

University of Strathclyde
Mechanical Engineering Department

An Investigation Into The Implications of Using Very Wet
Biomass As A Fuel

Alexander Thomson

Thesis Submitted in Partial Fulfillment of the Requirement for the
degree of

MSc. in Energy Systems and the Environment

September 2006

Declaration of Author's Rights

“The copyright of this dissertation belongs to the author under the terms of the United Kingdom Copyrights Acts as qualified by the University of Strathclyde Regulation 3.49. Due acknowledgement must always be made of the use of any material contained in, or derived from, this dissertation”

Acknowledgements

I would like to express my gratitude to the following people who have helped me during the course of this Masters degree.

Mr David Palmer for first bringing this idea to my attention.

Mr. Barry Grant, my contact at the Forestry Commission for his help and advice.

My supervisor, Mr. Craig McLean, and all my lecturers, for their help and encouragement and for making this course both enjoyable and stimulating.

And finally to my partner Andy, for putting up with me during the course of this project.

Table of Contents

	Page
Acknowledgments	iii
Table of Contents	iv
List of Tables	v
List of Figures	vi
Abstract	vii
Chapter One	Introduction
	1.1 Background 1
	1.2 Objectives 4
Chapter Two	Biomass
	2.1 Intro 5
	2.2 What is Biomass? 5
	2.3 History 8
	2.4 Sources of Wood Waste 9
	2.4.2 Scottish Wood Waste Sources & Characteristics 12
	2.4.3 Forestry Harvesting 15
	2.4.4 Timber Processing 16
	2.4.5 Scottish Wood Waste Source Overview 17

	2.5 Wood Waste as a Biofuel	19
	2.6 Summary	22
Chapter Three	Conversion Technologies	
	3.1 Direct Combustion	23
	3.2 Pyrolysis	24
	3.2.1 Thermal Depolymerisation	26
	3.2.2 History	26
	3.2.3 Theory and process	27
	3.2.4 Limitations	30
	3.2.5 Current status	30
	3.3 Gasification	31
	3.4 Anaerobic Digestion	
	3.4.1 Stages	34
	3.4.2 Operating Parameters	36
	3.4.3 The Digestate	39
	3.4.4 The Anaerobic Digester	40
	3.5 Ethanol Production	
	3.5.1 Background	41
	3.5.2 Ethanol from Cellulose	44
	3.5.3 Acid Hydrolysis	44

	3.5.4 Enzymatic Hydrolysis	48
	3.5.5 Thermo-chemical Processes	50
	3.5.6 Commercialisation Efforts	51
	3.5.7 Summary	51
	3.6 Summary	52
Chapter Four	Using Very Wet Biomass as a Fuel Source	
	4.1 Introduction	53
	4.2 Direct Combustion of Wet Wood	54
	4.2.1 Understanding Combustion	55
	4.3 Biomass Drying	
	4.3.1 Why Dry Fuel?	58
	4.3.2 Principles of Drying	60
	4.4 Types of Dryer	61
	4.4.1 Rotary Dryers	63
	4.4.2 Flash Dryers	66
	4.4.3 Disk Dryers	67
	4.4.4 Superheated Steam Dryers	69
	4.5 Heat Recovering	71
	4.5.1. Air Drying Heat Recovery	71
	4.5.2 SSD Heat Recovery	72

4.6	The Problems with Drying	73
4.6.1	Summary	75
4.7	Wet Biomass Gasification	
4.7.1	Background	76
4.7.2	Experimental results	77
		78
4.8	Summary	79
Chapter Five	Further Work	80
Chapter Six	Discussion and Conclusion	82
Appendix		84
	Appendix A The RITE – Honda Process	
References and Bibliography		86

List of Tables

Table	Name	Page
2.4.1	Common Sources of Wood Waste	12
2.4.2	Potential Contaminants in wood wastes	14
2.4.3	Scottish Wood Waste Sources	17
3.2.1	Feedstock and Outputs with Thermal Depolymerisation	28
3.3.1	Typical Chemical Composition of Wood Gas	32
3.5.1	Ethanol yield from glucose	46
3.5.2	Ethanol yield from xylose	46
4.6.1	Dryer Advantages and Disadvantages	72

List of Figures

Figure	Name	Page
1.1	Carbon Cycle	6
1.2	Simplistic Biomass Cycle	7
3.2.1	Simple Pyrolysis cycle	24
3.5.1	Conventional Flow Diagram of EFC Process	43
4.4.1	Basic Single-Pass Rotary Dryer	61
4.4.2	Basic Flash Dryer	64
4.4.3	Disk Dryer Configuration	66
4.4.4a	Basic "IVO" Superheated Steam Dryer	67
4.4.4b	MoDo-Chemetics SSD Dryer Configuration	68

Abstract

The Implications of Using Very Wet Biomass Fuels.

A significant issue with the expansion of the biomass market into the UK is the absence of supplies of sufficiently dry wood fuel.

Timber-processing companies (with about 6 large sawmills in Scotland) produce tens of thousands of tonnes of sawdust and woodchips, of an appropriate size, from the cantor heads on their sawmills annually. These however are at a moisture content of 55% - 70%, making them unsuitable for direct use in traditional biomass boilers.

This report shall look at other non-traditional methods of biomass use that can utilise such wet biofuel sources without the energy intensive need to pre-dry the biomass first.

Chapter 1 Introduction

1.1 Background

Growing concerns about the sustainability and impact on the global climate of our current energy sources are an unavoidable consequence of our society's heavy dependence on fossil fuels. With the expected peaking of world conventional oil reserves in the very near future^{1, 2}, it has been put forward that current reserves of other sources of fossil fuel energy, such as coal, oil shale etc, can make up for the deficit, for at least a few more decades³. Growth in the other existing primary energy sources, nuclear and mature renewable technologies such as hydro and wind power, are also expected to carry their share of the load to keep up with the increasing demand for energy brought about by increasing world population and economic developments. Biomass energy, though currently contributing only a small fraction to world electricity supply, is considered to be a vast and promising resource due to its availability, sustainability and near CO₂-neutrality. Though existing technologies for bioenergy production are plagued with concerns about economic feasibility and applicability in the short term, various studies all over the world are on going to find a way to build upon the information we currently possess from the pre fossil fuel era.

There is enormous potential to be tapped in biomass, with the development of new and more efficient technologies to utilise mankind's oldest source of energy. No longer is organic matter simply burned to produce heat and light, as advanced technologies now convert raw biomass into more useful forms of energy that are easy to use and transport; liquid or gaseous fuels, processed solid matter and electricity.

Although relatively new in the UK, biomass technology is already well established and widely available across continental Europe, specifically in Germany, Austria and Scandinavia. These established technologies focus on using biofuels in their traditional role as a source of heat, albeit in a more high tech approach than how our ancestors used such fuels.

The greatest problem for the fledgling biomass industry in this country is the lack of suitable resources to be used with these established 'bio-heating' technologies.

The forestry sector and timber processing industries however are both keen to develop biomass use in UK. One readily available resource is the vast amounts of 'very wet' wood waste that is created annually from sawmills.

The 6 large mills in Scotland alone produce tens of thousands of tonnes of woodchip, of an appropriate size, from the cantor heads on their sawmills annually.

This source of wood waste unfortunately has moisture content of 55% to 70%, making it unsuitable for direct use in traditional biomass boilers.

However new technologies are becoming available that can utilise very wet biomass and convert it to heat and power, without the need to dry the organic matter out first; an expensive and energy intensive process.

1.2 Objectives of This Thesis

In the following chapters, an overall appraisal of using very wet biomass as a potential energy resource will be attempted.

The main objectives are thus:

- Examine the biomass resources available and why very wet biofuels may be a potentially rich resource.
- To conduct a literature review on the technical feasibility of biomass technologies.
- Determine whether fuel-pre-drying, using a proportion of the heat produced by the boiler, is desirable.
- Examine the implications of the use of very wet biomass compared to dry biomass in technological, economic and social terms.
- Evaluate the potential for latent heat recovery from the boiler flue and identify methods of achieving this.

1.3 Notes

Unless otherwise specified, all measurements of biomass mass will be in Oven Dry Tonnes, even though the project is concerned with wet biomass. This is for balanced comparative reasons.

Chapter Two: Biomass

2.1 Introduction

Wonder Fuels?

With the price of oil and gas at an all time high, there is once again an increased interest in finding a suitable alternative to provide affordable, and sustainable heat and power. One such alternative is biomass.

2.2 What Is Biomass?

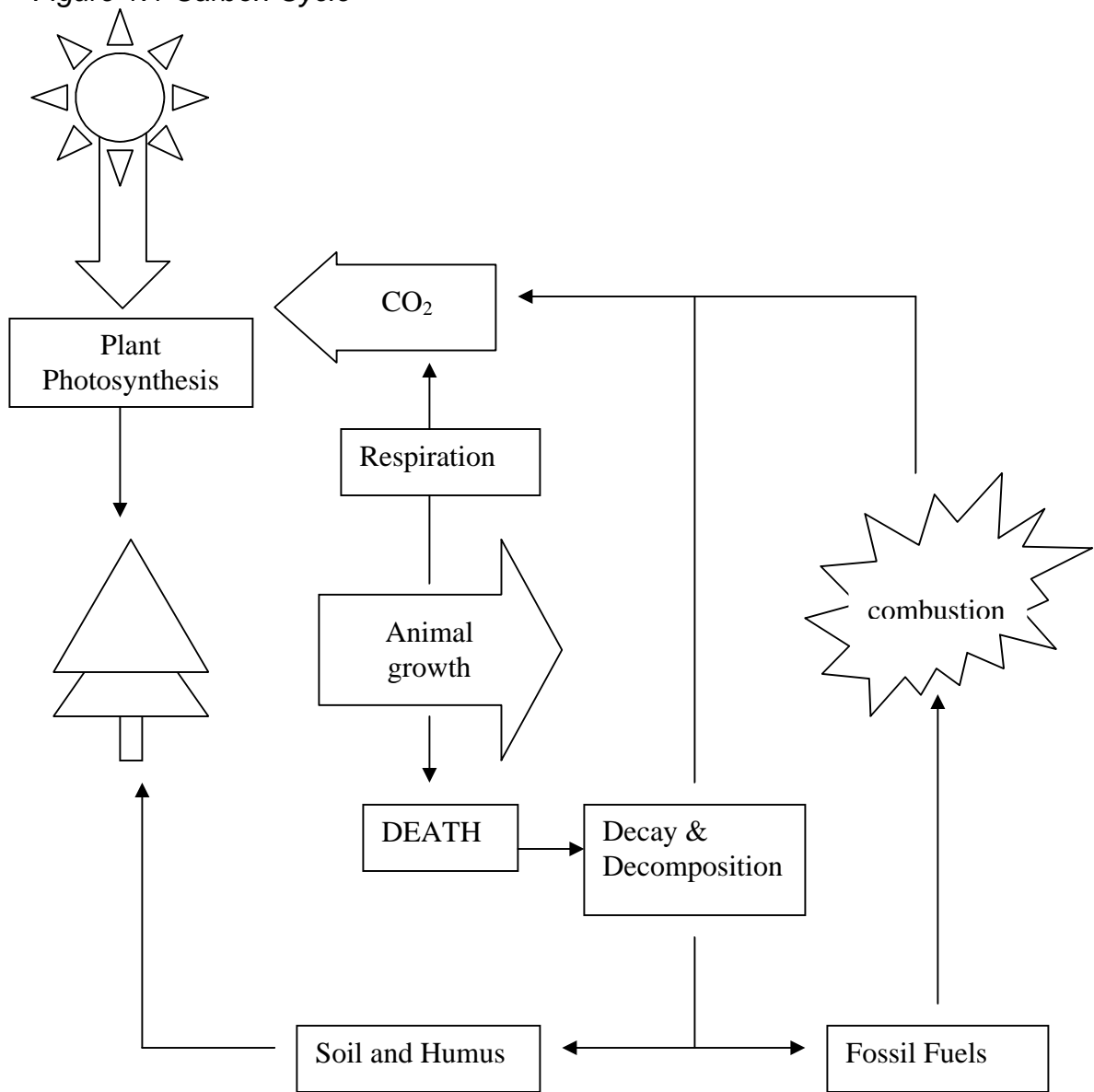
In terms of renewable energy, Biomass is any form of organic matter that can be used as a source of fuel. This includes wood, fuel crops, such as oil seeds specifically grown for energy production, plants with high sugar content, for conversion to alcohol, and even algae. It also includes agricultural and industrial 'waste' such as effluent, sludge, manure and plant residues (husks, stalks etc).

In the broadest terms it is used as a description of materials of recent biological origin that can be used either directly as a source of energy or for its chemical components.

The term Biomass can be further divided into more specific terminology, with different terms for different end uses: heating, power (electricity) generation or transportation. 'Bioenergy' is a term for biomass energy systems that produce heat and/or electricity. 'Biofuels' for liquid/gaseous fuels used for transportation. Bioenergy can also be used for cooling using absorption chillers that work on the same principle as refrigeration.

As with all forms of renewable energy, the energy from using biomass ultimately comes from the sun. Living organisms have harnessed the energy in sunlight to grow, via the process of photosynthesis. So, like coal and oil, biomass is a form of stored solar energy. This energy is liberated when the biomass is burnt in the reverse process of aerobic combustion.

Figure 1.1 Carbon Cycle



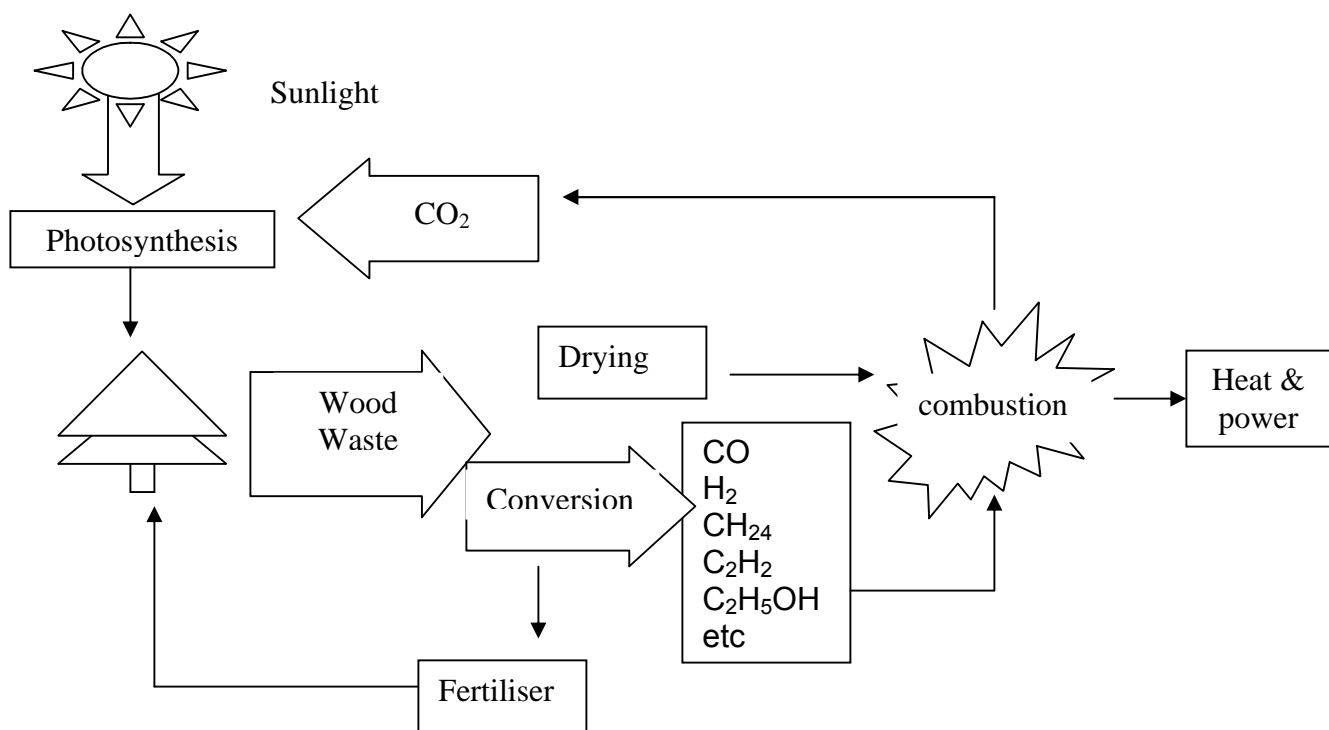
Like the other methods used to generate energy, the combustion of biomass generates pollution as a by-product, most notable carbon dioxide.

However, unlike fossil fuels, which have locked away this CO_2 for millions of years below the earth's surface, biofuels have a short life cycle. The carbon liberated from the combustion is used by the next generation of growing plants to be used as biomass, thus the overall process is carbon neutral.

However this is not entirely true as fossil fuels are still required in the production and transportation of the biomass, be it in the form of fertilisers or petrochemicals.

One advantage of biofuel in comparison to most other fuel types is that the energy within the biomass can be stored for an indefinite time-period and without any danger.

Fig 1.2 Simplistic Biomass Cycle



2.3 History

Biomass is mankind's oldest form of energy that we have harnessed since the Stone Age when we learned to make fire. Biofuels have been the primary source of energy humans have used for the majority of our history. Used throughout human history mainly for the purpose to provide heat, biomass is still a very important source of fuel, meeting an estimated 13% of the current global demand for energy. This is especially true in the developing world, where much of it is traditional fuel-wood used for heating and cooking, whilst it is beginning to show resurgence in use in the developed world.

However the historical method of simple burning the fuel is less efficient than modern day, high tech systems. Scientific advances and improved technologies, combined with government legislation in the wake of awakening environmental awareness, have paved the way for Biomass-to-energy conversion to become cleaner and more energy efficient processes.

In Europe for example, 5% of the European Union's energy supply already comes from biomass, which has the potential to rise to 20% under new legislation to help meet Kyoto obligations⁴.

2.4 Sources of Wet Biomass

Wood Chips

Timber, and timber-based product consumption has been steadily rising in the UK for a number of years now, with an estimated 48 million m³ of timber being consumed annually⁵, the equivalent of the average person consuming 1 tonne p.a.

The current land area covered by forestry in the UK is 9.3%, the majority of which has been planted during the second half of the 20th century.

Historically natural woodland was over-felled due to the demands of industrialisation and led to the reliance of timber imports. Despite the post war effort to rectify this, the UK still only produces a fifth of its own timber needs⁶.

With these vast quantities of timber and timber products consumed in the UK each year, there is a significant quantity of wood residues and waste produced in a variety of conditions, variable in both quality and quantity.

There is currently little accurate information on the levels wood waste produced, making it difficult to plan out expansion of the infrastructure necessary for harvesting this potential biomass resource. However in this section, the main sources of wood waste, the characteristics of the different

forms of the waste and there potential in the energy sector shall be examined.

In most cases there will be, to some degree, contamination of the wood waste that would require treatment before further processing.

The Timber Research and Development Association (TRADA) has stated that it is very difficult to obtain reliable information on wood waste partly due to quantitative data on waste not being available at the company level. Many companies don't collate exact figures on volumes of wood residues generated, but rather estimates on containers used such as bins, skips, trucks etc⁷

The UK wood industry employs approximately 35000 people in forestry and primary wood processing. The total value of the timber production industry to the UK economy is approx £2.5 Billion per year⁸. In 2001, UK timber production was approx 2.5 million m³ of sawn wood. The UK currently imports approx 85% of the softwood it requires, and is one of the largest European markets for forest products. Softwood timber constitutes approx 80% of the wood products in the UK⁹. With such vast quantities of timber

products being consumed in the UK, a considerable volume of wood residues and waste will be produced each year through the life cycle of the products. In some cases less than half of the timber feedstock ends up in the product.

Contamination

The quantity and condition of wood waste will determine the final disposal route. Historically heavily contaminated wood waste is consigned to landfill or incineration. Cleaner residues are utilised, principally for board manufacturing. However new technologies, and the developments of alternative markets, have created a greater range of uses for this resource.

Greater volume of contaminations can now be consistently extracted from wood waste, producing a high quality material suitable for a variety of end markets. Generally, wood residues decrease in value and degenerate into 'waste' materials, the smaller the particle size and greater the destruction of the wood fibre, for example sawdust is generally less valuable than woodchips suitable for chipboard or paper pulp manufacture⁸.

New fiscal and regulatory drivers such as the Climate Change Levy and the Packaging Regulations are also significantly encouraging wood waste recycling in the UK.

2.4.2 SCOTTISH WOOD WASTE SOURCES & CHARACTERISTICS

Wood waste comes from all stages of the material's lifecycle, with residue being generated at each of processing stages. The following table summarises the types of residues produced by each of the main processing operations.

TABLE 2.4.1 Common Sources of Wood Waste⁷

Sector	Source	Output
Forestry	Thinning, Logging, harvesting	Bark, branches, leaves, rejected trees, roots, stumps, thinning, top wood
Primary Processing	Sawmills, board manufacturing	Bark, edgings, off-cuts, rejects, sawdust, slab-wood, shavings, wood chip
Secondary Processing	Flooring, furniture, joinery, pallet & packaging	End-trim, damaged products, off-cuts, reject material/products, sander dust, sawdust
Traders	Distributors, importers, merchants, timber salvage	Possible secondary processing residues & rejected/damaged products.
Construction &	Construction,	Cable drums, coated material,

demolition	demolition, refurbishment, scaffolding	cladding, doors & frames, flooring, fencing, pallets, wood composites, piles, poles stakes etc
Landfill, SMW	Residential, commercial, industrial products	“End-of-life” products, damaged goods, packaging, paper, parkland waste etc

Each source has its own forms of contamination, the level of which can vary greatly, and affects the end market for the wood waste. As a result, not all wood waste can be utilised for use as biomass, with landfill or incineration being the only option.

However because of the variation in contaminants, they can be removed via mechanically, physically or chemically.

The table below lists the types of separation

Table 2.4.2 Potential Contaminants in wood wastes

Mechanically Separable	Physically & Chemically Separable
Aggregates, bricks, ceramic tiles, glass	Creosote
Asbestos	Waterborne/Organic Preservatives
Asphalt	Waxes and oils
Carpets and Linoleum	Paints and Lacquers
Dirt, Soil and Stones	Glues and other adhesives
Drywall Lining	Fire Retardants
Fibreglass insulation	Water
Metallic compounds	
Plastic compounds	
Paper, cardboard, tarpaper and wall paper	

Moisture may also be considered a contaminant by some end users, such as board manufacturing of wood fuel production, where further processing may be required to remove excess water.

A detailed examination of all these biomass sources is beyond the original scope of this dissertation, however a closer look at the harvesting and primary processing stages is required to investigate potential sources of wet biomass materials.

2.4.3 Forestry Harvesting

Wood waste is inevitably produced during forest harvesting. A staggering 50 – 60% of the total material produced at harvest can end up as waste i.e. branches, bark etc. This is often left in-situ to biodegrade naturally rather than be collected and transported elsewhere. This is more to do with economic reasons but ultimately leaving this resource on site has the additional benefit of returning valuable nutrients to the soil for the next generation.

The Forestry Commission and the Forest Industries Development Council of Great Britain regularly collect information regarding timber and their data indicates that whilst the UK timber production is set to expand to around 25 million m³ by 2025¹⁰, the UK is likely to exceed 25% self sufficiency in timber and wood products¹¹. UK forestry waste has been estimated as 1.5M tonnes per year. However with approximately 45% of the UK's forest being located in Scotland⁷, there could potentially be up to 675,000 tonnes of wood waste being produced in Scotland per annum, from this source. Some of this is material is chipped and sold to board manufacturers, but most is left to decompose in-situ or sent to landfill.

2.4.4 Timber Processing

Once wood has been felled it is generally taken to sawmills where primary processing occurs. At the sawmill vast quantities of waste can be produced with the final product in some cases only accounting for 20 to 30% of the input log; however this is more often 40 to 50% depending on the feedstock, equipment and end product.

Most sawmills not only rely on the revenue from the timber they produce, but also from the residue material generated by processing operations; therefore end markets such as board and paper manufacturing are important. The residue generated at this stage is considered to be relatively 'clean' and consistent, proving attractive to end users such as chipboard manufacturers and increasingly wood pellet manufacturers. The Sawmill Survey 2000, conducted by the Forestry Commission, identified 85 operational sawmills in Scotland, with a softwood consumption recovery rate of 55%, which indicates that approximately 790,000 tonnes of softwood residue were produced. Hardwood consumption with a 56% recovery rate produced almost 3,500 tonnes of hardwood residue. Therefore there are potentially 793,500 tonnes of clean wood waste revenue being generated from this source alone in Scotland.¹²

This residue can be in the form of cut-offs, wood chip and sawdust, the majority of which will be utilised by the board manufacturing sector, however

other markets must be found for the remaining residue which consists of approximately 7% bark, 10% sawdust and 25-30% wood chip⁸.

2.4.5 Scottish Wood Waste Source Overview

Table 2.4.3 below shows the volume of wood residues being produced in Scotland from the major sources of wood waste every year and some of the contaminants that may be present.

Table 2.4.3 Scottish Wood Waste Sources⁹

Source of Residue	Volume (T)	Possible Contaminants
Forestry	675,000	Grit, Soil, Moisture
Sawmills	793,500	Grit, Soil, Moisture
Construction / Demolition	125,600	Rubble, Asbestos, Creosote, Laminates, Carpet, Gypsum, Adhesives, Glass, Metals
Packaging	140,000	Plastics, Metals
Furniture	33,500	Preservatives, Adhesives, Metals, Fire Retardants
Fencing	6,000	Preservatives
Municipal Solid Waste	121,000	Preservatives, Plastics, Metals, Adhesives

It can be seen from Table 2.4.3 above that the majority of wood residues are produced by forestry and sawmill operations.

These residues and other pre-treated residues from secondary processing operations are considered 'clean'. Other than forestry waste, which is left in-situ, these residues will principally be utilised by board manufacturers but can be potentially used for on-site heating and power.

Urban wood waste, which includes packaging, MSW and construction/demolition wastes will in comparison often have some degree of contamination. These sources of wood waste are largely considered post-consumer and will normally have gone through several processing stages before disposal. These waste streams will normally be collected and processed by specialist wood re-processors. In Scotland these waste streams account for approximately 386,600 tonnes of wood waste per annum. However there may be a significant proportion of wood waste, which largely remains unaccounted for simply due to the diverse nature of the industry and lack of accurate data. Therefore it is estimated there may be up to 400,000 tonnes of urban wood waste being produced in Scotland every year.

It is estimated that Scottish wood re-processors recycle approximately 150,000 tonnes of wood waste per annum, which represents a recycling rate of 37.5%.

2.5 Wood Waste as Biofuels

In the UK, like most of the world, wood has traditionally been used as a fuel in both commercial and domestic applications. However when compared to most northern European countries, Scotland is perhaps 15 years behind in terms of the development of a biomass industry¹³.

Advances in technology are increasing the potential to utilise wood waste as a source of both a source of heat and electricity. The recycling of wood waste by thermal conversion offers the opportunity to utilise the calorific value of wood, as discussed below, whilst diverting considerable volumes of wood waste, which might have otherwise been consigned to landfill.

In some cases where treated wood is present, waste to energy plants may offer the Best Practicable Environmental Option (BPEO), particularly where the plants have facilities for the removal of dioxins. In the UK it was estimated that the volume of wood waste available as a fuel in the UK in 1998 was approximately 1.1M oven dried tonnes (ODT), with this figure potentially rising to approximately 1.7M ODT by 2013¹⁴

Wood waste can be utilised as a fuel in a variety of forms such as solid wood, woodchip and sawdust, fuel pellets and charcoal. Wood waste can be treated by pyrolysis or carbonisation, which involves burning the material in

the absence of air, breaking it down into liquids, gases and charcoal¹⁵. This option offers a high volume high value market particularly for hardwood waste.

In order for the biofuels market to successfully utilise recycled wood, there must be a ready supply of fuel available locally. There must also be demand for the heat and or energy produced.

At present the market largely consists of producers of waste wood utilising wood-burning boilers to generate heat and/or power to their premises. However, discussions with timber processors indicated these boilers were originally installed primarily as a waste management solution, with the heat and energy generated only being an additional benefit. This has been largely influenced by the increasing cost of landfill in the UK. Pilot biomass power stations are currently being developed in the UK, which could utilise the vast quantities of 'dry' wood waste as fuel. Wood waste can also be burnt in general waste-to-energy incinerators. Operators of large incineration plants will often require vast quantities of waste to feed the incineration plants as wood has a high calorific value, an attractive quality to these operations.

A UK wood fuel resource study is currently being undertaken by the Scottish Enterprise, which aims to map the available wood fuel resource in the UK,

which should aid strategic planning and the development of future bio-energy schemes.¹⁶

Currently Lanarkshire Biomass, a project funded by the Scottish Clean Energy Demonstration Scheme, is conducting technical evaluations of 12 locations in the Lanarkshire region, including schools, hospitals and visitor centres, which could potentially be used to demonstrate to potential of these technologies.¹⁷

There is considerable potential for this market to utilise large volumes of wood waste; however there must be considerable expansion of the supply infrastructure.

2.6 Summary

Wood recycling in Scotland is increasing, principally through the rising cost of landfill, and with this set to increase in coming years the trend is likely to continue. Also with the EC Landfill Directive requiring the amount of biodegradable municipal waste (BMW) sent to landfill to be reduced by 75% of the 1995 baseline by 2010¹⁸, other outlets for materials such as wood waste are increasingly being sought.

Development of biomass energy is an ideal opportunity for producers of wood waste. However there are still some barriers that need to be addressed. Wood re-processors identify lack of local markets as one of the main obstacles to further expanding wood waste as a biomass fuel source. With wood recycling likely to increase, greater volumes of waste material will likely generate wood waste that is increasingly contaminated. Therefore greater effort must be made to implement source separation schemes and also to source material which is best suited to the desired end use. Re-processors must work closely with their sources to help recover wood waste in the best possible condition.

Chapter Three Conversion Technology

There are many different method of extracting energy from biomass. The four principle methodologies shall be discussed here.

3.1. Direct Combustion

By far the oldest and most wide spread use of biomass is to burn it. Primarily this has been done to provide heat, but modern techniques are now utilising biomass combustion for the production of electricity.

In the case of very wet biomass as a fuel source, direct combustion is not feasible. Time and energy need to be spent drying the fuel first. If wet biomass is burnt, energy released from the combustion of the organic material is used to boil the water present in the fuel, leaving little to no net energy output.

However there are techniques that utilise the waste gases produced from combustion that aid in the evaporation of the excess water pre-combustion.

See Chapter Four below.

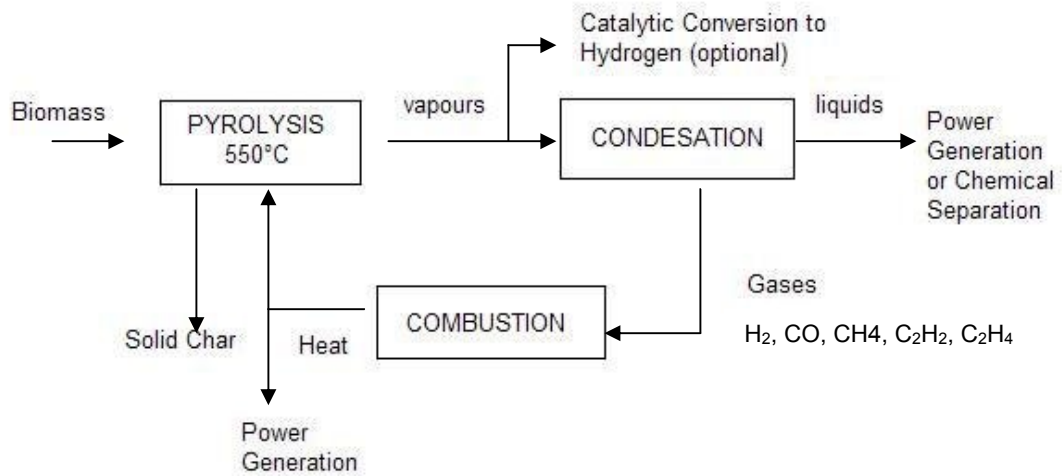
3.2. Pyrolysis

“Fire Splitting”

Pyrolysis is another method of extracting energy from biofuels that has been utilised for some time, defined as the chemical decomposition of organic materials when heated in the complete absence of oxygen. Pyrolysis is best known as a process for transforming hazardous organic materials into gaseous components, small quantities of liquid, and a solid residue (coke) containing fixed carbon and ash. The gases produced from pyrolysis of organic materials are combustible. They include carbon monoxide, hydrogen and methane, as well as other hydrocarbons. If the off-gases are cooled, liquids condense producing an oil/tar residue and contaminated water. Pyrolysis typically occurs under pressure and at operating temperatures above 430 °C.

Essentially pyrolysis is the process of making charcoal. But improvements in technology and our understanding of the science behind the process have improved the efficiency further still.

Figure 3.2.1 Simple Pyrolysis cycle



Currently pyrolysis systems are seen as a method to dispose of hazardous wastes rather than a dedicated biomass heat and power generator. There is potential to be used as such, but the process requires low moisture content of the input biomass feedstock.

3.2.1 Thermal Depolymerisation

Thermal Depolymerisation (TDP), sometimes known as Direct Hydrothermal Liquefaction, is a pyrolysis technique for reducing the complex organic materials found in biomass to an oily liquid, but in the presence of water at elevated temperatures (300-350°C) at sufficient pressures to maintain the water in the liquid phase (12-20 MPa) for residence times up to 30 minutes. An alkali may be added to help promote the organic conversion. The primary product is an organic liquid with reduced oxygen content (about 10%) and the primary by-product is water containing soluble organic compound. It mimics the natural geological processes thought to be involved in the production of fossil fuels. Under intense pressure and heat, long chain polymers of hydrogen, oxygen, and carbon decompose into short-chain petroleum hydrocarbons with a maximum length of around 18 carbons.

Thermal Depolymerisation can change many carbon-based materials into crude oil and methane, and is not limited to manure or vegetable waste.

3.2.2 History

Thermal Depolymerisation is similar to the geological processes that produced the fossil fuels that are used today, except that the technological process occurs in a timeframe of hours rather than thousands of years. Until recently, the artificial fossil fuel processes were not efficient enough to serve

as a practical source of fuel, as more energy was required in the creation of the fuel than was produced in the products.

Many early methods that create hydrocarbons through Depolymerisation use dry materials (or anhydrous pyrolysis), which requires expending a lot of energy to remove water. However, there has been work done on hydrous pyrolysis methods, in which the Depolymerisation takes place with the materials in water. Earliest examples were first seen in 1939, where a method for obtaining oil from wood in which the wood is heated under pressure in water with a significant amount of calcium hydroxide added to the mixture was first patented¹⁹. Hydrous pyrolysis methods were further investigated during the oil crisis in the 1970s, where the focus was on the production of oil from sewer sludge and municipal refuse by heating the material in water under pressure in the presence of carbon monoxide.²⁰

The technology has since been further refined for commercial use with a demonstration plant opening in Philadelphia, U.S.A. in 1999 by a company called Changing World Technologies. A full-scale commercial plant has since been constructed in Carthage, Missouri, where it now processes about 200 tons of turkey waste into 500 barrels (80 m³) of oil per day.

3.2.3 Theory and process

The water present in the biomass actually improves the heating process and contributes hydrogen to the reactions.

The feedstock material is first ground into small chunks, and mixed with water if required. This ground biomass is then fed into a reaction chamber where it is heated to around 250°C under 4 MPa for approximately 15 minutes, after which the pressure is rapidly released to boil off most of the water. The result is a mix of crude hydrocarbons and solid minerals, which are separated out. The hydrocarbons are sent to a second-stage reactor where they are heated to 500°C, further breaking down the longer chains, and the resulting mix of hydrocarbons is then distilled in a manner similar to conventional oil refining.²¹

The commercial CWT plant operates with turkey offal as the feedstock, the process proved to have yield efficiencies of approximately 85%. Since the energy content of the feedstock is essentially free (i.e., waste material from some other process), the energy efficiency of the process can be considered to be 566% (85 units of energy made available for every 15 units of energy consumed). The company claims that 15 to 20% of the feedstock energy is used to provide energy for the operation of the plant. The remaining energy

is available in the bio-oil product. Higher efficiencies may be possible with more carbon-rich feedstock, such as waste wood or plastics.²²

TABLE 3.2.1 TDP Feedstock and Outputs²²

Feedstock	Output
Plastic bottles	Oil 70 % Gas 16 % Carbon solids 6 % Water 8 %
Turkey offal	Oil 39 % Gas 6 % Carbon solids 5 % Water 50 %
Tires	Oil 44 % Gas 10 % Carbon solids 42 % Water 4 %
Sewage sludge	Oil 26 % Gas 9 % Carbon solids 8 % Water 57 %
Paper (cellulose)	Oil 8 % Gas 48 % Carbon solids 24 % Water 20 %

The fixed carbon solids produced by the process have multiple uses as a filter within the reactor, a fuel source and as fertiliser. It can also be sold for use as activated carbon in wastewater treatment facilities.

3.2.4 Limitations

The process only breaks long molecular chains into shorter ones, so small molecules such as carbon dioxide or methane cannot be converted to oil through this process. Neither can thermal Depolymerisation be used to remove radioactivity from radioactive waste.

Many agricultural and animal wastes could be processed, but many of these are already used as fertiliser, animal feed, and, in some cases, as feedstock for paper mills or as boiler fuel.

3.2.5 Current status

According to a recent article by Fortune Magazine²³, the Carthage plant is currently producing about 400 barrels per day of crude oil. This oil is being refined as No. 2 (a standard grade oil which is used for diesel and residential heating oil) and No. 4 (a lower grade oil used in industrial heating).

3.3 Gasification

Rather than burn the biomass directly, the organic material can first be turned into a gas, which can then be used to power a gas turbine or used as an added fuel source.

Wood gas, also known as producer gas or blue gas, is the product of thermal gasification of biomass and other carbon rich materials, such as coal, in a gasifier. It is the result of a high temperature ($>700\text{ }^{\circ}\text{C}$) reaction, where carbon reacts with steam or a limited amount of oxygen producing carbon monoxide (CO), molecular hydrogen (H_2), and carbon dioxide (CO_2).

In several gasifiers the actual gasification process is preceded by pyrolysis, as described above, where the biomass is turned into char releasing polycyclic aromatic hydrocarbon (PAH) rich tar and methane (CH_4). Wood gas is flammable because of the carbon monoxide, hydrogen and methane content.

Wood gas can be used with ordinary internal combustion engines. During the Second World War, wood gas was utilised for civilian transport in Europe due to the oil shortage generated by the war. More recently, wood gas has been touted as a clean and efficient method to heat and cook in developing

countries, or even to produce electricity when combined with a gas turbine or internal combustion engine. Compared to the technology of the early 20th century, modern gasifiers have become more sophisticated.

Typical wood gasifiers take wood chips, sawdust, charcoal, coal, etc as fuel and burn these incompletely in a firebox. This produces wood gas as well as solid ashes and soot (which have to be removed periodically from the gasifier). The wood gas is filtered for tars and soot/ash particles, and is either cooled and stored or directed to a generator such as an internal combustion engine, gas turbine, Stirling engine or fuel cell to produce electricity. Most of these devices have severe requirements to the purity of the wood gas, so the gas often has to pass through extensive gas cleaning in order to remove or convert (i.e. to "crack") tars and particles it may contain. (See table 3.3.1 below for typical chemical composition)

The heat of combustion of producer gas has a value of 5.7 MJ/kg versus 55.9 MJ/kg for natural gas and 44.1 MJ/kg for gasoline²⁵.

Table 3.3.1 Typical Chemical Composition of Wood Gas²⁵

Nitrogen N ₂	50.9%
Carbon monoxide CO	27.0%
Hydrogen H ₂	14.0%
Carbon dioxide CO ₂	4.5%
Methane CH ₄	3.0%
Oxygen O ₂	0.6%

The quality of the gas can vary from different types of gasification process. Staged gasifiers, where pyrolysis and gasification occur separately can be engineered to produce essentially tar-free gas (<1 mg/m³), while single reactor fluid-bed gasifiers may exceed 50,000 mg/m³ tar[#]. The fluid bed reactors have the advantage of being much more compact (more capacity per volume and price). Depending on the intended use of the gas, tar can be beneficial by increasing the higher heating value of the gas.

Gasification also has the added benefit of converting biomass such as wood waste into more

Purification of the gas and feeding it into the natural gas pipelines is one variant to link it to existing refuelling infrastructure, liquefaction by the Fischer-Tropsch process is the other possibility.

3.4 Anaerobic Digestion

Anaerobic Digestion (AD) is a natural biological process, where microbes and enzymes break down organic material in the absence of oxygen. This bacteria produces energy rich methane, often called 'biogas', which can then be used to power a gas turbine, as well as a nutrient rich digestate, which can be used to fertilise land for new biomass growth. This process occurs in three stages:

1. Hydrolysis,
2. Acidogenesis and,
3. Methogenesis,

Which are described below.

3.4.1 Digestive Stages

Hydrolysis

AD begins with enzymatic hydrolysis. Hydrolytic bacteria produce extra-cellular enzymes that begin the decomposition of the organic material in the substrate, rather than an internal bacterial cell process. Hydrolysis breaks down long chain molecules, such as cellulose, starch, proteins and fats, into their smaller constituent molecules, such as simple sugars, amino acids and fatty acids. The bacteria can then use these simpler molecules in the next stage of digestion.

Fermentation

Also known as acetogenesis or acidogenesis, this second stage of AD involves acetogenic bacteria breaking down the hydrolysed products, using them as food to grow. The metabolic products consist of fatty acids, CO₂ ammonia and hydrogen.

Because the bacteria require a high rate of contact with the hydrolysed products, agitation (mixing) of the substrate enhances the efficiency of the process. This can be done by mechanical mixing, or via bubbling gas back through the substrate, which could also help to keep the substrate at the optimum temperature range of around 30°C for bacterial action.

Methanogenesis

The final stage of the AD process results in the production of methane gas. Using the products from the fermentation, methanogenic bacteria produce methane by one of two processes. Approximately 70% of the methane is created from the volatile fatty acids by acidotrophic bacteria.

Hydrogenotrophic bacteria use hydrogen and carbon dioxide to produce the other 30% of methane. The action of the hydrogenotrophic bacteria has the added benefit of removing hydrogen from the vessel. If the level of hydrogen was to rise, it could inhibit the action of the acetogenic bacteria in stage two resulting in a drop off in the rate of biogas production.

3.4.2 Operating Parameters

AD is a very complex biological process and as a result it is very susceptible to changes in the digester environment. Several variables can affect the production rates and performance of the bacteria, it is therefore necessary to monitor the environment within the digester and ensure stable conditions are maintained. Temperature changes, presence of large amounts of oxygen and overloading of the reactor can all result in the cessation of biogas production.²⁶

Other factors that are also important to consider are:

- PH – An optimum operating range of between pH values of 6 and 7 is required for the different types of bacteria involved in the digestion.
- Carbon: Nitrogen ratio – The optimum range is from 20:1 to 30:1. Lower ratios are an indication of high levels of ammonia, which can be harmful to the methanogenic bacteria. Higher ratios show that nitrogen is being consumed too fast, which again impedes methane production.

- Biomass Load Rate – This is the amount of degradable biomass fed into the digester tank, in relation to the volume and retention time. This is usually expressed as the Chemical Oxygen Demand (COD)/m³ of digester tank volume. If there is an excess of organic compounds it can lead to overproduction of volatile fatty acids which, as described earlier, increases the acidity of the substrate and thus retards the production of methane.
- Dry Solid content - This depends on the material used as a feedstock. Optimum DS content is normally below 35%, so some feedstock may require the addition of water. However this is not such a high concern when using very wet biomass, which typically has moisture content of 50-75%.
- Agitation – It is important to mix the substrate to maximise the exposure between the organic compounds and the bacteria. Mixing also helps keep the temperature constant throughout substrate and prevents a build up of a scum layer on the surface by providing homogeneity throughout the tank.
- Retention time within the digester unit. – The time required to achieve sufficient digestion of the biomass varies between the two main processes. Thermophilic digestion occurs between 12- 15 days while the mesophilic digestion requires between 20 and 35 days to complete.

Controlled AD has been used for years in the production of alcohol, via the action of yeast.

The biogas produced in AD is typically made up of around 60% Methane, with the rest composed of Carbon dioxide, and trace amounts of Hydrogen and Ammonia. The methane can be used in a Combined Heat and Power (CHP) System for immediate electricity and heat generation, or can be stored for use in other applications. Another benefit of AD over direct combustion is the secondary products produced. The solid and liquid digestates are rich in nutrients, which can be used as fertilisers.

Energy derived from AD technology qualifies for Renewable Obligations schemes, which can help, offset the cost of the technology being implemented.

Biogas derived from AD consists of between 55-75% methane. The remainder is composed of CO₂ and trace amounts of hydrogen sulphide, nitrogen molecular hydrogen and carbon. Of these product gases, the hydrogen sulphide has the greatest implications for reactor design. At concentrations in the range of 200-4000 ppm, hydrogen sulphide is quite corrosive- forming sulphuric acid if combusted, which has a detrimental effect to the equipment.

Therefore it is important to remove this harmful gas from the biogas before it reaches the boiler unit. This can be achieved using several different methods, the most common of which is to scrub the gas using ferrous salts. Use of high alkaline engine oil, when changed frequently, can also neutralise any acid formed. New techniques are also being developed that use the bacteria *Thiobacillus spp.* By bubbling small jets of air through the top most layer of the digesting sludge, the bacteria can oxidise the hydrogen sulphide into water and sulphur³⁷.

3.4.3 The Digestate

The rest of the material produced by AD is normally separated into two categories:

Liquor – The nutrient rich liquid

Fibre – solid compost like material

Application of the digestate to land for arboreal or agricultural purposes offers many benefits over traditional fertilisation techniques, such as:

- Reduction of pathogens and weed seeds
- Reduction in strong odours since the concentration of volatile fatty acids and other odorous compounds are significantly decreased.
- Stabilisation of organic matter
- Increase in the availability of nutrients for plants since less organic nitrogen is converted to ammonia.

- Reduced need for artificial fertilisers, derived from fossil fuels.
- A reduction in nutrient run off and environmental pollutions.

This is a secondary benefit to Anaerobic Digestion as part of a biomass power generation. Rather than see beneficial nutrients literally go up in smoke; AD produces both a clean burning biogas and nutrient rich by-products that can be used to promote the growth of next generation biomass. Thus is much closer to a sustainable system of power generation.

Both forms of digestate are exempt from waste management licensing requirements under Scottish law ³⁸

3.4.4 The Anaerobic Digester

The anaerobic digester is an enclosed vessel in which AD takes place in a continuous cycle, operating as a system of wet biomass input and digestate off-take. This ensures minimum retention time within the unit but also reduces the risk of removing raw biomass from the digester in the off-take before it has been digested.

3.5 Ethanol from Cellulose

Ethanol, more commonly known as alcohol, is a combustible liquid that can be used as an alternative motor fuel. Ethanol, unlike gasoline, is an oxygenated fuel that contains 35% oxygen, which reduces particulate and NO_x emissions from combustion.

Ethanol can be made synthetically from petroleum or more commonly by microbial conversion of biomass materials through fermentation. The fermentation method generally uses three steps:

- (1) The formation of a solution of fermentable sugars,
- (2) The fermentation of these sugars to ethanol, and
- (3) The separation and purification of the ethanol, usually by distillation.

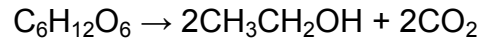
3.5.1 Background

The ability to make ethanol has been with man since the dawn of civilisation via the process of fermentation. This involves microorganisms that typically use 6-carbon carbohydrates sugars, most commonly glucose, for food.

Ethanol is produced in the metabolic process along with other by-products.

Saccharomyces cerevisiae, also known as Baker or Brewer's yeast, is the most commonly used although other microbes produce ethanol by fermenting sugars.

Fermentation is the metabolism of sugar in the absence of oxygen, where the microbes produce ethanol and carbon dioxide. The overall chemical reaction conducted by the yeast may be represented by the chemical equation



However sugar and starchy materials are in the human food chain and are thus expensive. Therefore there is currently a great deal of research underway into using cellulosic materials (i.e. wood). As discussed, wood residues are an abundant material that is outside the human food chain, making cellulosic materials relatively inexpensive feedstock for the production of ethanol.

Wood and other cellulosic biomass is comprised of lignin, hemicellulose, and cellulose and thus sometimes referred to as lignocellulosic materials. The primary function of lignin is to provide structural support for the plant. Thus trees have higher lignin contents than other biomass sources. Unfortunately, lignin, which does not contain any sugars, encloses the cellulose and hemicellulose molecules.

Cellulose ($C_6H_{10}O_5$) is a long-chain polymeric polysaccharide carbohydrate i.e. cellulose molecules consist of long chains of glucose molecules, but have a different structural configuration. These structural characteristics plus the encapsulation by lignin makes cellulosic materials more difficult to hydrolyse than sugary and starchy materials.

Hemicellulose is also comprised of long chains of sugar molecules; but contains, in addition to glucose, pentoses (5-carbon sugars). The exact sugar composition of hemicellulose can vary depending on the type of wood. Since 5-carbon sugars comprise a high percentage of the available sugars, the ability to recover and ferment them into ethanol is important for the efficiency and economics of the process.

Recently, special microorganisms have been genetically engineered which can ferment 5-carbon sugars into ethanol with relatively high efficiency.

One example is a genetically engineered microorganism developed by the University of Florida that has the ability to ferment both 5- and 6-carbon sugars. {US patent 5,000,000}. Other researchers have developed microorganisms with the ability to efficiently ferment at least part of the sugars present. Bacteria have drawn special attention from researchers because of their speed of fermentation. In general, bacteria can ferment in minutes as compared to hours for yeast.

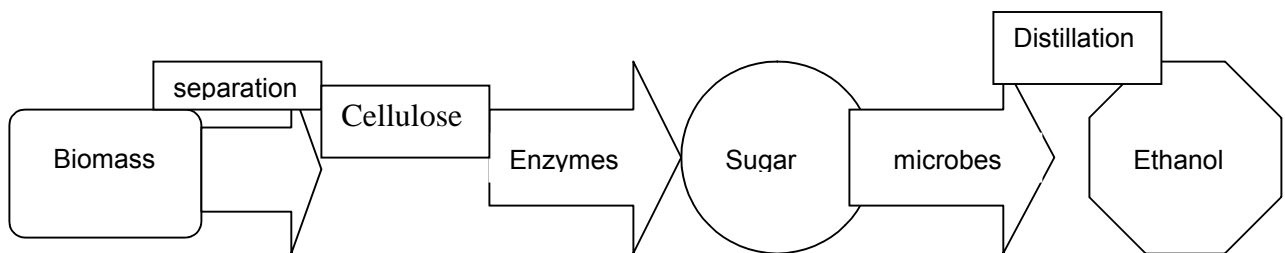
3.5.2 ETHANOL FROM CELLULOSE

It is has only been recently that cost-effective technologies for producing ethanol-from-cellulose (EFC) in the US have started to emerge. There are three basic types of EFC processes:

1. Acid hydrolysis,
2. Enzymatic hydrolysis, and
3. Thermo-chemical

With variations for each. The most common is acid hydrolysis. With sulphuric acid being most commonly used since it is usually relatively inexpensive, although other acids can be used.

Figure 3.5.1 Conventional Flow Diagram of EFC Process



3.5.3 ACID HYDROLYSIS

There are two basic types of acid processes: dilute acid and concentrated acid, each with variations. Dilute acid processes are conducted under high temperature and pressure, and have reaction times in the range of seconds or minutes, which facilitates continuous processing.

As an example, using a dilute acid process with 1% sulphuric acid in a continuous flow reactor at a residence time of 0.22 minutes and a temperature of 237°C with pure cellulose provided a yield over 50% sugars. In this case, 0.9 t of dry wood would yield about 189 L of pure ethanol. However this can be very expensive as the combination of acid and high temperature and pressure require special reactor materials.

Most dilute acid processes are limited to a sugar recovery efficiency of around 50%. The reason for this is that at least two reactions are part of this process. The first reaction converts the cellulosic materials to sugar and the second reaction causes a degradation of the sugars to other chemical products that can be poisonous to the fermentation micro-organisms.

Unfortunately, the conditions that cause the first reaction to occur also are the right conditions for the second to occur. The sugar degradation problem limits yields to around 272 L/t of dry wood.

The biggest advantage of dilute acid processes is their fast rate of reaction, which facilitates continuous processing. Their biggest disadvantage is their low sugar yield. For rapid continuous processes, in order to allow adequate

acid penetration, feedstock must also be reduced in size so that the maximum particle dimension is in the range of a few millimetres.

The concentrated acid process uses relatively mild temperatures and the only pressures involved are usually only those created by pumping materials from vessel to vessel. One concentrated acid process developed and further refined by Purdue University and the Tennessee Valley Authority is the TVA concentrated acid process, in which corn stalks are mixed with dilute (10%) sulphuric acid, and heated to 100°C for 2 to 6 hours in the first hydrolysis reactor. The low temperatures and pressures minimise the degradation of sugars. To recover the sugars, the hydrolysed material in the first reactor is soaked in water and drained several times.

The solid residue from the first stage is then dewatered and soaked in a 30% to 40% concentration of sulphuric acid for 1 to 4 hr as a pre-cellulose hydrolysis step. This material is then dewatered and dried with the effect that the acid concentration in the material is increased to about 70%. After reacting in another vessel for 1 to 4 hr at 100°C, the reactor contents are filtered to remove solids and recover the sugar and acid. The sugar/acid solution from the second stage is recycled to the first stage to provide the acid for the first stage hydrolysis. The sugars from the second stage hydrolysis are thus recovered in the liquid from the first stage hydrolysis.⁴¹

The primary advantage of the concentrated process is the high sugar recovery efficiency, which can be on the order of over 90% of both

hemicellulose and cellulose sugars. The low temperatures and pressures employed also allow the use of relatively low cost materials such as fibreglass tanks and piping.

Unfortunately, it is a relatively slow process and cost effective acid recovery systems have been difficult to develop. Without acid recovery, large quantities of lime must be used to neutralise the acid in the sugar solution.

This neutralisation forms large quantities of calcium sulphate, which requires disposal and creates additional expense.

Using some assumed cellulose conversion and fermentation efficiencies, ethanol yields from glucose can be calculated for corn stover (the stalk of the corn plant, less the ears) as shown in Table 3.5.1 showing ethanol yield from glucose. Similarly, ethanol yields from the xylose can be calculated as shown in Table 3.5.2 below.

Thus, in this example, the total yield/t of dry stover is about 227 L of ethanol.

These numbers also show how critical sugar conversion and recovery efficiencies and fermentation efficiencies are. If one could attain 95% for both efficiencies, then the yield would be approximately 350 L/t (103 gallons of ethanol/ton).

Table 3.5.1. Ethanol yield from glucose

Dry stover	1 metric ton (1000 kg)
Cellulose content	× 0.45
Cellulose conversion and recovery efficiency	× 0.76
Ethanol stoichiometric yield	× 0.51
Glucose fermentation efficiency	× 0.75
Yield from glucose	131 kg ethanol = 151 L

Table 3.5.2. Ethanol yield from xylose.

Dry stover	1 tonne (1000 kg)
Hemicellulose content	× 0.29
Hemicellulose conversion and recovery efficiency	× 0.90
Ethanol stoichiometric yield	× 0.51
Xylose fermentation efficiency	× 0.50
Yield from xylose	66 kg ethanol = 76 L

3.5.4 Enzymatic Hydrolysis

Another basic method of hydrolysis is enzymatic hydrolysis. Naturally occurring plant proteins, enzymes cause certain chemical reactions to occur. However, for enzymes to work, they must obtain access to the molecules to be hydrolysed. For enzymatic processes to be effective, some kind of pre-treatment process is needed to break the crystalline structure of the lignocellulose, removing the lignin to expose the cellulose and hemicellulose molecules. Depending on the biomass material, either physical or chemical pre-treatment methods may be used.

Physical methods may use high temperature and pressure, milling, radiation, or freezing, all of which are high-energy consumption techniques. The chemical method uses a solvent to break apart and dissolve the crystalline structure.

The National Renewable Energy Laboratory (NREL) is currently developing an enzymatic hydrolysis-based process. After a dilute acid pre-treatment, the biomass slurry is detoxified, removing chemicals that would be poisonous to the bacteria used in the process. These microbes are grown to produce the cellulase enzyme used in the process. Another part of the treated biomass is sent to another vessel to maintain and grow a yeast culture for fermentation.

In the NREL process, both enzymes and the fermentation micro-organisms are added at the same time to the slurry, and sugar conversion and fermentation occur simultaneously in a process called simultaneous saccharification and co-fermentation (SSCF).

Due to the tough crystalline structure of the lignocellulose, the enzymes require several days to achieve good results. Since this relatively long process time ties up reactor vessels, they have to either be quite large or have many running concurrently for sufficient quantities of ethanol to be produced economically. Either option is expensive. Continuing research is also underway to bring down the cost of enzymes by engineering the bacteria that produce them to be more efficient. If less expensive enzymes can be developed enzymatic processes hold several advantages:

- (1) Efficiency is quite high and by-product production can be controlled
- (2) Unlike acid hydrolysis, the mild process conditions do not require the equipment to be constructed out of expensive materials.
- (3) Overall energy requirements for the process are relatively low.

3.5.5 Thermo-chemical Processes

There are two ethanol production processes that are currently under development that employ thermo-chemical reactions in their processes.

The first system is actually a hybrid thermo-chemical and biological system. Biomass materials are first thermo-chemically gasified and the synthesis gas (a mixture of hydrogen and carbon oxides) bubbled through specially designed fermentation tanks. A genetically engineered microorganism that is capable of converting the synthesis gas is introduced into the fermentation vats under specific process conditions allowing ethanol to ferment.

The second thermo-chemical ethanol production process does not use any microbes. In this process, the biomass materials are first converted to synthesis gas, which is then passed through a reactor containing catalysts that cause the gas to be converted into ethanol.

An intensive effort was made by Germany during World War II to develop these processes for fuel. Numerous efforts have been made since then to develop commercially viable thermo-chemical-to-ethanol processes.

Ethanol yields up to 50% have been obtained using synthesis gas-to-ethanol processes. Some processes that first produce methanol and then use catalytic shifts to produce ethanol have obtained ethanol yields in the range

of 80%²⁴. Unfortunately, like the other processes, finding a cost-effective all-thermo-chemical process has been difficult.

3.5.6 Commercialisation

Several EFC plants were built and operated in various countries during the Second World War, including Germany, the USSR, China, Switzerland, and the United States among other countries. Today only a few of these plants are still operating, mainly in former Soviet states.

A paper manufacturing plant in Quebec operates off of by-product sugars contained in “sulphite liquor,” which contains about 2% fermentable sugars. This is the only facility of its kind in North America. This facility is operated by Tembec, Inc., and produces 18.1 L per year of ethanol²⁵. This is currently being used for vinegar production.

3.5.7 Summary

Ethanol from cellulose has great potential mainly in as a replacement motor fuel due to the widespread availability, abundance, and relatively low cost of cellulosic biomass. However, although several EFC processes are technically feasible, cost-effective processes have been difficult to achieve. It is only recently with the increasing oil price, has EFC technologies begun to emerge as cost effective.

In September 2006, the Honda car company announced that they had developed a cost-effective approach to producing ethanol fuel from cellulose, and were planning on building this technology up to an industrial level. See Appendix A for more details.

3.7 Summary of Conversion Technology

There are several methods of converting raw organic biomass materials into more useful forms of energy, which have been explored above.

However conversion methods are currently unable to compete with traditional sources of heat and power. At best some of the more mature technologies may break even at current fossil fuel prices, but with the price of oil set to rise, biomass conversion technologies may come into their own in the future energy market.

These are mainly emerging technologies, with regards to the use of very wet biomass, but the potential of this resource has been seen and further research and development can only lead to improvements in the efficiency, technology and operating costs.

Chapter 4: The Case for Using Very Wet Biofuels

4.1 Introduction

The greatest challenge to the growth of biomass industry in the UK is the current lack of adequate resources. However the Scottish timber industry is a traditional, well-established business that produces thousands of tonnes of wood waste, in the form of sawdust and woodchips, per year. The main hold up with using this rich resource as a biofuel is the high moisture content of the wood residues, a result of the timber manufacturing process. This makes the timber industry an incompatible source of biofuel for traditional bio-heating technologies.

4.2 Direct Combustion of Wet Wood

Wood boilers can only operate with high efficiency and low emissions if the fuel wood has about the right moisture content. Properly seasoned wood should have moisture content of less than 20 percent.

Poor performance related to wet wood include:

- Difficulty getting combustion to begin and keeping it burning well,
- Smokey fires with little flame,
- Rapid creosote build-up in the equipment,
- Low heat output,
- Shorter burn times,
- Excessive fuel consumption
- Blue-grey smoke from the chimney.

4.2.1 Understanding Combustion

As wood burns, it goes through three phases:

1. Water

As the wood is heated in the fire, the water it contains is boiled off. Even prepared wood, such as wood pellets, have moisture content less than 20%. This consumes heat energy. The wetter the wood, the more energy is consumed. That is why wet wood hisses and sizzles while dry wood ignites and burns easily.

2. Smoke (or flame)

As the wood heats up above the boiling point of water, it starts to smoke. The hydrocarbon gases and tars that make up the smoke are combustible if the temperature is high enough and oxygen is present. When the smoke burns, it makes the bright flames that are characteristic of wood combustion. If the smoke does not burn efficiently in the burner, it may condense in the chimney, forming creosote, a volatile oily liquid containing phenols and creosols that can be detrimental to the equipment.

3. Charcoal

As the fire progresses and most of the hydrocarbons have vaporized, charcoal remains. Charcoal is almost 100% carbon and burns with very little

flame or smoke. Charcoal is a good fuel that burns easily and cleanly when enough oxygen is present. Of the total energy content of the wood burn, about half is in the form of smoke, and half is charcoal.

The challenge in burning wood efficiently is to burn off the smoke before it leaves the burner thus getting more heat from the wood, and reduce creosote deposits and air pollution.

Wet fuel wood obviously provides far less heat, and causes greater quantities of creosote and other compounds to form in the equipment

Heat is extracted from wood in two ways. The primary source of heat is the combustion of the wood itself: the secondary source is the combustion of the gasified resins and unburned wood particles that result from the primary fire.

When wet wood is burned, the water contained in the wood heats up and turns to steam, which mixes with the exhaust gases and extinguishes the secondary burn. This will cut the heat output by up to 50%, and results in cool, water-laden exhaust filled with unburned particles and exhaust gases. This wet, heavy, high-density smoke travels very slowly through the exhaust, where it will cool further still, condensing onto the walls of the flue and causing excessive creosote formation which can lead to a dramatic increase in the risk of chimney fires.

In short, trying to directly burn wet wood is a wasteful use of resources. Not only does burning wet fuel wood provide far less heat but it also creates excessive pollution and makes no economical sense in terms of biofuels. Burning properly 'seasoned' or dry wood can eliminate these problems.

4.3 Biomass Drying

If burning the wet biomass directly is out of the question, then what methods are available to pre-dry the fuel before being used in a biomass boiler?

4.3.1 Why Dry Fuel?

Dry fuel is used in direct combustion boilers as it results in improved efficiencies and increased steam production, reductions in fuel use, emissions and ancillary power requirements.²⁶

The overall improved operation of the boiler when using dried fuels comes about by the increased flame temperature. With wet fuels, some of the heat of combustion goes into evaporating the excess water from the fuel. With dry fuels, all the energy goes into heating the air and the products of combustion. It should also be noted that in colder climates, such as Scotland, the heat of fusion of ice that may be present in the wood would also have a significant effect on overall boiler efficiency.

This increase in flame temperature has a number of benefits. Firstly it results in more heat transfer taking place in the same boiler tube area, thus increasing the production of steam for power generation. This can also mean smaller boilers for the equivalent amount of heat transfer²⁷. Also with higher flame temperatures comes a more complete combustion of the fuel, increasing efficiency and reducing pollution leaving the boiler, which again can lead to smaller boiler sizes²⁷. With a more complete combustion, less

excess air is required, reducing the amount of heat of combustion that gets wasted by heating air. For moist fuels, there need to be an approximate 80% of excess air to prevent smoke formation. For dried fuel wood, this is only 30% resulting in less sensible heat loss in flue gases, and will require less energy to power fans that are needed to provide air to the boiler firebox for combustion²⁷.

Overall thermal efficiency can amount to an increase of 5%-15%, with steam production increases of 50%-60%^{28, 29}.

4.3.2 Principles of Drying

The three requirements for drying are:

- A source of heat,
- A method of removing evaporated water vapour
- Some form of shake-up to expose new material for drying³⁰.

Different types of dryer satisfy these requirements in different ways. The principle of drying itself remains the same no matter which technique is used. At first the biomass material is heated from its initial temperature it entered the dryer at, up to the wet bulb temperature, T_{wb} . This produces the driving force needed for the water to leave the wet biomass. Surface moisture is evaporated fairly quickly and the material must continue to be heated to drive the internal moisture to the surface so that it can evaporate off. This is the “falling rate period” when the rate of drying drops as the biomass becomes dryer. At this time the surface temp of the material remains close to T_{wb} . However once it is completely dry, the fuel no longer has any water content to cool it and thus heats up to the surrounding temperature. It's at this latter stage in the drying process where there is an increased risk of spontaneous ignition of the biomass.

4.4 Types of Dryer

Broadly speaking, dryers can be separated into two categories depending on how the heat is provided:

Indirect Heat Dryers

Indirect dryers use an intermediate heat exchanger between the heat source and the material to be heated. An important consequence of this method is the ability to recover the latent heat of evaporation from the water vapour. This can be recovered using a vacuum pump, drawing a vacuum on the biomass as it is heated and condensing the vapour.

Direct Heat Dryers

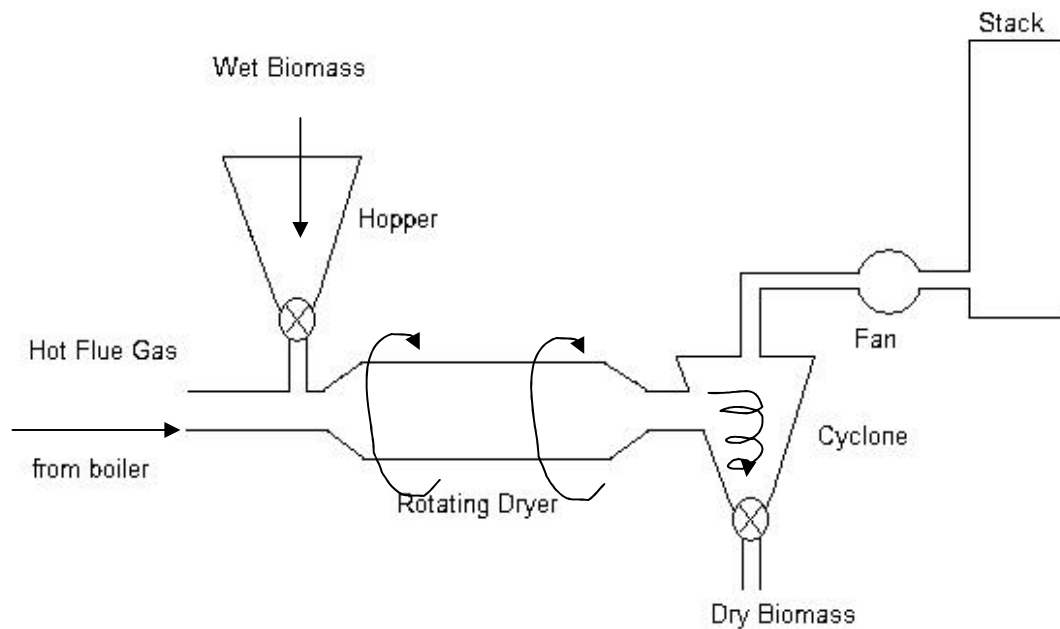
Direct dryers allow direct contact between the material to be heated and the fluid that provides the heat- typically either hot air or steam. In air dryers, the hot air loses its sensible heat and provides the latent heat of evaporation as it passes over the material. It also removes the water vapour as it passes through the dryer.

In superheated steam dryers (SSDs) the concept is essentially the same as the air dryer, except the heating fluid is steam rather than hot air. Sensible heat is lost by the superheated steam to provide the latent heat of evaporation to the water in the biomass. However because it is superheated, the steam remains above saturation temperature and thus doesn't condense as it moves through the dryer. This results in a net increase in steam leaving the dryer, but at a lower temperature than steam entering. Like the indirect approach, latent heat of evaporation of the water vapour can be recovered in a SSD system because the vapour is not diluted by air.

4.4.1 Rotary Dryers

The rotary dryer is the most common type of dryer used for biomass. There are a number of this type of dryer designs, but the most commonly used is the directly heated single-pass rotary dryer {See Fig 4.4.1 below}.

Figure 4.4.1 Basic Single-Pass Rotary Dryer



In this type of dryer, hot gases, which could include the hot flue gases from the boiler (if contamination is not a concern), come into contact with the biomass material inside a rotating drum. Because the drum is rotating, the solid materials are lifted and thus tumble through the hot gases, much like a

tumble dryer for clothes. Using a steam heater or burner before the air enters the dryer can also produce the hot gas.

Normally this hot gas flows co-currently with the flow of the biomass through the dryer insuring that the hottest gases come into contact with the wettest material. However if the temperature of the output material is not of concern then the gas can be introduced in counter-flow to the biomass so that the driest solid material is exposed to the hottest and less humid gases ensuring the lowest moisture content of the end product leaving the dryer. However this method also increases the fire risk, as the dry biomass will be hot when it is exposed to air at the end of the process and may ignite.

The exhaust gases need to be processed to remove any fine material from entering the air. This can be done using scrubbers, electrostatic precipitators, filters or cyclones.

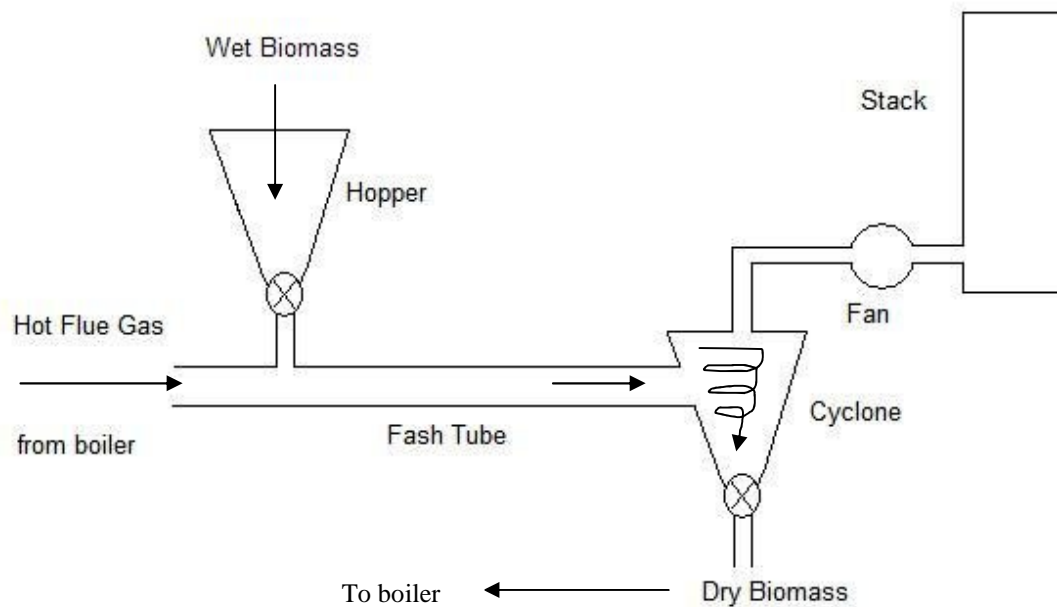
Indirectly heated rotary dryers use an external heat source, usually steam or hot air, passing through the outer wall of the drum or through a central shaft to heat the air in the dryer by conduction. This method can utilise the heat from the flue gases without contaminating the biomass with particles from the waste gas. A hybrid can also work, with the very hot flue gas first passing through the central shaft to indirectly heat the dryer and then on a second pass enters the drum to dry the solid biomass.

Input temps for rotary dryers can be from 232°C to 1093°C while the output varies from 71°C to 110°C. A higher output temp is desired to prevent the condensation of resins and organic acids that can corrode the machinery. Retention times for a rotary dryer can be as little as under a minute for small particles up to half an hour for larger biomass material.²⁷

4.4.2 Flash Dryers

In flash or pneumatic dryers, the solid biomass material is mixed with a stream of high velocity hot air. This surrounding overall contact with the hot air provides very fast drying. The solid material is then separated from the gas via a cyclone (the gas is then scrubbed and purified as before to remove small particle and aerosols from the exhaust) {SEE FIG 4.4.2 below}

Figure 4.4.2 Basic Flash Dryer



Because of the very rapid drying, material doesn't need to spend too much time in a flash dryer, thus reducing the size of the equipment. However electricity consumption is greater in a flash dryer because of the need to

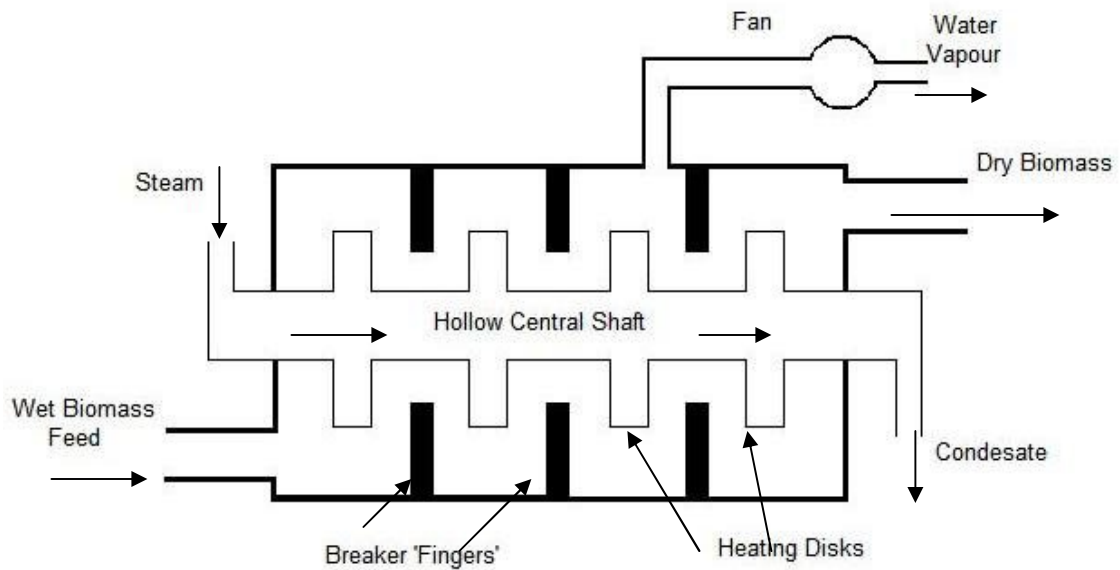
provide a fast flow of hot air and the prerequisite of shredded/grinded biomass.

Gas temperature can be slightly lower in flash dryers than in rotary but still above the combustion point for wood. However retention time in a flash dryer is usually under 30 seconds reducing the risk of fire.

4.4.3 Disk Dryers

Disk, or 'porcupine', dryers {See Fig 4.4.3 below} are an option for small flows of biomass material. The biomass solids are heated by condensing steam inside a central shaft with many hollow disks, which increase the surface area for heat transfer. The material is constantly mixed to keep the disks free of build up. Disk dryers can operate under vacuum or high pressure and the condensed steam in the central shaft can be recovered and returned to the boiler.

Figure 4.4.3 Disk Dryer Configuration



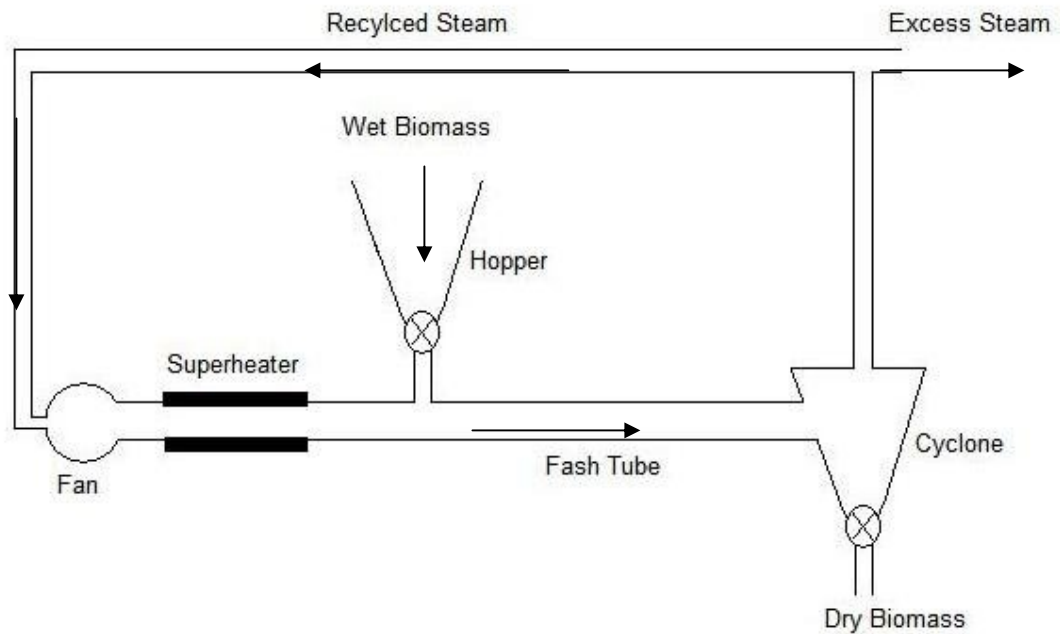
Note: Biomass doesn't come into contact with the heating fluid (in this case steam), which is contained in the central heat exchanger core. The 'fingers' act to churn up the biomass as it passes through the dryer, helping to prevent any build up on the heat exchange disks.

4.4.4 Superheated Steam Dryers

Similar to a flash dryer, SSDs utilise superheated steam to provide the heat instead of air. Enough steam is provided to both mixed and dried the wet biomass and still end up superheated. Under typical operation up to 90% of the steam is circulated within the dryer whilst the remaining 10% drawn from the biomass can be utilised in other parts of the plant³¹

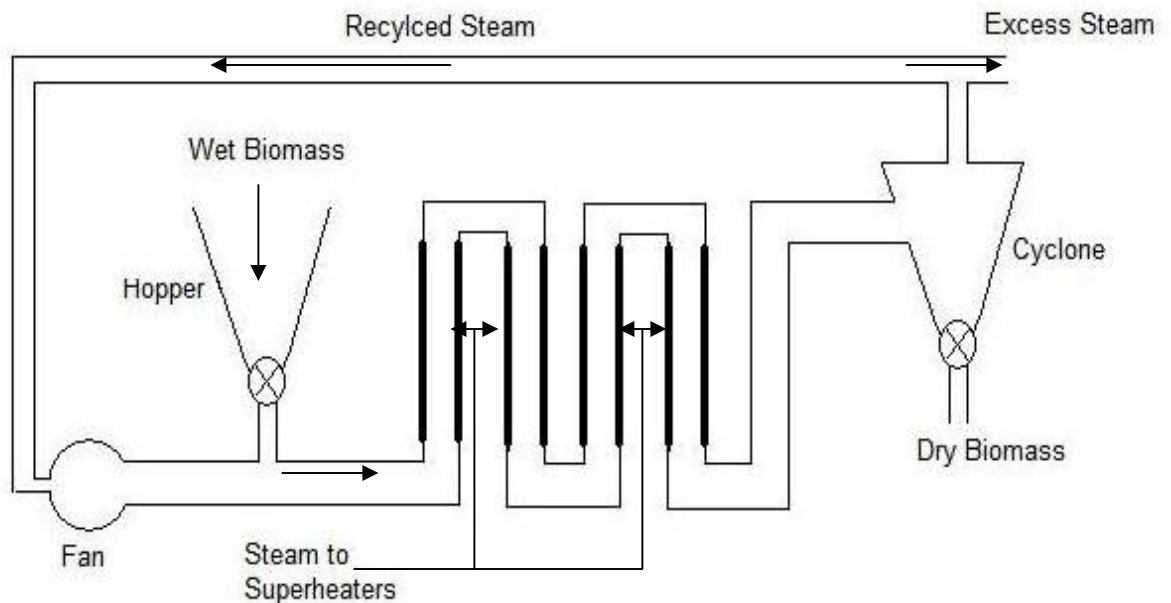
Figure 4.4.4 below shows a basic IVO SSD dryer made by the Finnish power company Imatron Voima Oy.

Figure 4.4.4a Basic “IVO” Superheated Steam Dryer



Just as in a flash dryer, the biomass and superheated steam pass through a flash tube, with the dry solid being separated via a cyclone. The majority of the steam gets recycled in the dryer, powered by a fan and passes through a heat exchanger before taking on more wet biomass. Excess steam is removed from the system and is either condensed in order to recapture the latent heat or used elsewhere in the plant. With high-pressure operation, the steam could be injected into a gas turbine to increase the power output. Other more complex SSDs are also available, such as the MoDo dryer (see fig 4.4.4b), made by MoDo-Chemetics which works on the same principle as the basic IVO design but also uses high temperature steam to heat the walls of the flash tube, providing the heat of evaporation for the water in the biomass²⁷.

Figure 4.4.4b MoDo-Chemetics SSD Dryer Configuration



4.5 Heat Recovering

As previously stated, drying very wet biomass is an energy intensive process. Not only does energy get used to provide the latent heat of evaporation to the water present, but it goes into heating the air and solid biofuel as well. However to increase the overall efficiency of the drying process, some of this heat can be recovered from the system (usually at some initial capital cost).

4.5.1. Air Drying Heat Recovery

Improvement of the energy efficiency of an air drying system can be achieved by:

- Using Heat Exchangers. There are two types: Recuperative, where the heat is directly transferred from exhaust to the inlet gas through the walls of the exchanger; and Regenerative, where an intermediate fluid is heated by the exhaust before it goes on to heat the initial input air.
- Recirculating exhaust gases. The hot moist air leaving the dryer is not necessarily saturated, allowing for it to be fed back into the dryer. As it is still warm, no extra energy is needed to heat it. The exhaust gas could be used as preheated burner air, if it had high enough oxygen content. This has the added benefit of incinerating any volatile organic compounds that may be present after drying the biomass.

- Using multistage drying. Rather than a burst of hot air at the initial stage of drying, hot gas can be introduced in multiple stages throughout the dryer to boost air temp.
- Using a Heat Pump can recover some of the latent heat of evaporation from the waste gas by condensing and dehumidifying the air. This can then be provided to the initial air inlet of the dryer.^{32 33}

4.5.2 SSD Heat Recovery

In Superheated Steam Dryers, the latent heat is easier to recover because there is no dilution of the water vapour, as its steam not air that does the drying, allowing for the vapour to be condensed directly.

As mentioned earlier, another option available in SSDs is integration into a combined-cycle gasifier. The steam, if under high enough pressure, can boost the output of the turbine.

4.6 Disadvantages

As already stated, it requires energy to dry out the wood. Energy that would have been profitable in the form of heat or electricity is used to prepare the fuel for use in the first place, thus producing a lower net energy output to the process.

However burning dry fuels also have their drawbacks. While the higher flame temperature results in an overall more efficient boiler it also has the side effect of turning the ash into slag. As the flame temperature increases it approaches the fusion temperature of ash. If it starts to flow as a slag it can be detrimental to the boiler. This is not usually a problem as the fusion temp is much greater than the flame temp would ever reach, but contaminants mixed in with the fuel can lower the fusion temp.²⁷

Secondly, when the hot flue gases from the boiler are cooled below their dew point, Sulphur Trioxide (SO_3) can condense resulting in the formation of Sulphuric acid, which can seriously corrode downstream equipment. The formation of Nitrous Oxides (NO_x) are another environmental concern due to increased flame temps.

Table 4.6.1 below gives a summary of the advantages and disadvantages of each type of dryer.

Table 4.6.1 Dryer Advantages and Disadvantages

Type	Require Small Material Size?	Require Uniform Material Size	Ease of Heat Recovery	Fire Hazard	Use of Steam
Rotary	No	No	Difficult	High	Can do
Flash	Yes	No	Difficult	Medium	No
Disk	No	No	Easy	Low	Saturated Steam
Superheated Steam	Yes	No	Easy	Low	Produces Excess Steam

4.6.1 Summary

Using dried biomass provides a significant benefit to traditional combustion boilers, namely an increase in efficiency and overall improved performance. The three main choices for drying biomass are the rotary, flash and superheated steam dryer systems. The most common, the rotary dryer, doesn't have constraints on the size of the material being dried, though it does pose the greatest fire risk. Flash dryers on the other hand are much more compact, simpler design that are easier to control but are limited to small particle sizes. While SSDs are still mainly in development, they are the most energy efficient of the three dryer systems, although come at a higher capital cost due to the equipment needed to handle the high-pressure steam they use.

4.7 Wet Biomass Gasification

Wet biomass feedstock is difficult to gasify using traditional gasification technology, due to the high moisture content. However, research has shown that wet biomass can be converted to a methane-rich gas at relatively low temperatures of around 350°C, using metal catalysts³⁴. Basic studies have also shown that high yields of hydrogen can also potentially be produced under different conditions. Both these products are valuable fuels to be used.

Pacific Northwest National Labs (PNNL) is currently conducting a project in the development of a catalytic gasification technology for the recovery of energy from wet biomass.

Researchers at PNNL are trying to develop a catalyst system that can effectively convert the wet feedstock into a gas product, primarily composed of methane and carbon dioxide in a low temperature, high-pressure water environment. A near total conversion of the organic structure of the biomass to gas has been achieved in a pressurised-water environment of 20Mpa with the presence of Ruthenium as a metal catalyst.³⁵

However while good rates of gas production have been demonstrated, trace components in the biomass feedstock have caused some problems with the processing in the fixed bed tubular system used for catalytic gasification.

The key issue is the ability of the catalyst to withstand the reaction conditions within the vessel. Preliminary tests involve wet biomass materials in batch reactors, and bench-scale continuous-flow to validate process kinetics and addressing various material handling issues.

4.7.1 Background

Catalytic hydrothermal processing between 250°C and 360°C at pressures up to 22Mpa has the potential to convert very wet biomass, as well as other organics-in-water residues (such as sewage sludge) and contaminants, into useful fuel gases. This is still a relatively new area of study and research has so far been limited. Recent biomass related work has concentrated on the chemical breakdowns of biomass components, although applications of this process have shown how heterogeneous metal catalysts accelerate the reaction of organic compounds with water and the resulting production of methane and carbon dioxide gas. So far this technique has only been reported as a means of recovering useful energy as part of an overall water treatment system, rather than as a distinct biomass power system.

Development of suitable metal catalysts for use in the process are an important factor in making the gasification of very wet biomass processing technology viable. Early experiments on continuous-feed reactors provided successful short-term results, but they also showed that there is an inherent problem with biomass contamination of the catalyst during long-term operation.

4.7.2 Experimental results

Tests were carried out in fixed-bed catalytic tubular reactors. Long-term tests of liquid feedstock have been carried out in micro scale reactor at a rate of 80mL/h³⁶. Mobile scaled-up reactor systems (MSRS) units, based on the bench-scale experiments, have also been tested at a feed rate of 10L/h, designed to obtain engineering data for further scaled-up reactor units.

Gas samples were analysed every 30 minutes. These samples were analysed using gas chromatography and were found to be mainly composed of CO₂, CH₄, H₂ and other hydrocarbons as well as water vapour. In the reaction process, the product gasses are “scrubbed” by the liquid by-products. This results in the product gasses becoming dissolved in the liquid; most notably the carbon dioxide is retained in the water by participating in acid/base chemistry with alkali and ammonium from the wet biomass feedstock.

5 Further Research

Lack of time and availability of resources have been two major obstacles in the research of this thesis.

As a lot of these emerging technologies discussed above are still in the research and development stages, it has been difficult to find accurate and suitable information about their use with regards to very wet biomass. The lack of specifications or even experimental data published regarding the use of cellulosic biomass have made it impossible to construct any sort of comparative model to investigate the different potential technologies; be it in energy efficiency, economics or technical feasibility.

The impact of diverting wood waste for use as a biofuel and away from other recycled uses has been touched on, but further investigation into other current uses of wood waste would be required for a full economic feasibility study.

Another obstacle that hampered progress with the project is the lack of publications in English. Whilst there is research being undertaken in Europe, most publications are in the native languages, namely Finnish and German. This has left most of the reference citations in this thesis to come from American and Canadian sources.

Further research will be needed to accurately identify all sources of wood wastes and the types of contaminants they may contain. By developing a greater understanding of the quantities and types of wood wastes arising in Scotland, greater measures can be implemented to help attain not only increased recovery of wood waste but also the highest possible technical and economical value from this valuable material. Research into other very wet biomass fuel sources could also have been conducted. For example, the potential use of seaweed in an AD system etc.

To summarise, more detailed analysis could have been accomplished if the resources were there to do so.

6 Conclusion

Large areas of forestry are expected to come into season over the coming years, increasing the volume of virgin material entering the marketplace, and with it an increase in the wasted wood produced from the manufacturing process. A high percentage of this will be in the form of very wet sawdust and woodchips.

The sporadic nature of wood waste sources in many instances can also have an adverse effect on using wood waste as a biofuel, making collection cost-prohibitive. On-site conversion of the raw biomass to more useful forms of energy, be it electricity sold to the national grid, or the production of liquid or gaseous fuels can help with transportation costs and reduce the dependence on a large centralised bio-power plant

There have been several methods of converting wet biomass materials into more useful forms of energy explored in this thesis. At best some of the more mature of these technologies may break even at current fossil fuel prices. However with the price of oil set to rise, biomass conversion technologies may come into their own in the future energy market.

These are mainly emerging technologies, especially with regards to the use of very wet biomass, but the potential of this resource has been seen and

further research and development can only lead to improvements in the efficiency, technology and operating costs.

As it stands today, the best option for using biomass with moisture content greater than 50% is still to pre-dry it before being fired in a traditional boiler. This is a well established technique for using biomass, and if dryer and boiler are integrated, such as using the flue gas to dry or latent heat recovery, then high energy efficiencies can be achieved.

Until the technologies are further developed, other methods such as gasification, AD and EFC will not make economical sense to install in terms of using wood waste as a biomass feedstock.

It is hoped that this report has shed some light on the implications of using very wet biomass as a fuel source to provide heat and power. Not only for the technological point of view of the equipment required, but also the broader implications involved.

The use of very wet biomass is not just a simple case of shovelling wet wood waste into a boiler and burning it. Other factors need to be considered such as potential other uses of this waste as well as the most efficient method of extracting the energy from the wet biomass waste, either by drying the resource or using novel new technological approaches that don't require an external energy source to reduce the moisture content pre-burn.

Appendix A

RITE-Honda EFC Process

It was recently announced that the collaboration between the Research Institute of Innovative Technology for the Earth (RITE) and the car company Honda has resulted in successful production of ethanol from biomass. The research project has established the basic technology to convert cellulose and hemicellulose into ethanol for use as motor fuel.

The RITE-Honda process consists of

- I. Pre-treatment to separate the cellulose from the rest of the biomass material
- II. Saccharification of cellulose and hemicellulose.
- III. Conversion of sugar into ethanol using microorganisms
- IV. Ethanol refinement

Current EFC technology is held back due to the build up of fermentation inhibiting chemicals during the first stage of the process, where the cellulose is separated from the non-fermentable material. This has been the biggest obstacle in the commercialisation of EFC biofuels.

The RITE-Honda process has managed to overcome the harmful influence of fermentation inhibitors, by utilising of an engineered microorganism,

developed by RITE for converting the sugar into alcohol in conditions that traditional EFC microbes would find toxic. This results in a significant increase in bio-ethanol production, and holds great potential as a sustainable fuel source.

RITE – Honda intend to pursue further research for mass production, including the development of systems to integrate currently independent operations into a continuous flow within one plant, thus “recycling energy” on an industrial scale.

They also plan to establish bio-refineries for mass production of ethanol, and various other industrial commodities that can be derived via similar processes from biomass.

References

- [1] Deffeyes, K.S., "*Beyond Oil*". 2005.
- [2] Greene, D.L., J.L. Hopson, and J. Li, "*Have we run out of oil yet? Oil peaking analysis from an optimist's point of view.*" *Energy Policy*, 2006. 34: p. 515-531.
- [3] Greene, D.L., J.L. Hopson, and J. Li, "*Running out of and into oil: Analysing global oil depletion and transition through 2050.*" (2003), Oak Ridge National Laboratory: Knoxville, Tennessee.
- [4] The European Commission website on Energy Research, "*What are the Key Advantages of Biomass?*"
http://europa.eu.int/comm/research/energy/nn/nn_rt_bm2_en.htm
- [5] Dr Georgina Magin, "*Fauna & Flora International (UK): An Introduction to Wood Waste in the UK*" (2001)
- [6] Remade Scotland: "*Wood Waste Arising in Scotland,*" October 2002
- [7] Riddoch TRADA: "*Wood Residues; Waste or Resource?*" (1999)

- [8] Timber Recycling Information Centre, “*The UK Timber Market*”
www.recycle-it.org
- [9] Forestry Commission (2002): “*UK Wood Production and Trade*”
- [10] Keys, J (2001) “*The Tree Station Project*,” The Forestry Commission
- [11] Timber Recycling Information Centre: “*Timber Utilisation*” (2001)
- [12] V Balachandran and A Henderson, “*Economic & Statistics Unit, Forestry Commission*” (2001)
- [13] Steve Luker, Scottish Enterprise Lanarkshire, “*Bioenergy for Scotland article in Woodweb Newsletter*”, Issue 3, Spring 2002
- [14] Energy Technology Support Unit (ETSU). “*UK Industry Wood Fuel Resource Study for DTI*” (1997).
- [15] The Regional Wood Energy Development Programme (RWEDP) web-site: www.rwedp.org

- [16] Woodweb. "Scottish Forest Industries Cluster newsletter",
Issue 4, Summer 2002
- [17] North Lanarkshire Council; "*Lanarkshire Biomass Project*"
<http://www.northlan.gov.uk/your+council/news/news+archive/biomass+heat+project+boosts+environment.html>
- [18] EC Landfill Directive, via Scottish Environmental Protection
Agency
<http://www.sepa.org.uk/wastemin/legis/landfilldir.htm>
- [19] U. S. patent 2,177,557
[<http://www.freepatentsonline.com/4553978.html>]
- [20] U. S. patent 3,733,255
[<http://www.freepatentsonline.com/4177079.html>]
- [21] Brad Lemley *Discover magazine*
<http://www.discover.com/issues/apr-06/features/anything-oil/>
- [22] Terry N Adams et al "*Converting Turkey Offal with CWT Thermal Process*", Changing World Technologies

- [23] Ellyn Spragins Jan 2005
http://money.cnn.com/magazines/fsb/fsb_archive/2005/02/01/8250633/index.htm
- [24] Bioenergy Update, Sept 1999, Vol. 1 No. 2
- [25] Charles Taylor, *Internal-Combustion Engine in Theory and Practice*, 2nd Ed, 1985, p.46
- [26] Anaerobic Treatment Options – Matresa
<http://www.sri.bbsrc.ac.uk/science/matresa/book.html>
- [27] MacCallum et al (1981). “*Cost Benefit Analysis Systems Using Flue Gas or Steam Drying of Wood Waste Feedstocks.*”
- [28] Technology Application Laboratory (1984); *Industrial Wood Energy Handbook*
- [29] C.E. Linderoth (1992). *Biomass: Drying Wood Waste*
- [30] Liptak (1998) “*Optimising Dryer Performance through Better Control*”. *Chemical Engineering Vol 105*

- [31] Hultkonen et al (1994) *"Drying Wood Biomass at High Pressure Steam Atmosphere Experimental; Research and Application"*
- [32] A. Mercer (1994). *"Learning from Experiences with Industrial Drying Technology."* Sittard, Netherlands
- [33] J.B. Wilson (1990) *"Application of Heat Pump Dehumidification."*
- [34] U.S. D.o.E. *"Energy Efficiency and Renewable Energy: Gasification of Wet Biomass Project"* September 2004
- [35] Douglas C. Elliott et al. *"Chemical Processing in High-Pressure Aqueous Environments. 7.Process Development for Catalytic Gasification of Wet Biomass Feedstocks."* Industrial Engineering. Chem. Res., Vol. 43, No. 9, 2004
- [36] D. C Elliott et al, *"Low-Temperature Catalytic Gasification of Wet Industrial Wastes"*; Pacific Northwest National Laboratory.

- [37] Anaerobic Digestion, storage, oligolysis, heat and aerobic treatment of manure. FEC Services 2003
<http://www.scotland.gov.uk/Resource/doc/1057/0002224.pdf>
- [38] Waste Management Licensing Amendment (Scotland) Regulations 2003- Scottish Executive. The Stationary Office 2003
- [39] P.C Badger, Bioenergy update magazine 1999
- [40] J. Janick and A. Whipkey (eds.) *Ethanol from cellulose: A general review Trends in new crops and new uses*. 2002.. ASHS Press, Alexandria, VA
- [41] Concentrated Acid Hydrolysis, US DoE Biomass Program
http://www1.eere.energy.gov/biomass/concentrated_acid.html

Bibliography and further reading

Other sources consulted during the course of this project

Forestry and other Biomass sources

- The Forestry Commission Website
<http://www.forestry.gov.uk/woodfuel>
- Wood Fuel Resources
<http://www.woodfuel.org.uk/WoodfuelsProject/pages/AboutWoodfuel.jsp>
- http://www.bioregional.com/programme_projects/forestry_prog/urban_forestry/urbfor_woodchip.htm

Biomass

- Wood pellets
<http://www.earthscan.co.uk/news/article/mps/uan/702/v/3/sp/>
- Finnish Sawmills
http://www.hightechfinland.com/2005/energy/energy/en_GB/wartsilabo/?show=all
- Department of Energy Website:
<http://www1.eere.energy.gov/biomass/>

Gasification

- Wood to motor fuel <http://car.pege.org/2005-wood/>
- Biomass Energy Foundation (American) extensive site on wood gas and gasifiers, <http://www.woodgas.com/>
- Food and Agriculture Organization of the United Nations: Wood Gas as Engine Fuel, 1986,
<http://www.fao.org/DOCREP/T0512E/T0512e00.htm>
- Hans Hochwald: Wood gas producers,
<http://highforest.tripod.com/woodgas/woodgas.html>.
- GasNet, European Union biomass gasification research coordination,
<http://www.gasnet.uk.net/>
- Information to build/use your own wood gasifier
<http://www.gengas.nu/byggbes/index.shtml>

Anaerobic Digestion

- <http://www.enviro-control.co.uk/waste/technology/configuration.htm>

Ethanol

- <http://www.oilcrisis.com/Patzek/>