRF plant is shown in Figures 4.18. The conversion factors were sourced from BEAT$_V$2 and are shown in Table 4.5.

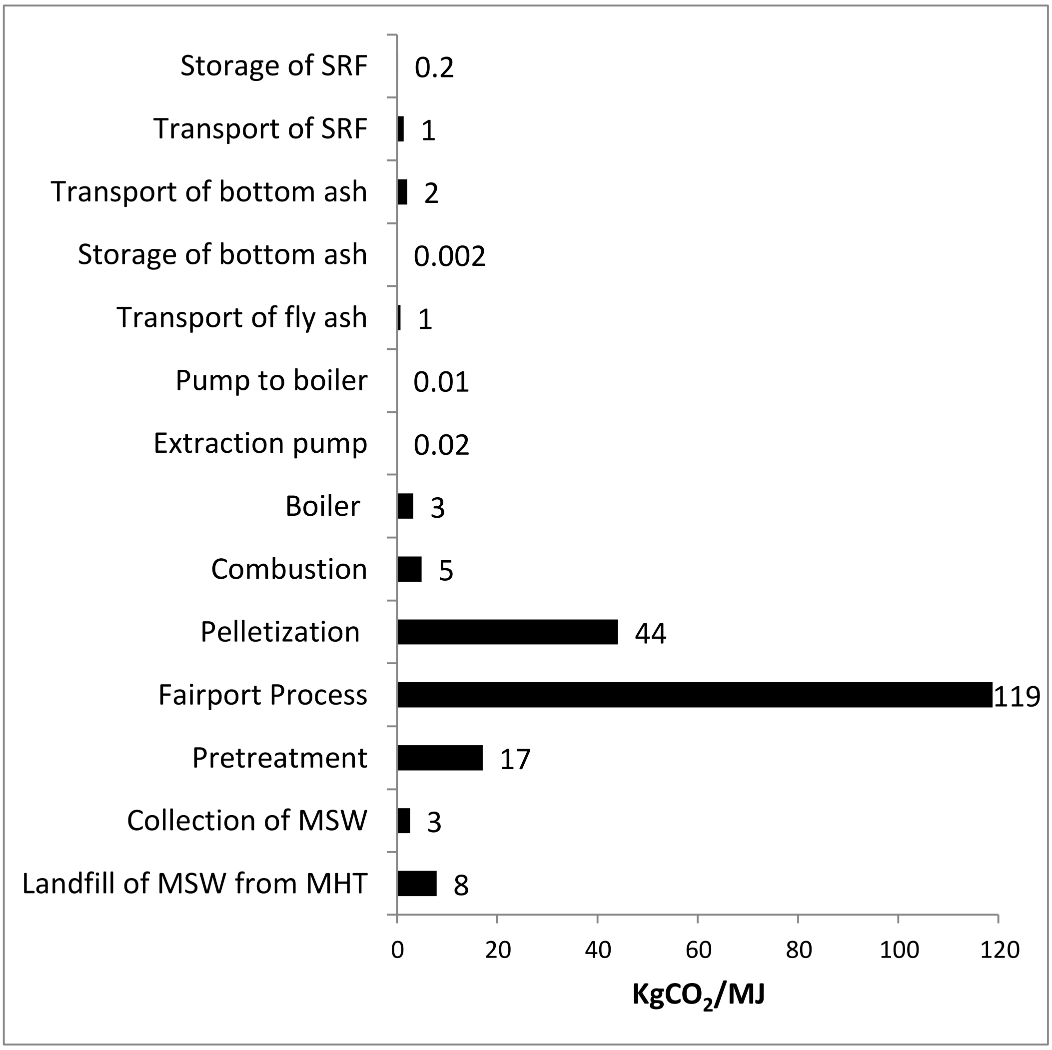


Figure 4.18 Hot-spot analysis for the SRF plant

The Fairport Process releases the largest amount of CO_2. The process uses a number of machines (See section 4.2, Figure 2.5) and converts 25 tonnes of MSW to 12.5 tonnes of SRF. As a result it has a large contribution to the overall release of CO_2. The SRF is produced from MSW which will include bulk items that need to be broken down significantly (Section 2.8.2.2) through a complex process including several stages and units hence making the Fairport Process an energy intensive one.

As with the FWWC plant earlier in Chapter 4, the transport distance for the SRF plant presumes a 20 km distance; transport distance must be minimised to avoid increased carbon emission from transport (Figure 4.9 and Figure 4.10). Currently energy plants in the UK are of a large scale, needing a large amount of feed to ensure that the plant runs at full capacity. In order to meet this demand, especially with energy from waste plants, in addition to indigenous feed, there is a need to import feed. This study is novel and proves that small scale plants utilising waste from the town or city that will be supplied by the energy result in lower carbon emissions from transport, because the plant is situated only 20 km away from the Mechanical Heat Treatment processing facility (see section 2.8.2).

4.4. Conclusions

This chapter investigated the LCA of energy from FWWC and SRF using combustion technology at different scales. The goals and scopes for the FWWC were answered in this study. The global warming potential for the FWWC plant considering attributional analysis is -294 E_{GWP} kgCO_2equ/FU. The FWWC plant resulted in a negative E_{GWP} because the amount of energy produced by this plant would have displaced a more energy intensive process of energy from electricity mix.

A base case was also investigated. The base case showed the amount of carbon sequestered from three different types of wood. This base case was chosen because in practice, thinned forestry is often left in the forest to decompose and the carbon within the wood is sequestered. Without considering energy displacement, energy from FWWC resulted in a 78 E_{GWP} kgCO_2equ/FU. The three different types of wood resulted in a value of 47 E_{GWP} kgCO_2equ/FU. However, results were also shown when considering energy displacement (Figure 4.6). These results show that energy from FWWC is environmentally favourable over energy from alternative fuels and simply leaving the wood in the forest to decompose.

The hot-spot analysis showed that harvesting creates the most emissions. This study assumed RT farming was used when harvesting the wood. One of the benefits of using RT methodology is that there is a reduction in the use of diesel fuel needed to run machinery. As a result it will be difficult to reduce the emissions associated with harvesting unless there is a development in the harvesting method to further reduce the emissions.

The study was developed further by investigating the difference in E_{GWP}

when using average or marginal data. The results showed that it is vital the type of data used is documented and kept consistent throughout the study because the resulting E_{GWP} can vary significantly. In this study the E_{GWP} varied by 50% when comparing the same scenario and system boundary using either average or marginal data.

The goals and scope of the LCA for the energy from SRF plant were also answered. The base case in this study was landfilling the MSW that would be collected by the local authority. The results showed energy production from SRF resulted in 467 E_{GWP} kgCO_2equ/FU compared to 6965 E_{GWP} kgCO_2equ/FU for landfilling.

The energy from the SRF system was expanded, to compare to energy from electricity mix. Producing energy from SRF was considered in the results and included landfill and recycling of parts of the MSW sub systems. The results showed that energy from SRF resulted in the least E_{GWP} when compared to an electricity mix plant. When producing SRF this study did not consider the fluctuations that may occur with the associated burdens from landfill and savings from recycling; these figures may vary as human behaviour changes. Human behaviour is unpredictable and as a result, data from $BEAT_V2$ was used to estimate the amount of waste that is recycled and sent to landfill. These figures were considered reliable because the data was taken from an actual plant in Merseyside over a one year period.

The hot-spot analysis showed the Fairport Process produces the most emissions. In future work it would be interesting to see the environmental burden of the Estech Process (section 2.8.2.1) analysed or perhaps to try to find ways of decreasing the environmental burden of the Fairport Process.

In conclusion, under the conditions and assumptions made in this study, energy from SRF and FWWC is an environmentally viable option compared with non-renewable alternatives and can contribute to future energy production.

5. Techno-economic and environmental impact assessment of energy from RSO using internal combustion engine technology

Summary

This chapter reports the work carried out during my second visit to Germanà & Partners Consultant Engineers in Rome, Italy as part of a three month industrial placement programme for this research. The results of a techno-economic performance analysis of a RSO internal combustion engine plant for the production of energy and heat are reported. Small and medium scale plants treating 27 ktpa and 40 ktpa of RSO are investigated. The technical assessment includes calculations for electricity generation, heat produced and overall system efficiency. The economic viability of the different scales is investigated through a discounted cash flow analysis. The levelised cost is used to calculate the cost of production of one unit of electricity. The effect on the economic performance of changing model input parameters is evaluated. Seven different system variables have been chosen and the effect of a ±10% and ±30% change on the levelised cost has been examined.

This chapter also investigates the LCA of the economically viable 40 ktpa RSO plant. The purpose of the LCA is to quantify how environmentally competitive the energy from RSO plant is, when compared to traditional fossil fuels such as coal and gas. Where the economic evaluation showed that the viability of renewable energy plants may be dependent on the plant scale, taxation and subsidies, the LCA will highlight the greenhouse gas emissions savings that can be achieved.

The techno-economic analysis and LCA coupled together are investigated to ascertain if electricity and heat can be produced at this small scale in the UK in both an economical and environmentally friendly way. Large combustion plants (excess of 50 MW) are the norm in the UK, by proving that these technologies are viable at small scales, this work will help in promoting district heating (providing renewable and efficient electricity and heat to small cities situated

close to the plant).

Parts of this chapter have been published in:

Patel, C., L., Lettieri, P., Simons, S.J.R., Germanà, A. (2011). Techno-economic performance analysis of energy production from biomass at different scales in the UK context. Chemical Engineering Journal, Issue 171, pages 986-996.

5.1. Biomass characteristics and system layout

The medium scale plant investigated at Germanà & Partners corresponds to a plant which was at the design stage for the region of Sicily. In this study the plant was subsequently scaled down to investigate whether it would be technically and economically viable at an even smaller scale; the plant was scaled down from 40 ktpa of RSO to 27 ktpa and from three to two engines for energy production. A flow chart for the plant is shown in Figure 5.1. Rapeseed oil is investigated because it is a first-generation type of biomass in a liquid form and grown in increasing amounts in the UK. It is mainly used for diesel production; but in this work the RSO is used to produce energy and heat.

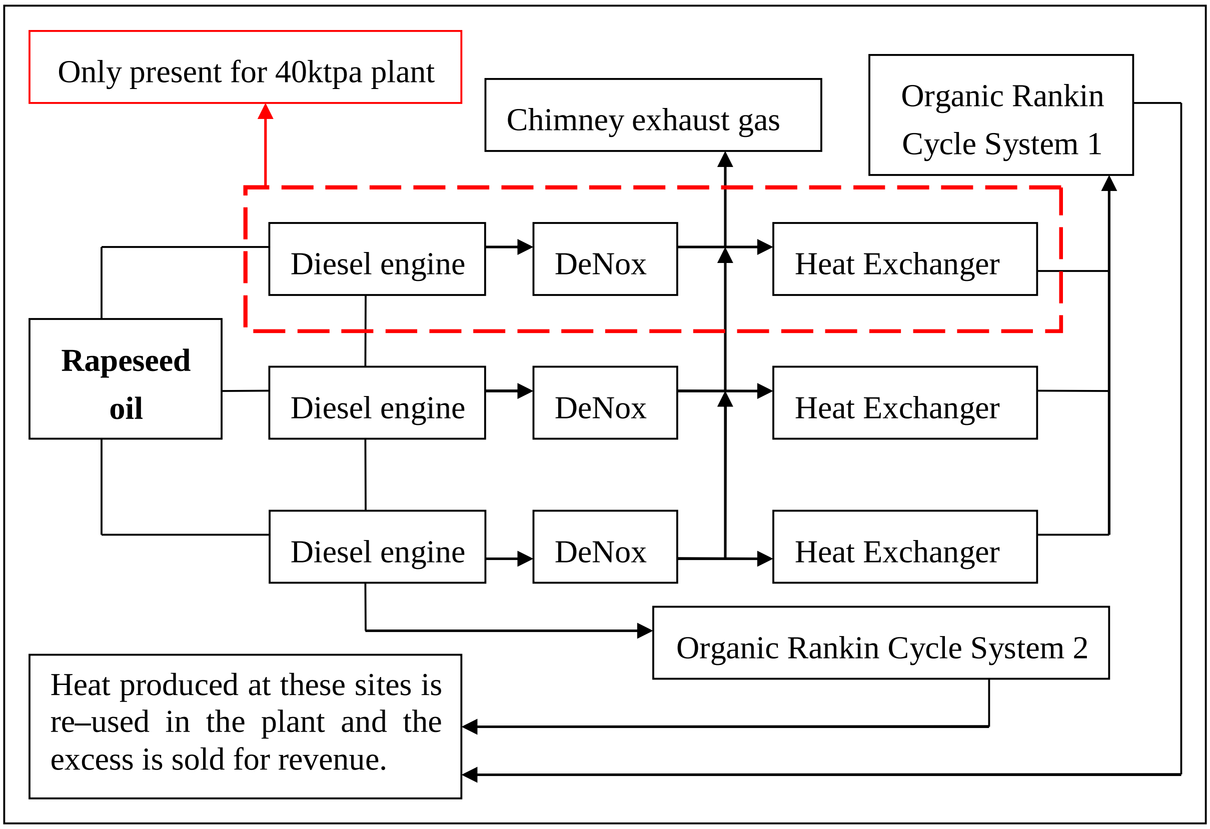


Figure 5.1 Energy recovery from RSO utilised in internal combustion engines with heat recovery using ORCE technology

The RSO characteristics used for developing the technical model for this work were provided by Germanà & Partners Consulting Engineers. These are summarised in Table 5.1. The proximate analysis shows the moisture content, combustibles, inert content and lower heating value (LHV) (kJ/kg) of the RSO. The ultimate analysis gives the elemental composition on a dry basis in terms of carbon, hydrogen, oxygen, nitrogen, sulphur and chlorine. The internal combustion engine plant is run on RSO of specific characteristics which are compliant with the limits for biofuel characteristics as specified by Wartsila, (2009). If a non-conventional fuel is used, the engine may not operate efficiently and could suffer from corrosion, especially if fuels have high acid numbers (above 5 mg KOH/g). This would in turn affect the maintenance costs.

Table 5.1 Proximate and ultimate analysis of the biomass

Biomass type	**Proximate analysis**			**Ultimate analysis**					
	Combustibles	**Inerts**	**LHV (kJ/kg) (based on wt.%)**	**C**	**H**	**O**	**N**	**S**	**Cl**
RSO	100	-	37000	86	13	1	-	0.03	-

5.2. Technical Analysis - Overall system efficiency calculations

The energy calculations are used to assess the technical performance, the methodology of which is reported in Chapter 3. In addition to these the heat generated through the ORC unit is calculated using Eq (21):

Heat generated = $H_{generated}[MWth] = \eta_{diathermic\ oil\ turbine}(\%) * O_{th}[MWth]$ **(21)**

Where $\eta_{diathermic\ oil\ turbine}$ 80% and O_{th} is the thermal capacity of organic fluid which is equal to 24 MWth (given by Germanà & Partners). These are standard values for the turbine efficiency and the thermal capacity of organic fluid.

The thermal capacity of the rapeseed oil, R_{th}, is calculated using Eq (22):

Thermal capacity of rapeseed oil = $R_{th}[MWth] = LHV[kJ/kg] * m[kg/h]$ **(22)**

Where *LHV* is the calorific value of the rapeseed oil and *m* is the rapeseed oil feed rate.

The overall system efficiency for the internal combustion engine plant is calculated using Eq (23):

Overall system efficiency (%) = $\frac{H_{generated}[MWe] + E_{generated}[MWe]}{R_{th}[MWth]} * 100$ **(23)**

Where $E_{generated}$ is the amount of electricity generated by the engines.

Each engine generates 8 MW of electricity according to Wartsila specifications (Wartsila 2010).

5.3. Results and Discussion

5.3.1. Technical analysis

Both the electricity and heat produced by the plants are shown in Table 5.2. In addition to the overall system efficiency, the engine electrical efficiency and the efficiency for the diathermic oil turbines.

The two plants have overall efficiencies of 57 – 58% this is mainly due to the high calorific value of the rapeseed oil and the high efficiency of the internal combustion engine (45%). The RSO plant generates 50% more power at the medium scale (24 MWe) when compared to the smaller scale (16 MWe). The amount of energy produced by the RSO plant however depends on the fuel characteristics, which have to fall under specific limit specifications. If a non-conventional fuel is used then this may decrease the amount of electricity produced and affect the maintenance costs of the plant.

Table 5.2 Overall electrical efficiencies and heat and power results of the plants

Plant scale (ktpa)	RSO 27 Engine	RSO 40 Engine
Electricity produced (MWe)	16	24
Heat produced (MWh)	12	19
Engine electrical efficiency (%)	45	45
Efficiency of diathermic oil turbines (%)	36	36
Efficiency of electricity generated from internal combustion engine (%)	34	37
Overall system efficiency (%)	57	58

5.3.2. Economic Assessment

The economic evaluation and development model consists of capital costs, operating costs and working capital, projected annual revenues, depreciation and corporation tax. The indicative costs and revenues resulting from the economic model can be used to compare the different scales as a consistent methodology has been adopted for this analysis. However, costs and revenues are contract values and can depend on suppliers, plant scale, technology used and type of energy recovery system employed, as well as local area factors. The scaling equation (Eq 5) was used to calculate the capital and operating costs for the 27 ktpa plant.

The results are presented in Table 5.3. It is assumed that prices for the recycled material and power costs are constant. A discount rate of 6% is used in this analysis to take into consideration public sector borrowing; the corporation tax is calculated at 28%, but the effect of inflation is excluded, as it is assumed that it will influence all cash flows to the same degree. Standardised financial tools, such as the NPV and IRR, are employed to assess the profitability of the different options. An investment is economically viable when the IRR is greater than the rate of return that could be earned from an alternative investment. The IRR is calculated as the discount rate that makes the NPV equal to zero (Sutherland, 2007). The levelised costs are also shown in Table 5.3.

Table 5.3 Economic performance of the biomass plants

Plant scale (ktpa)	**RSO 27**	**RSO 40**
Plant lifetime (years)	**20**	**20**
Fixed capital cost (£m) (sum of Total direct plant costs and working capital)	**32**	**36**
Total direct plant costs (£m) (sum a.)	**26**	**33**
• Equipment and machinery	-	22
• Purchased equipment and installation	-	3
• Piping and valve	-	0.6
• Electrical installation	-	2
• Instrument and control installation	-	0.5
• Civil work	-	4
• Land purchased	-	1
Working Capital (£m) (sum b.)	-	**3**
• Engineering and supervision	-	0.3
• Construction expenses	-	0.5
• Contingency (accounts payable, accounts receivable, cash kept on hand for monthly payments)	-	2
Operating cost (£m)	**18**	**25**
Biomass	-	20
Workers	-	0.5
Electrical energy consumed	-	0.44
Maintenance	-	0.5
Chemicals	-	0.4
Specialist and consultant fees	-	0.06

General insurance, taxes and expenses	-	3
Unforeseen expenses	-	2
Revenues (£m)	**22**	**38**
Electrical energy sold (€m)	9	19
Green certificates (ROCs) (£m)	0.9	4
Levy exemption certificates (LECs) (£m)	12	14
Bottom ash sold (£m)	0.7	1
Annual depreciation on capital investment (not including land) (£m)	**0.9**	**1**
Operating profit (£m) (revenue - operating costs - depreciation)	**3**	**12**
Corporation tax (£m)	**0.8**	**3**
NPV (£m)	**-13**	**76**
IRR (%)	**-2**	**23**
Levelised cost (£/MW)	**191**	**149**

The results indicate that the RSO plant is uneconomical at the smaller scale. The RSO plant has significantly high operating costs which at a smaller scale cannot be offset because the amount of energy produced and revenues generated are too low. In this model, the RSO plant is economically viable at 40 ktpa with a 23% IRR, but operating costs are difficult to predict and vary from one country to another. The sensitivity analysis discussed below shows how much they may affect the economics of the plant.

The levelised cost shows the unitary cost of electricity produced during the plant life-time. Table 5.3 shows that the levelised cost decreases as the scale of the plant increases, due to the trade-off between the amounts of electricity produced and the costs of production. The levelised cost for the RSO biomass plant at 27 ktpa is significantly higher than for the 40 ktpa, because the smaller plant makes much less energy whilst still having high operating costs. The plant is uneconomical at 27 ktpa, because it only produces 16 MW of electricity, which is not enough to offset its costs. High operating costs are seen with a levelised cost of £149/MW. In the future purchase cost of RSO may decrease resulting in turn in a decrease in the levelised cost. It should be considered that, even though the 40 ktpa plant produces higher revenues and has a low working capital, it has to pay £2.2m more corporation tax.

5.4. Economic Sensitivity Analysis

In this section, the effect of changing model input parameters on the economic performance is evaluated. The remainder of this chapter will only focus on the 40 ktpa plant because this plant is economically viable. The sensitivity analysis is a useful procedure in evaluating the model input parameters. It can then direct us to where the uncertainties lie, identifying the most influential parameters and testing the robustness of the assumptions made. Six different system variables have been chosen and the effect of a ±10% and ±30% change in these variables on the levelised cost has been examined. The sensitivity analysis was performed on the large scale plant (40 ktpa), as this was the economically viable option. Results are shown in Figure 5.2. The capital cost has been increased and decreased by 30% to see its effect on the levelised cost (Figure 5.2).

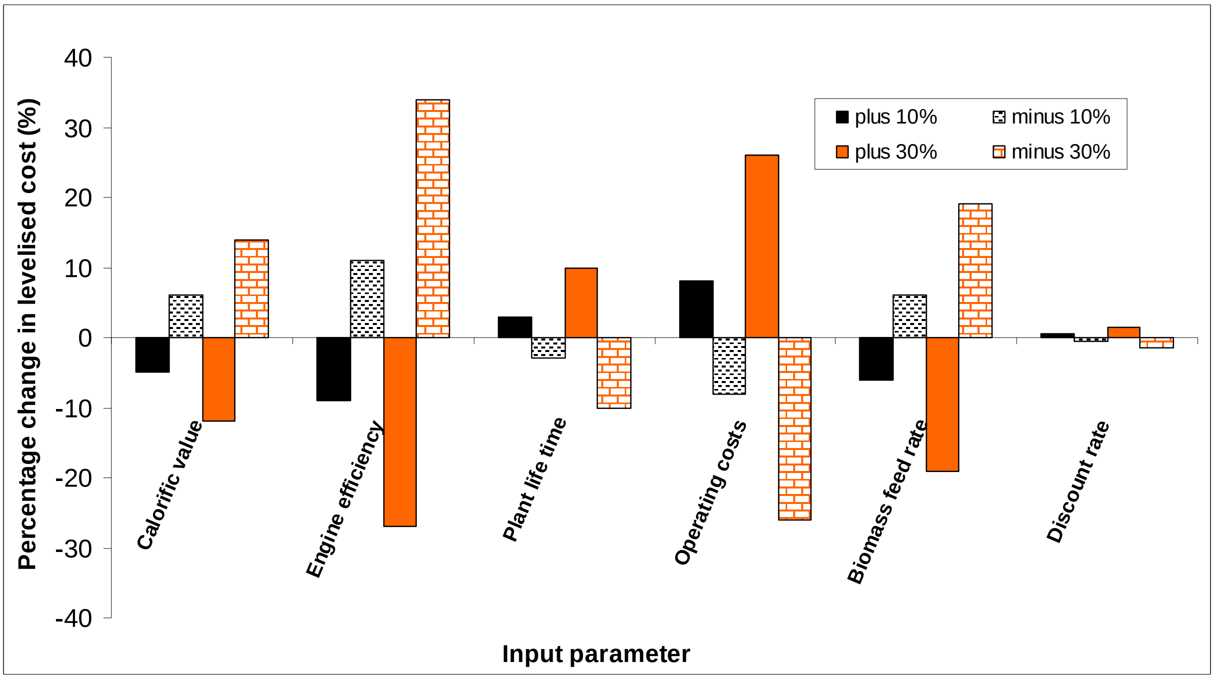


Figure 5.2 Sensitivity analysis on the levelised costs

Depending the input parameter that is changed, the levelised cost and the viability is effected by varying percentages. In order for the plant to be unviable the levelised cost would have to increase by 40% making the IRR negative. The

40% value was established through the discounted cash flow analysis, where decreasing the operating costs by 60% results in a decrease in levelised cost of 40% and a negative IRR. Figure 5.3 shows that by decreasing the operating costs by 30%, the levelised cost only decreases by 18%, further highlighting the percentage that the levelised cost must reach (at least 40%) before the plant becomes economically unviable.

5.4.1. Changes in Biomass Calorific Value

The calorific value of the biomass is an important parameter for the evaluation of the levelised costs. LHV is used to calculate the amount of electricity generated, if the LHV is high then the amount of energy produced is also high. When calculating the levelised cost per MW produced, the higher the amount of the energy produced, the lower the levelised cost. A change in the value of the LHV of ±10% shows a 5 – 6% change in levelised cost and ±30% shows a 12 – 14% change. The levelised cost does not change significantly because the revenues are able to offset the costs for the plant. A 30% decrease in calorific value still results in a positive IRR, but although the calorific value does not significantly affect the levelised cost, it is important to maintain a high value as this drives revenue.

5.4.2. Changes in steam turbine efficiency and engine efficiency

The engine efficiency is used to calculate the amount of electricity produced. Increasing and decreasing the efficiency can cause severe changes in the levelised cost. For example a 10% increase or decrease results in 9 – 11% percentage change and a 30% change results in 27 – 34% change in levelised cost. A 10% decrease in efficiency results in the plant being uneconomical. As highlighted in section 5.1, engine efficiency can be affected by a high acid number (above 5 KOH/g) in the RSO. Crude RSO has an acid number below 5 KOH/g but if monitored, it should not affect the engine efficiency.

5.4.3. Capital and Operating Costs

The capital and operating costs are very difficult to predict for the economic performance as they rely on external factors such as feed costs, labour, chemical costs, equipment costs, suppliers, plant scale, technology used and type of energy recovery system employed, as well as local area statistics. Low capital investment for the RSO plant enables three engines to be incorporated in the plant, increasing the electricity production. Low capital costs also enable the plant to install ORC circuits to recuperate waste heat, which can be subsequently sold for a profit or used within the plant itself. Low capital investment however is counteracted by the high operating costs, £25 m/year, which are due to the high purchase cost of the biomass. Changes in capital cost of 10% result in high percentage changes in levelised cost, quantified at 18%. As mentioned in section 3.3.3, capital costs and operating costs have been seen to change quite drastically from country to country and with time. As a result an elevated 30% change in capital cost was investigated in the sensitivity analysis. A 10% change in the operating costs has an influence of 8% on the levelised cost and a 30% change in the operating costs result in a 17% change in levelised cost. (Figure 5.3).

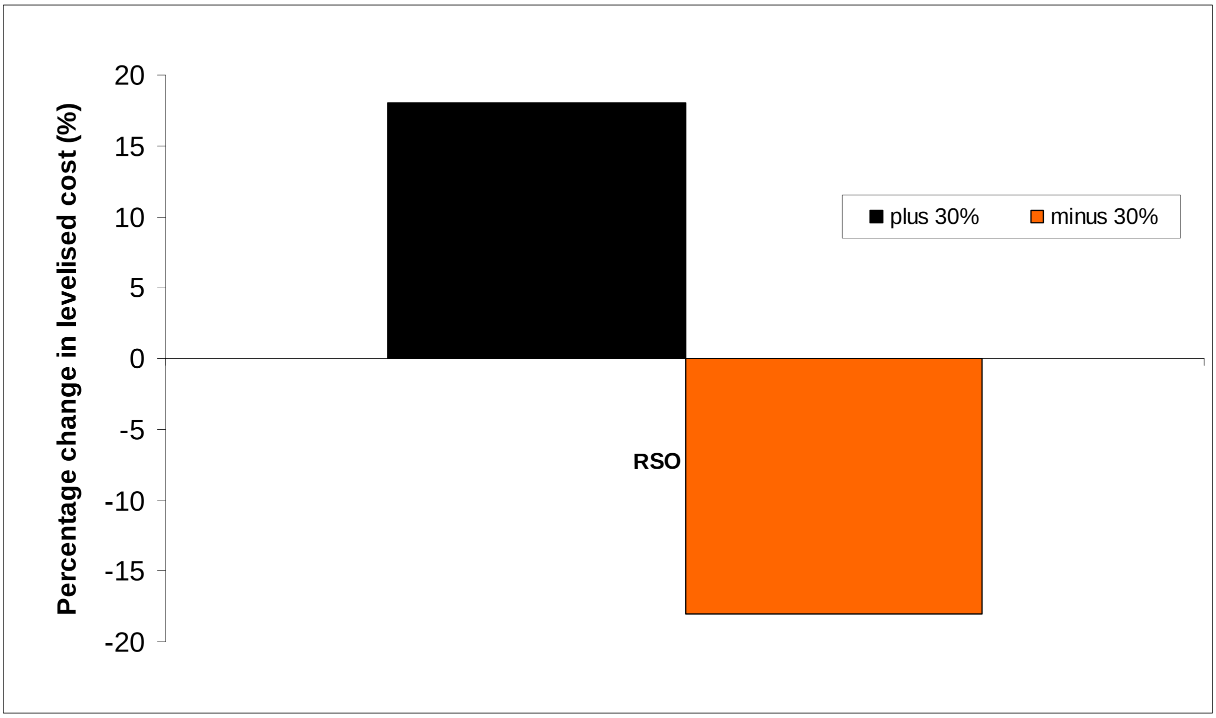


Figure 5.3 Sensitivity analysis percentage change in levelised costs by changing the capital costs by± 30%

The capital costs for the RSO plant are considered to be low compared to

FWWC and SRF combustion plants. However capital costs and operating costs in the UK are high (as demonstrated in the Table 3.4) and as a result, in the UK energy is generated at a large scale (>50MW). As plant scale increases, capital costs are outweighed by profits, therefore the larger the scale the more economically viable the plant becomes (Figure 5.4). The actual points in Figure 5.4 are not in a straight line, the reason for an uneven distribution is due to the way the electricity networks are managed to cope with the varying energy demand. The operating reserve is the generating capacity available to the system operator within a short interval of time to meet changes in demand. The operating reserve is made up of the spinning reserve as well as the non-spinning or supplemental reserve. The spinning reserve is the extra generating capacity that can be made available by increasing the power output of generators that are already connected to the power system. The non-spinning reserve or supplemental reserve is the extra generating capacity that is not currently connected to the system but that can be brought online after a short delay. As a result the costs vary depending on the operating reserve as shown in Figure 5.4. Despite the high costs in the UK, this study has proven that with Government incentives such as ROCs and LECs, these plants are economically viable at the small scale (see section 5.4.7). A sensitivity analysis is not performed on LECs because they are not a market based measure and therefore their price does not fluctuate like the ROC selling price does (see section 3.1.3.5), the LECs price is fixed by DEFRA (Defra[e], 2007). This study has also proven that the 40 kpta RSO plant is affordable, with lower investment costs in 2012 compared to 2001. This work proves that the UK may move towards affordable small scale heat and power production.

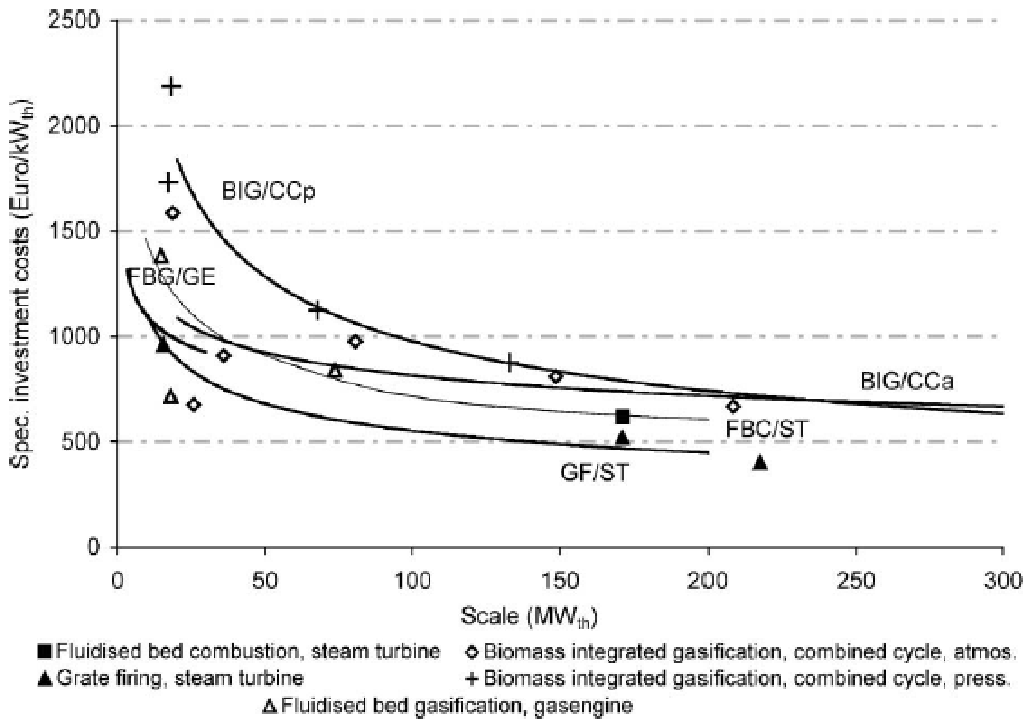


Figure 5.4 CHP capital and operating cost against plant scale in the UK

(Taken from Dornburg et al, 2001)

5.4.4. Changes in plant lifetime

The plant is considered operational for 20 years. The changes in levelised cost for the plant lifetime are small, with a 3% change in levelised costs. Changing the plant lifetime by ±30% results in a 10% difference in levelised cost for the plant. A 30% decrease in plant lifetime would make the plant uneconomical, because the plant would not be able to make enough revenue over the years to pay for its capital investment. The plant is very unlikely to increase in operational time because the machinery would need to be replaced after 20 years.

5.4.5. Changes in Biomass Feed Rate

The plant is considered to operate at full capacity. The biomass feed rate affects the amount of electricity produced and therefore the revenues received. The biomass feed rate must be used on full-scale production if the best value for levelised cost is to be achieved. The results show that if the biomass feed rate is decreased by 10% and 30%, the cost of production increases by 6% and 19% respectively. This is expected, as the plant is not utilised to its full potential, resulting in a decrease in the amount of electricity produced with no change in the cost of purchase for the biomass.

5.4.6. Changes in Discount rate

The discount rate is generally fixed and should not change. However, if the lending rate does change or a different rate is obtained, the levelised cost does not change significantly and even with a 30% increase it would result in an economically viable plant. The change in levelised cost with a 10% and 30% change in discount rate results in 0.5% and 1.5% respectively.

5.4.7. Changes in electricity selling price and ROCs selling price

The price of electricity and ROCs are subject to change. Therefore, a change in electricity price from ±10% up to ±60% is performed to analyse the effect on the IRR. Separately, a change in ROCs price from ±10% up to ±50% on the IRR is analysed. Table 5.4 shows the resulting IRR (%) from changing the electricity price.

Table 5.4 Sensitivity analysis results of percentage changes in electricity

Electricity Price	Percentage change in IRR (%)	Resulting IRR (%)
Plus 10%	+17	26
Minus 10%	-17	18
Plus 20%	+34	29
Minus 20%	-34	15
Plus 30%	+52	33
Minus 30%	-52	11
Plus 40%	+65	36
Minus 40%	-65	8
Plus 50%	+82	40
Minus 50%	-82	4
Plus 60%	+101	44
Minus 60%	-101	-0.2

The results in Table 5.4 show that the price of electricity would need to drop by 60% before the plant becomes uneconomical. In this instance the price of electricity would need to reach £42 /MW based on a current value of £105 /MW. The price of electricity has not reached £42 since 1995 and 2005 and it has been increasing since (Figure 5.5). However in 2010 there was a decrease in electricity price from £83 to £75. As a result the price of electricity is not expected to drop to £42 from current prices.

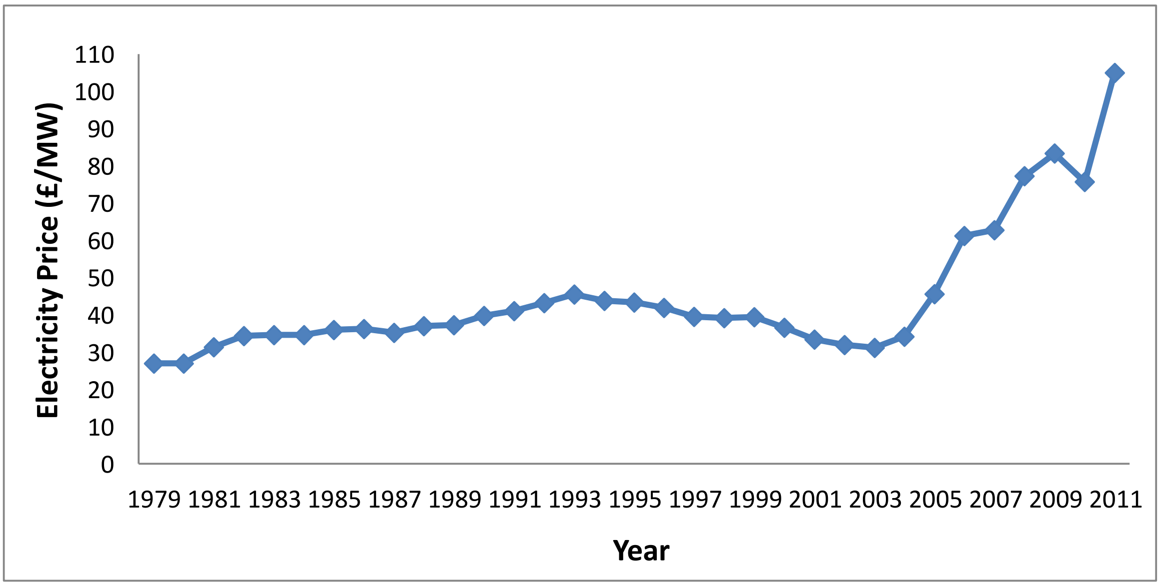


Figure 5.5 Changes in electricity price per year from 1979 to 2011

The results in Table 5.5 show that the ROC price would need to decrease by 40% before the plant would be uneconomical. The ROC price would need to reach £22.19 /MW based on the 2011 value of £36.99.

Table 5.5 sensitivity analysis results of percentage changes in ROC price

ROC price	Percentage change in IRR	Resulting IRR (%)
plus 10%	26	27.72
minus 10%	-26	16.28
plus 20%	52	33.44
minus 20%	-52	10.56
plus 30%	73	38.06
minus 30%	-73	5.94
plus 40%	100	44
minus 40%	-100	0
plus 50%	121	48.62
minus 50%	-121	-4.62

The RO scheme came into action in 2002 and since then the value of the ROC has never dropped below £30 /MW (Table 5.6). The ROC buy out price is set depending on the year’s retail price index. If the index decreases then the ROC buy out price will decrease, depending on the price of a ROC for the previous year. Table 5.6 shows the ROC prices are increasing year on year except for year 2011, where it had decreased by 20p. Data shows that, unless the retail price index decreases dramatically, the ROC prices will either stay stable or increase.

Table 5.6 ROC buy out prices per year from 2002 to 2013

Obligation period (1st April – 31st March)	Buy-out Price (£)
2002-2003	30.00
2003-2004	30.51
2004-2005	31.39
2005-2006	32.33
2006-2007	33.24
2007-2008	34.30
2008-2009	35.76
2009-2010	37.19
2010-2011	36.99
2011-2012	38.69
2012-2013	40.71

5.5. Conclusions

RSO is a form of biomass that can be used to produce electricity in internal combustion engines. In recent years, the production of RSO in the UK has increased greatly as it serves as a break crop and can be used for the production of electricity.

Techno-economic analysis of RSO combustion was performed at Germanà & Partners Consultant Engineers in Rome, Italy. This study investigated the design of a 27 ktpa and a 40 ktpa RSO plant with 57% and 58% overall efficiency respectively. The 40ktpa plant is economically viable with a 25% IRR, whilst the 27 ktpa plant is uneconomical with an IRR of -2%. Although only the 40 ktpa plant was economically viable, when put into context, this plant is still a small scale plant compared to energy production plants in the UK (>50 MW). Large plants are popular in the UK because they are considered the most economically viable solution, mainly due to high capital and operating costs. However this study has shown that small scale plants are economically viable, mainly due to incentivised schemes such as the RO and LEC's.

The results of the sensitivity analysis indicate that the main parameter affecting the levelised cost for the plant are the operating costs with 8% - 26% change when changing the operating costs by ±10% or ±30%. The calorific value of the feed and the engine efficiency have a smaller effect. When changing the operating costs by 10% or 30%, the differences in levelised costs, were significant. This is due to the purchase cost of the RSO. In the future, costs for feeds may change depending on how the market develops and RSO prices may decrease as competition from suppliers take place. The sensitivity analysis shows that the ROC buy-out price and electricity selling price would have to decrease by 40% and 60% respectively, before the plants will no longer be economically viable. This result shows that government incentives are the key to render such renewable energy plants feasible. The price of electricity would have to decrease to £42 to become uneconomical. Analysing past data shows electricity prices do fluctuate but have not been down to £42 since 2005. The buy-out price of a ROC would have to decrease to £22.19 to become uneconomical; however the buy-out price of a ROC has never been lower than £30.00 so far.

This plant produces both electricity and heat. Generally in the UK energy plants are large scale >50 MW and the novelty of this study is investigating small scale energy production. This plant has the benefit of producing economically viable electricity and recuperating heat which can be used in small towns and cities close to the plant through a district heating connection as happens in Sweden and Denmark. These plants have been functioning in Europe for many years due to the low costs of establishment. Despite high capital costs in the UK this work proves that energy from RSO at a scale of 40 ktpa is economically viable and the heat produced can be used by local towns and cities through district heating. Over the past nine years, Government has been incentivising district heating connections through schemes such as the carbon emission reduction target (CERT) and the community energy saving programme (CESP) (see section 2.1).

The work presented in this chapter is further developed to assess the environmental burden of the large scale RSO plant. The technological assessment is used to calculate the energy required at each stage of the processing plant.

5.6. Case study: Life cycle assessment of energy from RSO at medium scale

The LCA presented in this case study provides information about the consequences of changes in how we use our land, arising from the output, consumption and disposal of RSO. This type of LCA is called a consequential LCA (CLCA) and this CLCA investigates the change in total emissions as a result of a marginal change in the production of a product. CLCA investigates the consequences of changes to current practice when introducing new systems. As a result system expansion is used to compare in account for consequences in implementing the new system. CLCA uses marginal data and so, this study uses marginal carbon intensity of the electricity grid and more specifically, coal and natural gas. A comparison of energy from RSO with energy from coal or natural gas is also investigated. The marginal conversion factors are sourced from the BEATV2.

5.6.1. Goal and Scope Analysis

The goals of the LCA are to:

- Discover what is the overall environmental burden of energy production from RSO using internal combustion engine technology?
- Determine which activities in the chosen life cycle contribute most to the environmental impact associated with energy from RSO using internal combustion technology?
- Compare the base case scenario of keeping set aside land or growing rapeseed on that land.
- Investigate what is the environmental consequence of growing rapeseed on set aside land to subsequently be used to produce energy?
- Compare the environmental impact of energy from alternative fuel producing the same amount of energy to the chosen system boundary

The functional unit for this study is 1 MJ of electricity. LCA is performed to assess the environmental impact of this process technology and discuss some of the social aspects that may arise when using RSO for energy production. The process investigated is an internal combustion engine utilising 40 ktpa of RSO with ORC heat recovery technology. Land use represents temporary carbon sinks. Since the embodied carbon is retained outside the atmosphere for a period of time, some radiative forcing is postponed (radiative forcing is a measure of the influence that a climate forcing factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system). The method of counting for temporary storage is an on-going one. This study uses the Moura-Costa and Wilson (2000) method of accounting for carbon sequestration and storage on a t CO_2-eq per year basis (see section 5.6.2).

In this study RS is grown on set aside land and subsequently processed into RSO and used in diesel engines to produce energy. The amount of set aside land in England at present is around 400,000 hectares, where one hectare of land can produce 3.5 tonnes of RS. Therefore this study assumes that the RS will be grown on set aside land and as a result this will not interfere with current crops produced for food consumption.

Hot-spot analysis is used to define the unit operations within the LCA that contribute to high emissions. The environmental burdens are calculated and compared with energy from coal or natural gas at similar production scales.

The calculation methodology used for the transport boxes in Appendix 3 is the same used for the FWWC plant as shown in section 4.1.1.1.

The system boundary includes power production and heat recovery, crushing hot pressing and solvent oil extraction and transportation of oil to the power production facility. This would make up the foreground system i.e. those processes on which measures may be taken concerning their selection or mode of operation as a result of decisions based on the study. Production of energy from an alternative fuel, harvesting, cultivating, sowing seeds and rolling soil, nitrogen fertiliser application and harvesting using direct cutting technique, all form the background system i.e. all other modelled processes which are influenced by measures taken in the foreground system (see Figure 5.6).

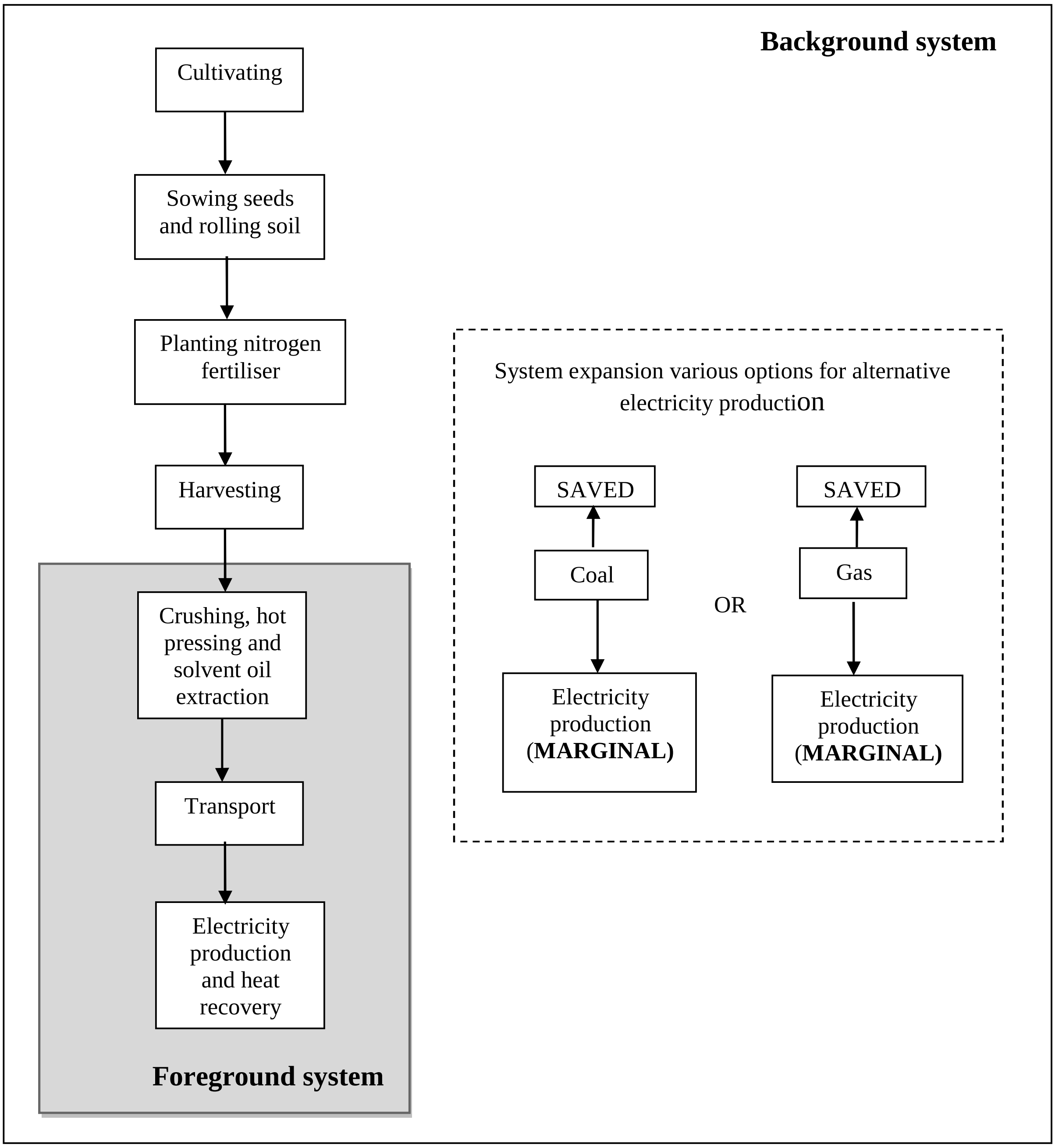


Figure 5.6 System boundary and sub-systems for the RSO plant

5.6.2. Inventory Analysis

The foundation of the LCA calculations resides in energy calculations for the RSO plant. BEAT$_V$2 was used to provide conversion factors expressed in terms of CO_2, CH_4 and N_2O for the energy utilised in each box shown in Appendix 3, which are reported in Table 5.8. The N_2O for farming practice is also reported below in particular fertiliser application. The following section explains how the amount of CO_2, CH_4 and N_2O released was calculated in all of the boxes described in Figure 5.6 and shown in Appendix 3. In addition to the energy calculations shown in Chapter 4, specific energy calculations for the production of RS are shown below:

Production of RS and RSO

This process involves:

- Cultivation (with power harrow) – 199 MJ/ha
- Fertiliser application (N_2O) – 102 MJ/ha on the basis of spreading fertiliser twice a year of 211kg/ha (the N_2O contribution to the E_{GWP} of this study from fertiliser application is considered in this study)
- Top dress – 102 MJ/ha
- Pesticide application – 393 MJ/ha
- Combine harvesting – 1210 MJ/ha
- Minus sequestered carbon from RS and displaced wheat – (-) 97 kgCO_2equ/yr

This study uses the Moura-Costa and Wilson (2000) method of accounting for carbon sequestration and storage on a kg CO_2-eq per year basis. The Moura-Costa approach uses the value of 48 tonne-years of CO_2 to calculate an equivalence factor between radiative forcing, carbon sequestration and temporary storage. Table 5.7 shows the characterisation factors applied to different time frames, this study uses GWP_{100} logic applied throughout the thesis.

Table 5.7 Characterisation factors for carbon storage on GWP

	GWP_{20}	GWP_{100}	GWP_{500}
1 tonne-year carbon dioxide	-(1/14.6) = - 0.074 t CO_2equ	-(1/47.8) = - 0.021 t CO_2equ	-(1/157.3) = - 0.006 t CO_2equ

In this approach, sequestration from the atmosphere and storage in the biosphere (plant biomass and soil) of 0.48 tonne of biogenic CO_2 for 100 years is the equivalent factor to avoid the radiative forcing of a pulse-emission of one tonne of CO_2 integrated over 100 years. Therefore biogenic carbon sequestration and temporary storage can compensate for the impact of fossil-carbon emissions to the atmosphere in a way consistent with the GWP_{100} logic.

The GWP_{100} logic is used throughout this thesis and as a result, the Moura-Costa and Wilson approach is adopted in this study. In this way, sequestering and storing carbon is accounted for consistently, regardless of when that sequestration and storage occurs in the life cycle of the product. However there is a limitation to this method; by choosing a fixed time horizon, it is assumed that this time period is critical and that it is important to look mainly at the impacts during this particular period. In my opinion, considering the uncertainty of technology and circumstances after the 100 year period it is reasonable to use this time frame. After 100 years we may be more equipped to deal with changes in land use and the release of sequestered carbon, with improvements in technology and in the general understanding of sequestration. Additionally a long time period can be selected (500 years), or even a smaller time frame (20 years). In my opinion the consequences of using a 20 year time frame, is that this time frame is too short to truly understand any changes in emissions or the consequences of changes in processes that have an effect on the emissions that are reported in a 20 year time frame. Whilst a time frame of 500 years, in my opinion is too large because many changes may occur in terms of policy and as a result how we manage our energy production, potentially resulting in misreporting. The approach used in this study counts each year equally, and is therefore being a consistent methodology and in line with the GWP_{100} used throughout this study. In addition, using this methodology allows us to account for carbon in a dynamic way, for example if in the near future new studies emerge and we find out that the amount of carbon released of time is not what we had thought, the amount of emissions per year can be easily corrected.

Figure 5.6 shows the system boundary for producing RS for energy production. RS is grown on set aside land. Figure 5.7 shows the original purpose of the land which is set aside (base case) and the option of using the set aside land to produce RS.

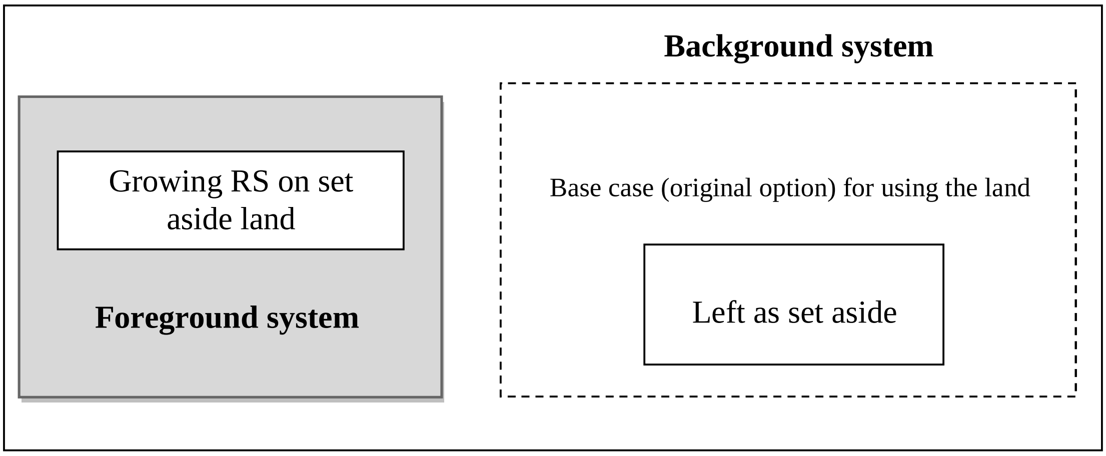


Figure 5.7 System boundary for growing RSO on set aside land and the base case option on leaving the land as set aside

The E_{GWP} for energy from RSO is compared to the base case scenario where land is left as set aside.

The E_{GWP} of the base case compared to the E_{GWP} of energy from RSO is shown in Figure 5.8. The results presented of the base case in Figure 5.8 is the E_{GWP} of the sequestered carbon from not producing RS on set aside land, whilst the Energy from RS bar is the emissions from producing energy from RS and the sequestered carbon from growing RS rather than leaving the set aside land bare (explained further below).

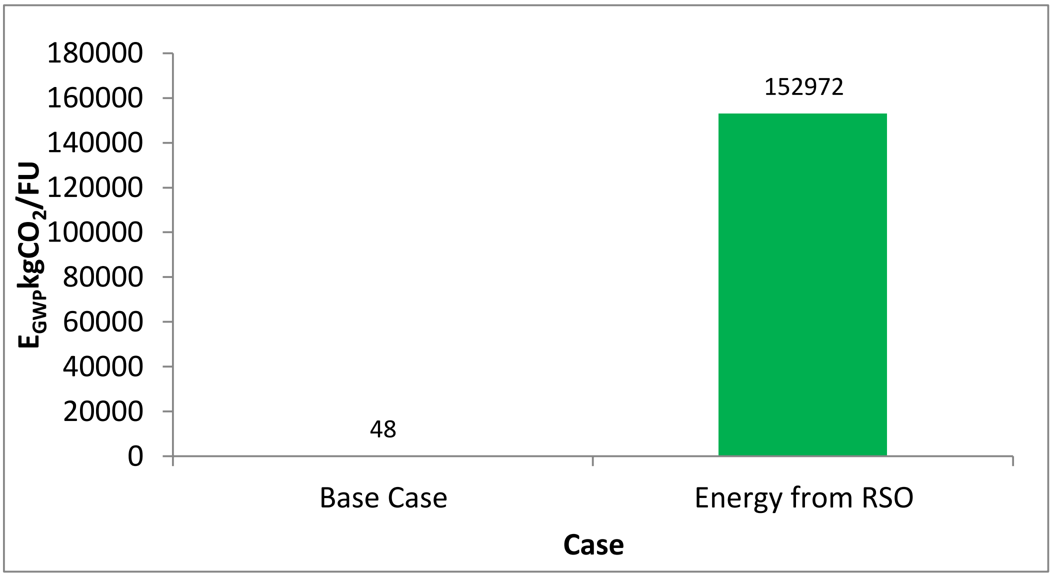


Figure 5.8 Base case versus Energy from RSO

Figure 5.8 compares the base case where emissions from sequestered carbon from growing RS would no longer be grown because the set aside land is left bare. In the base case the RS is not being grown and as a result would not be sequestering carbon. Therefore the base case value includes an addition of the carbon (as emission) that would have been sequestered by growing RS (avoided burden). The energy from the RSO case includes a subtraction of the amount of sequestered carbon from growing RS on the set aside land.

By growing the rapeseed the following steps are included; crushing hot pressing and solvent oil extraction use 158 MJ/t of energy per tonne of rapeseed supplied from the national grid ($BEAT_V2$, 2009). Once the volume of diesel utilised in each box of Appendix 3 is calculated, this value is multiplied by the corresponding conversion factor for CO_2 or CH_4 or N_2O (Table 5.8). The conversion factors are taken from the $BEAT_V2$ tool, developed by the Atomic Energy Agency (AEAT) and Defra. The tool uses data from actual plants and case studies and is considered a reliable and accurate source ($BEAT_V2$, 2009).

Table 5.8 shows the energy used in each box presented in Appendix 3, whilst conversion factors used to calculate the emissions released were taken from $BEAT_V2$, (2009) and are also presented in Table 5.8.

Table 5.8 Energy used for boxes in the RSO plant

Boxes	Energy (MJ)	CO_2 (kgCO2/MJ)	CH_4 (kg CH_4/MJ)	N_2O (kg N_2O/MJ)
Cultivating	796	13	0.02	0.002
Fertiliser application	407	7	0.01	0.005
Pesticide application	176	26	0.04	0.004
Top dress	407	7	0.01	0.0001
Combine harvesting	2800	80	0.1	0.002
Crushing, hot-pressing and solvent oil extraction	2054	0.15	0.0004	-
Transport	96	0.07	0.0001	-
Diesel engine	310	0.03	0.00001	-
Heat exchanger 2	112	0.03	0.00001	-
Lubrication oil pump	25	0.03	0.00001	-
Compressor	200	0.03	0.00001	-
Heat exchanger 1	170	0.03	0.00001	-
Heat exchanger 4	172	0.03	0.00001	-
Pump 1	18	0.03	0.00001	-
Vaporiser 2	180	0.03	0.00001	-
Turbine 1	186	0.03	0.00001	-
Generator 1	146	0.03	0.00001	-
Condenser 2	134	0.03	0.00001	-
Organic fluid pump	32	0.03	0.00001	-
Heat exchanger 3	122	0.03	0.00001	-
Heat exchanger 5	117	0.03	0.00001	-
Vaporiser 1	180	0.03	0.00001	-
Heat exchanger 6	130	0.03	0.00001	-
Pump for thermal oil	47	0.03	0.00001	-
Turbine 2	186	0.03	0.00001	-
Generator 2	150	0.03	0.00001	-
Condenser 1	135	0.03	0.00001	-
Pump for organic fluid	18	0.03	0.00001	-

5.6.3. Impact Assessment

The E_{GWP} is now calculated for the energy utilised in each box. E_{GWP} are equal to the sum of emissions of the greenhouse gases, CO_2, CH_4 and N_2O where these are multiplied by their respective global warming potential classification factors (Azapagic et al., 2004) as expressed in Eq (19). Total global warming emissions are then calculated using Eq (18) to Eq (20).

The values of E_{GWP} calculated for the RSO plant were compared to those obtained for non-renewable coal or natural gas plants of similar scales. The emissions for the RSO plant are those that use non-renewable types of fuel such as grid electricity and diesel oil in machinery. The results are presented in Figures 5.9.

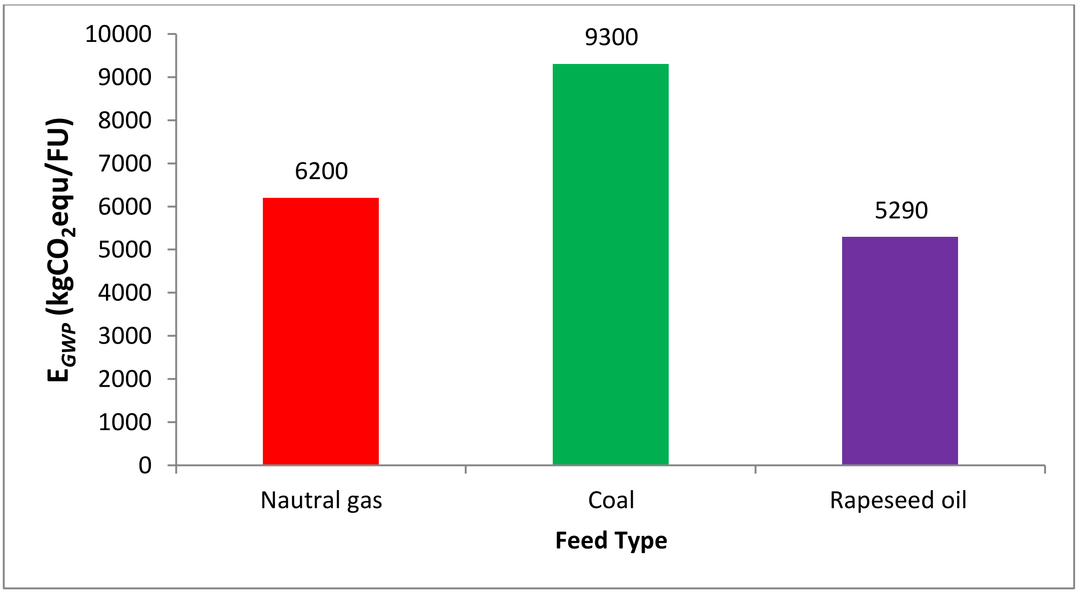


Figure 5.9 E_{GWP} of RSO compared with coal and natural gas

Figure 5.9 shows RSO plant releases fewer emissions than coal and natural gas. This comparison is developed further in Figure 5.10, where the results take into consideration energy displacement and therefore avoided burdens, i.e. the emissions produced from the non-renewable energy plants and those that have been avoided by operating the RSO plant instead. The conversion factors for the non-renewable plants were taken from Defra's annual conversion factors for company reporting (Defra[i], 2009). The conversion factors for the non-renewable energy plants are reported in Table 4.3 (see Chapter 4).

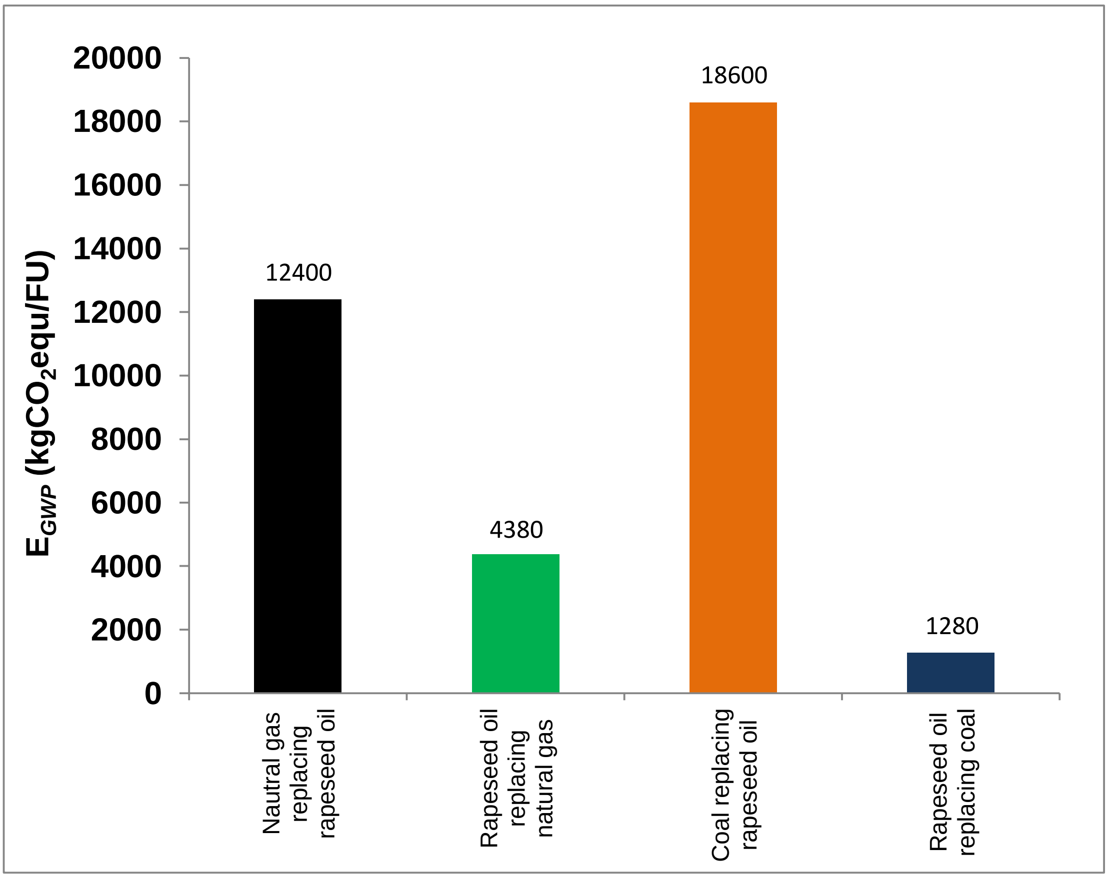


Figure 5.10 E_{GWP} of RSO compared with coal or natural gas plants of similar scales including emissions displacement

Figures 5.10 shows that the values for E_{GWP} are always less than those for the non- renewable alternatives. From a sustainable point of view, the results show that the RSO plant is both economically and environmentally viable. In order for the RSO plant to remain environmentally favourable compared to non-renewable alternatives, it must be administered in the same way as presented in this study, which includes using the farming methods as described in this study. If conventional tillage is used, then the emissions will increase for the energy from RSO plant and could affect the conclusions made in this study.

Hot-spot analysis for the plant was also conducted to quantify the CO_2 emissions released from each unit. This analysis isolates the different processes for energy from RSO and can be used to understand from where the most emissions are released. The hot-spot analysis results are shown in Figures 5.11.

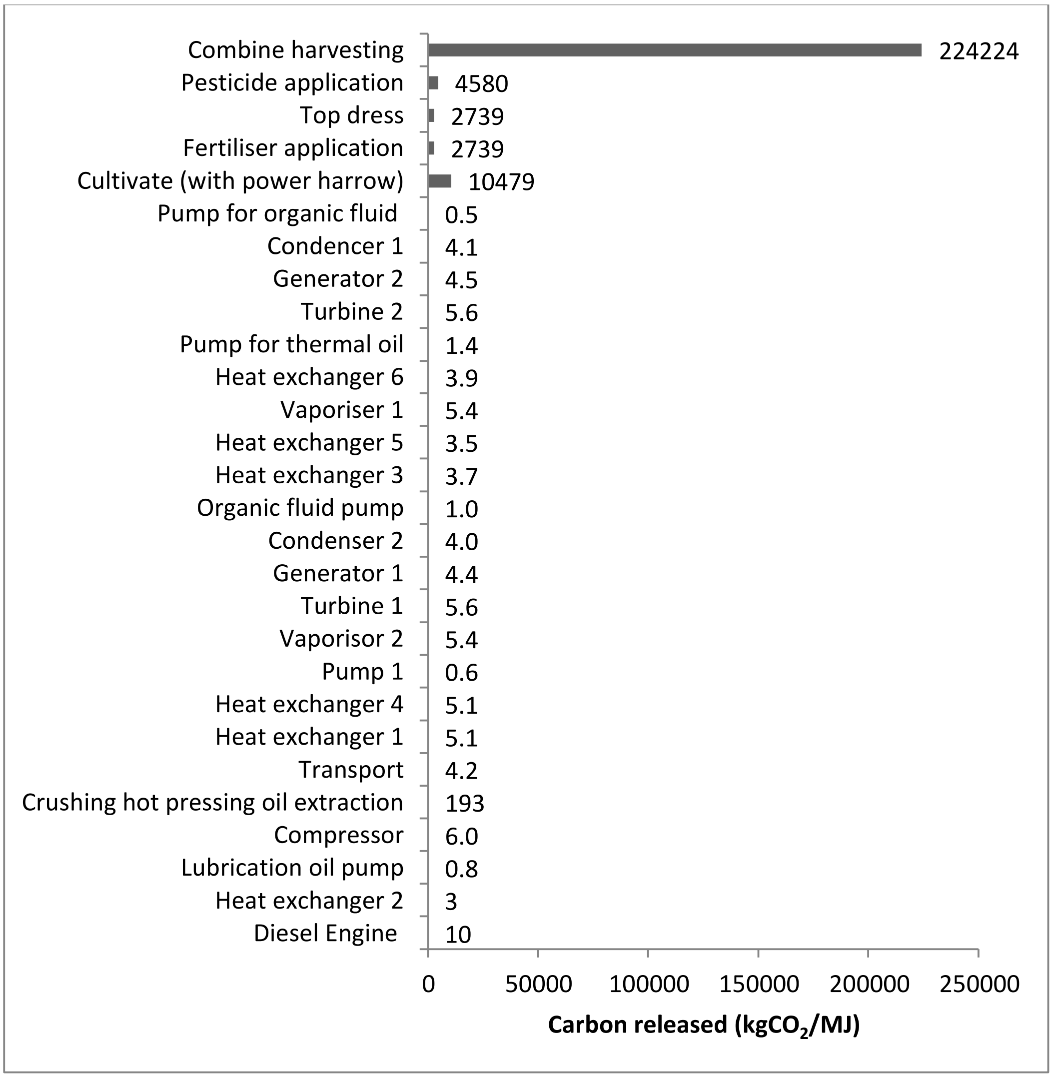


Figure 5.11 Hot-spot analysis for the RSO plant

The hot-spot analysis shows that the units contributing most to CO_2 emissions are those employed for the production of the RS. More specifically, combined harvesting contributes 224224 $kgCO_2$/MJ and cultivation is quantified at 10479 $kgCO_2$/MJ. This analysis demonstrates the importance of defining the type of farming to be used when producing RS for energy conversion. In this study reduced tillage (RT) methodology is used to produce RS. There are two methods of cultivation and they affect the amount of carbon released during production. RT minimises soil disturbance and allows crop residues or stubble to remain on the ground instead of being thrown away or incorporated into the soil.

The benefits of RT are savings on machinery use, fuel, labour time, improved soil structure, better soil aeration and improved soil fertility. CT is a tillage system using cultivation, with methods such as ploughing and harrowing, to produce a fine seedbed. The benefits of CT are a loosening of the soil (which allows for deeper penetration of roots), control of weeds and mixed organic matter and closer mixing of fertiliser and manure with the soil.

The LCA in this study considers only the RS grown using the RT methodology. If conventional tillage is used, then the emissions from RS production will increase and could result in higher emissions then energy produced from natural gas. We must ensure appropriate land and farming methods are used, resulting in fewer emissions without compromising the land or resulting crops. From a social point of view, although the rapeseed is grown on set aside land there are still concerns that inappropriate land (such as forests and grass land and land that should be used for food) is being replaced with rapeseed, resulting in negative image in the eyes of the public and resulting in emissions from carbon that would no longer be sequestered by forests and grass land (see Chapter 2). As a result we must ensure RS is produced sustainably. In addition the LULUCF (See Section 2.2.2) will hopefully be developed to include a quantitative methodology of accounting for carbon avoided burdens in the future though policy. LULUCF is seen as having potential for additional emission reduction. Therefore if policies are developed to maintain and restore natural carbon sinks, we can ensure that we will be able to produce sustainable RS and account for avoided burdens in a comprehensive and controlled way in the future. This activity will help to provide confidence in the production of energy from RS and other grown crops.

As with the FWWC plant and the SRF plants investigated in Chapter 4, the emissions from transport are minimised in this study by ensuring that the plant is situated only 20 km away from the RSO production facility (Figure 4.9). In addition, the RSO plant produces heat to be distributed to a small town or city through a district heating connection. To date, to be economically viable, most energy generating plants are large scale in the UK and as a result the plants are situated far away from towns and cities, making district heating connections and small scale plants difficult to promote and set-up. This study proves great savings can be achieved environmentally in terms of transport by situating plants close to the area RSO production facility and the towns and cities that will receive the heat and electricity produced.

5.7. Conclusion

This section investigated the techno-economic and LCA of energy from RSO using internal combustion engine technology of small (27 ktpa) and medium scaled (40 ktpa) plants. A techno-economic assessment was carried out on the 40 ktpa scale plant based on a plant in the design phase in Italy. This plant was then scaled down to 27 ktpa to investigate its techno-economic performance. The technical assessment was carried out to determine the plant efficiency and power output. The economic assessment was carried out to assess their economic viability, as part of the sustainability triangle. The results demonstrated that the 40 ktpa plant was economically viable whilst the 27 ktpa scale plant was uneconomical, because the costs of the plant could not be covered by the revenues obtained. As a result, a consequential LCA of energy production from the 40 ktpa scale plant was conducted. The system was expanded using marginal data to compare to traditional fossil fuels such as coal and natural gas plants. The results showed that the RSO plant was more environmentally friendly than the alternatives investigated.

This work proved it is economically and environmentally viable to produce electricity and heat in the UK at small scales. These plants can be used to supply heat through district heating networks, which are being installed in the UK through Governmental programmes such as CERT and CESP. The UK commonly produce electricity in large scale plants (>50 MW) because of high capital and operating cost here. However this work has proven novel small scale plants can be established in the UK using RSO as a feed source.

In conclusion, under the conditions and assumptions made in this study, energy from RSO is a sustainable and viable option compared with non-renewable alternatives and can contribute to future energy production.

6. Results and main conclusions

The main objectives of this research were to investigate the techno-economic and life cycle assessment of different types of biomass, more specifically MSW and FWWC combustion using steam turbine technology for energy production. MSW and FWWC were chosen as viable options in the UK because we have an underutilised supply which is currently sent to landfill. In addition, the implications of generating energy from a mixed form of waste (MSW) and for a single waste source (FWWC) are discussed. Separately investigated is RSO, a liquid form of biomass which is grown and processed to produce energy. RSO production in the UK has been increasing, its main use being to produce bio-diesel as RSO can be used in internal combustion engines to produce electricity and heat. RSO is better used in an internal combustion engine for energy production rather than the alternative route of producing bio-diesel via transesterification, followed by pyrolysis and combustion. This method requires pre-treatment of the RSO before being processed into bio-diesel, followed by energy production. In this thesis, the method adopted utilised crude RSO and eliminates the bio-diesel production units, resulting in a simple process flow sheet.

A techno-economic assessment of small to medium scale MSW, FWWC and RSO plants was investigated; this was done to inform the subsequent environmental impact analysis by identifying the plant scale at which a LCA would be undertaken.

Within this framework, the thesis began with a comprehensive assessment of renewable energy and policy in the UK, followed by a review of the use of biomass for energy production. The UK Biomass Strategy is presented; this has led to a focus on the three types of biomass investigated: MSW and FWWC (second generation) and RSO (first generation). Issues related to food vs. fuel and lands vs. fuel were discussed in particular for the second generation biomass.

Advanced thermal treatment processes, namely pyrolysis, gasification and combustion are presented. Although pyrolysis and gasification have various advantages, this thesis focuses on combustion, which in the UK is considered a more bankable option than other advanced thermal treatments for the processing of biomass.

The technology and scales for the FWWC plant were investigated during my first visit to Germanà & Partners Consultant Engineers in Rome (Italy) in 2009. The main aim of my placement was to gain an in-depth understanding of the design methodologies and engineering principles applied in the detailed design of industrial scale energy recovery plants. The work facilitated energy and efficiency calculations on a 160 ktpa FWWC combustion plant using steam turbine technology. The techno-economic performance of a 100 ktpa MSW combustion plant was extracted from a previous study by Yassin et al., (2008) to analyse the implication of treating 1st or 2nd generation waste biomass. The economic data has been updated in the current study. During my second visit to Germanà & Partners Consultant Engineers in 2010, a 40 ktpa RSO plant was investigated to determine energy production and efficiency of the plant.

A consistent methodology was adopted to investigate the techno-economic performance of the plants. Two different scale scenarios of 50 ktpa and 100 ktpa plant capacities were considered for the SRF combustion plant as identified by Yassin et al., (2008). Three different scenarios of 50 ktpa, 80 ktpa and 160 ktpa were considered for the FWWC plant. Initially the FWWC plant was scaled down to 50 ktpa as for the SRF plant, followed by a scaling down to 80 ktpa to employ a consistent methodology of scaling down by the same ratio (half the size of the medium scale plant) as for the SRF plant. Two different scale scenarios of 27 ktpa (two engines) and 40 ktpa (three engines) were investigated for the RSO plants. The cost effectiveness of the plants was assessed using a discounted cash flow analysis. Additionally, a sensitivity analysis was performed to identify the most influential model input parameters and test the robustness of the assumptions made.

Life cycle assessments were developed from scratch to investigate the environmental impact of the larger scale MSW, FWWC and RSO plants. The energy calculations from the technical assessments were used to determine the energy used at the combustion plants to produce electricity and heat. The three plants investigated have different unit operations and the levels of complexity vary. An attributional LCA was investigated for the FWWC plant and the SRF plant and a consequential LCA was investigated for the RSO plant. Conversion factors for CO_2 and CH_4 were obtained from BEATV2. The results of the LCA for the FWWC and SRF renewable biomass plants were compared to non-renewable energy from coal and natural gas; the RSO plant was compared to an electricity mix plant at a similar scale. Additionally, a landfill reference system was investigated for the SRF plant and a comparison made of energy from FWWC using harvested forest wood left on the forest ground. The RSO plant also investigated changes in land use, specifically if rapeseed is grown for energy production.

6.1. Results

The main results from this research are summarised below:

- The thesis presented a review of the various types of biomass, both solid and liquid. Biomass can be categorised as first generation for feeds such as food crops, where the biomass is grown and subsequently used for energy production. Second generation biomass includes feeds such as MSW, forestry residue and non-food energy crops. Second generation biomass such as MSW and forestry residue, benefit from avoiding the food vs. fuel and land vs. fuel debate, whilst also avoiding the use of landfill and resulting in a better waste management option. MSW also has the benefit of being processed into a higher calorific value fuel for SRF.
- First generation biomass benefits from high calorific value creating more energy. However, unless the method of biomass production is monitored sufficiently, it can be negatively impacted by public perception because of the food vs. fuel and land vs. fuel debate as it is potentially using land that could be used to produce food. Although the UK Biomass Strategy explains that a large amount of biomass will need to be imported to the UK for energy production (the exact amount is not yet determined), it is important to efficiently use the biomass resources already available in the UK. As a consequence, this research focused on case studies that can be applied to the UK and were based on national biomass

resources, specifically MSW, FWWC and RSO that are applicable in the UK context.

- The public perception of energy of biomass is less than favourable and has to some extent hindered the development of energy from this source. However with more studies being published and the Government backing, this method of energy production, particularly through the UK Biomass Strategy and Government bodies such as DECC, Ofgem and Defra, renewable energy from biomass is becoming a key to the future strategy to tackle climate change. Additionally, the increased publicity for climate change has helped sustainable energy production to move up the political agenda and the public are starting to embrace the need for efficient affordable and environmentally-favourable renewable energy. The Government has further shown its commitment to energy from biomass and energy efficiency through schemes such as CESP and CERT, where an eligible measure for obligated parties is district heating.

- The literature review of combustion and more advanced thermal treatment processes, including gasification and pyrolysis, reveals that combustion processes are the most established, when processing biomass and consequently energy from biomass technologies in the UK are predominately combustion processes. These systems are well proven worldwide, are available from credible suppliers with a proven track record and benefit from a proven track record in controlling emissions. Reciprocating engines are also a long established technology and have been used extensively since the nineteenth century. These types of heat engines have a higher efficiency and meet the requirements of industry and transport. The great advantage of these engines is that they are compact, operated without a boiler and other auxiliary devices and crude RSO can be used directly in the engine. Due to their compact design and low capital investment, internal combustion engine plants also benefit from the option of installing an Organic Rankin Cycle unit which recuperates heat that can then be sold for revenue or recycled within the plant itself. Although combustion technology is very successful with non-renewable fuels in the UK, it is vital to assess the techno-economic viability of producing energy from biomass as a function of plant scale and feed used. In the UK, energy plants are generally large scale (>50MW) because at this scale plants are generally economically viable.

- The case study presented in Chapter 3 investigated the techno-economic assessment of SRF and FWWC combustion using steam turbine technology at different scales. The SRF plants were based on previous work conducted by Yassin et al., (2008), where 50 ktpa and 100 ktpa capacity plants were investigated. The FWWC plant was investigated at 50 ktpa, 80 ktpa and 160 ktpa. The FWWC plant was scaled down to 50 ktpa as in the SRF plant study and then for consistency of ratio, scaled down to 80 ktpa. The technical assessment includes calculations for electricity generation and overall system efficiency. The economic viability of the different plants was investigated through a discounted cash flow analysis. The levelised cost is used to calculate the cost of production of one unit of electricity. The effect of changing model input parameters on the economic performance was evaluated. Seven different system variables have been chosen and the effect of a 10% and 30% change on the levelised cost was examined.
- At 50 ktpa and 100 ktpa, the SRF plants produce 5 MWe and 13 MWe respectively. At 50 ktpa, 80 ktpa and 160 ktpa, the FWWC plant produces 5 MWe, 8 MWe and 17 MWe respectively. The overall efficiency for the 50 ktpa SRF plant was 26% and for the 100 ktpa plants 28%. For the FWWC plants the efficiencies were 50 ktpa at 26%, 80 ktpa at 27% and 160 ktpa at 28%. The SRF plants are economically viable at both scales in light of the low operating costs, with a positive 10% IRR for both cases. The FWWC biomass plant is only economically viable only at the larger scales (with 17% IRR), whilst the smaller 50 ktpa FWWC plant has a -3% IRR and the 80 ktpa FWWC plant has a -5% IRR. These results suggest that the SRF plant is the most flexible in terms of scale. SRF can be utilised to produce energy and it has a high calorific value, however it is still a mixed waste stream and as shown by the economic assessment, it requires £100,000 more for chemicals and an additional 1 £m in capital investment for neutralisation of contaminants such as chlorine, sulphur and NOx.
- The results of the sensitivity analysis indicate that the main parameter affecting the levelised cost for the SRF plant is the turbine efficiency. A change of 10% or 30% for the turbine efficiency causes a variation in levelised cost of 25% to 40% respectively. The variables most affecting the FWWC biomass plant are the calorific value of the biomass, with a 9% to 40% change in

the levelised costs when changing the calorific value by 10% or 30%. A change in the operating costs causes a variation in levelised cost ranging between 7% to 20%. The operating cost changes for the FWWC plant changed more than the SRF plant, due to the purchase cost of FWWC.

In the future, costs for feeds may change as the market develops. SRF may no longer have a gate fee and charge for its use instead; FWWC prices may decrease as competition from suppliers takes effect. If this was to occur in the future, small scale FWWC plants may become economically viable. The sensitivity analysis shows that if the ROCs and electricity selling price decreases below 10%, the plants will no longer be economically viable, demonstrating that government incentives are vital to the development. In the UK capital and operating costs are known to be high, leading to large scale plants becoming the norm (>50MW). However with incentives for the use of biomass, small scale (<50MW) energy plants can become economically viable.

- The techno-economic assessment formed the basis for the LCA of the 100 ktpa SRF plant and 160 ktpa FWWC. The LCA's of energy from FWWC and SRF provide information about the impacts of the processes used to produce, consume and dispose of electricity. The EGWP for the energy from FWWC was compared to a base case scenario where the forest wood is thinned and left in the forest to decompose along with other debris. This is a common practice which helps to sequester carbon, increase other soil nutrients and also improve the forest habitat. The results showed that production of energy from FWWC results in a significantly higher global warming potential than the base case scenarios. This would be expected, as the base case scenario does not have as many units; however, these results did not include carbon from the avoided burdens generated by a non-renewable plant.

As a result of the above, the E_{GWP} calculated for the FWWC plant were compared to those obtained for a non-renewable electricity mix plant of a similar scale. The results showed that the renewable plant is both economically and environmentally viable. The comparison was developed further when the results took into consideration energy displacement, i.e. the emissions generated from the non-renewable energy plants that have been displaced by operating instead the biomass plants under investigation. The base case and the energy from FWWC plant was compared to the electricity mix plant and included energy displacement. The results showed energy from FWWC has the lowest GWP because emissions are displaced.

Hot-spot analysis was conducted to quantify the CO_2 emissions released from each unit in the life cycle assessment. The most polluting unit for the FWWC plant is the harvesting stage, quantified to be 47 $kgCO_2/MJ$. This study assumed RT farming was used when harvesting the wood. One of the benefits of using RT methodology is that there is a reduction in the use of diesel fuel needed to run machinery. It will be difficult to reduce the emissions associated with harvesting unless there are new developments in harvesting methods to reduce the emissions even further.

The emissions for transport were analysed further; firstly the emissions for transport are very low because these plants are designed to be installed close to the biomass feed source as well as to residents receiving the electricity, resulting in lower emissions released at the transport stage. In the UK plants are generally large scale (>50MW) for economic viability and are consequently situated far away from residents, making the possibility of district heating connections unlikely. Although this system does not include heat production, it is a small plant designed to be situated close to small towns and cities to provide electricity.

Most energy plants in the UK have to transport the feed for the plant over long distances and often from abroad. As the plants are very large, they must import most of the feed because the capacity of the plant is too large to be met by an indigenous feed (Forth Energy, 2010). Promoting small scale plants as shown in this study will ensure appropriate scaling is performed for the town or city in question so that the demand could be met by indigenous feeds. The benefit of this is that the plants would utilise an indigenous feed sourced close to it (20km away) and therefore minimise transport costs and transport emissions.

The economic assessment and LCA for the FWWC confirm that the plant is economically viable at 160 ktpa and environmentally favourable to leaving wood in the forest, producing energy from electricity mix. This work has also proven that a small scale FWWC plant, situated close to a small town or city is economically and environmentally viable in the UK. In order to ensure the highest carbon savings, plants of this scale and type must be situated close (20 km) to the forest from which the wood is sourced. This ensures emissions are not lost in transport which is a growing concern with plants in the UK, especially if biomass is to be sourced from abroad.

- The LCA of the energy from SRF plant was investigated. Firstly the E_{GWP} for energy from SRF was compared to a base case scenario where the original MSW is collected and disposed of immediately into a landfill. The comparison takes into account energy displacement. The results showed that energy from SRF is an environmentally favourable option compared to landfill. The Government incentivises energy from waste and one of the main reasons is to divert waste from landfill. This is further influenced by increasing tax on landfill, making it an uneconomical option for local authorities.

The E_{GWP} calculated for the SRF plant (214 E_{GWP} kgCO_2equ/FU) was then compared to that obtained for a non-renewable electricity mix plant of similar scale. The results show that energy from SRF has a lower GWP when compared to non-renewable alternatives. This comparison was developed further to include energy displacement, i.e. the emissions generated from the non-renewable energy plant that have been displaced as a consequence of operating the SRF plant. The results in Figure 4.7 show that energy from SRF has a significantly lower E_{GWP} (-6072 E_{GWP} kgCO_2equ/FU) than a non-renewable electricity mix plant (13000 E_{GWP} kgCO_2equ/FU) when considering emission displacement.

Hot-spot analysis was also conducted to quantify the CO_2 emissions released from each unit in the life cycle. The results showed that the Fairport Process releases the highest amount of CO_2. The process uses a number of machines (See section 4.2) and converts 25 tonnes of MSW to 12.5 tonnes of SRF. As a result, it makes a large contribution to the overall release of CO_2. The Fairport Process produces a high calorific valued SRF. This process is vital to ensure that sufficient energy is produced to make the plant economically viable.

The transport distance for the SRF plant presumes a 20 km distance.

Transport distance must be minimised to avoid increased carbon emission from transport. Currently energy plants in the UK are large scale needing a large amount of feed to ensure that the plants run at full capacity. In order to meet this demand, especially with energy from waste plants, there is a need to import feed. This study is novel in that it proves small scale plants, utilising waste from the town or city that will be supplied the energy, result in lower carbon emissions from transport. Minimising transport distance not only minimises emissions but also cost for the local authority, as they can avoid travelling far distances to dispose of the waste and avoid landfill disposal costs.

Economic assessment has proven that SRF plants are economically and environmentally viable at small scales, can be used to treat the waste of a small town or city and can supply the town or city with the electricity generated. The SRF plant investigated in this study proves that energy from the SRF plant is economically and environmentally preferable to a non-renewable electricity mix plant of a similar scale.

- The study was developed further by analysing the techno-economic and environmental impact assessment of energy production from RSO. The economic assessment investigated two scales - 27 ktpa and 40 ktpa. The results showed that only the 40 ktpa plant was economically viable, although when put into context, this plant is still small scale plant when compared to other UK energy production plants (>50 MW). These large plants are popular in the UK because they are considered the most economically viable, mainly due to ‘artificially’ high capital and operating costs. A possible reason why the costs are high compared to Europe is because there is a tax applied to the producer and depending on the time that the works are planned to go ahead, delays are caused which inevitably adds to costs. This tax and delay are applied through the Street Works Act 1991. However this study has shown small scale plants are economically viable, mainly due to incentivised schemes such as the RO and LECs.

A sensitivity analysis was performed and it indicates that the main parameter affecting the levelised cost for the plant was the operating costs, whereas the calorific value and engine efficiency had a smaller effect. When changing the operating costs, the difference in levelised costs was significant, due to the purchase cost of the RSO. In the future, costs for feeds may change as the market develops. RSO prices may decrease as competition from suppliers takes place. Additionally the sensitivity analysis shows that the ROC buy-out price and electricity selling price would have to decreases by 40% and 60% respectively, before the plants will no longer be economically viable. This result shows that Government incentives are key to rendering such renewable energy plants feasible, given the unlikely scenario of the price of electricity decreasing to £42 and the buy-out price of ROC decreasing to £22.19.

The novelty of this study lies in the investigation of small scale energy production. The plant under investigation has the benefit of producing economically viable electricity and recuperating heat, which can be used in small towns and cities close to the plant through a district heating connection. Sweden and Denmark produce energy from biomass at a small scale and utilise district heating and similar plants have been functioning in Europe for many years. The deterrent in the UK is the significantly higher capital and operating costs. Despite high capital costs, this work proves energy from RSO at a scale of 40 ktpa is economically viable. Over the past nine years, the UK Government has been incentivising district heating connections through schemes such as CERT and CESP and this study demonstrates that small scale electricity and heat generation from RSO could be used through such district heating connections in the UK.

- The RSO economic assessment was further developed to assess the environmental burden of the 40 ktpa plant. The LCA provided information about the consequences of changes in how we use our land because of the use of RSO. Therefore a CLCA type of LCA was investigated using marginal data.

The E_{GWP} for energy from RSO was compared to a base case scenario where the land is kept as set aside land. The results showed that the base case had a lower E_{GWP} (48 E_{GWP} $kgCO_2equ/FU$) than to energy from RSO (152972 E_{GWP} $kgCO_2equ/FU$). In the base case, the RS is not being grown and the land is left as set aside.

The E_{GWP} was calculated for the energy utilised in each unit in the life cycle. The value of E_{GWP} calculated for the RSO plant was compared to those obtained for non-renewable coal or natural gas plants of similar scales. The results showed that the RSO plant releases lower emissions than a coal or a natural gas plant of a similar scale. The comparison was developed further when the results took into consideration energy displacement (avoided burdens). The results showed that the E_{GWP} of the RSO plant is always less than for the non-renewable alternatives. From a sustainable point of view, the results show that the RSO plant is both economically and environmentally viable. However, in order for the RSO plant to remain environmentally favourable when compared to non-renewable alternatives, it must be administered in the same way as presented in this study, including using the same farming methods as described and ensuring the transport distance is minimised.

Hot-spot analysis for the plant was also conducted to quantify the CO_2 emissions released from each unit. The hot-spot analysis showed that the units most contributing to CO_2 emissions are those employed in the production of the RS. More specifically combined harvesting contributes 224224 $kgCO_2/MJ$ and cultivation is quantified at 10479 $kgCO_2/MJ$. This analysis demonstrates the necessity of defining the type of farming to be used when producing RS for energy from RSO. The method of cultivation affects the amount of carbon released during rapeseed production. In this study RT methodology is used to produce RS; RT minimises soil disturbance and allows crop residues or stubble to remain on the ground instead of being thrown away or incorporated into the soil. The benefits of RT are saving on machinery use, fuel, labour time, improved soil structure, better soil aeration and improved soil fertility. We must ensure that appropriate land and farming methods are used that will result in less emissions without compromising the land or the resulting crop. From a social point of view, although the rapeseed is grown on a rotational basis over three years, there are still concerns that inappropriate land, such as forests and grassland, are being replaced with rapeseed. As a result we must ensure RS is produced sustainably. RS is being grown in the UK in increasing amounts. The climatic conditions favour it, crops are grown on a rotation but as a result, the replaced wheat needs to be grown on set-aside land. Even when using set aside land to grow wheat, the environmental profile favours energy production from RSO compared with non-renewable alternatives such as coal or natural gas.

6.2. Main Conclusions

In conclusion, this thesis has addressed the technical and economic viability of energy from different types of biomass using combustion technology at different scales. The UK Government has assured that the ROC's scheme will be available till 2037, although the exact scheme details could change each year. Nonetheless this study has proven small scale energy production can be economically and environmentally viable, despite high capital and operating costs in the UK.

This thesis also investigated the environmental benefits of energy from biomass in avoided significant amounts of fossil fuel based energy generation from non-renewable energy plants. Additionally, it has proven that energy from waste is an environmentally attractive option when compared to landfill, therefore complying with the waste management hierarchy.

In order for the UK to reach its renewable energy targets, biomass will play a crucial role and, as proven in this thesis, it can be economically and environmentally attractive using biomass readily available in the UK. However it is vital we:

1. Monitor these biomass feeds in terms of incentives for the FWWC and RSO
2. Increase landfill tax to deter councils from using them
3. Continue to provide incentives for energy from biomass
4. Ensure RSO is grown sustainably to avoid indirectly contributing to climate change.

That being said, in order for the UK to reach their renewable energy targets there must be relevant policy, planning and financial mechanisms in place to build a renewable energy industry in a sustainable way. Programmes such as CERT and CESP can help to make small scale plants viable through district heating connections and with appropriate legislation will support sustainable energy production from biomass.

6.2.1. Small Scale Energy Production

Small scale energy from indigenous biomass sources can be economical and environmentally friendly. This work highlights and proves the current incentives for these types of plants that make them economically and environmentally friendly. Small scale energy plants can be produced to utilise indigenous feed sources to heat and light small towns and cities. Within this context forestry thinning from nearby forests can be used to produce energy close to a small city.

MSW generated by the city can be converted into SRF (a higher calorific fuel) and used to produce energy for the town or city, instead of landfilling the waste. There are several positive outcomes of using MSW in this way, firstly we will be avoiding the use of landfills, which have increasing taxes and are running out. It is also on the political agenda to decrease the use of landfill significantly, by avoiding landfill, small scale energy production would result in a positive public opinion. This work has shown the environmental impact and economic viability of these small scale plants is transparent and trust worthy. Although it is important to highlight, these plants are economically viable because of Government incentives such as the ROCs scheme and where applicable, gate fees and LECs. These incentives are commissioned to continue until 2050, by which time the small scale energy production will potentially be well established.

Small scale heat and electricity plants using grown UK biomass such as rapeseed oil are very beneficial to supply heat and electricity to small towns and cities, mainly because we are able, and have been increasingly been producing rapeseed in the UK. Generally this rapeseed is being used to produce diesel fuel for use in vehicles, however this work proves crude rapeseed oil can be used to produce our ever increasing need to heat and light buildings. Once again Government incentives are encouraging these types of efficient and economically viable plants to be established in the UK. A completely transparent life cycle assessment showed, with the inclusion of avoided burdens, energy from rapeseed oil is more environmentally friendly than non-renewable alternatives. However it must be highlighted that the rapeseed must be grown on set aside land, and if grown as part of a rotation, the emissions associated with growing the alternative rotated crop must be taken into consideration. It is very important that the rapeseed is grown sustainably and included within the life cycle assessment, if this is not carried out then there is a risk if exploitation of our land and the risk of under estimating and over estimating emissions.

6.2.2. Transport

This work has proved small scale energy production in the UK is now economically viable. In the UK plants are built on large scale (>50 MW) because this was the only economically viable option. Fuel is generally transported over long distances because the plants are situated far from cities and require a large amount of energy to be able to sustain large scale production. This work has proven small scale energy production is possible in the UK and as a result will reduce transport distances. Although the transport does not seem to contribute significantly towards emissions released, the analysis showed longer distances can result in increased emissions and so these must be monitored and kept to the original design, especially if it is decided to import feeds.

6.2.3. Plant Location

The plants location inevitably influences and characterises the benefits of the plant, more specifically locating the plant close to a particular town or city and using their resources and wastes can result in minimal transport distances and disposal sites. As well as having other social benefits such as increased job potential. The Government has shown increased enthusiasm and interest in small scale energy production through incentives and programmes such as CERT and CESP. These programmes enable funds to upgrade existing inefficient plants to small scale efficient CHP plants or biomass plants and connect them to new district heating systems.

6.2.4. The Role of Legislation

Small scale plants are economically viable compared to common and popular large scale plants now because of Government incentives such as ROCs, LECs, landfill taxes, and Gate Fees. The Government realises the need to incentives these plants until a stable market is established, because these plants help us to become more efficient, transparent and reduce our carbon footprint. There is some legislation that could help develop the accounting methodology of grown types of biomass such as rapeseed. The LULUCF legislation, once established and implemented will give an agreed methodology which would be used globally to account for sequestered carbon. This methodology can be used in a universal and transparent way to account for carbon and further support the option of being able to produce renewable energy from grown types of biomass. LULUCF is seen as having potential for additional emission reduction. Therefore if policies are developed to maintain and restore natural carbon sinks, we can ensure that we will be able to produce sustainable RS and account for avoided burdens in a comprehensive and controlled way in the future. This activity will help to provide confidence in the production of energy from RS and other grown crops. In addition, if there is cross Government support on increased GHG target ambition and a renewables target, then the Government will be encouraging more efficient production of renewable energy production, to meet their targets. The UK is very vocal and wants to be a leader in pushing for increased ambition. The positive result will incentivise and make this work a key player in the centre of a key political topic.

6.3. Future work

- This work has focused on the suitability, effectiveness and environmental impact of energy, using combustion technology from different types of biomass in the UK context. Therefore, it would be useful for future work to consider how, technically and economically, energy from imported biomass would perform. This will put strain on the current technical assessment because the calorific value of biomass from different countries varies considerably especially if mixed with UK sources. From an economical and environmental point of view, assessing transport distances and the costs of importing the biomass to the UK could have considerable effects on the analysis. Additionally, different types of biomass could be investigated for energy production that are not readily available in the UK, because we do not have the appropriate climatic conditions for their growth or they must be grown on short rotation e.g. Coppice Willow and Miscanthus.

- The comprehensive LCA performed in this study can be followed-up and developed by investigating how different markets relating to the chosen biomass would be affected. If the plants are working on full capacity and all MSW (in an ideal situation) is used for energy production, what effect will this have on the secondary aggregate market? This may be an important development factor, because there will be an increase in the amount of bottom ash produced and its properties may affect the market in terms of being able to recycle such large quantities. We must also consider if it will be cost effective to dispose of increasing amounts of FA to specialist landfill sites and how this will affect the environmental impact assessment. In terms of RSO, it will be interesting to investigate the bio-diesel market and farming industry. If managed appropriately, the farming industry should benefit economically through the additional revenue from growing RSO on a rotational basis.
- In terms of LCA, further follow-on study could investigate the environmental impact of bio-diesel production at a similar scale as current energy production, to investigate which process is environmentally and economically superior. Additionally, further investigation on increases in RSO production and its effect on public health are vital, because it is thought that increased production of RSO can contribute to increased allergies such as asthma and hay fever.
- Finally, it would be useful to investigate the processes used in this study on a regional basis to assess and optimise the best location for the plants in terms of transport distances for biomass collection and FA disposal, as well as the possibility of district heating connections. Regional analysis could be used to investigate how much energy is used by different regions and to optimise the location for the biomass plants.

On a personal note, this PhD has been a memorable journey. I began this work as a spectator, with mere interests in what I thought chemical engineering entailed. I now have a completely different view and understanding of such a diverse and necessary subject. Working in a completely different field has opened my mind and developed my knowledge of how processes work and affect our everyday lives. It meant reading up on basic chemical engineering from the beginning of my PhD and developing an understanding of subjects I have never dealt with before. I now appreciate the importance and difficulties we face as a generation to become sustainable, to reduce climate change and to uphold our current standard of living. The additional analysis carried out has led me to investigate other aspects that would have an effect on land use and realise how important it is for us to ensure any action we take now that will positively impact how we handle land use in the future. This work has also helped me better understand my current role and made me realise that I am fortunate to be able to use my experiences and understanding to help develop future policy with an additional scientific and engineering perspective. This PhD has given me experiences, knowledge and a vast array of skills. It has truly been an experience I will cherish and value for the rest of my life.

Nomenclature

Abbreviations

AIA	Annual Investment Allowance
APC	Air Pollution Control
BA	Bottom Ash
BEATv2	Biomass Environmental Assessment Tool Version 2
BFB	Bubbling Fluidised Bed
CCGT	Combined Cycle Gas Turbine
CERT	Carbon Emission Reduction Target
CESP	Community Energy Saving Programme
CF	Conversion Factors
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
CT	Corporation Tax
DCF	Discounted Cash Flow Analysis
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DTI	Department of Trade and Industry
DPC	Direct Plant Costs
DUKES	Digest of UK Energy Statistics

EC	Equipment Costs
EU	European Union
FA	Fly Ash
FU	Functional Unit
FWWC	Forestry Waste Wood Chips
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
HHV	Higher Heating Value
HM	Heavy Metals
IEA	International Energy Agency
IPC	Indirect Plant Costs
IPCC	International Panel on Climate Control
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LEC	Levy Exemption Certificates
LHV	Lower Heating Value
MBT	Mechanical Biological Treatment
MHT	Mechanical Heat Treatment
MSW	Municipal Solid Waste
NPV	Net Present Value

OFGEM	Office of Gas and Electricity Markets
ORC	Organic Rankin Cycle
RHP	Renewable Heat Program
RO	Renewable Obligation
ROCs	Renewable Obligation Certificates
RSO	Rapeseed Oil
RT	Reduced Tillage
RTFO	Renewable Transport Obligation
SCR	Selective Catalytic Reduction
SRF	Solid Recovered Fuel
SNCR	Selective Non Catalytic Reduction
TPC	Total Plant Costs
UN	United Nation
VOC	Volatile Organic Compound
WID	Writing Down Allowance

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Appendix 1. LCA for FWWC plant

Appendix 2. LCA for SRF plant

Appendix 3. LCA for RSO plant

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