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Wood Chip Heating for Commercial Buildings in Ireland: an Analysis of Supply Methods and Financial Viability

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WOOD CHIP

HEATING FOR COMMERCIAL BUILDINGS IN IRELAND

-

AN ANALYSIS OF SUPPLY METHODS AND FINANCIAL VIABILITY

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ABSTRACT

Ireland has three central issues regarding the supply and use of fuel and energy: import dependency; competitiveness; and greenhouse gases emissions. Ireland is ranked as one of the most import dependent states in the EU, with over 90% of its fuel sourced from abroad [IAEA, 2005]. Combined with rapidly fluctuating oil and gas costs and uncertainty with future supply, it is essential that Ireland find a more secure and sustainable alternative to fossil fuels.

Wood chip represents one such alternative energy source since it is locally produced and considered to be carbon-neutral. The main objective of this research is to assess the financial and environmental feasibility of wood chip as a heat source in Irish commercial buildings. The commercial range of boilers, from 50kW up to 400kW, offers a good range of potential feasible and non-feasible arrangements that will provide important information regarding correct sizing and use. Secondary objectives include optimising production supply chains and heating system configurations as well as commenting on relevant national policies.

The scope of the research covers all aspects of wood chip production and use for commercial applications in Ireland. Key methodologies employed include cost versus value techniques to examine supply chain efficiencies; mathematical modelling of energy balances; and net present value models to analyse the financial viability of wood chip heating systems.

Results indicate that wood chip is an economically feasible replacement for oil and gas as a heat source in commercial buildings. Drying wood fuel both increases value and minimises supply costs. This increases the net present values of wood chip heating systems as they recoup their high initial capital costs with the increased savings from a cheaper fuel. Energy balance models show that installing wood chip boilers at part load offers more savings than boilers at full load, and that economic viability is highly sensitive to changes in fuel prices. Findings suggest that the regulation of wood fuel quality and the introduction carbon taxes will increase wood fuel uptake in the commercial sector.

DECLARATION

I certify that this thesis which I now submit for examination for the award of Master of Philosophy, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for another award in any Institute.

The Institute has permission to keep, lend or copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Signature ______________________________________

Date ________________

Candidate

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NOMENCLATURE

Symbol	Description	Unit
%EMC	Equilibrium moisture content of wood	kg/kg
%MC	Moisture content of wood	kg/kg
$\%MC_{dry}$	Moisture content of wood based on dry weight	kg/kg
$\%MC_{wet}$	Moisture content of wood based on wet weight	kg/kg
%RH	Relative humidity of air	
%WC	Ratio of Installed wood chip to system size	kW/kW
A	Area	m^2
CDD	Cooling degree day	
C_h	Building heating coefficient	kW/°C
CO_2	Carbon Dioxide	Tonne
CO_2e	Carbon Dioxide equivalent	Tonne
C_U	Fabric heating coefficient	kW/°C
CV	Calorific value	MJ/kg
C_V	Ventilation/Infiltration heating coefficient	kW/°C
CV_{dry}	Calorific value of dry wood	MJ/kg
CV_{wet}	Calorific value of wet wood	MJ/kg
C_Y	Thermal weight heating coefficient	kW/°C
DR%	Discount rate	
$dT / \delta T$	Temperature difference	°C
F_P	Thermal weight preheat factor	
GHG	Greenhouse Gas	Tonne
H_C	Cool-down period	hours
HDD	Heating degree days	°C/Day
HDD_{EQUIV}	Total energy demand as equivalent HDDs	°C/Day
H_O	Hours of operation	hours
H_P	Pre-heat period	hours
H_U	Unoccupied hours	hours
HWS	hot water demand per person	L/person
IR%	Interest rate	
NPV	Net present value	€
Q_e	Electrical consumption of boiler	kW
Q_F	Fabric heat loss	kW
Q_G	Heat gains	W/m^2
Q_L	Heat losses	W/m^2
Q_P	Daily energy required for pre-heating	kWh
Q_S	System size	kW
Q_{th}	Thermal output of boiler	kW
Q_V	Ventilation/Infiltration heat loss	kW
Q_{HWS}	Energy for water heating	kWh
ρ_O	Occupancy density	m^2/person

ρ_w	Density of water	kg/m^3
T_{AVG}	Average daily internal temperature	^{o}C
T_B	Base Temperature	^{o}C
T_C	Average temperature during cool down	^{o}C
T_G	Temperature rise due to internal gains	^{o}C
T_{ID}	Inside design temperature	^{o}C
T_{max}	Maximum daily temperature	^{o}C
T_{min}	Minimum daily temperature	^{o}C
T_{OD}	Outside design temperature	^{o}C
T_P	Average temperature during preheating	^{o}C
U	U-value	kW.m^{-2}.K^{-1}
V_g	Volume for 'green' (fresh) wood	m^3
W_d	Dry weight of wood	kg
W_T	Thermal weight	

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1.0 CHAPTER 1: INTRODUCTION

1.1 Overview

Ireland has three central issues regarding the supply and use of fuel and energy. These are the over dependency on imports, the cost of fuel and the emission of greenhouse gases. Ireland is ranked as one of the most import dependent states in the EU, with over 90% of its fuel sourced from abroad [IAEA, 2005]. The latest available Figures indicate that Ireland imports 121.0 TWh of oil, 48.1 TWh of natural gas and 0.75 TWh of electricity [SEI, 2008]. The greenhouse gas emission targets set out in the Kyoto protocol offers further incentives for switching to low carbon fuel. Ireland, as part of the EU, must contribute to the 'burden sharing' agreement of reducing Europe's Emissions by 8%. Combined with the rising cost of oil and gas and the uncertainty regarding future supply and peak oil theory [Campbell, 2007], it is essential that Ireland find a more secure sustainable alternative to fossil fuel.

Wood chip is an environmentally clean and locally produced fuel. It is classified as carbon neutral due to its carbon absorption during growth, and it is sustainable. Ireland has an excellent growing climate, financial resources and skilled labour, but due to the lack of foresight or initiative in previous years Ireland now lags behind most European countries in terms of wood fuel utilisation. This means Ireland is trailing in both experience and available information in comparison to mainland Europe, and this could be cited as the most significant barrier for Ireland advancing in wood chip production and use.

The scope of this thesis covers all aspects of wood chip supply and demand for commercial applications in Ireland, as illustrated below in Figure 1. The objectives of the research are to analyse the supply chain arrangements and to investigate the financial viability of wood chip in Irish commercial buildings. Secondary objectives include the optimisation of these results, searching for ways to lower the production costs of the wood chip supply chains and to increase the financial viability of wood chip heating systems. Key methodologies used are the use of cost versus value techniques to examine the supply chains and net present value models to analyse the financial viability of wood chip heating systems.

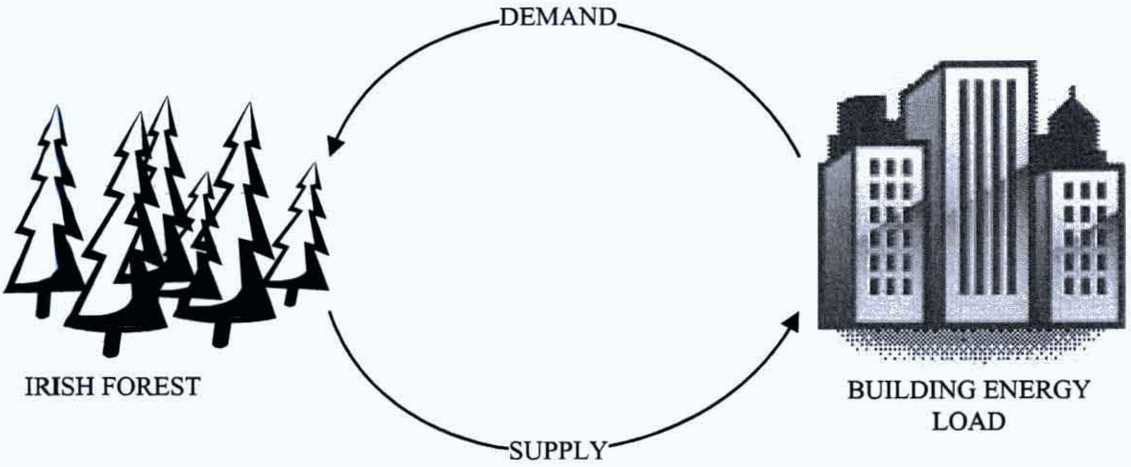


Figure 1: Overview of Wood Chip Supply and Demand

1.2 Supply Side – Wood Chip Supply Chains

The application of logistics and supply chain management techniques are essential in ensuring a product is delivered cost effectively. In a wood chip supply chain the order and cost of the processes greatly impacts the final price and, therefore, its cost competitiveness with conventional fuels. This thesis analyses the costs of each of the different processes in the wood fuel supply chain using Irish data. The identification of the different processes and the breakdown of the costs and values make understanding how a supply chain works clearer and establishes potential areas for improvement. Countries such as Denmark, Austria and Sweden have successfully established wood fuel markets and have developed supply chains particular to their needs. However, supply chains from other areas may not necessarily suit Irish conditions because of differences such as ground and weather conditions, equipment, infrastructure, available training, and economic factors such as fuel costs and wages. This thesis will analyse the wood fuel supply chain under Irish conditions and identify critical areas of the chain for further investigation and optimisation.

1.3 Demand Side – Financial Viability of Wood Chip Heating Systems

The objective of the demand side analysis is to establish the current and future financial viability of wood chip heating systems for commercial buildings in Ireland. While wood fuel is cheaper per unit of energy consumed than gas and oil, the initial investment cost in biofuel boilers is significantly higher, and even with constant annual savings the investment can still lead to net losses over the course of the system's life. One of the first steps in this analysis is the development of an Energy Model that can produce energy loads over a range of inputs, such as system size and wood chip sizes. The Energy Model is then combined with financial factors, such as system costs and fuel costs, to calculate the true cost of a wood chip system over its lifecycle. The viability of hybrid systems, which use both wood chip and fossil fuel, is also investigated. This is a long term and realistic cost evaluation model for potential investors. By investigating the viability of such systems the total life cycle cost of installing a wood chip system can be calculated, and optimum configurations identified. By implementing such optimum design strategies, the reputation of wood chip boilers can be enhanced by maximising potential savings, which will stimulate consumer confidence and the demand for wood chip. Having a financially viable alternative to fossil fuel is vital when promoting the switch from fossil fuels to sustainable fuels.

1.4 Thesis Aims and Objectives

The overall aim for the thesis is to investigate wood chip in Ireland. The thesis covers a broad area of topics including Irish forestry, supply chains, energy demand and financial viability; also included in the text are sections on policy and health and safety. This provides a large amount of information on the complete wood chip industry in Ireland and allows more specific objectives to be established within these areas.

The objectives for this thesis are:

- analyse the supply of wood chip in Ireland;
- suggest methods of improving the supply of wood chip in Ireland;
- investigate the financial viability of wood chip heating systems for commercial applications in Ireland; and
- optimise the design of wood chip heating systems for commercial applications in Ireland.

2.0 CHAPTER 2: BACKGROUND - WOOD CHIP AND WOOD CHIP POLICY

2.1 Introduction

This chapter serves as an insight to wood chip and wood chip policy. The first section of this chapter details the physical and chemical properties of wood chip, as well as defining various terms used in the industry. The natural properties of wood can help and hinder when using it as a source of energy. For example, its complex biological structure and physical attributes make it very different to the handling of more commonly used fossil fuels, such as gas and oil. Wood chip can be produced from a number of different sources, including forests, wood waste and woody weeds. The availability and accessibility of these wood sources is vitally important if the country aims to replace fossil fuels with wood chip, and these factors are largely controlled by national policy.

The second section of this chapter reviews the policies and directives issued by national and international agencies and their effect on the Irish wood chip industry. The chapter identifies emission targets and discusses how they affect the uptake of biomass, and wood chip, in the fuel market. Carbon tax is one of the main tools that will be used to meet these emission standards. Carbon tax aims to reduce the amount of carbon produced by heating, cooling and electrical systems by penalising carbon-emitting processes, such as burning gas or oil.

Finally, this chapter will have a brief look at some of the health and safety issues arising from the use of wood chip. Many of the recent policy changes in Europe, and internationally, are concerned with emissions; and while carbon and carbon dioxide are more commonly recognised, the emission of dust particles is a very important factor in air quality regulations, and subsequently Irish policy decisions.

The objectives of this chapter are to:

- examine the chemical and physical properties of wood fuel;
- review forestry terms used in wood chip production;
- discuss policies affecting the wood chip industry in Ireland;
- analyse the effect of carbon tax on the wood chip industry in Ireland; and
- outline health and safety issues arising from the use of wood chip.

The data for the first section of the chapter were obtained from a literature review ranging from basic chemistry and physics texts to more detailed papers on specific wood density and forest management.

The data for the second section of chapter were obtained from national publications on policies and directives, such as the White Paper [Government White Paper, 2007] and Bioenergy Action Plan [Bioenergy Task Force, 2007]. The numbers for the grants and incentives were taken from the relevant national agencies, such as Sustainable Energy Ireland. Carbon tax rates are estimated using the trade market price of carbon [www.pointcarbon.com, '08]. The trade market price gives a strong indication of the level of carbon tax being introduced.

The figures used in carbon tax calculations also include an embodied energy figure based on data issued by the University of Bath [Jones & Hammond, G., 2008]. These data are used to show how carbon tax will affect the cost of manufacturing wood chip boilers and equipment. Embodied energy is the total energy used in the production of a product and it will be considerably larger for wood chip boilers compared to gas and oil boilers. Embodied energy, and embodied carbon, can be used to examine the true carbon neutrality of wood chip production and use.

The health and safety aspects of this chapter are based on figures from boiler manufacturers, in addition to health regulations issued by the European Union [European Union, 2008] and the World Health Organisation [IARC, 1995].

2.2 Properties of Wood & Wood Chip

Wood chip is a natural, locally produced fuel created from the chipping of trees into small pieces. The size and quality of the wood chip will vary with the type of wood, such as spruce or pine, and with its source, such as pulpwood from forests or sawmill residues. The wood chip takes on all of the same chemical, physical and biological aspects as any wood produce. By examining its biological properties and then its physical and chemical properties it becomes clear how wood becomes a viable source of fuel.

2.2.1 Free Water, Vapour and Bound Water in Trees

A living tree can consist of over 60% water. Removing this water is vital in the production of wood fuel. The woody mass of the tree, the trunk and branches holds water in three different ways. They are as follows:

- as free (liquid) water in the cells;
- as water vapour in the cell space unoccupied by liquid water; and
- as bound water in the cell walls.

As wood dries, it will give up the liquid and vapour water more freely than the bound water. Bound water is chemically held in the wood by the attraction to the negatively charged hydroxyl in the cellulose of the wood [Haque, 2006]. The point at which only the bound water remains is known as the Fibre Saturation Point (FSP). The fibre-saturation point is the point at which the cell cavities have lost all their moisture but none has been removed from the cell walls, corresponding in most woods to a moisture content of about 30% of the dry weight [Simpson, 1991]. Wood will not re-absorb free water unless it physically is exposed to liquid. In addition, when wood reaches FSP it will start to shrink and distort, while this is of great importance to the timber industry it holds no real significance when dealing with wood chip and wood fuel.

2.2.2 Moisture Content, Dry & Wet Weight

The amount of water stored in wood is generally referred to the Moisture Content of the wood (%MC). It is the proportional amount of moisture in a substance. The units of measurement are either kg water per kg wood dry, $\%MC_{dry}$, or per kg wood wet ($\%MC_{wet}$). It is vital to understand which term is being used, as the results are very different. The basic formula for moisture content is:

$$\%MC = \partial kg / kg \tag{2.1}$$

In order to calculate the dry weight percentage value, the change in weight is divided by the oven dry weight, 0%MC. For wet weight percentage, the change in weight is divided by the initial 'wetter' weight of the wood. The most obvious difference is the range of values from the two methods. Dry weight results can often be in excess of 100% because of the high volumes of water found in fresh wood. While, wet weight results should never exceed 100% because the change in weight can never be larger than the original wet weight it was initially. A sample calculation showing the difference in results between dry weight and wet weight is shown in Table 1.

Table 1: Example of Dry & Wet Weight MC%

Wet Weight	7	kg
0%MC weight	3	kg
δkg	4	kg
%MCdry	133.3%	
%MCwet	57.1%	

2.2.3 Mass, Volume, Density & Specific Gravity

As the wood dries, it loses water and therefore becomes lighter. This affects factors like the transport and handling of the wood. Transport vehicles are by law restricted to a certain weight load, depending on the number of axles. To transport wood with a $\%MC_{wet}$ of 60% means 60% of the load is unusable water. Drying is an effective way to improve the efficiency of transport of wood and wood fuel, which is demonstrated in chapter 3. The volume of the wood remains largely unchanged until the wood reaches FSP. Taking this into account the density of wood is largely dependent on the mass of the wood until either the wood chip reaches the FSP or the volume of the wood chip exceeds the capacity of the trailer (see section 2.2.4). After the FSP, both the volume and mass of the wood are changing and this results in a more acute change in its density.

Another way of expressing density is specific gravity. Specific gravity is the degree of relative heaviness of any kind or portion of matter, which is commonly expressed by the ratio of the weight of a given volume to that of an equal volume of a standard substance, such as water for liquids and solids, and air for gases [Simpson, 1993]. Therefore, the specific gravity is the density divided by the density of water, commonly taken as 1000 kg/m^3. In forestry there is another commonly used expression known as the Basic Specific Gravity, calculated by:

$$(W_d/V_g)/\rho_w \tag{2.2}$$

where W_d is the dry weight, V_g is the wet volume and ρ_w is the density of water. This figure is used to give distinguishable markers to different types of wood. Since green, or fresh, volume and oven-dry mass are theoretically constant, basic specific gravity is easily reproduced in experimental work. Great care must be taken when switching between basic specific gravity and specific gravity. In some texts, specific gravity is referred to as specific density.

2.2.4 Bulk Volume & Bulk Density

The term bulk describes the properties of a group of objects, including the gaps and space between the individual objects. The bulk properties are very important when dealing with storage and transport as they give the total volume occupied by the wood fuel in a container. Bulk figures can vary and any kind of settling or changes in the space dimensions can lead to a change in the occupied volume. Only wood pellets occupy a smaller volume than the original solid wood. This is because the production of wood pellets involves a compressing stage to compact the pellet. Bulk density is the total mass divided by the bulk volume. The average figure for the bulk density of wood chip is between 200-350 kg/m^3 [BENET bioenergy Network, 2000] and 200-400 kg/m^3 [Biomass Energy Centre, 2008]. A bumpy road can significantly increase the bulk density by settling the load and reducing the air space between the individual chips. Due to the restrictions in the volume capacity of trailers, the bulk density value is an important factor in transportation. A problem with measuring bulk density is the moisture content of the wood chips; the higher the moisture content the heavier the chip and at the same time the wood chip doesn't change in volume until it reaches the FSP. This means that the volume occupied by an individual chip is constant and the weight is decreasing, making the bulk density decrease. To overcome this variance all bulk densities should be converted into the bulk density at 0% moisture content, or dry bulk density, to prevent errors in estimating weight and volume restrictions. Dry Bulk Density is represented by:

$$\text{Bulk } W_d/\text{Bulk } V_g \tag{2.3}$$

This is very similar to the Basic Specific Gravity.

2.2.5 Energy Content

The net energy available when fuel is burned is known as the energy content, fuel content or calorific value (CV) of the wood and is measured in MJ/kg or GJ/Tonne. The energy content of 0%MC (completely dry) wood is very similar for all woods of a comparable type, around 19 MJ/kg for softwoods with a typical standard deviation of 6% and for hardwoods about 18.2 MJ/kg with a normal standard deviation of 5% [ECN, 2008]. The net energy content of wood is heavily reliant on the moisture content of the wood. The relationship between energy content and moisture content is shown in Figure 2.

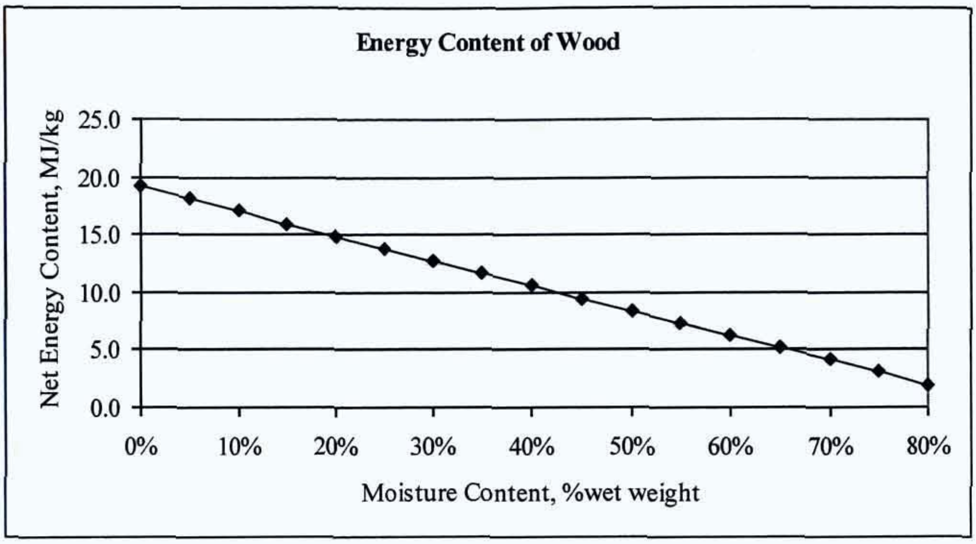


Figure 2: Energy Content of Wood

The relationship is linear and is based on the principle that at 100%MC_{wet} it is theoretically 100% water and will burn at a negative value, which means it takes in heat as opposed to giving out heat. Its latent heat of evaporation value is 2.2 MJ/kg, and even though this value depends on the pressure at which the evaporation occurs there seems to be very little change in energy content, less than 0.05 MJ/kg over 100 kPa. The mathematical formula for calculating the energy content of wood is:

$$CV_{wet} = CV_{dry} - (2.2 \text{ MJ/kg} \times \%MC_{wet}) - (\%MC_{wet} \times CV_{dry}) \qquad (2.4)$$

From this, it can be seen that energy is lost in two ways. The first term, [(2.2MJ/kg. %MC_{wet})], shows the energy lost evaporating the water from the wood. The second term, [(%MC_{wet}.CV_{dry})], shows how much of the original sample per weight is water and is therefore not capable of producing energy, since by having a lower percentage of wood means there will be less energy available. So water in the wood has a two-fold effect, it reduces the percentage weight of the wood; reducing the energy content and it then requires energy to evaporate the water.

2.2.6 Removal of Water

As seen above reducing moisture content is the key to effective wood fuel utilisation. As a fuel, wood chip has a very low energy density. From Figure 2, a wood fuel with a 30%MC_{wet} has an energy content of 12.75 MJ/kg. Using a bulk density of 250 kg/m^3 the energy content (bulk) becomes 3,187.5 MJ/m^3. This can be compared to the volumetric energy content for gas and oil, which are 38,700 MJ/m^3 and 35,000 MJ/L respectively. However, wood chip will have a lower unit cost, but the challenge is drying tonnes of wood without increasing this price to a level where it becomes uncompetitive. In theory, wood can be dried to its FSP as long as it is covered and left for a sufficient period. Leaving green wood dry naturally over the summer months it is possible to obtain a moisture content of around 28% to 30%, as seen in Figure 3 and explained below. Reducing the moisture content further requires better control of the immediate environment. Wood is very hygroscopic; it readily absorbs moisture from the air. Once the FSP has been reached the moisture content of the wood will start to converge on its Equilibrium Moisture Content (%EMC), which is the value where the moisture content stabilises; at this point the wood is highly dependent on the surrounding air temperature and relative humidity.

Figure 3 shows the equilibrium moisture content of wood over a range of relative humidities. Ireland has a damp climate, which results in a high Equilibrium Moisture Content.

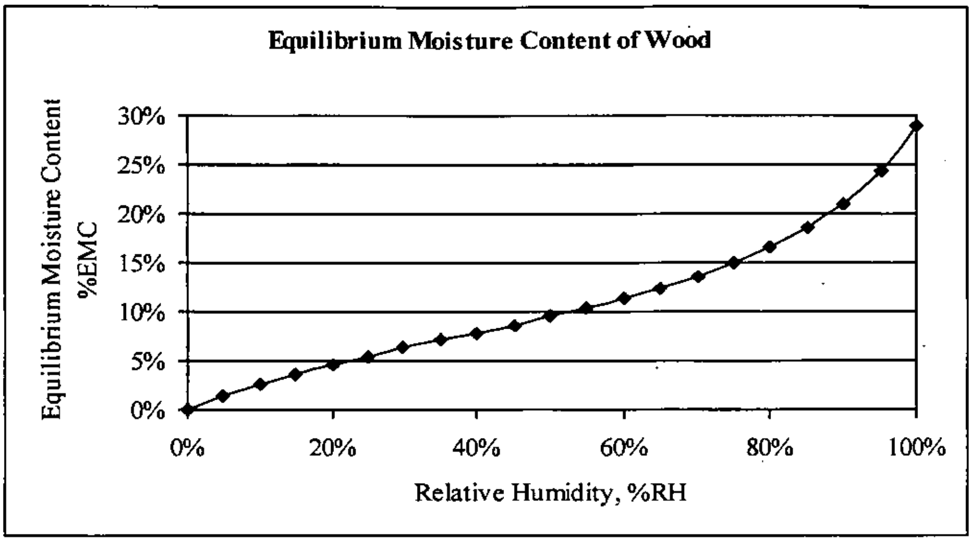


Figure 3: Equilibrium Moisture Content at 20°C

Wood also suffers from hysteresis, a phenomenon observed in some physical systems by which changes in a property lag behind changes in a parameter on which they depend. This means that after wood is dried, reverting the temperature and relative humidity to the original levels does not restore the initial moisture content. In Figure 4 the top line shows the path taken when drying the wood and the bottom line shows the path taken when the wood is getting wetter. Hysteresis will have an effect when estimating the moisture content of wood that has been in storage for extended periods. Wood measured after winter might have a lower moisture content than expected as it is following the lower line in Figure 4, and similarly, wood measured after summer will have a higher moisture content because it is following the upper line.

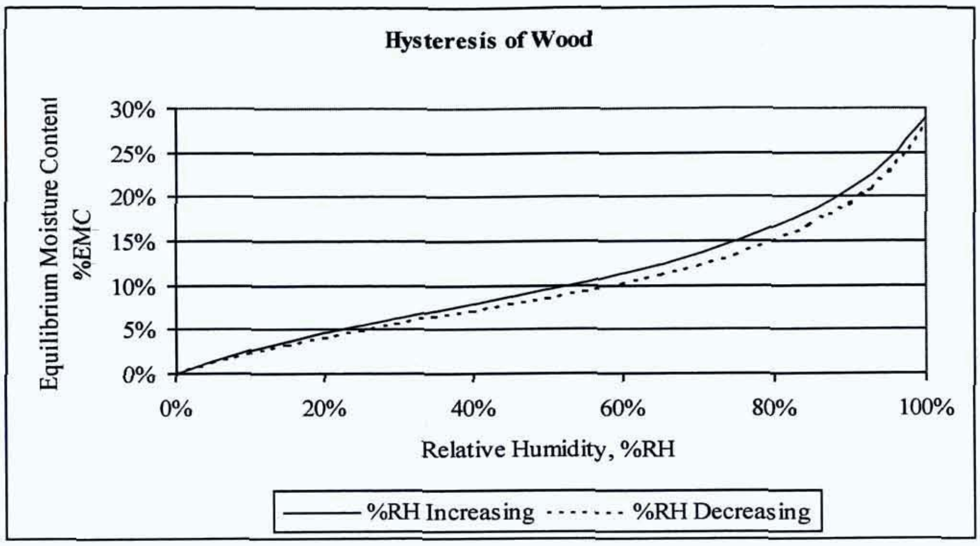


Figure 4: Effect of Hysteresis

2.2.6.1 Capillary Action and Diffusion

Wood dries in two ways; firstly, through capillary action, which is defined as the movement of liquid by the reactions between the liquid and the walls of a minute tube. This is vital in the first stages of drying as the wood loses the liquid and vapour water. The second way of losing water is through diffusion, which is the permeation of a gas or liquid through the cell wall caused by a difference in vapour pressure. Diffusion largely depends on the vapour pressure in the air, a property of both humidity and temperature. Diffusion can also occur due to the difference in moisture concentration in the air and wood, a form of transport known as the osmosis effect [Simpson, 1991]. Diffusion plays a significant role in releasing the bound water from wood during the latter stages of drying.

2.2.7 Chemical Composition of Wood

Wood is a complex organic material, and burning wood, therefore, involves the combustion of organic compounds such as cellulose, hemi-cellulose and lignin. An analysis of the elements found in wood is shown in Table 2. The products from the combustion of wood are shown in Table 3.

Table 2: Chemical Composition of Wood (pine/ fir/ spruce) [ECN, 2008]

Carbon	C	51.3%	%wt daf
Hydrogen	H	6%	%wt daf
Oxygen	O	42.4%	%wt daf
Nitrogen	N	0.15%	%wt daf
Sulphur	S	0.08%	%wt daf
Chlorine	Cl	0.05%	%wt daf
Total		100%	%wt daf

*daf = dry ash free

Table 3: Distribution of Pyrolysis Products [K.W. Ragland *at al.,* 1990]

Water	H_2O	25.0%	%wt
Carbon Monoxide	CO	18.3%	%wt
Carbon Dioxide	CO_2	11.5%	%wt
Hydrogen	H_2	0.5%	%wt
Light hydrocarbons	CH_4	4.7%	%wt
Tar	$C_6H_{6.2}O_{0.2}$	20.0%	%wt
Char & Ash		20.0%	%wt

Ash varies from trace amounts up to 20% of the total mass, largely depending on the parts of the tree burned; tree bark, particularly, contains very high amounts of ash. Ash is made up of a large selection of minerals, the most common of which are calcium, potassium, magnesium, phosphorus and sodium. An example of the breakdown of minerals found in ash is shown in Table 4 below.

Table 4: Minerals found in Ash [ECN labs, 2008] [Mohan et al., 2005]

Calcium	Ca	74.2%	%wt ash
Potassium	K	10.5%	%wt ash
Magnesium	Mg	4.2%	%wt ash
Phosphorus	P	2.7%	%wt ash
Sodium	Na	2.4%	%wt ash
Others		6.1%	%wt ash

There can be a large variation in the amount and type of minerals found in trees depending on factors such as species, location and soil conditions. For example, Sitka spruce is capable of absorbing calcium and phosphorus from ocean spray. This could be a significant problem in Ireland as calcium deposits can damage boilers, and so, the minerals absorbed into the wood needs to be taken into consideration when identifying fuel sources.

2.3 Environmental & Energy Policies

2.3.1 UNFCCC - Kyoto Protocol

The United Nations Framework Convention on Climate Change (UNFCCC) treaty came to being in 1992 as a means of tackling climate change at an international level. Changes to the treaty are known as protocols, of which the most famous is the Kyoto protocol, which came into force in 1997 with the aim of reducing global carbon emissions. Every participating country was set an individual target to be met by 2012. The target was in the form of a minimum reduction or maximum increase depending on the economic status of the country. Ireland, due to its rapidly increasing economy, was set a target of a 13% increase on 1990 emissions levels. The failure to meet this target is punishable by fines from the UNFCCC. However, there are ways around this, such as carbon trading. Carbon trading involves purchasing carbon credits from the carbon market, which at the time of writing was €28 per tonne of CO_2. Other ways of meeting the target are to either to invest in projects in developing countries or to initiate a joint venture with another treaty member. Fifteen members of the EU have agreed to a sharing of their emission allowances, known as 'Burden Sharing'. This group of countries have agreed to reduce their joint emissions by 8% under the Kyoto agreement. Below is a table showing Ireland's carbon emissions up to 2006, and the associated liability based on the trading price of carbon.

Table 5: Irelands Kyoto Protocol Targets [EPA, 2006] [UNFCCC, 2007]

1990 Base Year Emissions	55.4	$MtCO_2e$
Allowed Increase at 2012	13%	
2012 Maximum Emissions	62.6	$MtCO_2e$
2006 Emissions	69.9	$MtCO_2e$
Actual Increase	26.3%	
Surplus Emissions	7.4	$MtCO_2e$
Carbon Tax	28	€/TCO_2
Correction Cost	€206,426,640	€

The data shows that Ireland's increase has exceeded its agreed target (2006 is already at 2012 levels). The cost of reducing this to its baseline is over 200 million euro, and this does not include the costs of any future surplus emissions. However, this calculation is very sensitive to any changes in the trading price of carbon, and any significant changes in national emission policies.

2.3.2 White Paper

The Government White Paper is the Irish government's national energy policy plan to tackle energy consumption and environmental change. It outlines the energy policy framework for 2007-2020, a period in which Ireland is hoping to meet both its Kyoto targets and the more long-term targets set out by the Irish government. While this paper mainly deals with policy framework and issues regarding security of supply and dependency on imports, it does lay down targets for renewable energies that will greatly affect the wood chip market. The following is a list of actions prepared by the government white paper, which encourages the use of biomass as a fuel. [Government White Paper, 2007]:

- Increasing the percentage of national electricity consumption from renewable source to 5% by 2010, and increasing this by a further 28% to ensure by the year 2020 33% of the national energy consumption would be renewable sourced (RES-E);
- Expanding the use of renewable energies in the national heat market to 5% by the year 2010;
- Further expanding the use of renewable energies in the national heat market by another 7%, to an overall market penetration of 12% by the year 2020 (RES-H;
- A combined target for EU member states for an overall biofuel market penetration of 5.75% by the year 2010.

These targets are further discussed in the national climate change strategy, which was published alongside the government's White Paper.

2.3.3 National Climate Change Strategy

Following on from the government white paper is the national climate change strategy (NCCS). It follows up on the policy framework of the white paper with more detailed measures for helping Ireland to meet its Kyoto targets, and to better them by

2020. The measures seen here are significant for the future of wood chip use in Ireland. The strategy covers all of the main topics discussed in this research, such as energy demand profiles and wood chip supply, and aims to optimise their input into Ireland's energy plan. The following is a list of measures addressed by the national climate change strategy [NCCS, 2007] relevant to biomass:

- Building Regulations and Building Energy Rating;
- Energy Agreements Programme;
- Bioheat and CHP programmes;
- Carbon sequestration;
- Top-up to EU premium for energy crops;
- New supports for afforestation;
- Biomass Harvesting Scheme;
- Biomass heating in schools.

The measures proposed affect many of the variables previously discussed in the research, such as building energy profiles, expanding forestry, improving harvesting and developing demand.

2.3.4 Bioenergy Action Plan

The Bioenergy Action Plan is a further government publication tackling Ireland's climate control policies. While the White Paper dealt with national policy and the National Climate Change Strategy covered the measures to curb climate change, the bioenergy action plan deals specifically with the promotion of bioenergy and biomass. It builds on the two previous publications by identifying individual projects and details on government spending. The following is a list of relative actions [Bioenergy Task Force, 2007]:

- Expand the commercial Bioheat Scheme to include a combination of renewable technologies e.g. wood chip. This is being delivered through an additional €4m provided in the 2007 Budget;
- Introduce an additional €6m energy crop 'top up' payment of €80 per hectare on top of the existing EU Energy Crops Premium of €45 per hectare payment;
- Introduce an €8m Bioenergy Scheme to provide establishment grants to encourage farmers to plant new energy crops;
- Introduce a €1.2m dedicated Wood Biomass harvesting machinery grant programme for wood chippers and forest residue bundlers;
- Develop and support the forest wood energy chain to deliver quality wood fuel at a competitive price;
- Review within 2 months Part L of the Building Regulations to incentivise the use of renewable technologies for heating in buildings and raise the energy efficiency requirements in new buildings by 40%;
- Use biomass combined heat and power (CHP) technologies in future major site developments;
- Expand the existing programme of biomass heating in schools, starting with eight additional schools in summer 2007.

As seen in these few examples the government is actively promoting bioenergy, and therefore the use of wood chip, in Ireland.

2.3.5 Grants & Subsidies

Sustainable Energy Ireland (SEI), a government company set up to promote and assist in the development of sustainable energy, handles the various grant schemes and research programmes. It provides grant assistance for all 'green' energy projects in both residential and commercial sectors. The financial model, seen later in the thesis, shows that capital costs are a major obstacle to financial viability, so grant assistance can make a significant contribution to their viability. Listed below are details of relevant schemes for commercial buildings that want to install wood chip systems:

- Renewable Heat (Reheat) Deployment Programme – support of up to 30% of eligible capital costs and 40% of eligible costs for feasibility study projects;
- Combined Heat and Power (CHP) Deployment Programme – available government spending of up to €11M made for appropriate CHP projects, both fossil fuel and biomass (wood residue or anaerobic digestion).

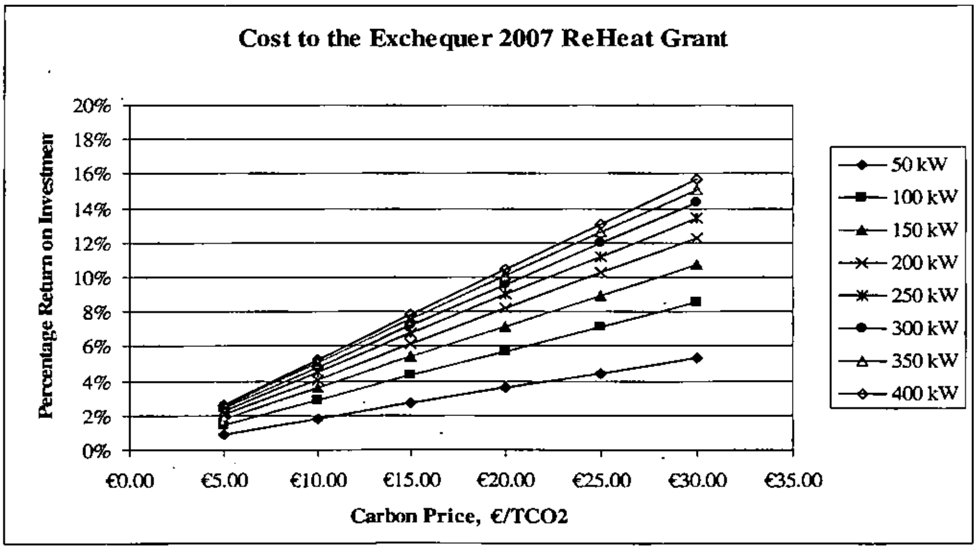


Figure 5: Cost to the Exchequer 2007 ReHeat Grant

Figure 5 shows the return of this grant in monetary terms, based on the information on grants detailed above and the cost of wood chip boilers from the financial model (financial model is the result of work from Chapter 4). By calculating the amount of CO_2 abated for each of the units and comparing this to a range of carbon prices a return of investment can be determined. The graph shows that the money used for grants returns at best 16% of the initial grant in carbon abated. The money in this case would be better invested in buying carbon credits rather than attempting to reduce carbon by aiding wood chip installations. The removal of the grant, however, would affect the viability of wood chip boilers. The investment may be poor when examined solely, the combined advantages of promoting the uptake of wood chip, such as dependency on imports and biomass heating market penetration do offer some legitimate reasons for its continuation. Additionally, the cost of carbon in the future may significantly increase making these grants even more effective in the future than they are now. A carbon value of €191.00 per Tonne would return 100% of the investment for 400kW boiler.

2.3.6 Greenhouse Gas & Global Warming Potential Factors

The most common gas responsible for global warming is Carbon Dioxide, or CO_2. It is, however, not the only contributor to global warming. Below is a list (Table 6) of recognised greenhouse gases (GHG) and the factors for converting them into carbon dioxide equivalent. The factors are based on the 1995 report on climate change from IPCC and the figures used in calculations for the Kyoto Protocol. CO_2 is the most common GHG emission in most scenarios and it is therefore the baseline for all other GHGs. The time horizon used in most GHG emission calculations is 100 years, even though the effect of GHGs can vary a great deal over time.

The true importance of these figures can be related back to carbon taxing. If carbon tax is based on the CO_2 equivalent, as opposed to just CO_2, the effect of the tax will be increased. This means it is important that policies and taxes should be clearly stated to be based on either CO_2 or CO_2e. The distribution of Pyrolysis products listed in Table 3 shows that light hydrocarbons make up 4.7%. From Table 6 CH_4 has a CO_2e of 21 times that of CO_2, which would have a significant effect on any emission or tax figures produced for wood chip.

Table 6: Global Warming Potential Values – Conversion to CO_2 Equivalent (IPCC, 1995)

Species	**Chemical formula**	**Lifetime (years)**	**Global Warming Potential (Time Horizon)**		
			20 years	**100 years**	**500 years**
CO_2	CO_2	variable §	1	1	1
Methane	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF3	264	9100	11700	9800
HFC-32	CH2F2	5.6	2100	650	200
HFC-41	CH3F	3.7	490	150	45
HFC-43-10mee	C5H2F10	17.1	3000	1300	400
HFC-125	C2HF5	32.6	4600	2800	920
HFC-134	C2H2F4	10.6	2900	1000	310
HFC-134a	CH2FCF3	14.6	3400	1300	420
HFC-152a	C2H4F2	1.5	460	140	42
HFC-143	C2H3F3	3.8	1000	300	94
HFC-143a	C2H3F3	48.3	5000	3800	1400
HFC-227ea	C3HF7	36.5	4300	2900	950
HFC-236fa	C3H2F6	209	5100	6300	4700
HFC-245ca	C3H3F5	6.6	1800	560	170
Sulphur hexafluoride	SF6	3200	16300	23900	34900
Perfluoromethane	CF4	50000	4400	6500	10000
Perfluoroethane	C2F6	10000	6200	9200	14000
Perfluoropropane	C3F8	2600	4800	7000	10100
Perfluorobutane	C4F10	2600	4800	7000	10100
Perfluorocyclobutane	c-C4F8	3200	6000	8700	12700
Perfluoropentane	C5F12	4100	5100	7500	11000
Perfluorohexane	C6F14	3200	5000	7400	10700

2.4 Embodied Carbon & Carbon Tax

Embodied carbon refers to the total carbon emission of all the processes involved in the manufacturing or production of a material. For example, the combustion of wood in a wood-fuel boiler may be carbon neutral but the production of the boiler itself will result in the emission of carbon. Embodied carbon includes the emissions from the production of the iron used in the boiler to the emissions arising from the transportion of the completed boilers. The main motivation for carbon taxation is to encourage consumers to consider more sustainable options. As will be seen in Chapter 3, the basic application of carbon tax does benefit the viability of wood chip systems, but there are also less desirable effects when carbon tax is applied to the embodied carbon of an item, as detailed in the following sections.

2.4.1 Embodied Energy

Embodied energy is the total energy required to manufacture a product and takes into account the materials used, the processes and the energy consumed in the production of the item, much like embodied carbon. Embodied energy is a key component of life cycle analysis. Below is a selection of common materials from the Inventory of Carbon & Energy where it is seen how everyday materials, such as plastic, are very energy and carbon intensive.

Table 7: Embodied Energy – Inventory of Carbon and Energy [Jones & Hammond, G., 2008]

Material	Energy	Carbon
	MJ/kg	$kgCO_2/kg$
Aluminium	155	8.24
Brass	44	2.42
Brick	3	0.22
Cement	4.6	0.83
Concrete	0.95	0.13
Glass	15	0.85
Insulation	45	1.86
Iron	25	1.91
Plastic	80.5	2.53
Steel	24.4	1.77
Timber	8.5	0.46

The data from Table 7 and the weights of wood chip boilers published by manufacturers provide data to produce an estimated embodied energy figure for the production of a wood chip boiler. Assuming the boiler is made from iron, neglecting the electronics, and finishing, a 100kW wood chip boiler has an embodied energy of:

997 kg x 25 MJ/kg = 24925MJ or 25GJ

If the whole system, feed systems containers, were taken into account, the total embodied energy of an Energy Cabin weighing 4.4T plus a 100kW boiler (0.997T); ignoring all electronics and aesthetics is roughly:

(4400kg x 24.4 MJ/kg) + (997kg x 25 MJ/kg) = 132000MJ or 132GJ.

In addition to the embodied energy of manufacturing of the boiler, the energy expended producing the fuel must also be considered. Research done by the Resources Research Unit in Sheffield Hallam University on carbon and energy balances shows how much energy is expended in producing wood chip. The following is a summary of the results [Elsayed M., Matthews R., Mortimer N., 2003]:

Table 8: Embodied Energy – Forest Residues and Coniferous

	Forest Residues		Coniferous		Units
	Total	StDev	Total	StDev	
Energy	429	43	360	38	MJ/T
CO_2	25	3	22	2	$kgCO_2/T$
CH_4	0.005	0.001	0.005	0.001	$kgCH_4/T$
N_2O	0	0	0	0	kgN_2O/T
GHG	25	3	22	2	$kgCO_2e/T$

Table 9: Embodied Energy – Broadleaf & Coppice

	Broadleaf		Coppice		Units
	Total	StDev	Total	StDev	
Energy	345	36	651	165	MJ/T
CO_2	21	2	31	8	$kgCO_2/T$
CH_4	0.005	0.001	0.005	0.002	$kgCH_4/T$
N_2O	0	0	0.004	0	kgN_2O/T
GHG	21	2	32	9	$kgCO_2e/T$

The embodied energy of the forest products, broadleaf, coniferous and residues, ranges from 345–429 MJ/T. The embodied energy of short rotation coppice (SRC) is higher at 651 MJ/T. The difference is that forest products are mainly waste products from the timber industry while the SRC exists for the sole purpose of producing energy and therefore incurs all the machinery and labour embodied energies. There are discrepancies in the report that do not match the results from this research, such as the assumption of 132 kg/m^3 bulk density and an energy content of 25% Moisture Content (17.8 MJ/kg). Both of which are very low. The impact, which these figures have on the embodied energies is unknown.

Assuming a 100kW boiler and an energy load of 178.4 MWh/yr the embodied energy and GHG for the supply of wood chips is as follows:

Table 10: Embodied Energy & GHG for Wood Chip Supply

kW	100	kW
Energy Load	178.4	MWh/yr
Moisture Content*	25%	%wet
Wood Energy*	4.9	MWh/T
Tonnes of Chip /yr	36.1	T/yr
Embodied Energy	13.6	GJ/yr
Embodied GHG	817.9	$kgCO_2e/yr$

The embodied energy and GHG for a year's supply of wood chip to a 100kW boiler is calculated to be 13.6 GJ and 817.9 $kgCO_2e$ respectively.

2.4.2 Effect of Carbon Tax on the Production of Wood Chip Boilers

According to SEI, Ireland's industrial sector consumed 2,686 ktoe, or 31.2 TWh, of energy in 2006 and emitted 15.8 $MTCO_2$ of greenhouse gases. This gives the Irish industry an equivalent carbon intensity of 0.506 $kgCO_2/kWh$, or 0.1405 TCO_2/GJ. If a wood chip boiler is manufactured in Ireland, including all aspects of the production of the iron, the carbon dioxide contained in a single 100kW boiler is as follows; embodied energy of boiler (25GJ) x Irish carbon intensity (0.1405 TCO_2/GJ) = 3.51 TCO_2.

At a carbon tax of 28 €/TCO_2 this represents an increase of €98.39 to the production of a single wood chip boiler. For the large metal storage container and feed equipment, this works out to be 18.55 TCO_2 and a tax worth €519.29. For the supply of wood chip to this 100kW boiler, the tax is calculated to be €22.90 per year, or €458.02 over a 20-year boiler life, based on the figures from Table 10. Therefore, the total tax applied to the complete life cycle of a 100kW wood chip boiler is €1,075.70. Compare this to the carbon tax costs of a 100kW gas or oil boiler in a single year of €949.10 and

€1598.50 respectively. While the additional costs on the wood chip boiler is undesirable the net changes in costs are very favourable for the viability of wood chip systems.

2.4.3 Carbon Sequestration

Carbon sequestration is the removal of carbon dioxide from the air into a carbon store, or sink. The largest carbon sinks are the oceans and forests. By expanding the size of a forest, the amount of carbon taken from the air and stored in the trees is increased. When a forest is harvested the carbon is released, resulting in a carbon neutral cycle. This means that there is no increase in the rate of sequestration unless afforested areas are increasing. The rate of carbon sequestration is proportional to the rate of forest growth. Carbon sequestration is included in the calculation of national emission levels under the Kyoto protocol.

2.5 Health & Safety

There are some associated dangers with using wood chip as a fuel. It is a fire hazard and can cause respiratory illness. The first health concern with wood chip is the inhalation of small dust particles or bacteria that can cause asthmatic reactions. If wood chip is stored over 40% moisture content it starts to decompose and that promotes bacteria growth. The emission of dust particles in the burning of wood fuel is another concern; the European Commission has set limits on the amount of dust particles that can be emitted by boilers, as seen in Table 11. [European Union, 2008].

Table 11: EU Particle Limits.

Pollutant	**Concentration**	**Averaging Period**	**Permitted Exceedences each year**
Fine Particles (PM2.5)	25 µg/m^3	1 year	n/a
PM10	50 µg/m^3	24 hours	35
	40 µg/m^3	1 year	n/a

Comparing these figures with results from a particle emission test on wood chip boilers (Table 12 & 13) it is clear that wood chip boilers are capable of producing a dangerous amount of dust particles in a localised area.

Table 12: Particle Emissions from Wood Chip Boilers [C. K. Gaegauf *et al.,* 2005]

Particle Emission per kg dry Fuel		
Total Particle Emission	1.450	g/kg (fuel)
PM10	1.210	g/kg (fuel)
PM2.5	1.135	g/kg (fuel)
PM1	0.997	g/kg (fuel)
Particle Emission per m^3 Flue Gas		
Total Particle Emission	62 -125	mg/m^3

Table 13: Wood Chip Boilers – Dust Emissions [KWB, 2007]

KWB Wood Chip Boilers, kW	15	25	30	40	50	60	80	100
Dust at Rated Power, mg/m^3	40	24	24	24	25.3	26.5	29	31
Dust at Partial Load, mg/m^3	n/a	23	18.7	10	12	14	18	n/a

The age and condition of the boiler used in the results from Table 12 is unknown. The inhalation of dust particles or the bacteria from wood chip can be at worst fatal, and the World Health Organization classified wood dust as a carcinogen in 1995 [IARC, 1995]. The danger of woodchip dust particles in comparison to oil or gas emissions is the size of the particle emitted. They are so small that they can not be expelled from the lungs, leading to serious respiratory problems. Table 12 shows that 78% of the particles emitted fall into the PM2.5 size range.

The fire hazard posed by the storage and use of wood chip is also a very real threat. Wood chip piles are flammable, self-ignitable and can cause dust explosions. Unlike oil or gas, wood chip is generally stored in the open, either outside or in an accessible storage container. This makes it easier for the wood chip to be exposed to an ignition source. Also unlike gas or oil, there are no specific safety regulations governing the use and storage of wood chip in Ireland. In addition, decomposing wood chip is capable of generating a high enough internal temperature (in the centre of the pile) that is can self-ignite.

From site visits to wood chip storages in Ireland the threat from dust explosions is clearly visible, mainly due to lack of knowledge and inexperience of both the supplier and the consumer. A dust explosion occurs when an enclosed volume of dust is exposed to an ignition source. While most of the manufactured equipment has in-built safety features to prevent the build up of dust and backfiring, the largest area of risk is the storage area. Wood chip is generally blown or tipped into an enclosed space to keep it dry and near the boiler. The storage area itself will have some sort of mechanical transport system to deliver the chip to the boiler, such as an auger or a rotating arm. All this movement can shift the wood dust into the air and then all that is required is an ignition source, such as a spark from a metal door or a static charge.

2.6 Summary

From this chapter it can be seen how the natural properties of wood are both problematic and beneficial when using wood as a fuel. For example, the natural tendency of wood to release water under the proper conditions means very little work has to be done in order to successfully convert it into a fuel with a high energy content. On the other hand, under bad storage conditions wood becomes a very expensive and relatively poor fuel, both in terms of energy content and transport costs. Key factors to the success of wood as a fuel are its moisture content (energy content) and its transportability (bulk density). Understanding how wood dries and burns are very useful to both suppliers and consumers as it provides them with information for calculating expected costs and delivery sizes.

The large bulk density of wood chips means that it is an expensive fuel to import from abroad, so Ireland's dependency on imported fuels could continue if there is no investment in the Irish forests.

Ireland's policy makers are encouraging the switch to sustainable green systems, such as wood chip, by supporting investors with grant aid and setting out plans to introduce carbon taxes that penalise the producers of GHGs. These steps are the result of international pressure on the country brought about through the introduction of international policies, such as the UNFCCC and the Kyoto Protocol.

Wood chip and biomass forms a significant part of Ireland's plan to combat GHG emissions. Market penetration targets, biomass powered electricity generation and minimum heating market percentages all involve the promotion and utilisation of wood chip in Ireland. The demand for wood chip is aided by the government's aim of switching schools and official buildings to biomass heating systems. The government is promoting biofuel by providing information and grant aid, as well as the possible introduction of carbon taxing. Information helps people to make rational decisions; grants give incentives to invest in the technology; and carbon-taxing sets a long term price for CO_2 emissions and allows the market to choose the most efficient solutions.

Carbon taxing does have a negative effect on wood chip production. Due to the size and level of technology used in the systems there is a considerable amount of embodied energy involved in the production, delivery and use of wood chip boilers. While the act of burning the wood fuel is carbon neutral and therefore exempt from carbon tax, the processes prior to it require predominantly taxable energy. However, the results show that even the whole lifecycle cost of a wood chip system is equivalent to roughly one year of oil or gas usage, dismissing any doubts about its 'green' credentials.

The last section in this chapter deals briefly with the health and safety issues regarding wood chip systems. While wood chip is considered a sustainable green technology, it still produces emissions that affect human health. The carbon produced from combustion is carbon neutral, and other GHGs produced are almost negligible, but the emission of dust particles is a large concern for policy makers and health organisations alike. Combined with the fire risk posed by wood chips, there are significant areas of concern for potential investors, especially in schools or hospitals where exposure to the storage area or delivery trucks could cause health problems. From a financial standpoint, the introduction of strict health and safety regulations to prevent dust inhalation or fire may result in higher costs as the storage areas are fitted with the appropriate safety equipment; as well as affecting the value of the risk factor accounted for in all financial investment calculations.

3.0 CHAPTER 3: METHODOLOGY

The methodology for this thesis focuses on two main aspects of the wood chip industry in Ireland, which are the supply and demand of wood chip, as illustrated in Figure 1. The supply side contains two parts, the source of the fuel and the supply of the fuel to the consumer. The demand side also contains two parts; these are the energy demand of the building and subsequently the cost of installing and running a wood chip system to meet this energy load.

3.1 Irish Forestry

Irish forestry plays a very significant role in helping wood chip penetrate the Irish fuel market. The accessible resources for wood chip directly affect the amount of fuel available to replace fossil fuels. Information was gathered from local forestry agencies and was assessed in terms of its progress in developing the wood chip industry. Also by estimating the yield of wood chips from Irish forests, the current size of the forests and the estimated annual increase in forest size it is possible to estimate the potential available wood chip supply in Ireland. Information on the Irish forests was attained from Coillte Ireland, Teagasc and COFORD.

3.2 Wood Chip Supply Chains

The origins of supply chain theory have their roots in military logistics optimisation. The military dictionary defines supply chain as *"the linked activities associated with providing material from a raw material stage to an end user as a finished product"* [DOD Dictionary of Military Terms]. Supply chain analysis requires the separation of the chain into individual processes; and establishing the costs and values of each of them. The processes are all the logistic steps in the production, storage and delivery of a product [Christopher, 1998].

The method used in this chapter to analyse the supply chain uses a cost versus value approach. This method is a simplified version of the value-added time versus cost-added time technique [Christopher, 1998] and does not include a time factor due to the limitations of field-testing. Planned field-testing was impossible due to lack of industry cooperation and financial restraints. Cost can be defined as *"That which must be given or surrendered in order to acquire, produce, accomplish, or maintain something"*, and value as *"The relative status of a thing, or the estimate in which it is held, according to its real or supposed worth, usefulness, or importance"* [OED, 2008]. Cost and value can be used to show whether the process incurs profit or loss. The market price and costs of each stage of the product along the supply chain is noted. From this, the total cost and total value for the whole supply chain is calculated and the location of profit and loss is identified.

Primary data were collected using surveys, questionnaires and interviews. The lack of any national agency dealing with wood chip means the acquisition of the majority of the data comes from private companies and research institutes. To locate and identify sources of information, government agencies such as Sustainable Energy Ireland (SEI) were very useful as they compile case studies and recommended suppliers for green energy fuels. This list was narrowed down from all green energy suppliers to just wood chip suppliers and contact was made by phone, email or in person.

The majority of the interviews conducted were semi-structured and non-structured. The use of non-structured interviews at demonstrations and forestry events proved the most useful as the equipment was there for reference. Semi-structured interviews, consisting of predetermined questions, were most useful in situations where the subject had free time to talk, usually after a demonstration or off-hours. The aim of all the interviews was to develop an understanding of the wood chip supply chains and to identify any differences in supply between the different companies.

A literature review was carried out identifying key areas of the chapter, such as supply chain economics [Christopher, 1998], transport economics [Quintet &. Vickerman, 2004] and Irish forest harvesting [Kofman & Kent, 2007].

The data for the cost analysis data for the chapter was obtained from surveys of wood fuel suppliers in Ireland. The scope of the survey was extended to include the UK for validation purposes. It was assumed that the conditions in the UK would be sufficiently similar to those in Ireland to compare the cost breakdown. The survey questions were kept relatively simple so that there is no misinterpretation and the data is directly comparable. An example of the questions asked; "What is the cost per tonne of delivering 10 tonnes of wood chip 50km at 30% moisture content?" The questions are specific and only leave one area for variation, which is the cost per tonne.

Several site visits were also undertaken. These visits provided access to many different aspects of the supply chain including the inspection of equipment and non-structured interviews with foresters, vehicle operators and landowners.

3.2.1 Process Identification

Identifying the steps, or processes, in a wood fuel supply chain was the first objective of the chapter. To identify the processes a number of different methods were used. The most straightforward was by the way of a literature search. A second approach was to interview an expert in the field about the process and then finally to validate the processes in person at a wood chip production site. From these not only are the processes identified but also a great amount is learnt from seeing the equipment involved and the amount labour required to operate and coordinate the machinery.

3.2.2 Process Cost Analysis

The process costs were taken directly from the survey results. The cost breakdown only includes the main processes. Costs generally consist of three different parts: a fixed part, a semi-fixed part and a variable part [Quintet &. Vickerman, 2004]. The fixed part is a cost that will occur regardless of use, for example insurance and tax. The variable part is dependant solely on use of the vehicle such as fuel and tolls. The semi-fixed part is a combination of fixed and variable parts such that it will occur when the vehicle is not in use and scale with use, for example depreciation.

3.2.3 Process Value Analysis

Using the survey results the value for each process can be calculated. The difference between the market price of delivered chip and the market price of undelivered chip will give the value of transportation. For example, delivered chip costs €110 per tonne, undelivered chip costs €70 per tonne, and this means the value added by transporting in this example is €40 per tonne; whether this is profitable or not will depend on the cost of transporting. The same method can be used for the other processes as long as the market values of each stage are known.

3.2.4 Process Margin Analysis

Process margin is the difference between the process cost and process value. The figure shows what economic effect the process has on the supply chain. Having a positive process margin, where value is greater than cost, is key for the success for all the processes involved in supply.

3.2.5 Optimisation

The general key to optimisation is maximizing output while minimizing input. Passive measures, such as natural drying, are much more effective than active measures, especially with a green energy fuel as reducing the work put into creating the fuel reduces its embodied carbon. To implement any kind of optimisation the cost and the value of each process must be identified. The goal of optimisation is to increase the margin by either reducing the cost or increasing the value. Some changes can produce changes in both cost and value but it is the overall change in margin that will determine its true worth.

3.3 Energy Model

The energy profile for a specific building is normally provided by a heating simulation package or a detailed manual calculation based on either CIBSE or ASHRAE standards (the standard design guides for the UK/ Ireland and the US respectively). However, the thesis requires an Energy Model capable of accurately estimating the heat loads of various sized installations under similar operation conditions so that several boiler combinations can be examined. The Energy Model developed in this thesis calculates the annual energy load and the energy ratio of wood chip to fossil fuel in the hybrid systems (hybrid systems refer to systems that incorporate a lead wood chip boiler with a fossil fuel secondary boiler for peak loads). The ratio of wood chip to fossil fuel in the system arrangement significantly affects capital costs, annual savings and subsequently the payback and financial viability of the system. The main assumptions in the model are taken from various specialised guides and handbooks [BSRIA, 2003] [CIBSE, 1999], such as expected heat gains, hot water consumption and heating times.

One of the main methodologies used to generate the profiles, specifically for Irish conditions, is the heating degree-day method [CIBSE, 2006]. Heating degree days (HDDs) are used to calculate the actual energy required to heat a space using the external temperature as a reference. Once the internal temperature is set, usually between 18 and 24 degrees Celsius, the temperature rise from the internal gains, such as people and lighting is taken away. This resulting temperature is known as the base temperature, and when it falls below the external temperature the heating system must respond and provide heat to the building. The Heating Degree Days method works on an average daily temperature basis so the occupancy hours and preheat times will affect the base temperature. One Heating Degree Day (HDD), °C/Day, would correspond to a base temperature of 15°C minus an average external temperature of 14°C. Heating Degree Days are converted into energy consumption by the following formula

$$\text{kWh} = \text{U.A.HDD.24} \tag{3.1}$$

U refers to the thermal transmittance of the building ($\text{kW/m}^2\text{K}$). A is the area of heat transfer (m^2) and 24 converts the units from per day to per hour. For the purposes of modelling, Heating Degree Days are used to show different daily energy consumption patterns and show that at a certain level of energy consumption one system will be more efficient than another. This is done by calculating the running costs of the boiler based on this daily energy demand. The other energy loads that make up the boiler load are the hot water services, the preheating of the building and, if applicable, the reheat coils in the air conditioning system. These loads are calculated using the CIBSE guide and the figures used are recorded in the results section.

The literature review was carried out using available resources, libraries and online facilities. The material reviewed in this chapter includes books, guides and published papers, including the CIBSE guide [CIBSE, 1999] and GP Guide [BRECSU, 2001]. They provide information on many of the main inputs in the energy model, such as the design data and operational data.

3.4 Financial Model

A financial model employing present net value (NPV) methods was used to analyse the financial viability of wood chip and hybrid wood chip systems. Model inputs include energy profiles, capital costs, annual running costs and a discount rate. Varying the inputs in the model allows the creation of different scenarios, and the sensitivity of the model to the inputs. The model is developed using Microsoft Excel, and it is an extension of the Energy Model created in conjunction with the thesis.

A literature review was carried out using available resources, libraries and online facilities. The material used in this chapter include books, Engineering Project Appraisal [Rogers, 2001], guides ,CIBSE guide [CIBSE, 1999], GPG [BRECSU, 2001] and published papers, 'The Choice of Discount Rate for External Reporting Purposes: Considerations for Standard Setting. Accounting Forum' [Eckel, L, Fortin, S., Fisher, K, 2003]. They provide information on many of the main inputs to the financial model, such as net present value calculations and discount rates.

A survey was undertaken to gather information on the price of gas, oil and wood chip boilers. A questionnaire was sent to a selection of companies requesting the prices for boilers in the range of 50kW to 400kW. The questionnaire also gathered data on peripheral system requirements such as flues, storage units and augers. The response rate from the survey was 10%. The survey provides all the information required for the inputting of the capital costs.

3.4.1 Capital Costs

The capital costs are the initial investments in machinery and equipment for the project. This investment will re-occur every time the boiler needs to be replaced, typically every 20 to 30 years, also as the boiler gets older its efficiency drops and the model will become inaccurate. The model is limited to 20 years based on this. In the Financial Model, the capital cost section combines all the information from the survey into an average price per kW installed, where the cost of any size boiler can be interpolated.

3.4.2 Annual Costs

The annual costs are the running costs of the installation taken at the end of each year. The unit cost of the gas, oil and wood chip is multiplied by the energy used to give a total annual cost. The following is a list of the factors affecting annual costs:

- Fuel cost
- Fuel quality – moisture content of wood chip
- Boiler efficiency
- Maintenance Costs
- Annual service charges
- Carbon tax
- Electrical consumption (parasitic power)

3.4.3 Simple Payback

Simple payback uses only the capital costs and the estimated first year savings (cost of fossil fuel minus the cost of wood chip for the same energy profile). By dividing the capital cost by the first year's savings a basic payback figure is calculated. The figure indicates how many years it would take the investment to reach a net cost of zero. The calculation presumes that there is no change in the annual costs and that the savings in 10 years time are as valuable as savings now. It is a very inaccurate way to compare the systems but it is a quick, easy and commonly applied financial appraisal method. However, the decision to invest in a long-term project should never be based solely on simple payback. Simple payback is calculated using the following formula:

$$\text{Simple Payback} = \text{Capital Cost}/\text{First Year Savings} \qquad (3.2)$$

3.4.4 Financial and Economic Variables

The effect of time on money is very important for evaluating a project that has a potential life span of 20-30years. Listed are the factors that will affect the financial viability of a project:

- Time value of money
- Inflation
- Interest rates
- Fuel prices
- Carbon tax
- Risk factor
- Discount rate

- Internal rate of return

3.4.4.1 Time Value of Money

The time value of money is the concept that money in the future is worth less than it is now, and this has a significant effect on long-term projects. An investor would prefer to receive a sum of money now rather than the same amount of money in 20 years. So if a €30,000 investment returns €80,000 in 20 years, but due to inflation the purchasing power of both amounts is the same then investor would prefer to receive €30,000 now rather than €60,000 in 20 years. This requires investments to have a certain level of profit to counteract the loss of purchasing power when the money is tied up in the project for 20 years.

3.4.4.2 Inflation

Inflation is the rate at which the purchasing power of money is decreasing. One euro today is worth ninety-five cent in one year with an inflation rate of 5%.

3.4.4.3 Interest Rate

Interest rates can be described as the cost of borrowing or as the *quantitative measure of the time value of money* [Rogers, 2001]. An investment of €30k over 10 years accruing a return of €35k is the equivalent of investing €30k at an interest rate of 1.55% over 10 years. Interest rates are closely linked with inflation, with many financial institutions using interest rates as a means to control inflation. The European Central Bank, ECB, sets the base lending interest rates in Ireland.

3.4.4.4 Fuel Prices

The effect of changes in fuel prices has a significant effect on the results of the financial model. Oil, gas and wood chip are very different in terms of production, energy content and cost so it is unsurprising that the rate of increase in price is not the same. They will follow a common trend due to inflation and demand but the rate at which they individually change will have an important effect on the financial returns of a wood chip boiler.

3.4.4.5 Carbon Tax

Carbon taxing is an initiative to try to reduce the amount of carbon produced by buildings by penalising carbon-emitting processes, such as burning gas or oil. The burning of wood fuel is considered carbon neutral because the carbon emitted on combustion is equal to the carbon absorbed during growth; the tax is therefore not applied to wood chip and makes it more competitive with gas and oil. In June 2008, CO_2 was trading at €28 per tonne on the carbon exchange. [www.pointcarbon.com, '08]. The trading price of carbon has risen steadily in the 2008. This will have a positive effect on the viability of wood fuel systems; making them cheaper in comparison to fuels such as oil and gas, which are not carbon neutral. If a carbon tax was introduced presently it would most likely be a fixed figure between €15 to €30 per tonne of CO_2.

3.4.4.6 Risk Factor

A risk factor is always taken into account when investing in a project. New technologies will present more of a risk than investing in a tried and tested system. The risk factor is a figure mainly based on experience and previous similar ventures. Investing in wood chip is a risk as the technology in Ireland is relatively new, there is no national agency and the supply of fuel is not completely reliable. For example, there may be no supply available in the locality of the building or there might not be sufficient quantities of wood chip to meet the required load. The current trend of increasing fossil fuel prices makes wood chip a more attractive investment but the much larger costs required for a wood chip boiler means there is still more to risk by installing such a system.

3.4.4.7 Discount Rate

The discount rate (DR %) is the rate at which the value of money is discounted each year. It is not calculated directly from the economic variables (risk, interest rates) but is based on an investor's experience of the variables. Currently, there is no general standard concerning the choice of the discount rate to be used when calculating the present value of an asset or liability for external reporting purposes [Eckel et al, 2003]. Technically a discount rate is a type of interest rate; discount rates and interest rates are mathematically the reverse of each other. Interest rates convert present value into future value while discount rates convert future value into present value. The relationship between them is:

$$DiscountRate(DR\%) = \frac{IR\%}{1 + IR\%} \tag{3.3}$$

$$InterestRate(IR\%) = \frac{DR\%}{1 - DR\%} \tag{3.4}$$

The mathematical formula for calculating the present net value in the financial model is known as the series present worth factor [Rogers, 2001]:

$$P = A \times \left[\frac{(1+i\%)^n - 1}{i\%(1+i\%)^n} \right] \tag{3.5}$$

Where;

P = Present Investment

A = End of Period Payment

n = Number of Years

i% = Discount Rate

So at n = 1 (after 1 years trading) the formula becomes:

$$P = A \times \left[\frac{DR\%}{1+DR\%} \right] \times \left[\frac{1}{DR\%} \right] \tag{3.6}$$

Simplifying it then becomes:

$$P = \left[\frac{A}{1+DR\%} \right] \tag{3.7}$$

Every year the project runs the returns are reduced by the factor 1/[1+DR%]. This effect is also compound so that after two years the returns will have been reduced by [1+DR%] x [1+DR%] or $[1+DR\%]^2$.

3.4.5 Net Present Value Model

Net Present Value (NPV) describes the total future savings, and/or losses, of an investment in present terms. For every year into the future savings become less valuable in the present, the NPV sums these diminishing savings and losses to give a total net present value of the investment. The NPV is calculated by discounting the savings every year by a discount rate. The effect is compound so that savings made far into the future are worth very little in the present. The equivalent of simple payback in the discounted model is referred to as discounted payback. To determine the discounted payback the discounted annual savings over the 20 years are used, but due to complexity of the calculations the optimum way to determine the discounted payback of an investment is to use a discounted cash flow. A table showing the annual discounted savings is recorded and the year where the net value is zero corresponds to the discounted payback. This will mean that the discounted payback will be longer than the simple payback, but it is a more accurate and realistic way of comparing the systems.

3.4.6 Sensitivity Analysis

While the NPV model is accurate under today's conditions it might not necessarily hold over the course of 20 years. Rising fuels prices, falling boiler prices, new carbon tax laws, new technologies or improved fuel quality are all very realistic scenarios that will affect the financial viability of wood chip systems. The following list of sensitivities was compiled so that each of the main inputs (energy profile, capital costs, annual costs and policy) was altered:

- Alter the energy profile of the building – incorporate HVAC
- Modify capitals costs and grants
- Vary fuel prices (wood chip quality and boiler efficiencies)
- Introduce carbon taxation

These factors make up the all of the main model inputs and their analysis will show which factors the model is most responsive to.

3.4.7 Scenario

The sensitivity analysis indicates which of the individual inputs the model is most responsive to, but it does not show the financial feasibility of a system where these changes have occurred simultaneously. It is highly possible that several of these inputs will vary during the course of systems life. The scenario results show what effect the implementation of all of the previously listed changes will have on the financial viability of wood chip heating systems. For calculating this scenario, the model will be run with the following changes:

- *Decreased capital costs*
- Increased fossil fuel prices
- Increased wood chip quality
- Carbon tax introduced

The full scenario is described in detail in the results section.

4.0 CHAPTER 4: RESULTS

4.1 Irish Forestry

Irish forests cover approximately 9% of the country. Coillte controls two thirds of these forests, while private owners make up the final third. Sitka spruce makes up 60% of Collites tree distribution [Coillte, 2008]. Sitka spruce is a very common source of pulpwood and therefore wood chip; it also grows very well in the Irish climate. To illustrate how the wood chip yield from a forest is estimated a sample calculation is completed. For the example calculation all of the Sitka spruce owned by Coillte is assumed to be used for wood chip production; a potential estimated yield for wood chip energy is then calculated based on these figures. A number of important assumptions are made for this calculation. Firstly, that all forest sites are accessible and manageable. Secondly, all yield calculations are based on figures published by Teagasc and COFORD, and finally that all the wood attained from the first two thinnings (the removal of young trees) are converted into wood chip.

4.1.1 Yield of Wood Chip from Irish Forests

4.1.1.1 Wood Chip from Thinnings

Thinning is an important task for maximising the timber output of a forest. The first type of thinning, the line system, involves removing every fifth, sixth or seventh line in a young stand (forest) to allow the remaining trees more space to grow. The second type is the selection system, which is the removal of individual trees that are weak, sick or abnormal. First thinnings occur at different times for different species of trees, and then every 5-10 years afterwards. Generally, the trees removed from first thinnings are too small for commercial use and can therefore be used for wood chip. The yield of wood chips from thinning is calculated using two methods. The first is based on defining the yield class, the amount available per hectare per year, and its thinning cycle (Teagasc); the second is based on a percentage basis of trees removed per thinning (COFORD).

Table 14: Wood Chip from Thinnings – Method 1 (Teagasc, 2002)

Yield Class	20	m^3/ha/yr
Cycle	5	years
Yield	70	m^3/ha/yr
No. of Thinnings	2	
Total	140	m^3/ha

The yield class is the growth rate of the tree and indicates at what age the first thinning occurs. For Sitka Spruce a yield class of 20 translates to first thinnings at 20years. The cycle refers to the time between thinnings, and the yield is the volume of wood removed from the forest at each thinning. The Yield figure is independent from the Yield Class and Cycle figures. The calculation simply becomes Yield x Thinnings = Total Available for Wood Chip. One of the assumptions made for these calculations were that the first two thinnings would be used for wood chip, so the No. of Thinnings is set at 2.

Table 15: Total % Thinning from Line and Selection Systems – Method 2 (COFORD, 2008)

Original Stand	100%
Line Thinning 1/7	86%
Selection, 25%	64%
Total % Thinned	**36%**

Line thinning is the removal of every one in seven lines of the forest. After the line thinning there is selection thinning; which is the removal of sick or abnormal trees from the stand, which is generally a further 25% of the remaining stand. This means 36% is thinned from the original stand and is made available for wood chip.

Table 16: Wood Chip from Thinnings – Method 2 (COFORD, 2008)

Trees Planted	2500	tree/ha
% Thinning	36%	
Trees for Wood Chip	900	tree/ha
Diameter of tree	12	cm
Height of tree	9	m
Volume of stem	0.034	m^3/tree
Total Volume (Solid)	50.9	m^3/ha
Total Volume (Chip)	141.4	m^3/ha

Both methods produce very similar results. The sources for the input data were obtained separately and the small difference in the results indicates that the yield estimate is accurate. Over a softwood forest life-cycle of 40 years (Teagasc, 2002) this represents 3.5 m^3/ha/yr of sustainable energy from thinnings.

4.1.1.2 Wood Chip from Forest Residues

The wood chip from forest residues corresponds to the left over woody material from commercial thinnings and clear felling, which is the complete removal of all the trees. The tops and branches of trees are of no commercial value and can be harvested for wood chip production. Assuming first thinnings took place at a tree age of 18-20yrs (Sitka spruce) and a cycle of 5 years (Table 14) there are three remaining thinning operations and the clear felling left remaining for a 40-year forest cycle.

Table 17: Data for Forest Residues [BENET bioenergy Network, 2000]

Density Sitka	450	kg/m^3
Ratio Stem to Residues	0.43	kg/kg

Table 18: Wood Chip from Forest Residues [BENET bioenergy Network, 2000] & [Teagasc, 2002]

		Timber Harvested, m^3/ha			
	Year	Teagasc	Jyväskylä	Average	Forest Residue, T/ha
2nd Thinning	25	70	30	50	6.8
3rd Thinning	30	70	35	52.5	7.1
4th Thinning	35	70	40	55	7.4
Clearfell	40	470	250	360	48.6
				Total	69.9

The yield rates for timber from forests can depend largely on the initial stand density, with increased wood chip production coming from larger stands. The data collected for these results did not include figures on the original stand density. Over a 40-year forest cycle 69.9 Tonnes/ha of harvested timber represents 1.75 Tonnes/ha/yr of sustainable wood chip.

4.1.1.3 Wood Chip from Pulpwood

Pulpwood is a cheap wood, which lacks the strength to be used in construction and is generally used in the paper and panel board industry. With the increase in the use of wood for energy, the paper and panel board manufacturers are coming into direct competition with wood chip suppliers for pulpwood. The amount of pulpwood available for the energy market is determined by the price. Currently in Ireland, many wood chip suppliers use pulpwood as their source of wood chip. It is possible to get very good quality wood chip from pulpwood as it can be stacked and stored reasonably well.

4.1.1.4 Wood chip from Sawmills & Waste Wood

The final source of wood chip is from sawmills and waste wood from construction. Due to recent regulations, most waste wood is illegal to burn because it may contain toxic coatings or have a laminated finish. Sawmills produce significant amounts of wood waste from the manufacturing of boards and timber. They also produce large quantities of sawdust, which is processed into wood pellets. The mills would generally use this waste to power and heat the mill itself. Occasionally there is excess energy from the mill and the remaining wood energy is sold on to a local user.

4.1.2 Energy from Irish Forests

Based on the previous calculations an estimate of the available energy from Irish forests can be completed, and is shown below in Table 19.

Table 19: Annual Wood Chip Energy Potential from Irish Forests

Wood Chip Yield per Year	2.6	tonne/ha
Sitka Spruce (Coillte)	231882	ha
Moisture Content of Chip	50%	
Energy Density of Chip	2.36	kWh/kg
Energy per ha	6186.9	kWh/ha
Total Energy	1.43	TWh

This table shows that current Coillte forests have the capacity to provide 1.43 TWh every year (Energy per ha x Sitka Spruce (Coillte)). This does not include the private sector or the energy available as wood waste, such as sawdust from sawmills.

and excess pulpwood, as information on the accessibility and operation of privately owned forests is unknown. Due to the origin of the wood, thinning and residues, the moisture content is not as low as wood chip produced from pulpwood. This is because maintaining the drying conditions of the forest wood is more difficult than maintaining a stack of wood in a shed or a field. The advantage is that it should be cheaper per tonne than the pulpwood sourced chip.

The strategic objectives of the Irish government and the Forest Service are to increase the forested areas in Ireland. The planting target was 25,000 ha/yr until the year 2000 and 20,000 ha/yr from 2001 [Forest Service, 2006]. This annual increase of trees will reflect directly in the amount of available energy from wood chip. For example, a 5% increase in the Sitka spruce will result in a 5% increase in available energy. Table 20 shows the estimated total energy for all wood fuel in Ireland from COFORD's 2003 report on maximising the potential of wood use for energy generation in Ireland. The results from Table 18 are similar to COFORD's results in Table 20 for forest residues. However, the energy calculated from forest thinnings is not comparable to COFORD's data as the thinnings are combined with pulpwood figures.

Table 20: COFORD Wood Fuel Source & Available Energy (COFORD, 2003)

Wood Fuel Source	**2005**	**2016**	**Unit**
Pulpwood	2.22	3.36	TWh
Sawmill residues	2.83	3.17	TWh
Available forest residues	0.53	0.67	TWh
Total	**5.58**	**7.19**	**TWh**

4.2 Wood Chip Supply Chains

4.2.1 Supply Chain Processes

As seen previously in section 4.1, there are numerous sources of wood for chipping, such as forest residues, thinnings, pulpwood and wood waste. However, the results of the surveys for the analysis of the wood chip supply chains only covered one main area of supply, which was the pulpwood supplier. This was not very surprising as the majority of high quality wood chip comes from the chipping of pulpwood. Wood residue and thinnings are more difficult to use in commercial applications due to their higher moisture content, and therefore lower energy content and more importantly their inability to be stored for long periods. For examining the supply chains to commercial buildings pulpwood was seen as the most logical source. The main processes involved in supply are detailed below.

4.2.1.1 Acquiring Wood

Acquiring wood is the first step in any wood fuel supply. All wood will originate from the forest and the options for obtaining wood will depend largely on the occupation and objectives of the landowner. A forester interested in only construction timber might hire a contractor to thin the forest, therefore allowing the contractor to sell the pulpwood (unusable as construction timber) as fuel. The forester might thin his own forest and sell the thinnings and forest residues as an additional income for himself. A wood fuel contractor could purchase pulpwood from the forester and supply wood chip by chipping the pulpwood. This initial step has a significant effect on the final price of the wood chip for the consumer. The payment of third parties for harvesting and transporting at this very early stage of supply can considerably change the cost of the raw product.

4.2.1.2 Drying

Wood can be dried in numerous ways and will benefit greatly from being covered or stored inside. Drying affects the weight, energy content and durability of the wood fuel. Forest thinnings can be dried in the forest where they are felled, covered by the forest canopy. Pulpwood can be stored in sheds or under a waterproof membrane. Certain applications require different levels of moisture content [Kofman, 2006] and different types of wood chip will be of different qualities and moisture contents. It is not cost efficient to leave a product sitting in storage and taking up space for any longer than is necessary [Blanchard, 2007], so knowing the moisture content required by the consumer is very important.

4.2.1.3 Chipping

Chipping is the act of turning trees, branches and logs into wood chip. The chip size can vary and there is an ISO standard for chip classification [NSAI, 2005]. The size of the chip required will depend largely on its use. Small domestic boilers require a small chip while large power plant applications can burn very large wood chips. Chipping affects the bulk density of the wood chip as smaller particles generally result in a higher bulk density [Knott & Shurson, 2004].

4.2.1.4 Transport

It is possible for transport to occur multiple times in one supply chain. Wood fuel can be transported in log form or chip form. Transport adds variable amounts of value to the product because the product is worth more at its point of use than at the roadside.

4.2.2 Supply Chain Arrangements

In a wood fuel supply chain there are two fixed points, acquiring wood at the beginning and delivering chip to the user at the end. Everything in between these points is interchangeable. Some arrangements, however, will work better than others. It will be necessary when looking at the costs to determine whether the order of the processes will have any effect on the overall price. The following are descriptions of the two most common arrangements seen during the research. Other set-ups will fall into one of these categories, but would be inefficient versions by comparison due to the additional handling and transporting of the wood chip. Figure 6 shows the shortest supply chain. Variations can include an additional transport stage before the drying process or an extra drying stage after chipping.

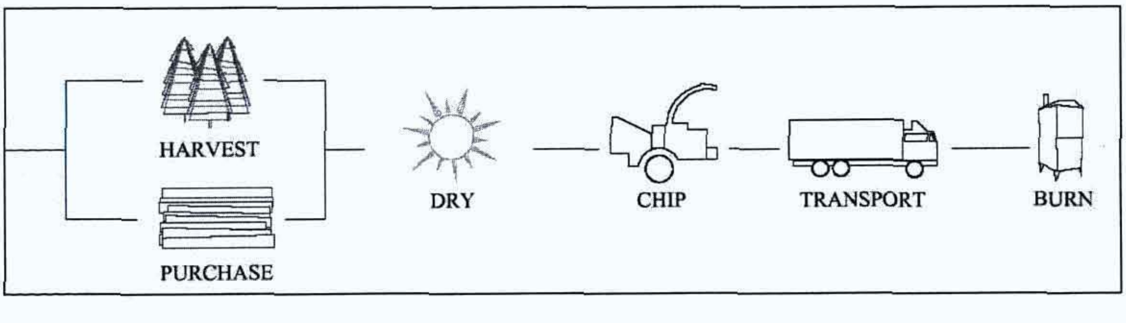


Figure 6: Typical Wood Chip Supply Chain

4.2.2.1 Single Agent

The single agent arrangement is where one company or individual controls all aspects of the fuel supply chain. An investor adopting this business model would probably already be involved in one or more of the processes, such as harvesting or haulage, and vertically diversifies into total wood fuel supply. Controlling everything from start to finish eliminates all third party mark-ups, as well as all additional handling costs that are required when multiple companies are involved. The most obvious example of this can be seen from the price of purchasing dry logs. Dry logs are sold at €40 a tonne excluding chipping and delivery. A company which harvests and chips wood could produce wood chip at a lower cost than purchasing logs; potentially, this represents a significant saving. However, this margin will be offset by the amount of capital required to start up this supply chain, but as the agent is most likely to be diversifying from either the haulage or forestry industries the only significant additional equipment that may be required is a chipper, which can be rented or hired for the required time. Figure 7 shows the arrangement of a single agent controlling the complete wood chip supply chain.

An adjustment that can be made to this arrangement is to bring in third party transport and/or third party harvesting, as illustrated by the hatched process boxes. This ensures that the fuel supply remains in control of the original company but a contractor, with experience in haulage/harvesting manages the more specialised logistic processes.

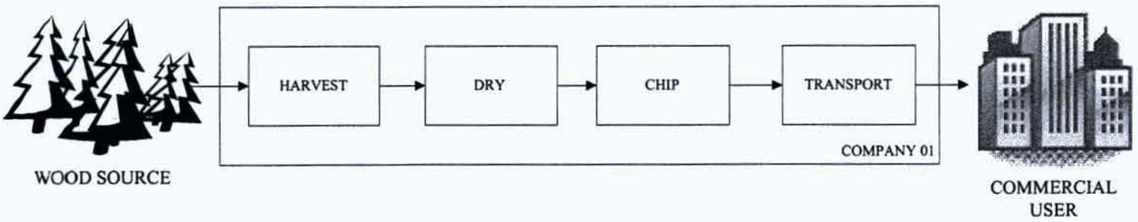


Figure 7: Single Agent Arrangement – no contract work

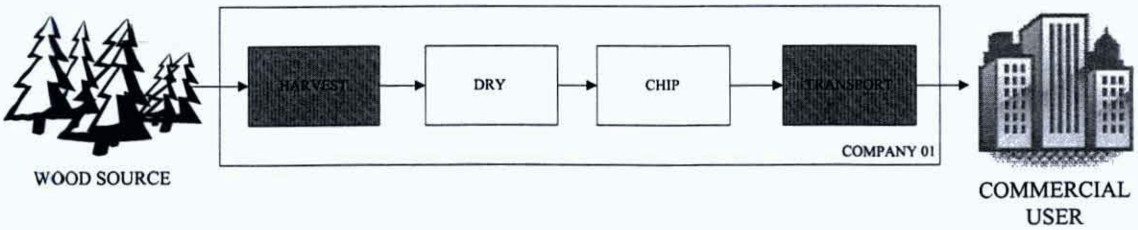


Figure 8: Single Agent Arrangement – contract work

4.2.2.2 Multi-Company Arrangement

Multi company arrangement describes the set-up where the ownership of the product changes hands at some point in between processes. This arrangement requires less capital to start up but there are many additional costs due to extra handling of the wood. A contractor acts as an intermediary between the harvester and the consumer. The harvester sells logs to the contractor. The wood is then dried, chipped and sold on to the consumer. While the extra stages incur extra costs and cause the price of the fuel to increase the capital required is split between more companies. One of the main benefits of a multi-company arrangement is security of supply. Unlike the single company, arrangement there is a certain amount of flexibility in the multi-company arrangement. If there is a problem with the supply of wood the wood fuel contractor (company two) can source another load. This provides the consumer with a guaranteed supply of wood.

Figure 10 shows one of the most complex arrangements. A landowner hires a harvesting contractor to thin or clear his forests. The harvested wood is sold to a wood fuel contractor who hires transport to bring the wood to his storage facility. The wood is then dried, chipped and delivered to the consumer via another hired transport. This arrangement has several benefits including less capital costs for both the initial landowner and the wood fuel contractor, but a comparison of Figure 7 and Figure 10 shows clearly how a supply chain can become overly complicated very easily. The additional costs of the contracting and price marks-ups between the companies will have an effect on the final price of the wood chip for the consumer.

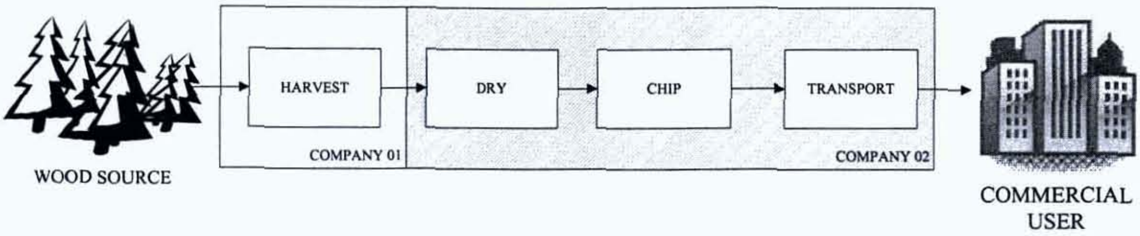


Figure 9: Multi-Company Arrangement –no contract work

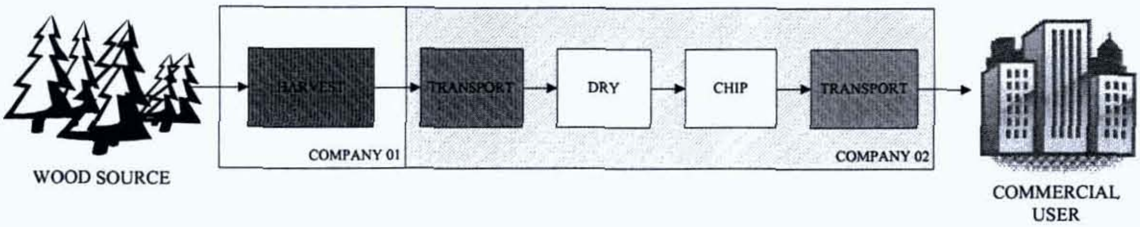


Figure 10: Multi-Company Arrangement – contract work

4.2.2.3 ESCo Arrangement

An ESCo, Energy Service Company, arrangement is identical to the previous arrangements up the point of handover of the fuel to the consumer. The difference between a normal supply and an ESCo supply is that a normal supply will provide a physical fuel to the consumer while the ESCo provides energy (heat). The ESCo retains ownership of all the equipment, burns its own fuel in its own boilers and then charges the consumer for the energy delivered plus the service. It is comparable to how electricity is supplied in that the consumer pays per kWh, unlike gas or oil, which is generally paid per unit volume or unit weight. ESCos are in the unique situation where the quality of fuel will affect their costs more than the consumers' costs because regardless of the quality of the chip the consumer is guaranteed a price per unit energy delivered. This puts the emphasis of improving the fuel quality on the ESCo suppliers, as it is more beneficial for reducing their own operational costs. The additional information on service charges and fuel value were not available for examination as the ESCo arrangement, at this level of power output, is a relatively new service.

4.2.3 Process Costs

Identification of the component costs - the smaller costs that combine to give the total cost for a process- is a useful way to analyse potential cost reductions. In this section, the main processes are broken down into their component costs.

Table 21: Fixed Costs

Fixed	Insurance	Tax
Transport	x	x
Chipping	x	
Drying		
Harvesting	x	x

Table 22: Semi-Fixed Costs

Semi-Fixed	Depreciation	Maintenance
Transport	x	x
Chipping	x	x
Drying		
Harvesting	x	x

Table 23: Variable Costs

Variable	Fuel	Labour
Transport	x	x
Chipping	x	x
Drying		x
Harvesting	x	x

4.2.3.1 Wood Costs

Tables 21, 22 and 23 show the component costs for the acquisition of wood. Harvesting costs are similar to transport costs in that they involve the coordination of large machines and factors such as down-time and economies of scale. Recent work by COFORD has shown that simpler harvesting arrangements are feasible and in some cases actually prove to be more cost-effective under Irish conditions than more advanced methods. Table 24 is an excerpt from the results of the COFORD Forest Energy Study 2006 [Kofman & Kent, 2007] showing the costs of harvesting and chipping using different machinery arrangements. The most basic arrangement is the chainsaw and tractor combination, which is more expensive than the more advanced combination of feller-buncher and Silvatec. For the purposes of comparing the survey results with the COFORD results the most important figure is the cost of harvesting and chipping the pulpwood, as pulpwood is the wood chip source used by the surveyed suppliers.

Table 24: COFORD Harvesting and Chipping Costs

Assortment	Felling Method	Chipper	Roadside Cost
Whole tree	Chainsaw	Tractor TP280	€19.34
Whole tree	Chainsaw	Silvatec	€14.31
Whole tree	Feller-buncher	Silvatec	€18.86
Whole tree chemical	Silvatech	Silvatec	€24.62
Whoel Stem	Harvester	Silvatec	€40.30
Tree section	Harvester/forwarder	Jenz	€52.43
Pulpwood	Harvester/forwarder	Jenz	€46.05

The alternative to harvesting is to purchase the wood. The price of pulpwood increased by 25% between March '07 and September '07, which makes wood chip supply chains with purchased pulpwood more expensive.

4.2.3.2 Drying Costs

Tables 21, 22 and 23 show the component costs for drying and storage. Drying costs should be zero as there is no direct energy input, but there are associated costs that can not be avoided, such as handling and monitoring. Leaving felled trees in the forest is a cheap way of drying. The trees are typically chipped as they are removed and delivered straight from the forest site, but will generally not achieve the same low moisture content as covered wood. For pulpwood, stacking the logs and covering them requires time and effort and therefore incurs a cost but they will provide a high quality wood chip. Another cost to consider is the rent or opportunity cost of the storage areas, such as shed areas or open fields. The opportunity cost is the profit lost from using the land to dry wood and not renting to another user for greater profit. It is a difficult value to calculate as one process from a long chain is being compared to a single process (renting). To identify the opportunity cost the value of the alternative use of the land would have to be known. While renting shed space might be more profitable than drying wood, the loss of profit from not supplying wood chip might be greater. The inclusion of opportunity costs is very important for fuel depots located on high value land.

4.2.3.3 Chipping Costs

Tables 21, 22 and 23 show the component costs for chipping carried out by the supplier. Like transport, and other machine based operations, chipping costs will vary more with use. Unlike transport, however, there is not as much emphasis on scale, due to less fixed costs. Consequently, the action of chipping will mainly incur costs only when the chipper is used. Insurance costs for chipping are smaller in comparison to transport insurance; for farm machinery the insurance is normally taken to be a percentage of the capital cost [Edwards W., Iowa State University, 2005].

4.2.3.4 Transport Costs

Tables 21, 22 and 23 show the component costs for transport carried out by the supplier. Calculations show that the scale at which the transport operates is critical to keeping it cost effective. For example, a small office complex requires roughly 100,000 kWh of heat per year. This is equivalent to six deliveries a year using an 18.75 tonne/ $78m^3$ truck. If the consumer were to purchase a truck to transport the wood chip from his fuel depot the fixed costs would dominate the total costs and make it too expensive. However, if the consumer were to take on a number of extra deliveries the fixed costs can be split between these additional journeys. The fixed and semi-fixed costs are now smaller because they are effectively divided between the additional deliveries.

4.2.3.5 Total Costs

Tables 25 and 26 show the results of a survey carried out as part of the thesis on Irish, British and European wood fuel suppliers. The response rate of this survey was 20% from 25, including European data. It summarises the response to the question "How much would 10,000 kg of wood chip at 35% moisture content cost if it is delivered 50km". The replies are all from suppliers using pulpwood as their source of wood. The replies also include the percentage breakdown to show how the costs distributed over the processes.

Table 25: Survey Results of Wood Chip Suppliers (Ireland & UK)

	Irish		British	
	Average	St.Dev	Average	St.Dev
Total €/tonne	€112.50	€3.54	€95.79	€10.42
Aquiring	35.5%	0.7%	36.0%	8.5%
Chipping	13.8%	1.8%	14.0%	1.4%
Transport	20.0%	7.1%	20.0%	7.1%
Storage (handling)	12.5%	3.5%	10.0%	7.1%
Markup	18.3%	2.5%	20.0%	7.1%

Other Information collected included market prices for the different types of available wood for purchasing. (Dated 06/'07)

Table 26: Cost of Wood & Wood Chip (Ireland)

Market Value, €/T	
Wet (Fresh) Log	30
50% Dry Log	38
30% Waste Wood	30
Roadside Chip	70
Delivered Chip	110

European results for delivered wood chip were €65.15 per tonne, compared to €110.00 in Ireland. The main sources of European information were their national bio energy agencies. The European prices suggest there is significant scope for lowering prices in Ireland and the UK.

4.2.4 Process Value & Optimisation

Having established a breakdown of the costs it is now necessary to identify the process values so that the margin can be estimated and maximised.

4.2.4.1 Drying Value & Optimisation

Drying is different to other processes in that the producer can affect the amount of value added. Figures 11 and 12 illustrate the effect of drying on weight, energy content and costs.

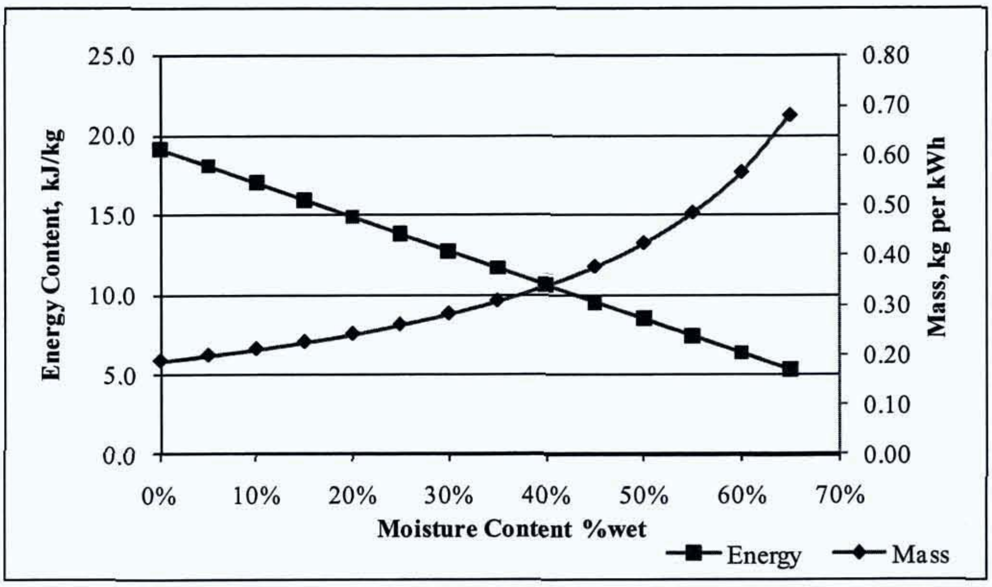


Figure 11: Effect of Moisture Content on Energy Content and Mass Required

From Figure 11 it is clear that the lower the moisture content, the less the amount of wood chip is required to meet the consumers' requirements. Less chip means less harvesting, less chipping and less transport. Not only has the drying increased the value of the chip, it has simultaneously lowered costs elsewhere in the supply chain. It also has the lowest cost implications. The key variables that must be considered include; the required drying, the target moisture content, stacking methods, testing moisture content and studying required weather conditions for optimum drying. The savings in transport costs can vary a lot as a step down from 3 deliveries to 2 deliveries means that a whole truck load of chip is displaced by the drying; in terms of transport costs there cannot be 2.5 deliveries of wood chip when dealing with transport.

4.2.4.2 Value from Drying

Results of drying on the process costs are presented in Figure 12, which highlights the importance of drying to the entire supply chain.

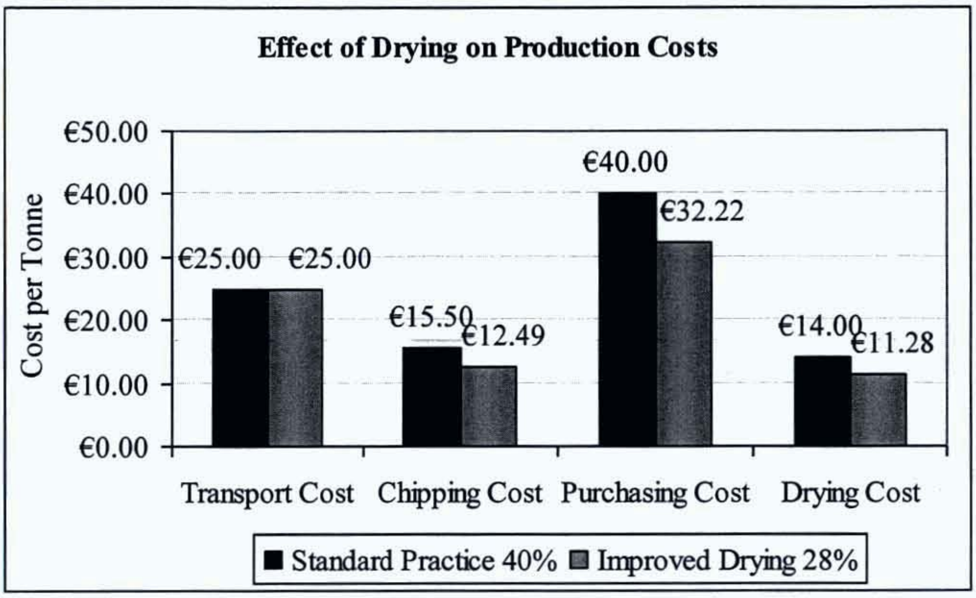


Figure 12: Effect of Drying on Production Costs

Figure 12 shows that increasing the energy content (lowering the moisture content) will have a significant positive effect on the overall costs. Improving the moisture content target should not increase the process costs, because the concept is to improve the quality of the drying as opposed to the increasing the work that would be involved in more drying. Time is not a factor in these results.

4.2.4.3 Methods of Optimising Drying

From previous work it is known that all wood has a fibre saturation point, FSP, that once attained can be kept until the wood comes in contact with liquid water and more importantly can be reached without the need for mechanical drying. This FSP is the goal of drying. Reaching this point quickly and without incurring excessive costs is the key to a competitive wood fuel supply. From previous chapters the FSP is shown to be 28% MC_{wet}, and it varies with climate conditions. The rate of drying depends on climate conditions: mainly temperature, humidity, wind speed and solar radiation. These four elements can be combined into a single 'evaporation rate' figure. In addition, when the wood fuel reaches the FSP, or the optimum drying point, it is no longer increasing in value; therefore it is best to sell the wood fuel on in order to avoid the costs associated with keeping a consumer ready product in storage [Blanchard, 2007]. From this information, a list of recommended practices is as follows:

- Keep wood dry – cover or store inside
- Monitor weather conditions and moisture content
- Ensure minimal handling
- Move wood fuel on when it reaches its target moisture content.

4.2.4.4 Chipping & Harvesting Value & Optimisation

The value added by harvesting can not be altered directly by the harvester. The value of the products produced by harvesting will be determined by market demand. Chipping, however, can reduce transport costs by increasing the bulk density of the wood chip. If the quality of the chipping is high and the wood chips chipped smaller it has the potential to reduce the amount of trucks needed for transport and therefore reduce transport costs in the same way as drying. This is not a guaranteed source of value because the size of the chip will depend on its intended use. The full effect of wood chip size on bulk density is relatively unknown.

An estimate of the value of chipping and harvesting can be completed using the survey data and market values. Roadside chip has a value of €70 a tonne, (see Table 26). That puts the value added by harvesting and chipping at a minimum of (roadside cost €70 – cost of harvesting and chipping €46.05) €23.95 per tonne, based on the COFORD harvesting results for pulpwood, which is the main source of material from the surveyed fuel suppliers. If the fuel contractor purchases fresh pulpwood at €30 per tonne and then dries, chips and delivers the wood fuel for €115 the value of these process to him is €85 per tonne. Whether this is profitable will depend largely on the costs of processes. In addition, the location of the drying site, at either the forest site or a nearby storage depot, will affect the transport costs, which could make the supply chain too uncompetitive. Profitability depends largely on the costs of production since value is market dependent, and it is therefore beyond the suppliers' control, with the exception of drying which is the only real method the supplier has to increase value.

Optimising harvesting costs is a complex logistics task. For optimisation, large-scale time trials would have to be completed along with detailed logs of working hours and machinery movement [Kofman & Kent, 2007]. Optimising chipping is an easier task. Ensuring the blades are sharp, that the machine is maintained and that only suitable wood put through the chipper should guarantee that the chipping is operating efficiently.

4.2.4.5 Transport Value & Optimisation

It may appear that the value added by transport is zero because it does not increase the quality of the product or reduce its bulk or volume. However, transport does add a relative value to the product. There is a change in the value added during transport when the market value is affected. If the price difference between a delivered fuel and a collected fuel is significantly different then the value of transport is high. However, if they are the same price then the value added by transport is zero. The value of fuel to an office building would be significantly lower than that of a hospital;

therefore, the value of transporting to hospital will be a lot higher, and the hospital will accept the higher costs to have the fuel delivered. The process margin can be optimised by minimizing costs: reduce fuel consumption by following the guidelines for economic driving; ensure that the truck is always running at maximum capacity; drive on good quality roads to reduce maintenance and depreciation; route selection; reduce loading times and downtime at fuel depots and ensure driver comfort.

4.2.4.6 Total Value

The combination of the calculated value added and the results from the survey are shown in Figure 13.

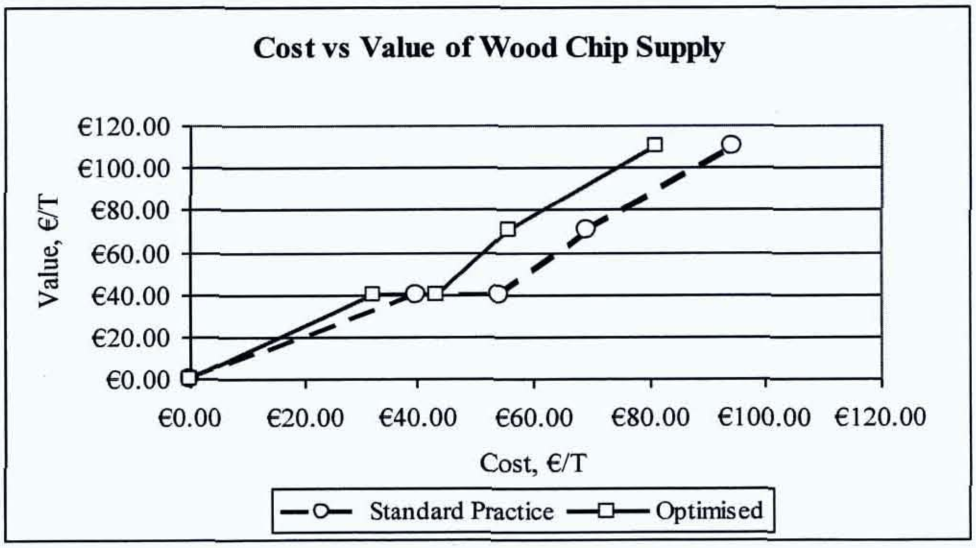


Figure 13: Cost versus Value of Wood Chip Supply

Figure 13 represents the following supply arrangement: purchasing, drying and storage, chipping and transport. The key point to note is the negative effect drying is having on the supply chain, shown as the second and third points on the dotted line; it has a margin loss of €15/T. This is mainly because wood is sold on a weight basis rather than on dryness (with the exception of ESCo arrangements, which deliver based on kWh), so drier wood to a forester does not have much effect on the price. However, the solid line shows the cumulative effect of drying on the other processes in the supply chain. While the values for each of the processes remain the same, the costs are reduced. The value of drying is calculated to be €19.76/T with a target moisture content of 28%, down from 40%. So while the drying does incur costs on the supply chain it also lowers other processes costs by a larger amount. Figure 14 and 15 shows the advantage of reducing the target moisture content from an initial target to an improved moisture content. The savings in reducing the moisture to the point where one less truckload is required is seen by the step the graph.

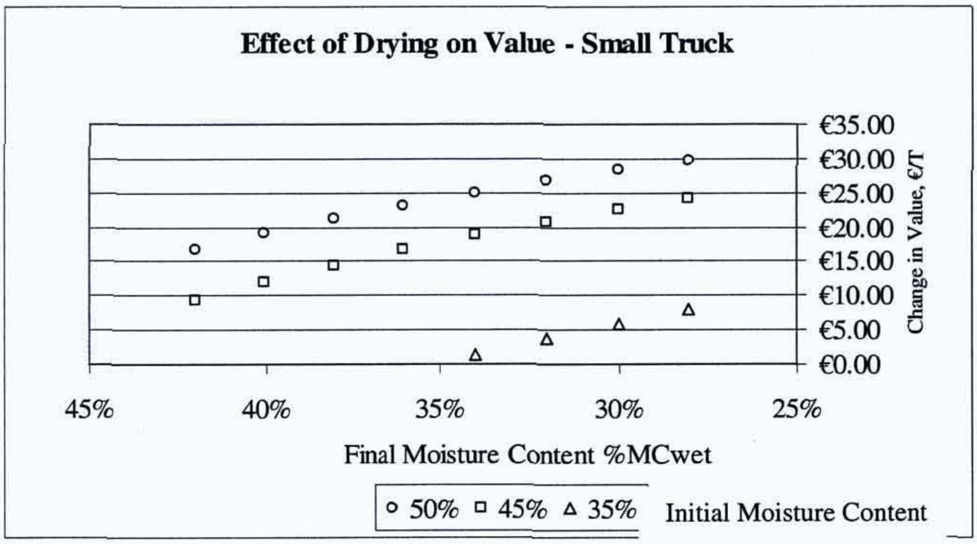


Figure 14: Effect of Drying on Value – Small Truck

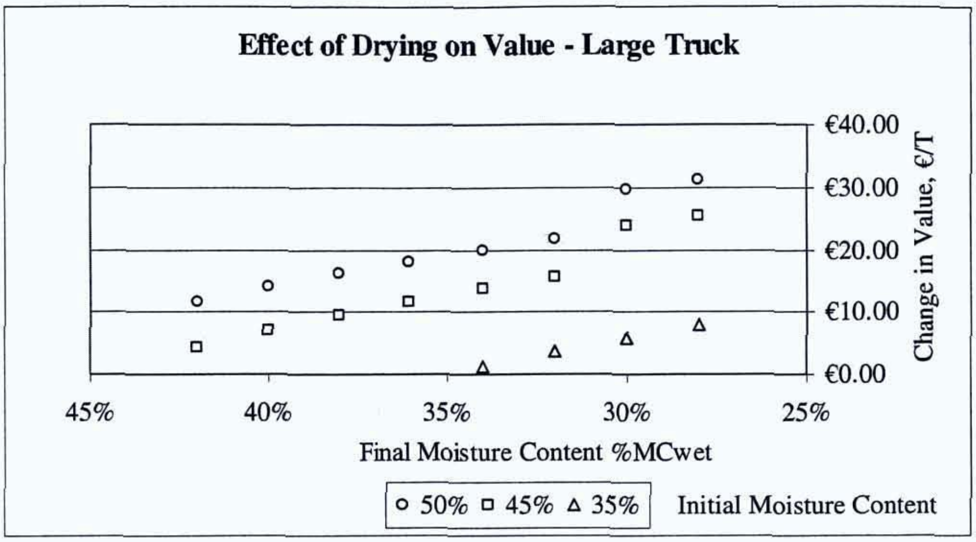


Figure 15: Effect of Drying Value – Large Truck

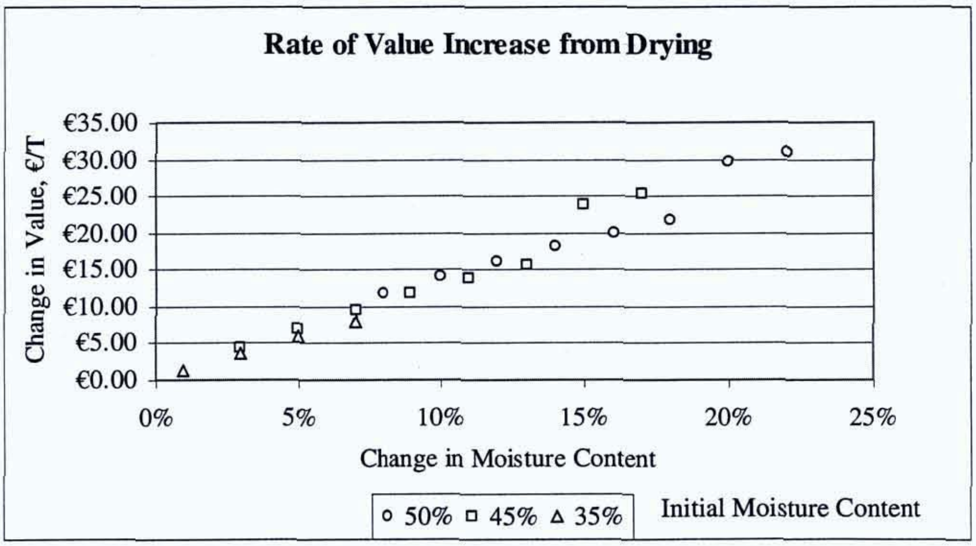


Figure 16: Rate of Value Increase from Drying

Figure 16 above summarises the effect of drying on the value of the supply chain. Starting from an initial moisture content of either 35%, 45% or 50% the change in value per change in moisture content can be seen to be very similar. While there is far more scope for improvement when the initial moisture content is higher the rate of increase of the value per tonne is consistent. In addition, it is only at the larger moisture content differences where the effect on transport occurs; unless the improvements are excessive the effect on transport is not very significant. The results are summarised in Table 27.

Table 27: Average Rate of Value Increase per Change in Moisture Content

Initial %MC	Average €/T per MC%	ST.DEV
35%	€1.19	€0.05
45%	€1.32	€0.09
50%	€1.32	€0.09

For every change in moisture content, there is a value increase of approximately €1.32 per tonne.

4.3 Energy Model

4.3.1 System Size

The system size, Q_S, is the peak boiler size for the building. It should include fabric losses; infiltration and ventilation losses and the thermal preheat loads. It should not include any additional safety margins or other services. The unit of measurement is kilowatts (kW).

4.3.2 Design Temperatures

The design temperatures are both the internal, T_{ID}, and external temperatures, T_{OD}, used in sizing the peak boiler load. The internal design temperature is commonly set to between 18°C to 21°C for office spaces. The external deign temperature can be calculated from local weather data history, but it is generally assumed to be between minus 5 °C to 0 °C for peak days in Ireland. The design temperature difference, δT, is taken to be (21 – (-3)) = 24°C for the majority of the calculations, but it is editable.

4.3.3 Thermal Mass

The thermal mass of the building is inputted as a dimensionless thermal weight figure, W_T, between 1 and 8. Ranging from very lightweight construction to very heavyweight construction.

4.3.4 Hybrid Ratio

One of the key variables for this model is the hybrid ratio between gas/oil and wood chip, %WC. It determines what size wood chip boiler is being installed. At 100% the wood chip boiler is meeting the complete system load. At 50% the wood chip boiler is sized to 50% of the system size, and so on. Having a wood chip boiler sized at 50% of the peak load does not however mean the wood chip will meet 50% of the energy requirement, and it is this relationship that will be looked at in detail later on.

4.3.5 Fuel Selection

The Energy Model has the ability to compare either gas or oil to wood chip from a drop down menu on the input screen.

4.3.6 Heat Losses & Gains

The heat losses, Q_L, and heat gains, Q_G, should be taken from a completed heat transfer calculation. They are inputted as W/m^2 and are subsequently used to size the estimated area of the building. Generally the heat losses for an office will range from 50 W/m^2 to 70 W/m^2 and the heat gains from 80 W/m^2 to 120 W/m^2. During normal office conditions it is common for the heat gains to exceed the heat losses. This results in a net cooling requirement during peak hours, which will have a diminishing effect on the energy load of the boiler. Ultimately, it is the net loss or gain that the model requires for the calculation. The amount the gains exceed the losses is irrelevant as even if it only exceeds it by 1 W/m^2 the heating system will be turned off.

4.3.7 Building Fabric

The makeup of the building is important for calculating energy use. In a thermal calculation, the individual U-values for the walls, floor, roof and windows are added together along with the ventilation conductance loss from infiltration and ventilation. In this model it is possible to reverse calculate the average heating coefficient, C_h, dividing the boiler size, without the adjustment for preheat, by the design temperature difference. The formulae $Q_F=U.A.dT$ (fabric heat loss) and $Q_V=C_v.dT$ (ventilation loss) are combined to give:

$$C_h = (Q_F + Q_V)/dT \tag{4.1}$$

This does not include the energy for pre-heating the building because of the difference in operating hours between standard operation and preheat times.

4.3.8 Operating Hours

The model uses standard operating hours, H_O, for an Irish office, 09:00 to 18:00. It is assumed that the building is preheated to operating temperature prior to the 09:00 and that there is hot water available at 09:00. The heat required for preheating and hot water is determined by other factors described later. It is also assumed that the building operates on a 5-day week. The model assumes a two hour preheat time, H_P, and a two-hour cool down time, H_C.

4.3.9 External Temperatures

The model's energy profile is highly dependent on the average outdoor temperature, T_O. For the thesis the temperature data from 1979 up to 2005 was gathered. In Figure 17 the mean temperatures from 1984 to 1998 and 1999 to 2004 are shown as separate plots. It can be seen that the later temperatures are both slightly higher and slightly lower in summer and winter respectively. Noting this, only the more recent years were used in the model so that the energy profile is accurate for current conditions.

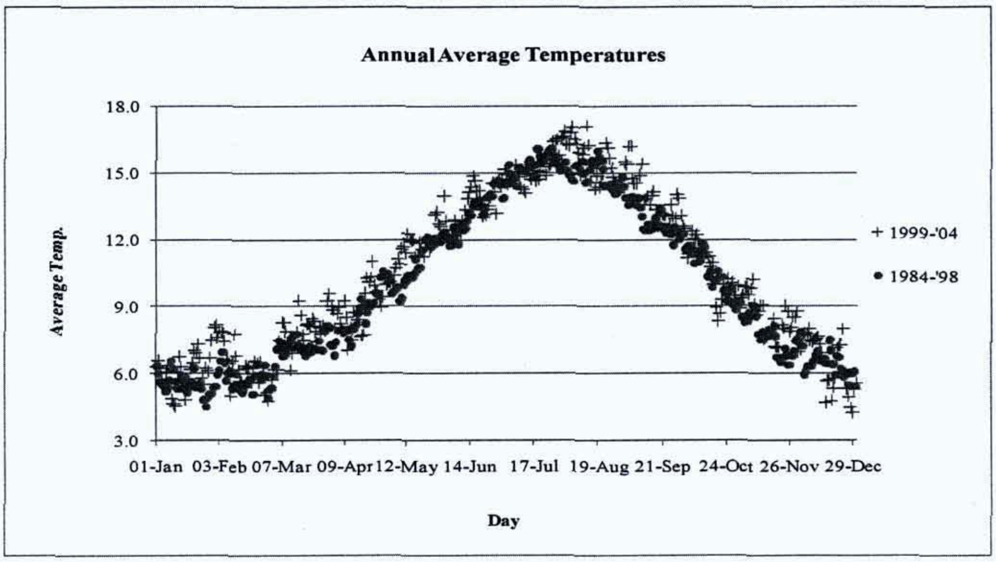


Figure 17: Annual Average Temperatures

4.3.10 Base Temperatures

The base temperature, T_B, is an average internal temperature. It is important that the units of this figure are identical to the average external temperature so that the units can be added together, the unit is the average temperature over 24hrs (°C). Calculating the average internal temperature requires the operating hours, preheat hours, unoccupied hours and an estimate of the cool down hours. Assuming a 2 hour preheat and cool down either side of a 10 hour day the unoccupied hours, H_U, becomes 24-H_P-H_C-H_O=10 hours. Next, the temperature for each period is required. The average temperature of preheating and cool down periods is the mean of the external temperature and the internal temperature. This gives the equation for average internal temperature as:

$$T_{AVG}= (T_I.H_O+T_O.H_U+T_P.H_P+T_C.H_C)/24 \quad (4.2)$$

Table 28: Average Internal Temperature

Average 24h Temperature	**Tavg**	**°C**
Internal Design Temperature	Ti	°C
External Design Temperature	To	°C
Preheat Temperture	Tp	°C
Cooldown Temperature	Tc	°C
Occupied Hours	Ho	hrs
Unoccupied hours	Hu	hrs
Preheat Hours	Hp	hrs
Cooldown Hours	Hc	hrs

The average temperature will change every day as the external temperature changes. The inclusion of the temperature rise from the internal gains turns the internal temperature into the base temperature used in the energy calculations. The gains only occur during operating hours, where F_P being the preheat factor as stated in equation 4.13.

$$T_G = (Q_P.Q_G)/(Q_L.C_H.F_P) \quad (4.3)$$

$$T_B = T_{AVG}-T_G.H_O/24 \quad (4.4)$$

Table 29: Base Temperature

Base Temperature	T_B	**°C**
Average 24h Temperature	Tavg	°C
Rise due to Internal Gains	T_G	°C

4.3.11 Degree Days

Degree-day is a method of calculating energy loads using the difference in average external temperatures and internal base temperatures. The formulas used for heating degree-days are:

$$T_{max} \leq T_b, T_b - (T_{max} + T_{min})/2 \qquad (4.5)$$

$$T_{min} < T_b \text{ and } (T_{max} - T_{min} < (T_b - T_{min}), (T_{max} + T_{min})/2 - (T_{max} - T_b)/4 \qquad (4.6)$$

$$T_{max} > T_b \text{ and } (T_{max} - T_b) > (T_b - T_{min}), (T_b - T_{min})/4 \qquad (4.7)$$

$$T_{min} \geq T_b, 0 \qquad (4.8)$$

The formulas used for cooling degree-days are similar, but the use of cooling degree-days is considerably less accurate due to the smaller effect the external temperature has on the heat gains. The correct calculation of the internal gains and latent loads are more important for the sizing of cooling equipment. The cooling degree-days are used in this model to show how an AHU system might affect the boiler heating load.

$$T_{min} \geq T_b, (T_{max} + T_{min})/2 - T_b \qquad (4.9)$$

$$T_{max} > T_b \text{ and } (T_{max} - T_b) > (T_b - T_{min}), (T_{max} - T_b)/2 - (T_b - T_{min})/4 \qquad (4.10)$$

$$T_{min} < T_b \text{ and } (T_{max} - T_{min} < (T_b - T_{min}), (T_{max} - T_b)/4 \qquad (4.11)$$

$$T_{max} \leq T_b, 0 \qquad (4.12)$$

4.3.12 Thermal Mass – Pre-Heating

The heating load due to fabric losses is only a part of the total heating load. The heating of the thermal mass of the building can account for 20-60% of the peak boiler load. Using the input data it is possible to calculate the thermal capacitance coefficient (C_Y), of the building, the daily energy required for preheating (Q_P), and the percentage of the peak load that is dedicated to preheating.

$$F_P = (24.W_T)/((W_T.(H_O+H_P)+24-(H_O+H_P)) \tag{4.13}$$

$$C_Y = (W_T.(C_U+C_V)-C_V) \tag{4.14}$$

$$Q_P = (C_H+C_Y).(T_I - T_{MIN}) \tag{4.15}$$

The model requires a user input for the thermal weight of the building (W_T), and preheat time (H_P). This figure is converted into a factor (F_P) which is multiplied by the fabric load and the ventilation load so that $(Q_F+Q_V).F_P = Q_S$. For complete accuracy the thermal weight should be calculated based on the building's construction materials.

4.3.13 Hot Water Services

The final part of the load is the hot water load. Using the input data the daily demand of hot water on the boiler is:

$$Q_{HWS} = (Q_S.HWS.64)/(Q_L.F_P.\rho_O) \tag{4.16}$$

The input data required for the hot water services is the occupancy density, ρ_O, of the space and the hot water requirement per person, HWS. For an office these figures are $\rho_O = 10\ m^2$/person and HWS = 14 L/Person/Day. [CIBSE Guide A]

4.3.14 Hour Profile

To estimate the energy load met by the wood chip boiler an hour-by-hour schedule of the system operation is needed. The model has an input section for configuring the hourly operation at peak conditions. The loads are scaled down as the temperatures outside increases. The settings used in the model are as follows.

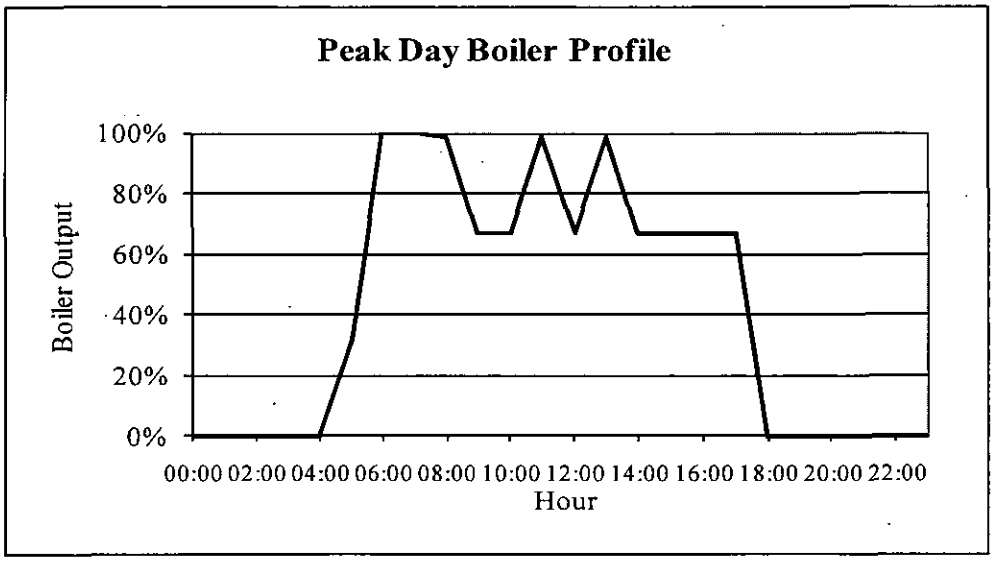


Figure 18: Peak Day Boiler Profile

The energy calculated per day is normally a lot smaller than the peak boiler conditions. For example, the energy profile for a summer day with large internal gains is shown in Figure 19.

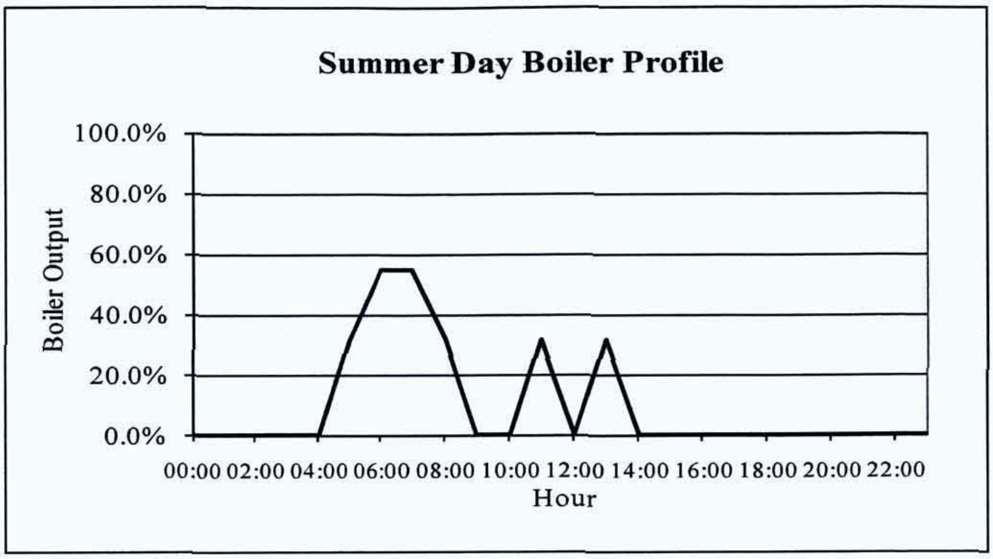


Figure 19: Summer Day Boiler Profile

The only load that remains the same is the HWS load, because it is weather independent. The heating load is gone due to internal gains and the preheat load is reduced due to the milder temperature. The model creates a similar profile for every day of the year based on the input data and the peak hour profile.

4.3.15 Re-heat Coils / HVAC

For one of the scenarios the model assumes that reheat coils have been installed in the HVAC system. While not common in Ireland's mild climate the installation of re-heat coils does have a significant effect on the heating load and warrants inspection. For calculating the reheat load the cooling degree-days (CDD) are calculated and a portion of them are turned into heating degree-days. In the model for every 1 CDD required by the cooling system the boiler needs to output 0.33 HDD. Another use of this technique would be to model absorption chilling which uses heat energy to power the chillers.

4.3.16 Total Equivalent Degree Days

After calculating all of the individual loads over hours, days and years, it is useful to convert them all into one single HDD figure.

$$HDD_{EQUIV} = HDD+(Q_P+Q_{HWS})/(C_H.24) \qquad (4.17)$$

4.3.17 Base Model - Energy Profile

The model is a close representative of a standard Irish office. The operation data for the base model is listed below:

Table 30: Operation Data

Operation Data

Internal Design Temperature	21	°C
External Design Temperature	-3	°C
Occupancy Hours	10	hrs/Day
Week Profile	5	Days/Week
Pre-Heat Hours	2	hrs
Thermal Weight Factor	3	

Both the heat gains and losses are taken from the BSRIA guide for building services [BSRIA, 2003].

Table 31: System Data

System Data

Heat Gains	120	W/m^2
Heat Loss	70	W/m^2
System Size	50-400	kW
HVAC	All Fresh	

This information along with recorded past external temperatures are used to calculate firstly the base temperature and subsequently the HDDs for the model. Using the internal design temperature, the external weather data and incorporating the pre-heat and cool down hours the average daily temperature is calculated. Figure 20 represents the HDD base temperature before the effect of the internal gains is taken into account.

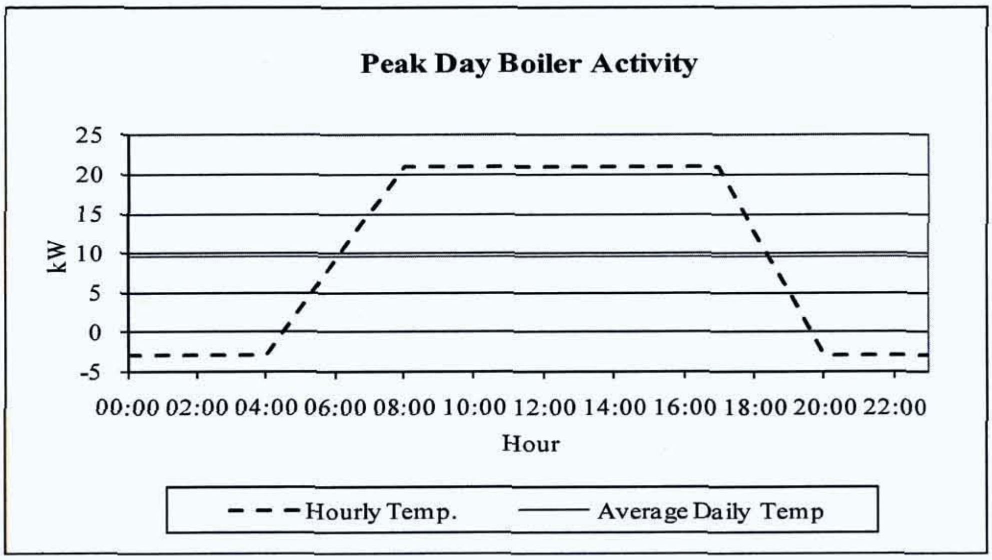


Figure 20: Average Daily Temperature

The unit for heating degree-days, external temperature and internal temperature is °C/Day, or °C/24 hours. Therefore, to keep the units the same the internal gains are averaged over a 24h day. 120 W/m^2 correlates roughly to a temperature gain of 56.1 °C over the operating hours. This averages out to 23.4 °C over 24 hours. Therefore, the correct base temperature (average daily temperature minus the temperature rise from internal gains) is 13.4 °C – 23.4 °C = -10 °C. This means that the internal gains are high enough to keep the heating off even at an average external temperature of –10 °C. There is a loss of accuracy by analysing daily compared to hourly or by the minute, and it is important to remember that an average external temperature of –10 °C could represent a day with a large temperature deviation and not just -10°C for 24 hours. These large internal gains have a significant effect on the energy profile and it will affect the sizing of the wood chip boiler. Figure 21 shows the total HDDs including and excluding the internal gains.

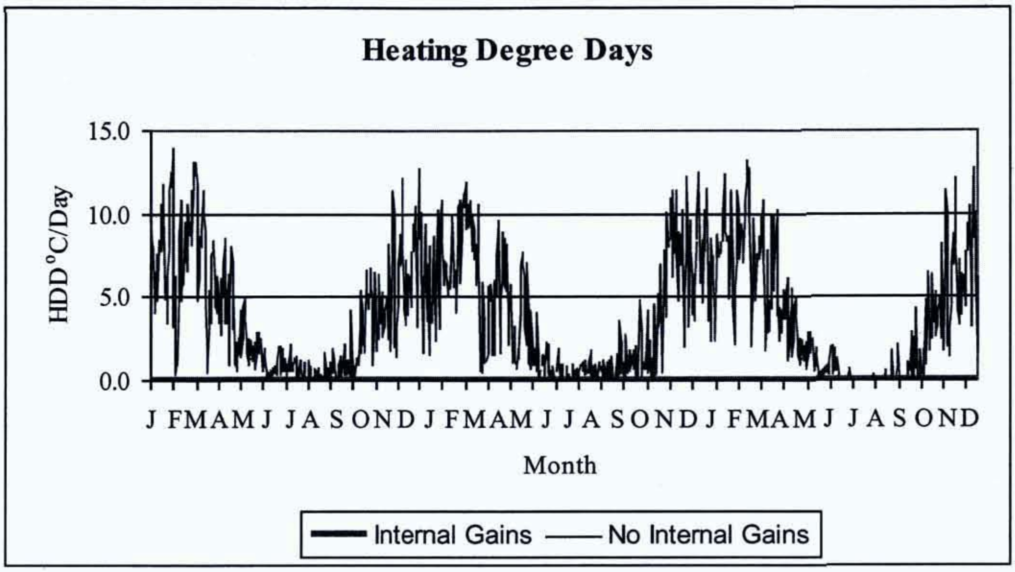
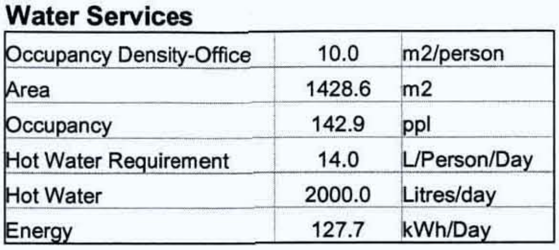


Figure 21: Heating Degree Days (HDD)

When there is a larger heat gain than heat loss in a space heating is not required, and this would be very common in any modern office or retail unit. An important assumption made above was the HVAC uses full fresh air, which is typical in Ireland's mild climate. The effect of a fully air conditioned building will be examined later on when for every kW cooling there will be a certain amount of re-heating required. With no heat losses, due to the large internal gains, the boiler load now becomes the sum of the pre-heat load of the thermal mass, and the water services load. These are calculated using the CIBSE guidelines and the previously stated operation and system data.

Table 32: Water Services Data

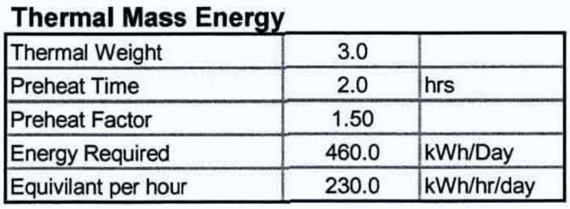


Water Services

Occupancy Density-Office	10.0	m2/person
Area	1428.6	m2
Occupancy	142.9	ppl
Hot Water Requirement	14.0	L/Person/Day
Hot Water	2000.0	Litres/day
Energy	127.7	kWh/Day

The inputs are the occupancy density of the office, which when multiplied by the total area gives a figure for the amount of people in the building. This figure is multiplied by the hot water requirement of 14 litres of hot water per person per day. Supplying hot water at 65°C results in a daily hot water demand of 127.7 kWh/Day. This figure is based on the area of the building, which is in turn based on the boiler size. Therefore, the calculation of the hot water services for the model is proportional to the boiler size.

Table 33: Thermal Mass Energy Data



Thermal Mass Energy

Thermal Weight	3.0	
Preheat Time	2.0	hrs
Preheat Factor	1.50	
Energy Required	460.0	kWh/Day
Equivilant per hour	230.0	kWh/hr/day

The thermal mass of the building provides one of the main heating base loads. The energy is calculated by bringing the structure from the minimum temperature per day to the operating temperature. During preheat the boiler is at its maximum design output. It is providing heat to counteract the loss of heat through the fabric and infiltration in addition to the extra heat required to heat the structure. Even in Ireland the minimum temperature in summer can be as low as 7°C.

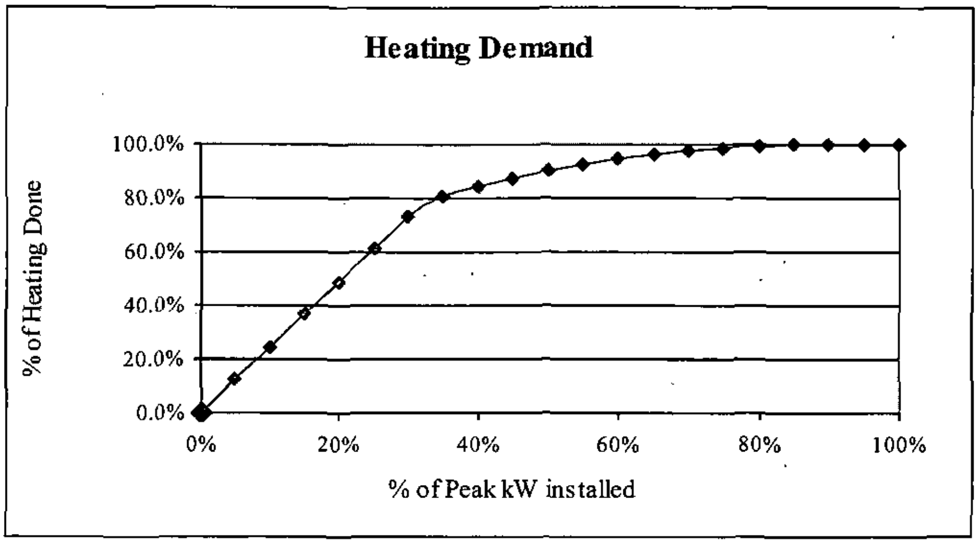


Figure 22: Heating Demand Curve

The difference between the peak day design and a typical summer day is very clear (Tables 18 & 19), and throughout the year, all the days will vary between these two extremes. Figure 22 shows how much annual heating a boiler sized at a percentage of the peak load can meet. The first section of the curve, from 0% peak kW installed to roughly 35%, shows the effect of increasing the size when there is a reliable load all year round, such as the water services and the pre heat loads, as seen on Figure 19 where the boiler can meet the water load at 30% peak power. After 35%, the boiler has to deal with the remaining pre-heat load, as seen on Figure 19 where above 35% peak load there is only the top of the pre-heat load left, so the curve begins to straighten out. The energy load is completely satisfied at 100% boiler output, but the last 20% of the boiler power covers 98% of the energy demand. Theoretically, it is only one or two days in the year that will need the full power of the boiler.

4.3.18 Energy Model – Graphical Representation

Figure 23 is a graphical representation of the Energy Model flow process. The main inputs into the model are the design temperatures, the system size, building heat losses and gains, and the occupancy hours of the building. From these manual inputs the Energy Model is capable of producing a detailed energy load profile for the Financial Model to calculate the system feasibility. The energy profile of the building is the source of demand for wood chip. The system costs will ultimately determine the level of demand, but the energy profile is the basis for those calculations.

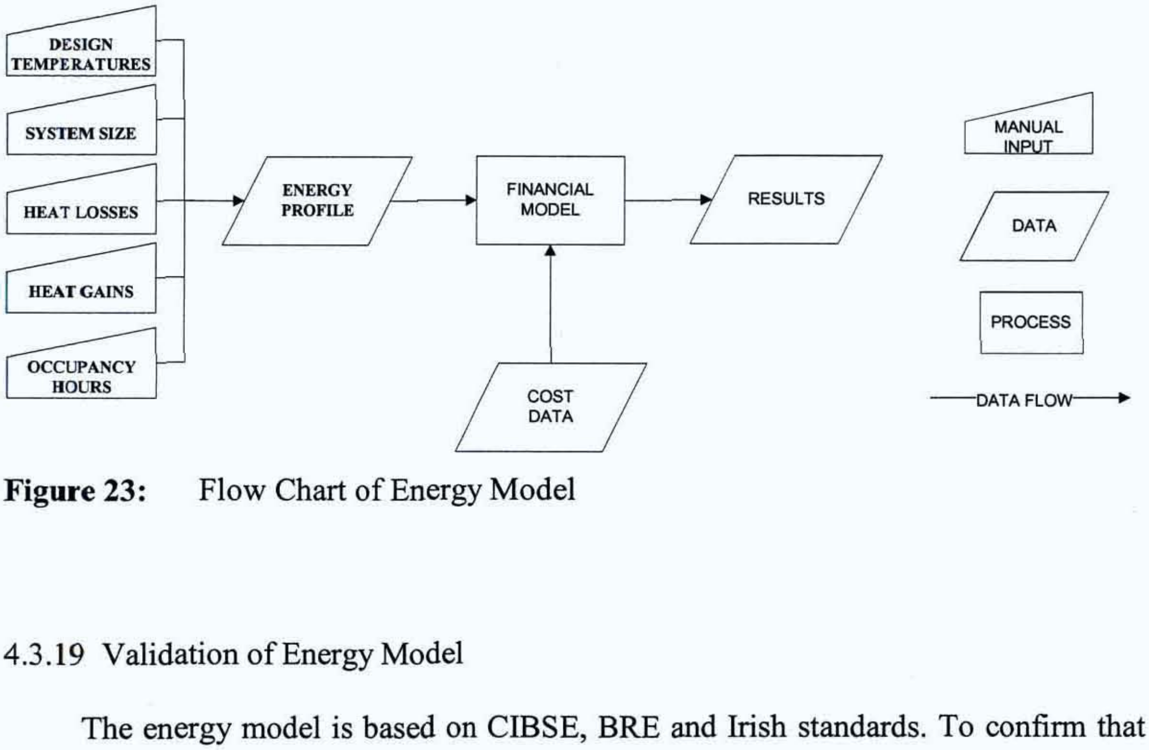


Figure 23: Flow Chart of Energy Model

4.3.19 Validation of Energy Model

The energy model is based on CIBSE, BRE and Irish standards. To confirm that the model operates correctly the outputs are compared to other published results of a similar operated building. Energy Consumption Guide 19: Energy Use in Offices and CIBSE TM 46 Energy Benchmarks lists energy benchmarks for various office configurations. The listed energy consumption for fossil fuels is 79.0 kWh/m^2 (good practice) to 151kWh/m^2 (typical), based on a 15.5°C base temperature and 2021 Heating Degree Days. These figures are common reference points for the collection of Heating Degree Data in the Technical Manuals. From the energy model the final energy consumption per m^2 floor area is 64.4 kWh/m^2 and 761.1 Heating Degree Days. There is no single base temperature used in the energy model as it is calculated on a per day basis. Adjusting the benchmark figures pro-rata to account for the difference in Heating Degree Days results in a new benchmark range of 51.9 kWh/m^2 (good practice) to 99 kWh/m^2 (typical). From these adjusted figures the energy rating of the Energy Model outputs can be considered good but not best practice.

4.4 Financial Model

4.4.1 Capital Costs

The capital costs of boilers in the range of 50kW to 400kW were surveyed. This is a level above the domestic range but below industrial; covering a large proportion of commercial applications. The cost of wood chip, gas and oil boilers follow a common trend, which is they all become cheaper per kW the larger the unit is. However, the initial cost for a wood chip boiler is significantly greater than that of a gas or oil boiler; as much as 15 times.

4.4.1.1 Wood Chip

The capital cost for installing a wood chip boiler is very high. It is the main drawback when assessing the feasibility of installing a wood chip system because it is so much larger than that of gas or oil. The promotion of biofuel in Ireland includes grants for wood chip systems and this helps make wood chip systems more viable. Figure 24 shows the modelled version of the survey data. By graphing the survey data, a fitted curve allows the interpolation of the costs of different boiler sizes. This is the basis for the capital cost for the rest of the model. It can be seen that as the installation gets larger the cost per kW of installed power decreases.

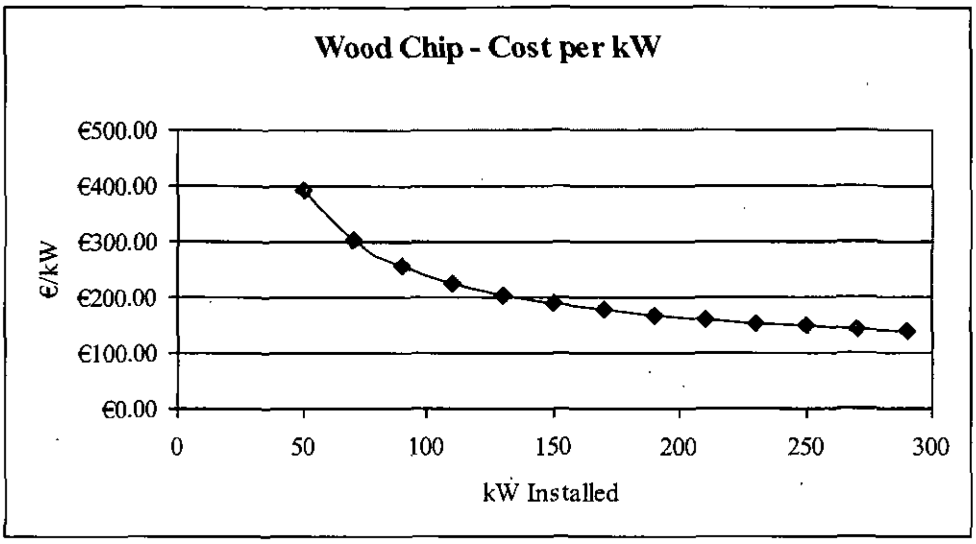


Figure 24: Capital Costs of Wood Chip Boilers

4.4.1.2 Gas

The cost of installing gas is relatively low compared to wood chip; the boilers are cheap and there is little maintenance. There is no need for fuel storage and the boiler runs with an efficiency of 98%. Figure 25 shows the capital cost of the boiler per installed power, kW.

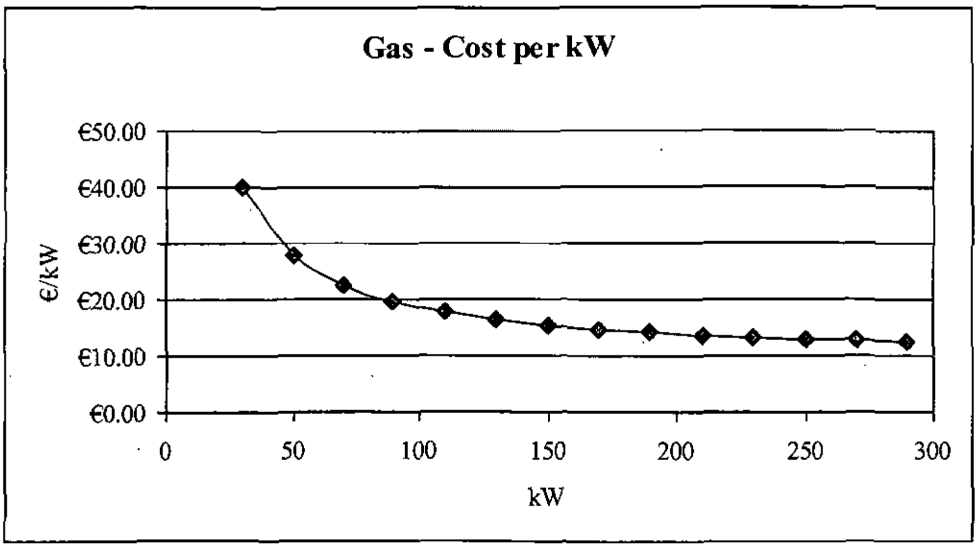


Figure 25: Capital Costs of Gas Boilers

4.4.1.3 Oil

The technology involved in the production of oil-fired boilers has taken considerable steps forward in recent years with newer condensing oil boilers even overtaking condensing gas boilers in terms of seasonal efficiency. However, the more common conventional oil boilers still run at a lower efficiency than both the gas and wood chip boilers. The costs for the standard oil boiler are similar to condensing gas boilers. The use of condensing oil boilers in medium size systems is not common practice, and because of the lack of demand for units of that size, the boilers are not readily available. For these reasons, the model uses the standard non-condensing oil boilers.

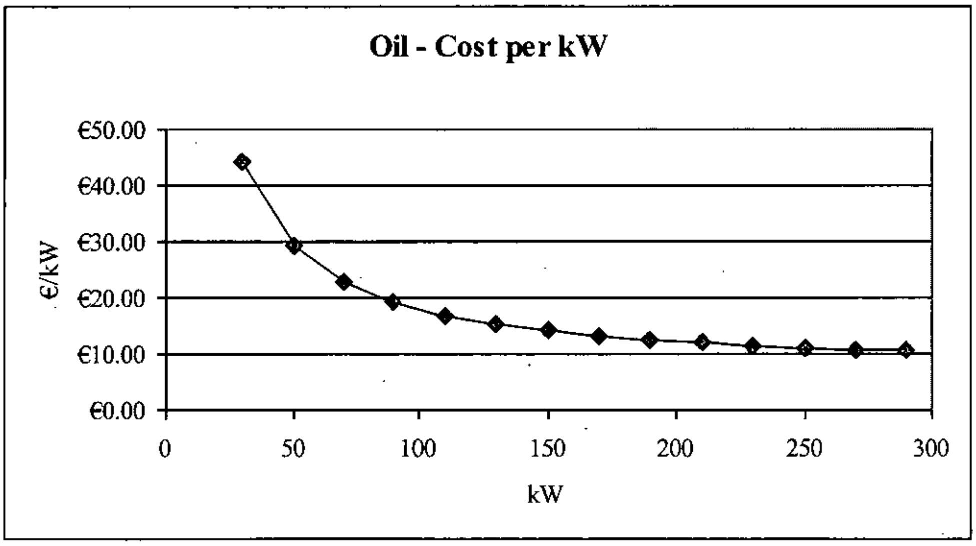


Figure 26: Capital Costs of Oil Boilers

4.4.2 Annual Costs

The annual costs are all converted to a €/kWh unit, and are calculated using the fuel prices, service charges, system efficiencies, annual maintenance charges, electrical consumption (parasitic power) costs, carbon tax and the energy demand of the buildings. To generate these costs the following input data is assumed. This will also provide a base model for the sensitivity and scenario calculations.

Table 34: Input Data for Base Model

	Wood Chip	Gas	Oil	Unit
Fuel Cost	3.54	4.51	8.5	c/kWh
Boiler %	90.0%	98.0%	85.0%	
Annual Fees	0	€50.00 +	0	€ /yr
Maintenance	€500	5%	5%	per year
Electrical Power	0%	0%	0%	of kWth
Electrical Cost	14.5	14.5	14.5	c/kWh
Carbon Emission	0 (0.30)	0.19	0.32	$kgCO_2/kWh$
Elec. Carbon	0.6	0.6	0.6	$kgCO_2/kWh$
Carbon Tax	0	0	0	$€/TCO_2$

The base model sets the carbon tax rate to zero, as it is not currently in operation. The parasitic electrical power for wood chip is calculated from a fitted curve of electrical power to thermal power, as seen in Figure 27. The parasitic electrical load for oil and gas boilers is negligible as there is no ancillary equipment required with their installations. The graph gives the percentage of electrical power (Qe) to boiler thermal power output (Qth). In the range of boilers examined the parasitic load is between 0.5% to 0.8% of the rated thermal power of the boiler.

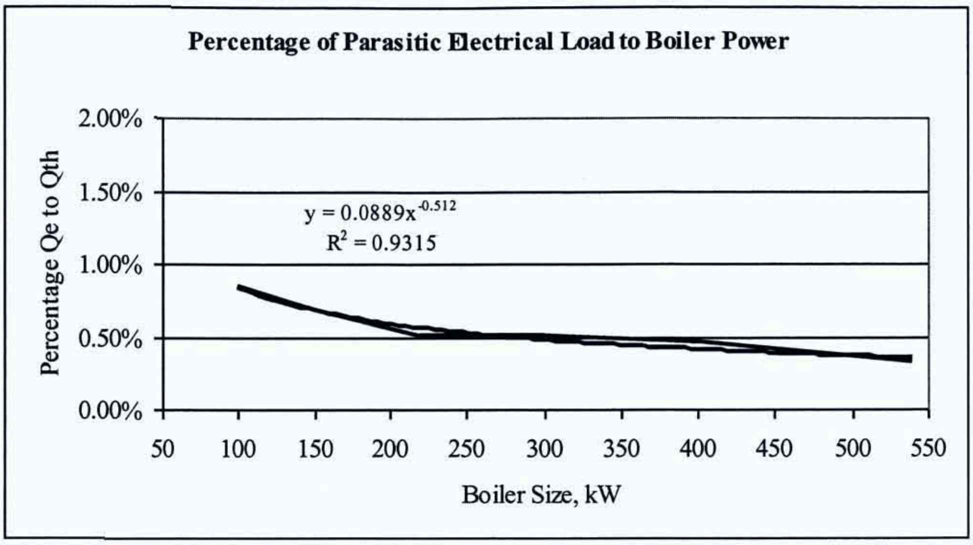


Figure 27: Percentage of Parasitic Electrical Load to Boiler Power

4.4.2.1 Wood Chip

The cost of wood chip at writing was 115 €/Tonne, which at the specified delivered moisture content of 35% equates to 0.0354 €/kWh. Taking into account the additional costs assumed in Table 24, the final cost of using wood chip is calculated to be 0.0445 €/kWh. The fact that wood chip is considered carbon neutral will have a very positive effect on the cost of the fuel when carbon tax is introduced in the scenarios. The electrical energy spent to run the wood chip boiler is calculated based on data taken from a boiler manufacturer. From analysing the size and workings of wood chip systems it assumed that the parasitic loss of the wood chip boilers is higher than that of either gas or oil so the impact of this figure will have a negative effect on the results for wood chip financial viability. Parasitic loss refers to the electrical power required to run a wood chip boiler, components such as the feed augers and the grate require constant power to operate.

4.4.2.2 Gas

Two gas tariffs have to be examined for the model. The small business tariff and the medium business tariff:

Small Business User Tariff: This tariff is applicable to business customers who consume less than 73,000 kWh and have a Supply Point Capacity of less than 3,750 kWh. This tariff consists of two elements:

- A Gas Commodity Charge for the gas consumed of 4.509 c/kWh
- A Standing Charge of €50.00 per annum

Medium Business User Tariff: This tariff is applicable to all business customers who consume more than 73,000 kWh and have a Supply Point Capacity of less than 3,750 kWh. This tariff consists of three elements:

- A Gas Commodity Charge for the gas consumed of 2.877 cent per kWh
- A Standing Charge of €50.00 per annum
- A Capacity Charge of €1.8629 per peak day kWh to contribute towards transmission and distribution costs.

The prices quoted from Bord Gais are exclusive of tax, which is 13.5%. The final average cost per kWh for the small business user tariff is 8.3 c/kWh. The medium business tariff will depend largely on the peak kWh day due to the capacity charge. The inclusion of carbon tax will have a negative effect on the final price of gas.

4.4.2.3 Oil

Oil is sold in litres, so taking a conversion of 10.30 kWh/L of oil and the price of 1000L to be €874.47 gives a base price for oil of 8.49c/kWh. Including the boiler efficiency, this becomes 10.00 c/kWh. The effect of introducing carbon tax will have the greatest effect on oil because it has the highest carbon output of the fuels used in the research (see Table 25). Combined with the poor boiler efficiency the cost of oil is the most expensive fuel per kWh.

4.4.3 Financial Model

The financial model shows the economic performance of a wood chip system compared to both a gas system and an oil system. It calculates the simple payback, discounted payback and the total net present value over 20 years in each instance. As the model is a comparison between two systems it is important to note that all the results represent the net difference, or savings, over 20 years. The model can analyse system ranges from a 50kW system size to 400kW and from 0% wood chip to 100% wood chip with the remainder of the installation made up by either gas or oil. The ratio of installed wood chip capacity to fossil fuel capacity will have large effects on the capital costs of the system as it significantly changes both the capital costs and the running. Figure 28 shows a flow diagram of the complete Financial Model, including the Energy Model detailed previously.

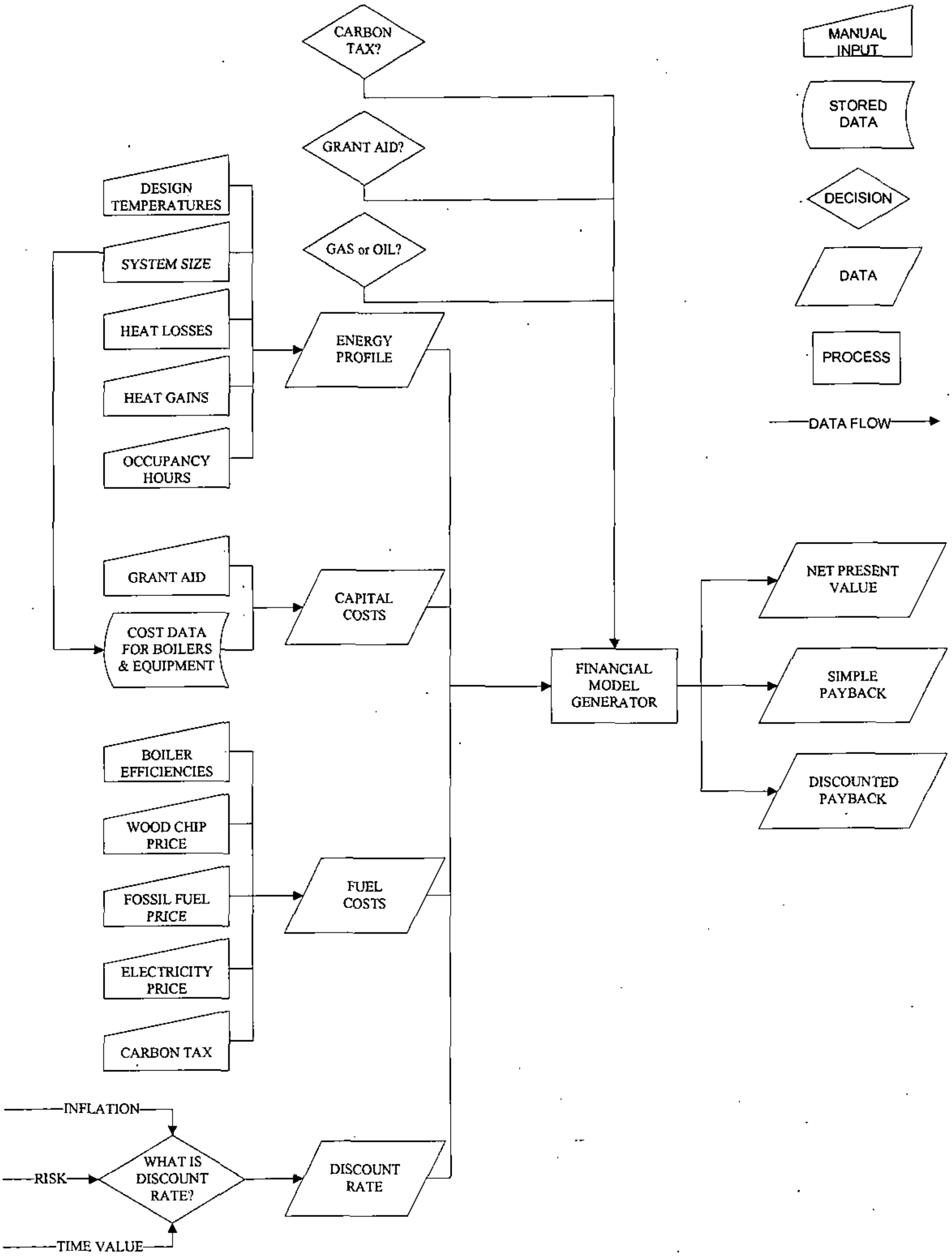


Figure 28: Flow Diagram of Complete Financial and Energy Model

This flow diagram is a visual representation of the Energy & Financial Model created for this thesis (pictured in Appendix A). The process box labelled 'Financial Model Generator' is the step in the calculations where the inputs (left side) are put into the formulas listed in the methodology and Energy Model section to give the output results (right side). Figure 28 and Appendix A provide a clear view of how the Energy & Financial Model operates.

The validation of the Financial Model is problematic, as the model runs over a 20 year cycle and involves technology that has not been in operation long enough to have anything to compare itself against. The best form of validating the model at the current time is to validate its components and to assume that if the inputs and calculations are correct that the outputs are reliable. The inputs are the energy profile, capital costs, running costs and discount rate. The Energy Model is validated using benchmark energy figures, as discussed previously in Energy Model section. The capital costs and running costs are taken from national suppliers and are deemed to be accurate enough to be used in the short term (new costs will have to be obtained if the calculations are to be redone in the future). The discount rate is within the range used in similar investments, GP Guide [BRECSU, 2001], and the formulas used in the model are taken from CIBSE and Engineering Project Appraisal [Rogers, 2001]. This means that all the components of the model are consistent and that the outputs of the model are considered reliable until information collected over several years becomes available for analysis and comparison.

4.4.3.1 Simple Payback

The first set of results from the model is the simple payback figures. The simple payback figures will give an initial estimate of what systems are feasible. They will also provide the first look at the effect of using two boilers in a system installation. Figures 29 and 30 show the simple payback for all of the system variations. The graphs show:

- wood chip vs. gas ranging from 0% wood chip to 100% woodchip compared to a 100% gas system, and
- wood chip vs. oil ranging from 0% wood chip to 100% woodchip compared to a 100% oil system.

These are comparative results showing hybrid systems compared to a fossil fuel system. The hybrid systems range from 100% wood chip powered to 100% fossil fuel powered, at which point the result would be zero, i.e. 100% oil versus 100% oil.

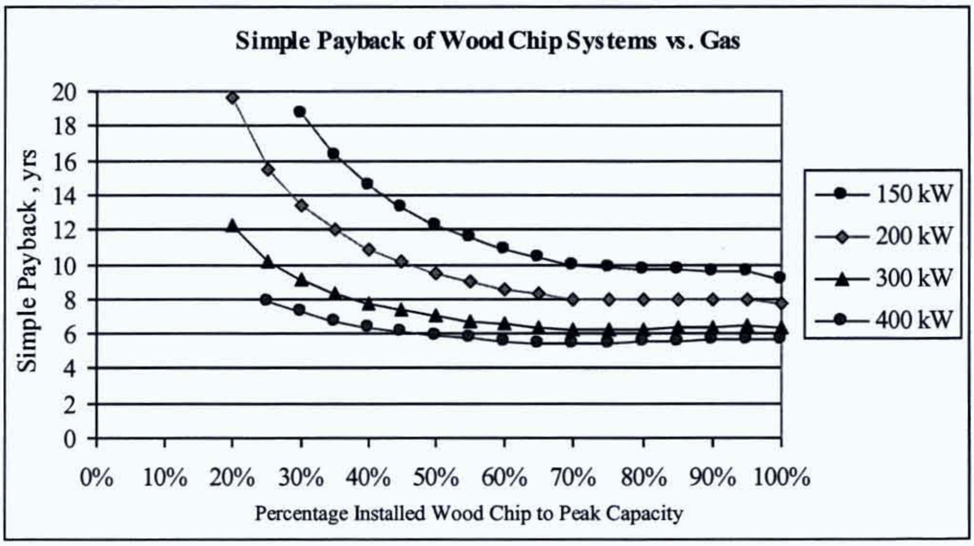


Figure 29: Simple Payback – Wood Chip Systems vs. Gas

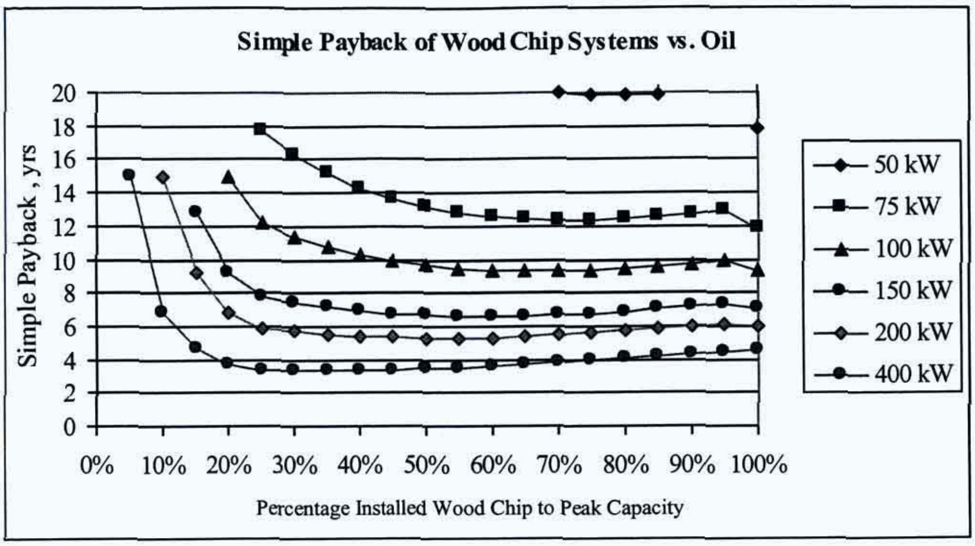


Figure 30: Simple Payback – Wood Chip vs. Oil

From the simple payback graphs, it can be seen that even before the cash flows are discounted the minimum feasible gas system (Figure 29) is 150kW because no other sizes make the 20 year payback cut-off. The oil systems (Figure 30) are feasible all the way to 50kW because of the high price of oil, and therefore higher savings compared to wood chip/ gas. The optimum ratio for these systems is the point where the payback is at a minimum. This represents the system arrangement with the quickest payback. The optimum ratio of wood chip to fossil fuel is changes with system sizes. Taking the optimum point for each system and plotting them shows how the system size affects the results.

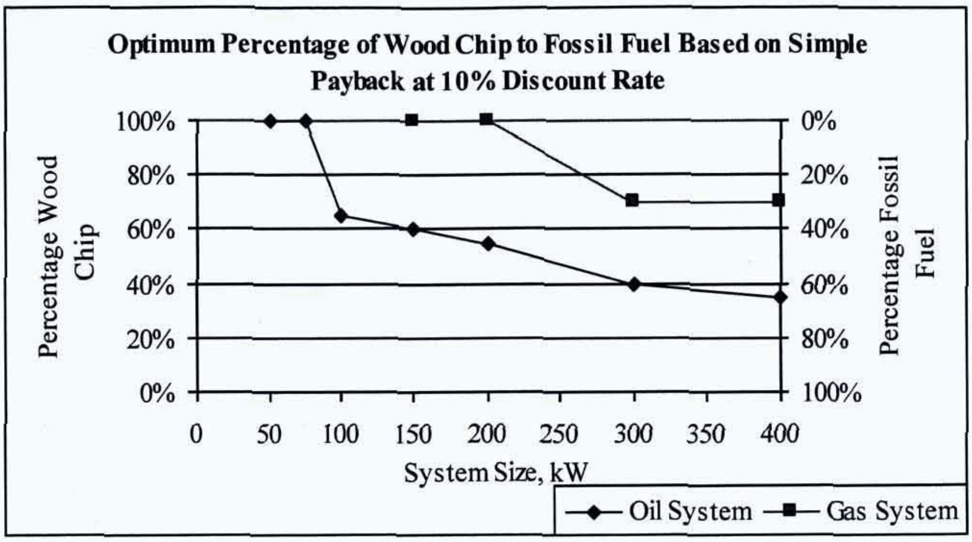


Figure 31: Optimum Percentage of Wood Chip to Fossil Fuel

As the system sizes increase, the capital costs decrease per installed kW and savings increase. For larger systems, the optimum return on the initial investment is lower than that of smaller systems. Having a smaller wood chip boiler reduces the capital costs; however, the smaller systems are so expensive per kW installed that they need every possible saving to be able to breakeven, which means 100% of the load needs to be met by the wood chip boiler so that the maximum amount of fossil fuel is being offset. Replacing oil with wood chip results in higher savings than replacing gas, and therefore, oil has a quicker payback and a lower optimum ratio. Lower ratios of wood chip mean smaller wood chip boilers and lower capital costs, but also lower annual savings, so the optimum ratio is balanced between the capital costs and the available savings.

4.4.3.2 Discounted Model

The discounted model takes individual future annual savings for a wood chip system and reduces it by a compound discount rate. This will have negative effects on both the NPV and the system's payback. The effect of discounting will make systems that were breaking-even under simple payback conditions unfeasible and the very significant savings of the larger systems smaller.

The relationship between simple payback and discounted payback is very dependent on the discount rate used. Figure 32 shows that for every discount rate there is a maximum allowable simple payback. If the simple payback is not below this figure then the discounted payback will never occur. This is because the system is taking so long to break-even that the savings are discounted close to zero and are not capable of breaking even. This assumes identical cash flows every year at the same discount rate, which is what occurs in the Financial Model.

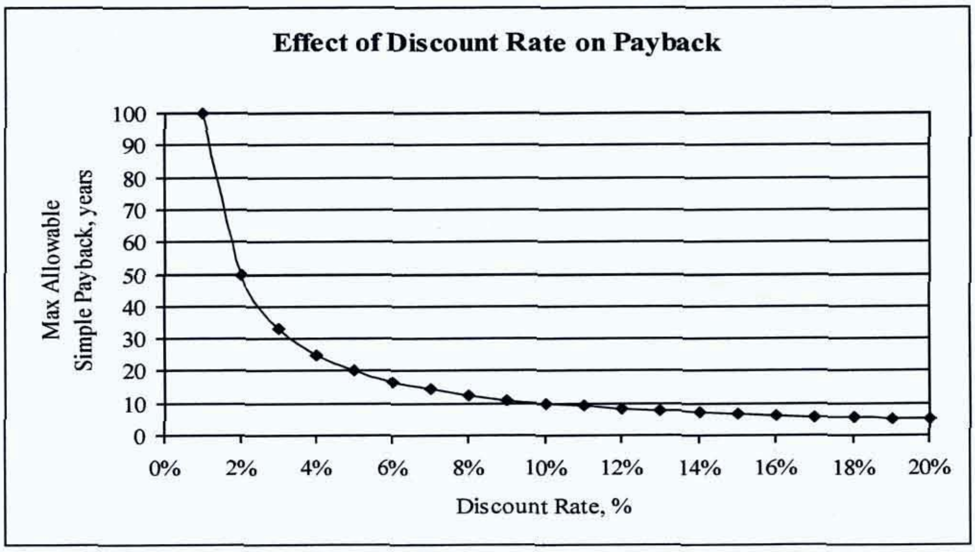


Figure 32: Relationship between Discount Rate and Simple Payback

The discount rate used in the financial model is 10% and based on Figure 28 any system that has a simple payback of greater than 10 years is financially unfeasible. The 10% discount rate will reduce the savings by so much in 10 years that the savings will be too small to achieve payback, regardless of the duration of the project. Further to this the lifetime of the boilers in the model are set to 20 years, because at this point they become either inefficient or have to be replaced. In Figure 32 the time limit on the project is infinite, and it shows the upper limit of the various discount rates. Setting the maximum project length to 20 years and the discount rate to 10% the maximum simple payback is 8.51 years, as seen below in Figure 33. Again, this assumes identical annual cash flows at a constant discount rate.

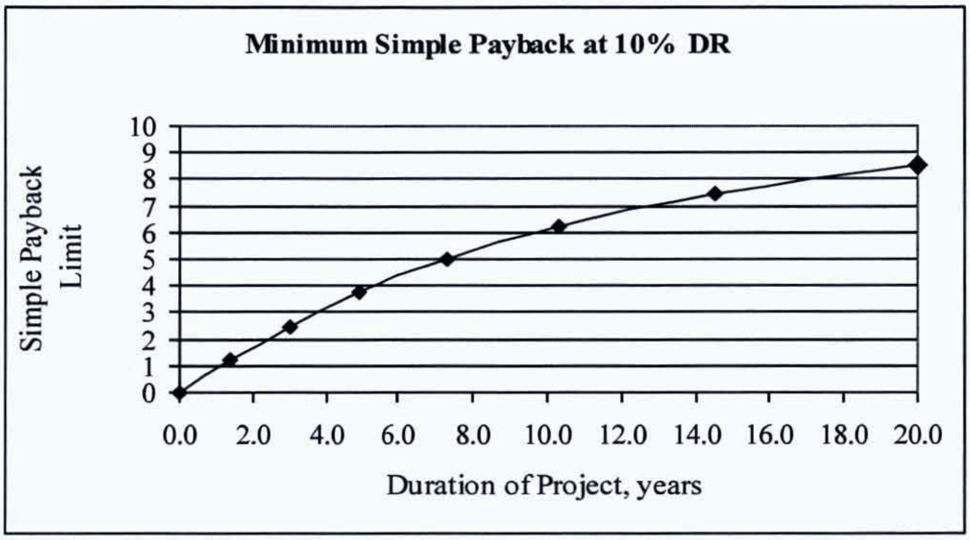


Figure 33: Maximum Simple Payback at 10% Discount Rate

Using a discount rate of 10%, the discounted payback graphs are generated. These graphs will show the minimum feasible systems, and confirm that the optimum point for wood chip to fossil fuel ratio remains the same as calculated with the simple payback.

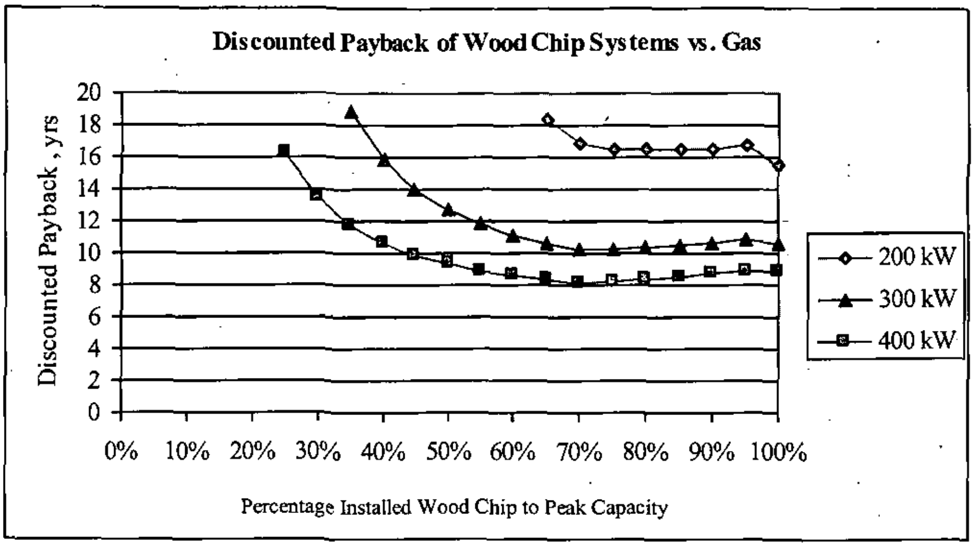


Figure 34: Discounted Payback of Wood Chip vs. Gas

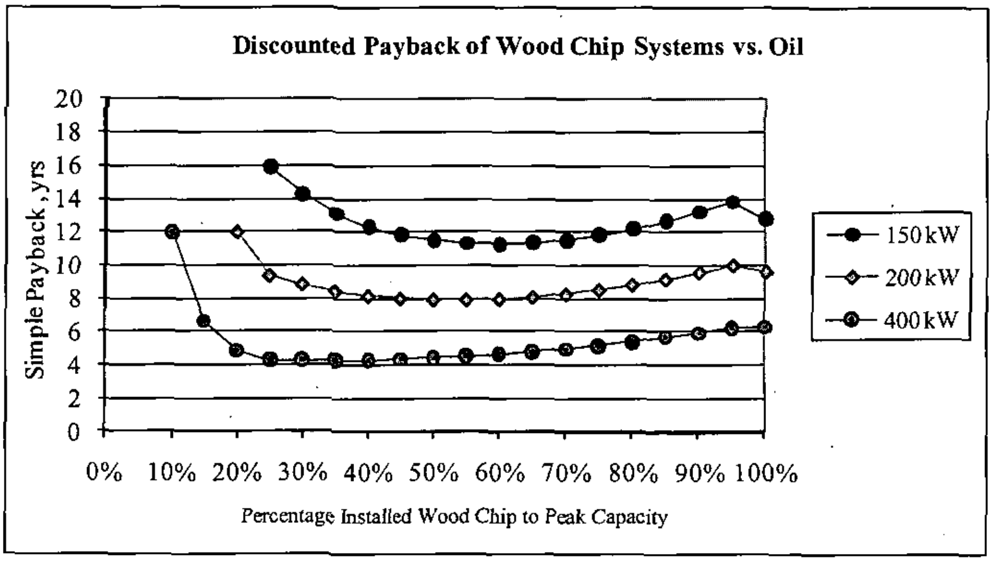


Figure 35: Discounted Payback of Wood Chip vs. Oil

The effect of discounting the cash flow is noted by its effect on the payback of the systems, as all of the paybacks have increased. The minimum feasible system sizes are now 150kW for oil systems and 200kW for gas systems.

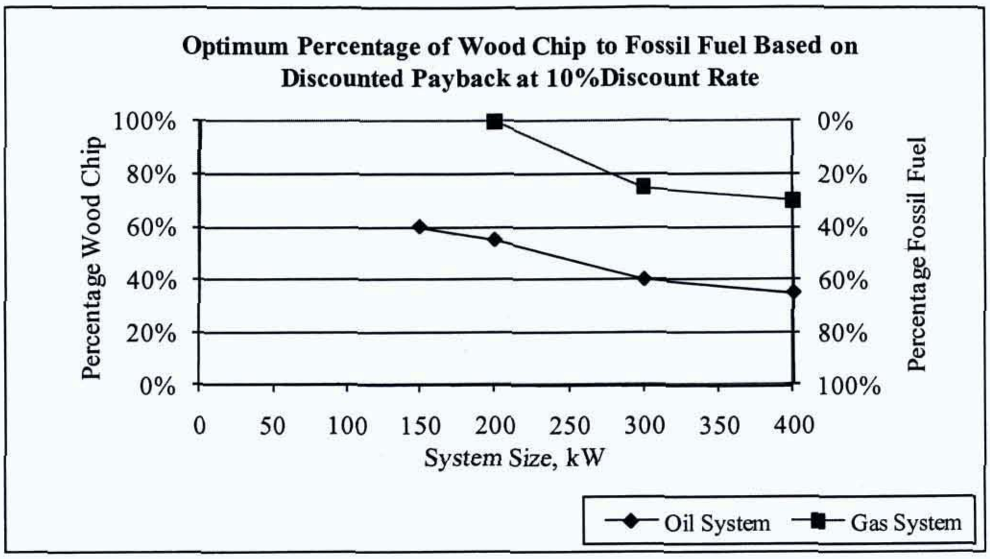


Figure 36: Optimum Percentage of Wood Chip to Fossil Fuel

The optimum points are the same as the results of the simple payback but some system sizes have now become unfeasible; the graph is identical except for the omission of these systems. The following graphs show the NPV for both the gas and oil hybrid systems over a range of 0% to 100% wood chip.

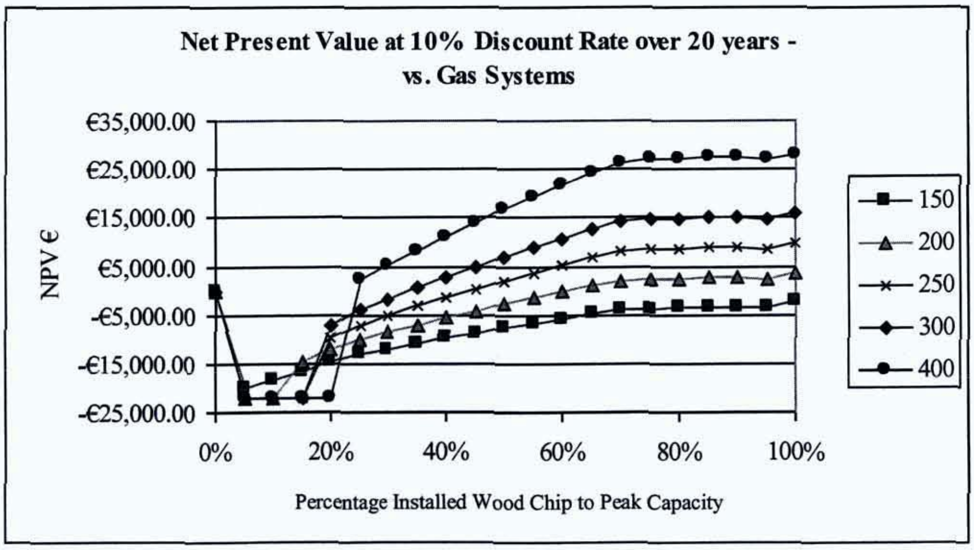


Figure 37: NPV of Wood Chip Systems vs. Gas

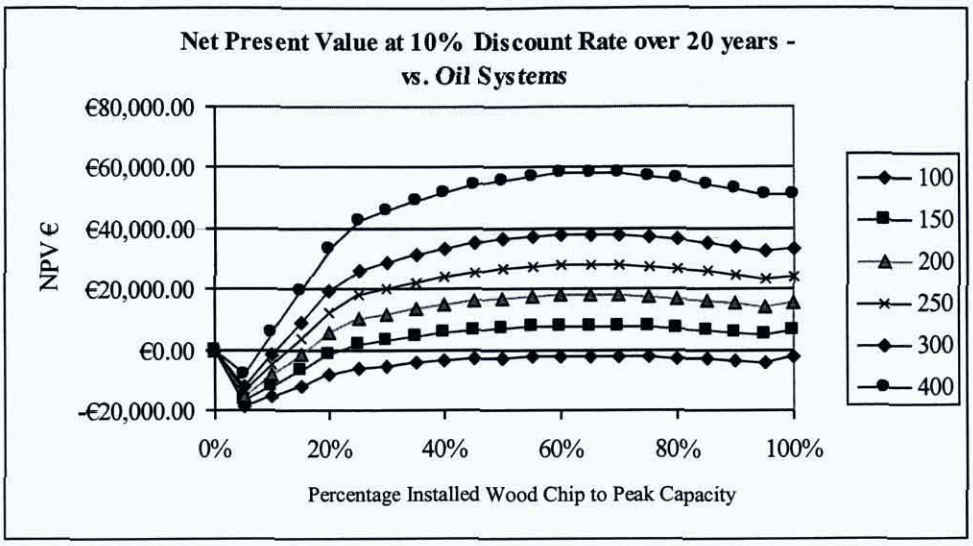


Figure 38: NPV of Wood Chip Systems vs. Oil

A common feature in both these graphs is the jump from 0% to 1% wood chip and, to a lesser extent, from 99% to 100%. This jump represents the effect of purchasing two boilers instead of one on the cash flow. At 0% wood chip, only a gas boiler is purchased saving the cost of a wood chip boiler, and likewise at 100% woodchip there is no need to purchase a gas boiler. The effect of not purchasing a wood chip boiler will be greater than not purchasing a gas boiler and this is seen in the magnitude of the step. In Figure 37 the effect of the different gas tariffs on the model can be seen. A low percentage of wood chip means that the peak gas consumption is higher, which based on the medium business tariff results in a high capacity charge. The optimum ratio for wood chip to fossil fuel based on NPV is different than the one based on payback. The payback based optimum ratio shows the ratio for the quickest payback while the optimum ratio based on the NPV shows the ratio for highest profits over a 20-year period.

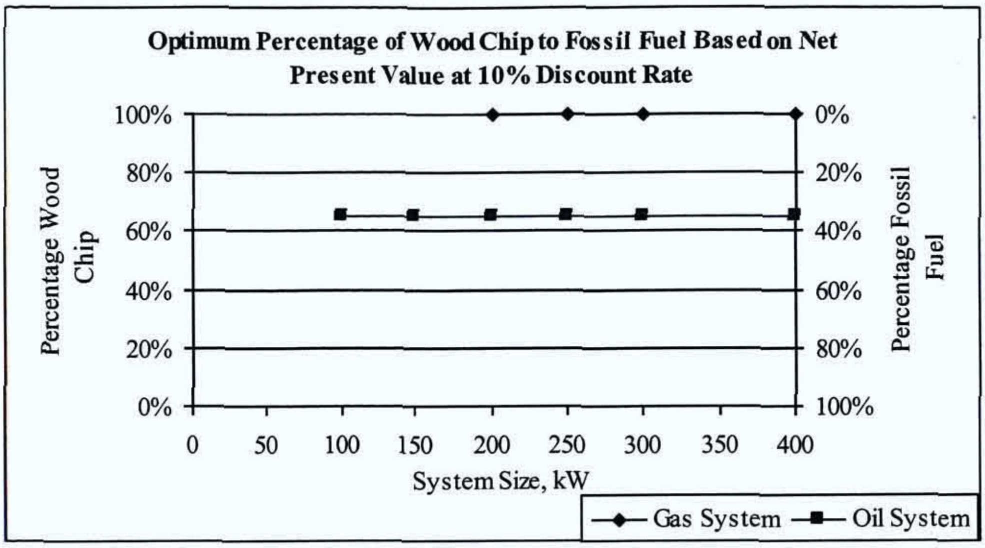


Figure 39: Optimum Percentage of Wood Chip to Fossil Fuel

The ratio for maximum NPV is different from the ratio for the shortest payback, mainly due to the scale of capital costs and annual savings. For a quick payback the emphasis is on lower capital costs, while for maximum profit it is on large annual savings. Here the optimum point for oil is a constant 65% ratio and the gas is 100%. The difference in shape is due to the different ways that the price of gas and oil are paid. The cost of gas is composed of more cost components, such as capacity charge and service charges, while oil is a straightforward cost per litre. This means that the optimum point for oil is more reliant on the amount of heat that the wood chip boiler is producing; compared to gas that will have a certain level of costs independent of the amount of fuel used, such as the capacity charge.

4.4.4 Sensitivity Analysis

The design conditions set in this model are based on 2008 figures and the most current building standards. However, there are many inputs used in the model that are likely to change significantly in the near future and they will have major influences on the financial viability of wood chip systems. This section examines some of the more realistic variations in the inputs to see what effect it has on the model outputs.

For this sensitivity analysis, two viable systems under the original inputs are used. The sensitivity analysis will examine how these systems react when the inputs in the model are changed. As before, the results are comparative; a hybrid system of wood chip and oil is compared to a complete oil system; and a gas / wood chip hybrid system is compared to a complete gas system. The two systems are;

- System 1, a 200kW system with 100% wood chip vs. 100% gas; and
- System 2, a 200kW system with 50% woodchip and 50% oil vs. 100% oil.

These two systems contain the main variations in system type and they are used to illustrate the effects of altering the fuel price, energy load, capital costs and carbon tax on both gas and oil systems, as well as over different ratios of wood chip. The base figures for these reference systems are:

Table 35: Base Model Datum Figures

	System 1 - vs. Gas	System 2 - vs. Oil
NPV 10% DR	€10,506.13	€29,586.71
Discounted Payback	10.8	5.3

4.4.4.1 Change in Energy Profile

In the base model the heat gains were greater than the heat losses. This resulted in there being no heating load for the majority of the year. While this is quite normal for an office with large internal gains it is possible that heat energy is consumed in other ways, such as reheat coils in the air conditioning system. In this scenario the sensitivity of the systems was calculated as the heating load increases to meet the re-heat coil load.

The reheat coil load is a heat load that is independent of the space-heating load. A plot on an air-conditioning graph (psychrometric chart) shows that for every kW of cooling there is a certain amount of reheat required in order to provide the air at the correct temperature. Under these conditions, heating will be required in the summer months, even with full internal loads. This means that even with large cooling loads a certain amount of heat is still required during the occupancy hours. To monitor this effect a percentage of the negative heating degree-days, or cooling degree-days, is added onto the energy load. The ratio of heat energy per cooling energy used in the calculation is 30%, so that is for every 1 kW of cooling there is 0.3 kW of heat needed. From the data, and as seen in Figures 40 and 41, for every percentage increase there is a corresponding increase in the NPV. The rates of change of NPV per percentage increase in the energy load were found to be:

- 1.3% increase in the System 1 NPV; and
- 2.2% increase in the System 2 NPV.

4.4.4.2 Change in capital costs

The capital cost of wood chip systems is the largest barrier to most investors. However, history shows that as time passes and the technology becomes more established the prices will fall [Harmon, 2000]. In the meantime, the large capital costs are offset by grants to make them more affordable. Current grant aid is as high as 30% of the capital costs. The effect of decreasing capital costs has similar effect on both systems. However, system 1 benefits more than System 2. Since the latter still requires an oil boiler, which has not been reduced in price because it is only the wood chip boiler that is affected by the grant. Reducing the capital costs affects the more expensive system, and this can be seen in the ratio of change between the capital costs and the NPV. The rate of increase in NPV per percentage change in wood chip boiler capital costs is:

- 3.4% increase in the System 1 NPV; and
- 1% increase in the System 2 NPV.

4.4.4.3 Change in fuel costs

The variation in fuel prices is the most difficult input to predict. At the time of writing it is expected that there will be a 20% increase in the cost of natural gas. This will considerably improve the viability of wood chip in Ireland. In addition, it is highly probably that a carbon tax will be introduced, and that will further increase the cost of fossil fuel. This sensitivity will look at the effect of increasing gas and oil prices by introducing different amounts of carbon tax, as well as increasing the quality of the wood chip by reducing the moisture content, which will reduce its cost per kWh. The carbon tax has a larger effect on the System 2 due to the ratio of 50%/50% wood chip to oil. The effect of increasing the cost of fossils fuels has a direct effect on both of the systems. The price of the fossil fuels is increased by introducing carbon tax into the models. Carbon tax has a larger effect on the cost of oil, but per percentage, System 1 is affected more because System 2 uses mainly woodchip and is therefore partially shielded from the price change of oil. The rate of increase in NPV per percentage change in fuel prices is:

- 8.6% change in the NPV and for the System 1; and
- 3.4% change in the NPV for the System 2.

The results of improving the moisture content from 35% to 28% had a significant effect on the feasibility. System 1 (gas replaced by woodchip) is vulnerable to a change in the price of wood chip because, unlike System 2 which is a dual boiler system, it does not have a secondary fuel to shield it from the change in wood chip costs. When the wood chip costs are decreasing this is an advantage, however, if the wood chip costs increase it will have a negative effect. The 7% decrease in moisture content had decreased wood chip costs by 1.8%, and results in a:

- 39% change in System 1 NPV; and
- 12.5% change in System 2 NPV.

4.4.4.4 Sensitivity results

Figure 40 and Figure 41 show the results of the sensitivity analysis for both the 100% wood chip system (System 1) and the 50% wood chip system (System 2). The angle and length of the lines show how sensitive NPV is to a certain factor. The steeper the plotline the more sensitive the system is to a change in that input. Each of the systems is examined individually below; however, an overall comparison of the two graphs does show significant differences. System 1 is more sensitive to each of the factors except the energy load. This is because System 1 is a 100% wood chip system, making it more vulnerable to changes in the price of both the fossil fuel and the wood chip. System 2 is protected slightly from varying inputs because it is a hybrid system of both oil and wood chip and therefore not as susceptible to a change in any one factor. For System 1, fuel price was shown to have the greatest overall impact on the NPV. This was followed by wood chip quality (wood chip prices), capital costs, and finally the available energy load was shown to have the least impact. However, when the ratio of wood chip to fossil fuel changes we see a shift in this order. For the 50% wood chip and 50% oil hybrid system (System 2) the order was found to be fuel prices, energy profile, wood chip quality (wood chip prices) and capital costs.

The scale at which these factors impact the systems is also very different as there is much greater scope for change in the capital costs and the energy load than the fuel costs. Capital costs can be reduced by 40% with grant aid while fuel prices may only increase by 5% annually. Therefore, while on a percentage basis the fuel price is the most significant factor, it might not have the largest effect on the final results if the capital costs or energy load can be reduced by 40%.

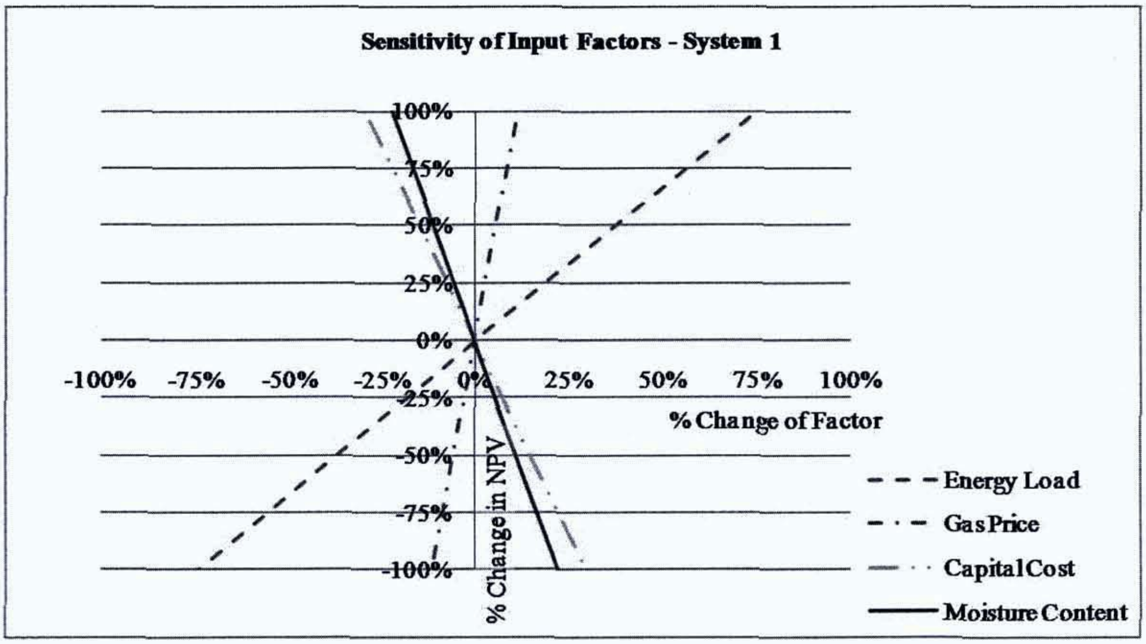


Figure 40: Sensitivity of Input Factors – System 1

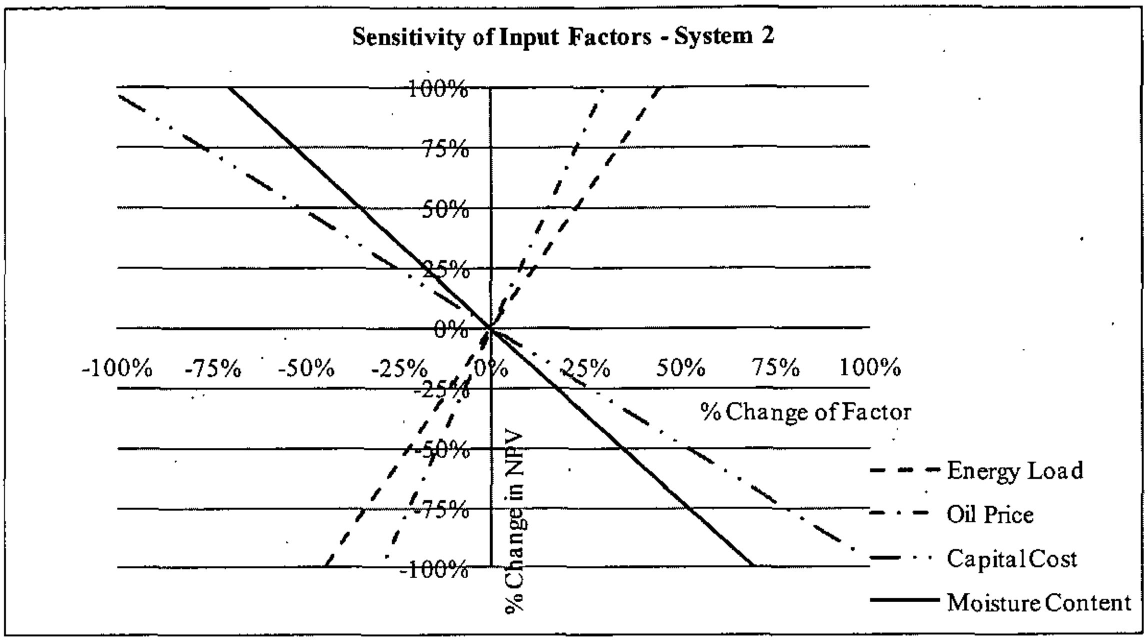


Figure 41: Sensitivity of Input Factors – System 2

4.4.5 Scenario

The purpose of running a full scenario is to test the potential financial viability of wood chip systems under predicted future changes to policy, fuels and design. The assumptions listed below draw on conditions that are very likely to occur in the near future. The same results are examined to determine how wood chip might perform in 2-5 years time – a period that should allow the assumed changes to come into effect. The following are the assumptions for the scenario:

- Inclusion of 30% capital cost reduction for wood chip boilers; this capital reduction could be the result of grant aid or the industry's experience curve pushing down the capital costs of the boilers. It will have a positive effect on the financial feasibility of wood chip systems
- Introduction of carbon tax at 20 €/T CO_2; this is an incentive tax that should be in operation within the next couple of years. It will increase the price of fossil

fuel and will be beneficial to the financial feasibility of wood chip systems as they are carbon neutral due to the absorption of carbon dioxide during their growth.

- Increase in fuel prices. In September '08 there was a 20% increase in the price of natural gas, as well as this the model increases oil prices by 10% and wood chip costs by 5% to represent the constant increase in fossil fuel prices and a basic annual increase in costs for wood chip.
- Improved wood chip quality. As the market matures, the techniques used in production will improve. This should result in higher quality fuels and lower moisture content for wood chip, somewhere near 30%. Methods would include better storage and more accurate monitoring.

Under these assumptions, the NPV and payback graphs are reproduced to analyse the potential future financial viability of wood chip systems.

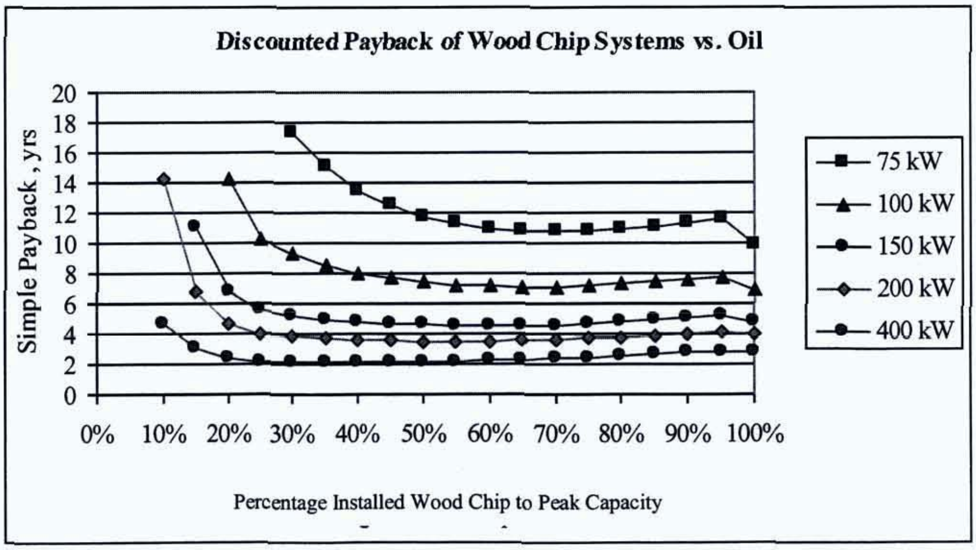


Figure 42: Discounted Payback of Wood Chip vs. Oil – Scenario Results

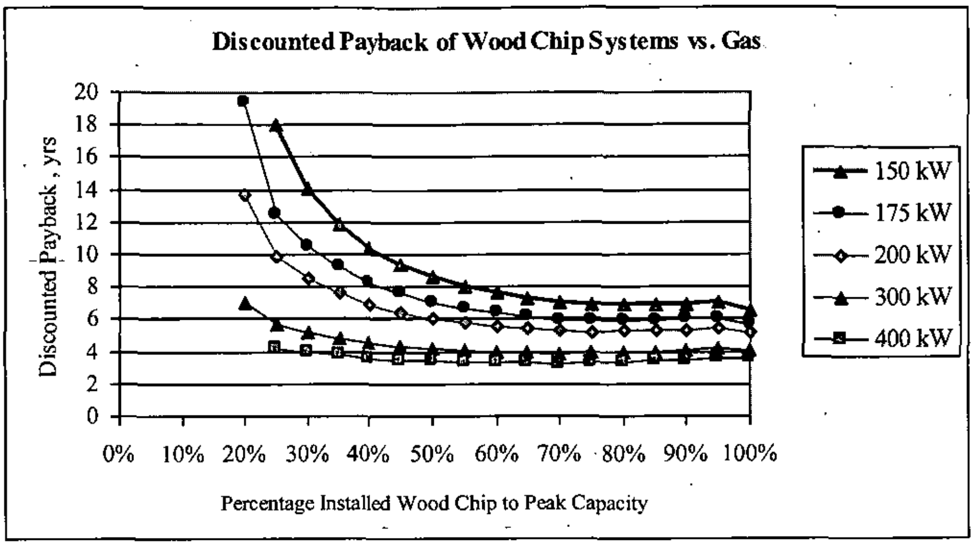


Figure 43: Discounted Payback of Wood Chip vs. Gas- Scenario Results

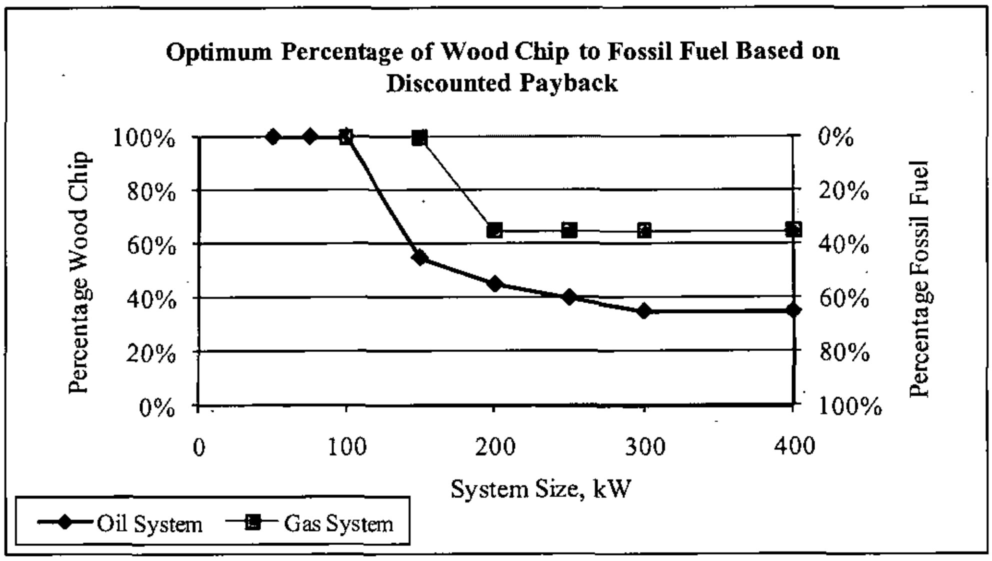


Figure 44: Optimum Percentage of Wood Chip vs. Fossil Fuel – Scenario Results

From the discounted payback results, it is seen that the minimum feasible size has changed. Oil is now feasible at 75kW (from 150kW) and gas is feasible down to 150kW (from 200kW). The optimum ratio of wood chip to fossil fuel has changed slightly, with some sizes previously running at a smaller optimum ratio. Both fuels, however, continue to advance towards the same optimum points, oil to 35% and gas to 70%.

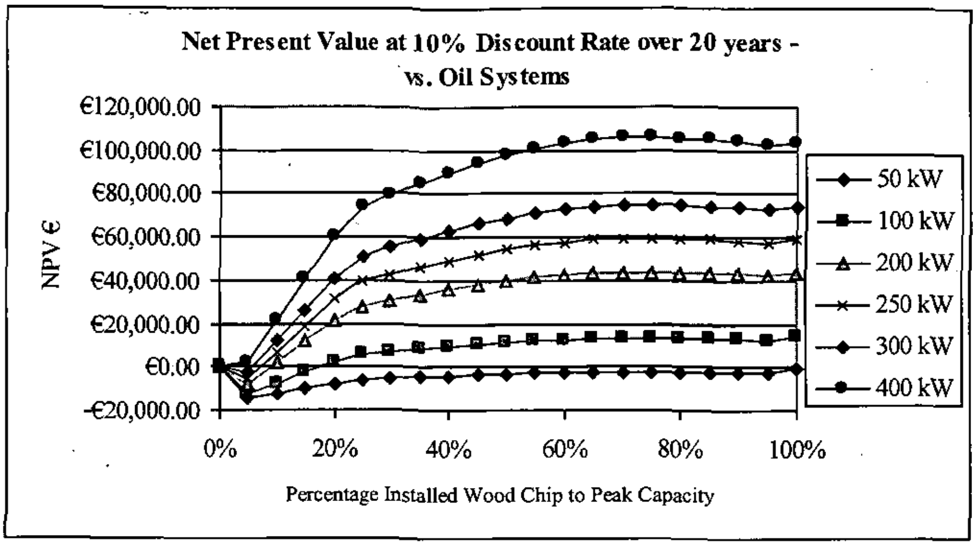


Figure 45: NPV of Wood Chip vs. Oil – Scenario Results

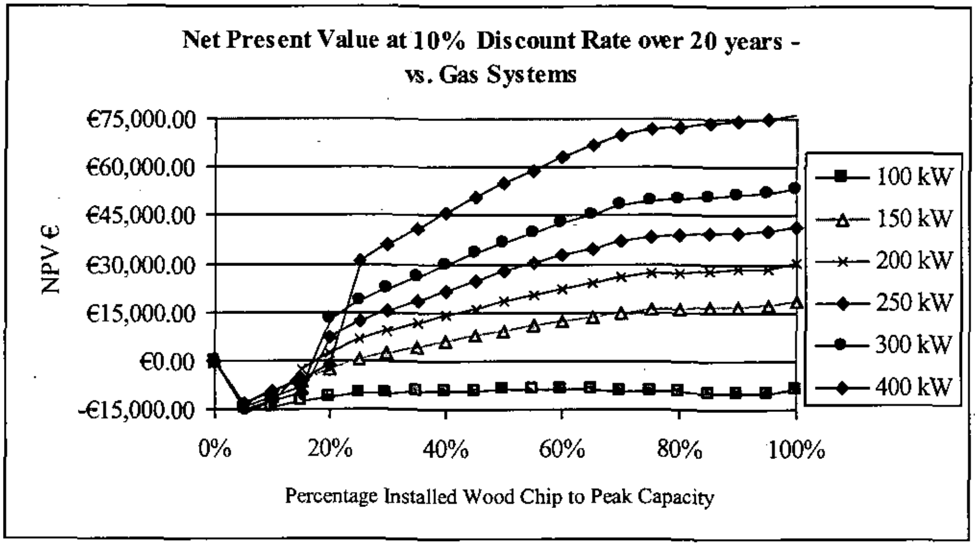


Figure 46: NPV of Wood Chip vs. Gas – Scenario Results

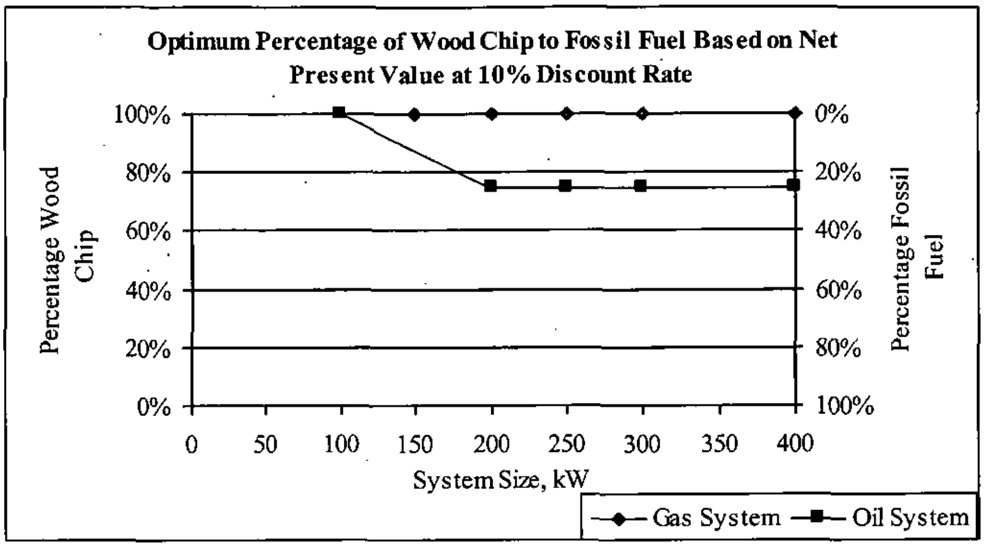


Figure 47: Optimum Percentage of Wood Chip to Fossil Fuel – Scenario Results

The NPV graphs show a large increase in the savings over 20 years. The shape of the curves for oil and gas has remained very similar. The optimum ratios for wood chip vs. fossil fuel have also shown a small change in feasibility with gas now clearly feasible to 150 kW (from 200 kW).

5.0 CHAPTER 5: SUMMARY and CONCLUSIONS

5.1 Introduction

There are three central issues regarding Ireland's current energy consumption; dependency on fuel imports, greenhouse gas emissions, and the high unit cost of energy in the country. These three factors are closely connected and if Ireland can switch away from gas and oil, it would be effectively solving all of the problems listed above. Wood chip is cheaper per kWh, cleaner and more sustainable than gas, oil or coal.

The main objective of this thesis was to investigate wood chip heating for commercial buildings in Ireland. This was accomplished by dividing the Irish wood chip industry into two main parts; the first part was the supply side and the second part was the demand side. Further to this, the supply side was broken down into source (Irish forests) and supply (supply chains); the demand side was broken into source (building energy load) and demand (financial feasibility), as seen in Figure 48 below.

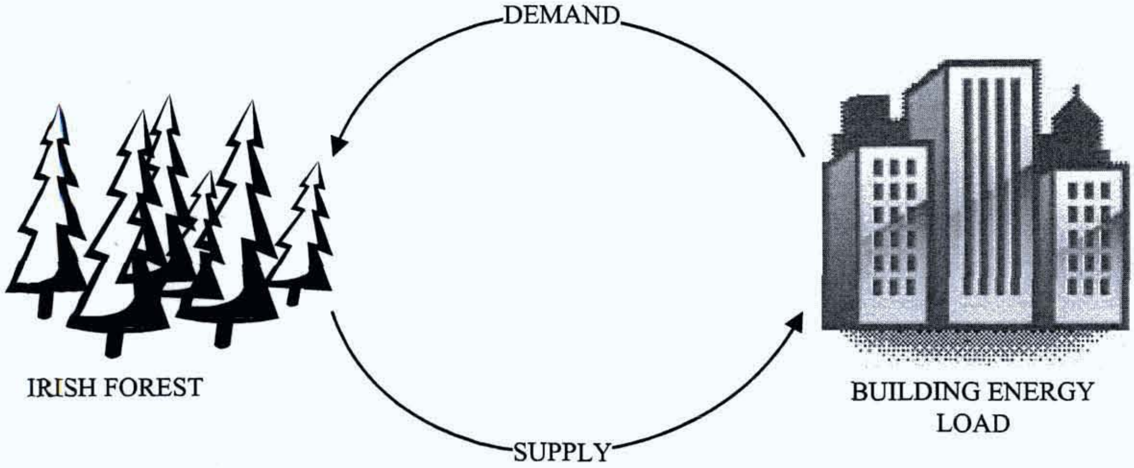


Figure 48: Overview of Wood Chip Supply and Demand

There is a certain amount of interdependency between both the supply side and demand sides of the wood chip industry. The level of demand (financial viability) will depend largely on the price of wood chip, which itself is dependent on the supply chain cost and profitability. The Irish wood chip market is currently in this period of simultaneous development of both supply and demand, which includes the promotion of forest growth to stimulate supply, and grant aid and fuel price management (carbon tax) to control demand.

5.2 Main Findings

The results of the research indicate that wood chip is a feasible replacement for oil and gas under the correct conditions. It is clean and locally produced which combats both the environmental concerns and the reliance on fuel imports. Policy is being constructed to encourage the uptake of wood fuel; incentives such as grant aid and carbon tax make the use of wood chip more attractive to consumers. The largest barrier to further expansion is cost, on both the supply and demand sides of the industry. Both suppliers and consumers face large initial starting costs when they decide to switch to wood chip. It is a large bulky fuel, which results in large and expensive machinery to chip, deliver, store and burn. These overheads affect both the total cost of wood chip production, and subsequently the financial viability of the wood chip systems. The results of the thesis highlighted several methods of improving the quality of the wood chip sector in Ireland, including minimising supply chain length and using hybrid systems of wood chip and fossil fuel, which are discussed in further detail below. However, throughout the thesis one common factor emerges that is beneficial to each aspect of the production, supply and use of wood chip. Drying the wood is the process in which the wood is converted into a fuel, and the level of dryness is seen to have significant advantages across the complete supply chain. The section in the thesis discussing supply chains shows that drying the wood can reduce production costs (Figure 12) and the financial model indicates that drier wood chip is cheaper per tonne, and has a positive effect on the financial viability of wood chip boilers. Drier wood also results in less bacteria growth, which decreases some of the associated risks of using wood chip; and it increases the duration it can be kept in storage. Finally, the level of carbon produced is reduced by drying; as the energy intensity of the fuel increases less is required, therefore, less carbon is emitted.

The success of wood chip for use in commercial buildings in Ireland ultimately depends on the simultaneous development of both the supply and demand for wood chip. This can be achieved in several ways, as discussed throughout the thesis, but the most common factor is undoubtedly the price of wood chip, which is strongly affected by the level of moisture content and also by policy changes, such as grant aid and carbon taxing.

The following is a summary of the findings from each of the sections of the thesis.

5.3 Wood Chip and Wood Chip Policy

The introduction to the thesis discussed the properties and sources of wood chip. Wood chip is composed primarily of Carbon, Hydrogen and Oxygen, similar in basic composition to most other fuels. Wood chip also contains various minerals and impurities. The amount of minerals in the wood chip can depend greatly on the type of tree and the location of the forest stand. Wood naturally dries down to a point known as the fibre saturation point (FSP). This is the point where only the chemically bound water remains in the wood and it can only be removed by adjusting the temperature and humidity of the air around it. The fibre saturation point of wood is roughly 28% moisture content and because of Ireland's humid climate, this represents the ideal achievable target for wood chip dryness. As the moisture content in wood decreases its energy content increases and its weight decreases. Dry wood has an energy content of about 19 MJ/kg for softwoods and 18.2 MJ/kg for hardwoods. The bulk density of wood chip is a key property of wood chip because of its impact on transport and handling costs. The volume of wood changes very little above the FSP and so it is only the weight that affects the bulk density. Commonly the bulk density for wood chip is taken to be somewhere in the region of 200-400 kg/m^3.

5.4 Irish Forestry

Wood is gathered from multiple sources, which include thinnings from forests, forest residues from harvesting, pulpwood, sawmill residues and more recently fast-growing crops such as miscanthus and willow. Aside from the last option, each of these sources represents a waste product from the forestry and construction industries. This makes them cleaner and cheaper as they are by-products of a bigger operation. As demand for wood chip increases, the supply of wood chip from forests may become insufficient and this allows more expensive sources such as miscanthus and willow to be considered. However, little information is available for estimating the energy available from these crops as the price of pulpwood is still competitive enough to prevent suppliers from switching these to alternative sources.

Ireland's forests represent 9% of total land area; compare this to an average of 35% in continental Europe and it is clear that expanding Irish forests is an important objective for the government. Larger forests will provide a larger carbon sink, more wood energy, and help create jobs in the forestry industry. An estimation of the available sustainable wood energy in Ireland shows that 1.43 TWh is available from thinnings and residues alone. According to COFORD, the total estimated figure including pulpwood and sawmill residues is 5.58 TWh. This represents approximately

3.72% of the total imported energy. With Ireland's small percentage of forested land, this is a significant figure and one which can improve significantly under current government policies.

5.5 Wood Chip Supply Chains

The main processes in a wood fuel supply chain are acquiring wood, drying (storage), chipping and transport. Survey results showed that acquiring the wood involved either purchasing or harvesting the wood. Both drying and transport may occur more than once in the supply chain and both processes can be carried out in either log or chip form. Chipping is a flexible process; the chipper unit can be located next to the forest or the depot. It is commonly rented for a short period, or even shared between foresters. Fresh wood should not be put through the chipper as it can block the machine. Fresh wood is wood that has a moisture content in excess of 55% MC_{wet}.

There are two main arrangements for wood fuel supply, single agent and multi-company. Single agent is when the product ownership changes hands once, from producer to consumer. Multi-company is when the product ownership changes hands several times, from the forester to the fuel contractor and then onto the consumer. Within these two arrangements, there are also variables, such as third party harvesting, transport and chipping. The shorter the supply chains the lower the costs of production due to less mark-ups and less processes.

Currently the two most common supply chains being operated in Ireland are a single company arrangement with substantial third party contract work and a multi-company arrangement with additional transport; the fuel contractor transports the wood from the forest to the depot and then transports to the consumer. The cheapest method of supplying wood is the single company arrangement because it involves the least amount of processes and, therefore, additional handling costs. This is followed by the multi company arrangement, which generally involves purchasing from a wood fuel agency as opposed to a forester/ landowner. An important factor to consider is the value of improved security of supply that a multi company arrangement offers; a multi company arrangement can source from multiple foresters, which makes them more flexible in events of shortages or forestry problems. So, while buying directly from the forester can be cheaper, the more reliable supply from a multi-company arrangement might be worth the extra cost depending on the importance of the heat; for example, a retirement home or a school where guaranteed delivery can be more important to the consumer. It may be the case where a single agent supplier, such as a local forester, may source additional wood for when demand is high. In this situation the supplier would be by definition both a single agent and multi-agent supplier. There would, however, most likely be additional costs on the forester as he acts as middle-man between the other supplier and the customer.

The cost analysis suggests that economies of scale dominate the transport and harvesting costs, which will push suppliers towards large scale production or contracting, as they cannot afford to invest in such expensive machinery when setting up production. From site visits, chipping and transport were often contracted out to save on capital expenditure. Transporting, harvesting and chipping processes are optimised by reducing their costs, such as reducing labour, distance travelled and loading times. Irish industry has experience with these kinds of cost based processes from other areas, such as forestry and haulage, so cost reduction techniques for them should already be available to the suppliers.

The value analysis shows that drying is the most critical process in adding value to the supply chain; drying has the ability to reduce the other supply chain costs as well as increase the value of the wood chip. The drying requirements for wood fuel are very different to those of construction timber as the value of timber and its costs for drying are on a much larger scale than wood fuel. The use of mechanical drying is a necessity in timber drying while mechanical drying in wood fuel supply is bad practice because of the associated costs of running a kiln for such a low energy density fuel.

One possible method of optimisation is to shorten the length of the supply chain. This can be achieved by trying to improve the relationship between the forester/ harvester and the wood fuel contractor. Currently under a multi company arrangement wood is being harvested, transported, dried, chipped and transported. This is not the most efficient set-up because the product is being transported twice. If an agreement between the forester and the fuel contractor could be reached to dry and chip on the foresters' land, it would have major effects on the quality of the wood chip, by reducing both handling and transport costs. The second optimisation option that would have significant effect on the supply chain is to put more emphasis on the drying. It has been stated previously that understanding how wood dries is key to knowing how to get the most value from a stack; for example, wood is highly hygroscopic and has a natural tendency to lose water once felled, therefore, protect the stack from rain and the wood will eventually dry itself. The key to maximising the value in a wood chip supply chain is to get wood chip as dry as possible, which would be 28% MC_{wet} under typical Irish conditions. To achieve this quality level the wood is covered from the rain and is adequately ventilated. This process is further optimised by monitoring the fuel and weather conditions over the drying period, and as soon as the wood has reached its ideal moisture content it should be passed onto the consumer. By doing this the supplier has the ability to deliver to more consumers with the same amount of product or even increase the price of the wood chip, as it is now a more valuable fuel than before. The extra cost required to ensure the wood is covered and that both the weather conditions and the wood moisture content is monitored can reduce the overall costs of the complete supply chain. The duration of the drying period is also a very important factor and while mechanical drying, such as kilns, is not cost effective for wood chip drying, a more passive drying technique might be more effective. The relationship between cost, value and time is important when dealing with goods in storage. If a very cheap source of heat, or waste heat, can improve the value of the product to the point where it exceeds the cost and it reduces the time the product spends in storage then it would be very beneficial to the supply chain. Sources of cheap heat might include solar or waste heat from heating systems/ power stations.

Further studies into optimum drying times and targets for the moisture content of the wood would be of great benefit to the industry. Other aspects like specialised machinery for transporting; similar to the skip system used in other countries could help optimise the Irish wood fuel supply chain by reducing loading times of the trucks. Currently in Ireland the wood fuel supply chains in place are very basic. As information becomes more readily available there will be an improvement in quality and subsequently a need for regulation and control on fuel quality and fuel price. This will put significant pressure on suppliers to ensure that their supply chains are operating efficiently.

5.6 Energy Model

The energy model created in this thesis generates hourly heat and hot water demand data for a commercial building over a year's operation. The calculations are predominantly temperature based, using the heating degree-day method. Key aspects of the energy model are its abilities to adjust the relative loads corresponding to a change in boiler size, and to separate the energy loads of a hybrid system. The energy model is primarily for viewing the relationship between boiler sizes and boiler ratios, it is not a substitute for either a full dynamic simulation or a heat loss calculation.

A significant result of the energy model was the production of Figure 22 which shows how much of the heating load at different levels of installed boiler power is satisfied. The graph is sensitive to a change in loads, such as the amount of hot water required and the thermal mass of the building. Given that the inputs in the model are representative of a typical Irish office then this graph represents the typical heating load pattern for Irish offices.

This energy demand model created forms the basis for the financial model. Therefore, the validation of the energy model by benchmarking is an important step in completing the financial viability. By adjusting the CIBSE energy benchmarks to the calculated Heating Degree Days, the model was shown to be accurate.

5.7 Financial model

The four main parameters affecting wood chip financial feasibility are the energy demand profile, capital costs, annual costs and the discount rate. The impact of these factors on the financial feasibility is dependent on the size of the system, the percentage installed capacity of wood chip to gas or oil, and the length of time the project runs over. By varying these inputs in the financial model an extensive range of results were obtained.

The energy demand profile is dependent on a number of factors, mainly the building fabric, the operation of the building and the external weather conditions. Of these variables, the operation of the building is the most important for this model. The internal gains, building operation hours and the function of the building have a large effect on the size of the installed wood chip boiler, especially for a hybrid system where the percentage of the heating provided by the wood chip boiler is key to correctly sizing a wood chip fossil fuel system. An over-sized or under-sized wood chip boiler has a significant negative effect on the financial viability of the investment due to the high capital costs, as seen in Figure 24. This makes sizing the boiler correctly the most important part of its design. If the boiler size is too small, or too big, it becomes too expensive per installed kW. For a standard gas or oil installation the building fabric and the external weather conditions are used to size the peak load and the internal gains are ignored. The gas or oil boiler will modulate for all other loads, but for a wood chip boiler the heat required on a monthly basis, or even daily basis needs to be accurately predicted. This is required to ensure that the investment is viable.

The high capital costs of the wood chip boilers are the main reason why the energy profile and annual costs have to be examined so closely. As seen from the results, the capital costs of wood chip boilers are very large in comparison to gas (see Figure 25 & 26). Currently SEI offers a grant of up to 30% of the total installed cost, and, as with most technologies, the price of wood chip boilers should come down as more companies start manufacturing them. Currently, even with guaranteed paybacks the large capital needed for a wood chip system still deters potential investors.

The annual costs - or more importantly - the difference between the annual costs of a wood chip system and gas or oil, are the source of payback in the feasibility analysis. Gas is a relatively cheap, clean and accessible fuel, which means that the wood chip has to be of a high quality and stored properly to be able to compete with gas. The larger the energy requirement of the building the greater the potential savings from wood chip, but this of course does not justify increasing annual energy use to make wood chip more feasible. Another benefit of wood chip is that the effect of improving fuel quality has significant effects on the viability. Drier wood chip is beneficial to everyone involved in the production, supply and use of the fuel, and improvements in this area will undoubtedly help wood chip become more viable.

The discount rate used has a significant effect on the final results. Deciding on a discount rate can be very difficult because a large proportion of it is based on the mindset of the investor. An optimistic investor might conclude that 5% is an acceptable discount rate based on the success of similar projects while other investors might claim the unknowns in dealing with new technologies justifies a 15% discount rate. In the financial model a 10% discount rate was used. Most financial appraisals referenced used a discount rate between 7%-12% [BRECSU, 2001]. Previous experience with similar investments should lower the discount rate and riskier new technologies where experience is low will increase the discount rate.

Figures 29, 30 & 31 deal with simple payback, a very commonly used term in feasibility checks. The results from the simple payback analysis cannot be used directly to determine the financial viability of a wood chip installation but they can however provide vital information on the optimum ratio of wood chip to gas or oil in a hybrid system, as seen when comparing Figures 31 & 36. In addition to this, there is a relationship between simple payback and discounted payback that can be used to convert one figure to the other. It was found that at a certain discount rate there is a maximum allowable simple payback, this produces a rule of thumb for estimating financial feasibility. In the model a 10% discount rate was used which meant the maximum simple payback was 10 years (Figure 32). Setting a 20-year project investment period on the discounted payback reduces this down to 8.51 years (Figure 33). Any project with a simple payback greater than 8.51 years can now be discarded as financially unfeasible with a discount rate of 10%. From the simple payback results we can estimate the correct ratio of wood chip to oil or gas and also, to a reasonable amount of accuracy, decide if a project is feasible or not.

The net present value and discounted payback results show the minimum feasible sizes for wood chip systems compared to both oil and gas. They show the NPV and discounted payback for a range of systems, and the optimum ratios for both maximum NPV and for the shortest payback. The minimum feasible sizes compared to oil and gas systems under the base model conditions were found to be 150kW and 200kW respectively. The optimum ratio of installed wood chip capacity to fossil fuel capacity varied depending on the aim of the investment. For shortest payback the ratio for wood chip/gas systems was 70%/30% and 35%/65% for wood chip/oil hybrid systems. For maximum NPV the ratios were 100%/0% for wood chip/ gas systems and 65%/35% for wood chip/ oil systems. These results indicate that there is more room for flexibility when installing wood chip boilers to replace a more expensive fuel since this results in higher savings. For example an oil boiler could be installed anywhere between the two optimum points (35% to 65% of installed capacity) and be sufficiently feasible.

The sensitivity analysis showed the percentage change in NPV when the inputs were varied. The results of the sensitivity for System 1 (gas replaced by wood chip) were found to be the following inputs (in descending order): fuel prices, wood chip quality (wood chip prices), capital costs and energy profile. This order is different when the ratio of wood to fossil fuel changes. For a 50%/50% hybrid system (System 2) the order was found to be fuel prices, energy profile, wood chip quality (wood chip prices) and capital costs. For all arrangements, the price of the fossil fuel has the largest effect on the results. Unfortunately, it is also the fossil fuel prices that are the hardest to predict, especially when the investment runs over a 20 year period. Capital costs are far more likely to fall by 30% than the cost of wood chip to drop by 30%. This means that even though the model was more sensitive to fuel prices there might be more scope for improvement by concentrating on the other factors.

The results from the scenario section showed the potential viability of wood chip in 2-5 years if the plausible changes in fuel prices, policy and quality were to occur. Assuming moderate changes the results showed that the viability of wood chip systems increases considerably in the coming years. The minimum feasible sizes reduce to 75kW for oil systems and 150kW for gas systems. The optimum ratio for shortest payback and largest returns did change for oil, up to 65% due to the greater savings from the more expensive fossil fuels. There were slight variations in the optimum ratio, but the optimum points remained constant (Figures 32 & 45).

Wood chip systems can prove to be a profitable investment under the correct conditions. The requirements of each of the factors (energy profile, capital costs, annual running costs and economics) are vitally important to its success. The operation of buildings such as offices and shops where there can be substantial internal gains means that wood chip should not be designed and installed under the same operating principles as an oil or gas boiler. More accuracy is required in estimating building loads and operation, as over sizing and under sizing could both lead to a poor investment.

5.8 Recommendations and Further Research

The most constructive recommendation that comes out of this research is the proposal of stricter fuel quality regulation. Consumers are not required to monitor the quality of other fuels such as oil or gas; and as these are the fuels that we are replacing it is logical to make wood chip just as consumer friendly. Wood chip for commercial heating should not be sold at more the 35% moisture content and quality tests should be carried out on suppliers. The knock on affect of quality control benefits the entire wood chip trade as consumer confidence is vitally important for the continued growth of the industry.

Further Research is needed in nearly every aspect of wood chip production, use and policy. To build on the results of this paper requires daily-data from harvesting, drying, storage and transport operations so that the time and money being invested into each of the processes can be analysed in detail. Additionally, new and existing wood chip heating systems should be monitored so that more accurate real-time financial viability calculations can be carried out. The time frame, however, required for generating such figures, due to the life cycle of both the forests and the heating system, can exceed 20 years, making the publication of results and findings required for improving the wood chip industry difficult to produce.

References

BENET bioenergy Network (2000). Wood Fuels Basic Information Pack. Sweden: Energidalen.

Bioenergy Task Force (2007). Bioenergy Action Plan for Ireland. Dublin: Department of Communications, Marine and Natural Resources.

Biomass Energy Centre. (2006). Chipping. Available: http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,17827&_dad=portal&_schema=PORTAL. Last accessed sep 2008.

Blanchard, David (2007). Supply Chain Management. New Jersey: Wiley. 103-154.

BRECSU. (2001). An Introduction to Absorption Cooling. Good Practice Guide. 256

BSRIA (2003). Technical Note TN 17/95: Rules of Thumb. London: BSRIA.

Campbell, Dr. Colin J.. (2007). Peak Oil - A Turning Point For Mankind. Available: http://www.aspo-ireland.org/index.cfm?page=speakerArticles&rbId=3. Last accessed 2007.

Christopher, M (1998). Logistics and Supply Chain Management. 2nd ed. Great Britain: Pitman Publishing. 101-124.

CIBSE (1999). Environmental Design. 6th ed. London: CIBSE.

CIBSE (2006). Technical Manual TM 41:2006 Degree-Days: Theory and Application. London: CIBSE.

COFORD (2003). Maximising the Potential of Wood Use for Energy Generation in Ireland. Dublin: COFORD. p25-35.

COFORD . woodenergy@gmail.com. Estimating Wood Chip Yield from a Managed Forest. 11th Sept 2008.

Coillte (2007). forest facts by county/national. Available: http://www.coillte.ie/forests/forest_facts/forest_facts_by_county/national/. Last accessed sep 2008.

Eckel, L & Fortin, S. & Fisher, K. (2003). The Choice of Discount Rate for External Reporting Purposes: Considerations for Standard Setting. Accounting Forum. 27 (1), p1-32.

ECN. (2008). The Composition of Biomass and Waste. Available: http://www.ecn.nl/phyllis/. Last accessed sep 2008.

Elsayed M., Matthews R., Mortimer N., (2003). Carbon and Energy Balances for a Range of Biofuel Options. Sheffield: Crown .

Environmental Protection Agency. (2006). Ireland's Greenhouse Gas Emissions in 2006. Available: http://www.epa.ie/downloads/pubs/air/airemissions/ghg_final_20061.pdf. Last accessed sep 2008.

European Union (2008). Ambient Air Quality and Cleaner Air for Europe.: European Union.

Gaegauf, C.K. et al (2005). Elemental and Organic Carbon in Flue Gas Particles of Various Wood Combustion Systems. Lisbon: International Conference on Energy for a Clean Environment.

Government White Paper (2007). Delivering a Sustainable Energy Future for Ireland. Dublin: Department of Communications, Marine and Natural Resources.

Haque, M.N. (2006). Modelling Of Solar Kilns And The Development Of An Optimised Schedule For Drying Hardwood Timber. Sydney: The University of Sydney. p37-45.

Harmon, C. (2000). Experience Curves of Photovoltaic Technology. Austria: IIASA. p7-9.

IAEA. (2005). Dependency on External Energy Supplies. Available: http://www.iaea.org/inisnkm/nkm/aws/eedrb/data/IE-enimco.html. Last accessed Aug 2008.

IARC (1995). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans. Lyon: World Health Organisation.

Iowa State University. Edwards W.(2005). Estimating Farm Machinery Costs. Available: http://www.extension.iastate.edu/Publications/PM710.pdf. Last accessed 2007.

IPCC (1995). IPCC Second Assessment - Climate Change 1995.: IPCC.

Jones, C. & Hammond, G. (2008). Inventory of Carbon & Energy (ICE). Bath: University of Bath.

Knott, J & Shurson, J (2004). Variation in Particle Size and Bulk Density of Distiller's Dried Grains with Solubles (DDGS) Produced by "New Generation" Ethanol Plants in Minnesota and South Dakota. Minnesota: University of Minnesota. p1-7.

Kofman, Pieter D & Kent, Tom (2007). Harvesting and Processing Forest Biomass for Energy Production in Ireland. Ireland: COFORD

Kofman, Pieter D & Kent, Tom (2007). Harvesting and Processing Forest Biomass for Energy Production in Ireland. Ireland: COFORD

Kofman, Pieter D. (2006). Quality wood chip fuel. Available: www.woodenergy.ie/iopen24/pub/finalfuelquality.pdf. Last accessed 2007.

KWB (2007). Technical Data - Wood Chip.

Mohan, Dinesh et al.. (2006). Pyrolysis of Wood/Biomass for Bio-Oil: A Critical Review. Energy & Fuels. 20, p.848-889.

NCCS (2007). National Climate Change Strategy. Dublin: Department of Environment, Heritage and Local Government.

NSAI (2005). Solid Biofuels - Fuel Specifications and Classes. Ireland: NSAI.
OED (2008). Oxford English Dictionary. Oxford: Oxford University Press.

Quintet, Emile & Vickerman, Roger (2004). Principles of Transport Economics. Great Britain: Edward Elgar Publishing Ltd. 120-163.

Ragland, K.W. & Aerts D.J.. (1991). Properties of Wood for Combustion Analysis. Bioresource Technology. 37, p161-168.

Rogers, M. (2001). Engineering Project Appraisal. Oxford: Blackwell Science.

SEI. (2008). Energy in Ireland. Available: http://www.cso.ie/px/sei/dialog/varval.asp?ma=sei01&ti=Energy+Balance+%28ktoe%29+by+Energy+Supply+and+Consumption%2C+Year+and+Fuel+Type&path=../Database/SEI/Energy%20Balance%20Statistics/&search=OIL&lang=1. Last accessed Sept 2008.

Simpson, W.T. (1993). Specific Gravity, Moisture Content, and Density Relationship for Wood. Madison , U.S.: US Department of Agriculture. p.1-4.

Simpson, W.T.. (1991). Dry Kiln Operator's Manual. Available: http://www.fpl.fs.fed.us/documnts/usda/ah188/chapter01.pdf. Last accessed Aug 2008.

Teagasc. (2002). Thinning - the first return. Available: http://www.client.teagasc.ie/forestry/technical_info/articles/thinning_firstreturn.asp. Last accessed sep 2008.

UNFCCC (2007). National Greenhouse Gas Inventory Data for the Period 1990-2005. Bali: UNFCCC.

APPENDIX A – ENERGY & FINANCIAL MODEL

Energy & Financial Model

Section	1
Function	Inputs

Legend

User Input	▨

Data Output Options

Gas or Oil	Oil	**01**	
Grant Aided	0%	**02**	
Compare to Fossil Fuel	Yes	**03**	

Operation Data

Internal Design Temperature	21	**04**	°C
External Deisn Temperature	-3	**05**	°C
Occupancy Hours	10	**06**	hrs/Day
Week Profile	5	**07**	Days/Week
Pre-Heat Hours	2	**08**	hrs
Thermal Weight Factor	3	**09**	

System Data

Heat Gains	120	**10**	W/m^2
Heat Loss	70	**11**	W/m^2
System Size	200	**12**	kW
Percentage Wood Chip	50%	**13**	

Fuel Data - Wood Chip

Wood Chip Boiler Efficiency	90.0%	**14**	
Wood Chip Cost	115	**15**	€/T
Wood Chip Moisture Content	35.0%	**16**	

Fuel Data	**Gas**		**Oil**		
Gas Boiler Efficiency	98.0%	**17**	85.0%	**18**	
Gas Base Cost	0.0451	**19**	0.0849	**20**	c/kWh

Policy

Carbon Tax Rate	0	**21**	€/T

Assumptions for Base Model

No Carbon Tax	No Loan Interest Rate
Internal Heats Gains	Full Fresh Air System
Manufacturers Efficiency	Discount Rate 10%
Water heated off hours	No Grants

Design Calculations

Peak Heat Loss Design Data **22**

Boiler Size	200.0	kW
Fabric Loss	73.3	kW
Air Loss	60.0	kW
Thermal Mass	66.7	kW
Design dT	24.0	°C
AU	3.06	kW/°C
Cv	2.50	kW/°C
AY	14.17	kW/°C
Heating Coef.	5.56	kW/°C
% Peak Heating	66.7%	

Operating Data

Design Temp.	21.0
Occupancy Hours	10.0

HWS **26**

Occupancy Density	10.0	m2/person
Area	2857.1	m2
Occupancy	285.7	ppl
Hot Water Requirment	14.0	L/Person/Day
Hot Water Demand	4000.0	Litres/day
Energy for HWS	255.4	kWh/Day
Equivilant running hours	1.28	hrs/day
or kW for x hr cycle	63.9	kW
% peak	31.9%	

Heat Gain Design Data **23**

W/m^2	120	
Heat Gains	342.9	kW
dT	61.71	°C

Thermal Mass Energy **24**

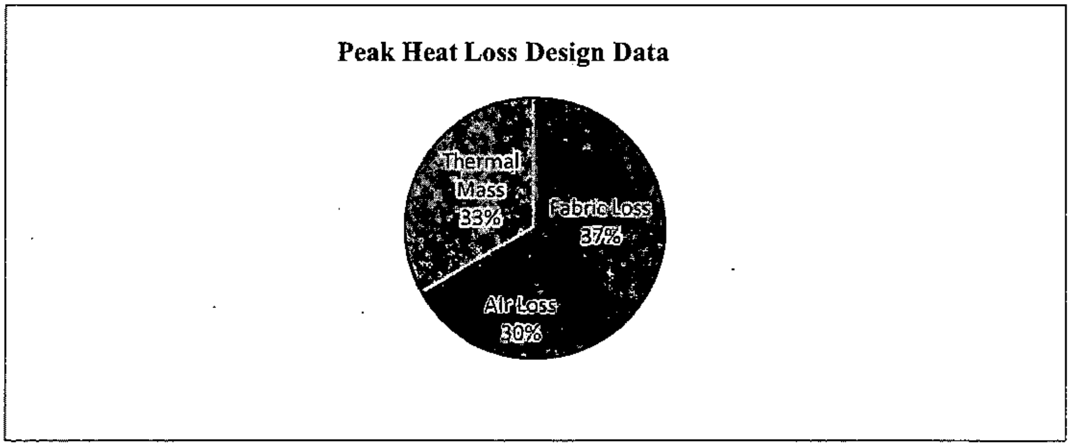
Thermal Weight	3.0	
Preheat Time	2.0	hrs
Preheat Factor	1.50	
Energy Required	473.3	kWh/Day
Equivilant per hour	237.0	kWh/hr/day

Dimensions **25**

70	W/m2
2857.1	Area, m2
7142.9	Volume, m3

Total Energy Required

Annual Energy	139053.2	kWh
equiv. HDD	1042.9	



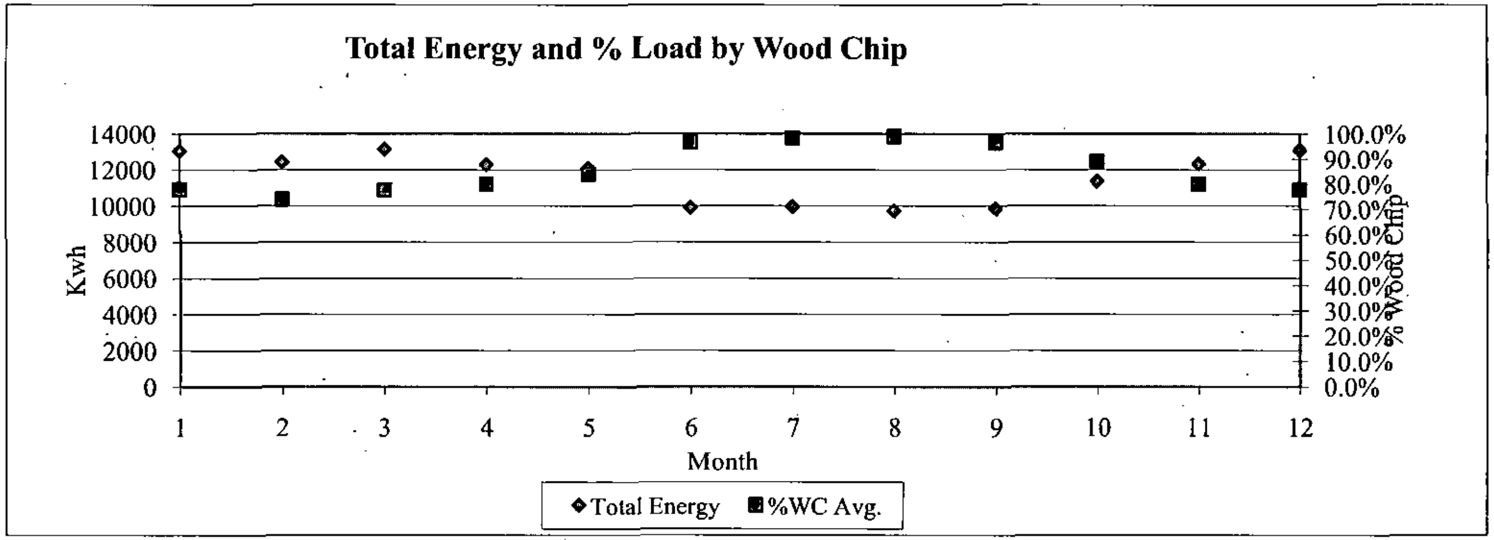
ON		1									
OFF		0									
		27		28		29				Peak kW	
	PEAK	Heating		Preheat		HWS		% Peak	PEAK	WC	Fossil
00:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
01:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
02:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
03:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
04:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
05:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
06:00	100%	0	0%	1	100%	0	0%	100.0%	200.0	100.0	100.0
07:00	100%	0	0%	1	100%	0	0%	100.0%	200.0	100.0	100.0
08:00	99%	1	67%	0	0%	1	32%	98.6%	197.2	100.0	97.2
09:00	99%	1	67%	0	0%	1	32%	98.6%	197.2	100.0	97.2
10:00	67%	1	67%	0	0%	0	0%	66.7%	133.3	100.0	33.3
11:00	99%	1	67%	0	0%	1	32%	98.6%	197.2	100.0	97.2
12:00	67%	1	67%	0	0%	0	0%	66.7%	133.3	100.0	33.3
13:00	67%	1	67%	0	0%	0	0%	66.7%	133.3	100.0	33.3
14:00	67%	1	67%	0	0%	0	0%	66.7%	133.3	100.0	33.3
15:00	99%	1	67%	0	0%	1	32%	98.6%	197.2	100.0	97.2
16:00	67%	1	67%	0	0%	0	0%	66.7%	133.3	100.0	33.3
17:00	67%	1	67%	0	0%	0	0%	66.7%	133.3	100.0	33.3
18:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
19:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
20:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
21:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
22:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
23:00	0%	0	0%	0	0%	0	0%	0.0%	0.0	0.0	0.0
Total		**10.0**	**1333.3**	**2.0**	**400.0**	**4.0**	**255.4**		**1988.8**	**1200.0**	**788.8**
Average		**0.4**	**0.3**	**0.1**	**0.1**	**0.2**	**0.1**		**82.9**	**50.0**	**32.9**
% WC										**60.3%**	

	Average Temps 04/05			**HDD Data**			**Heat Energy Required**				
	30	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Day	min	max	mean	Base Temp	HDD	**EqHDDHWS**	Heating	Preheat	HWS	Total	% WC
01-Jan	6.0	9.5	7.7	*-12.2*	0.0	**4.1**	0.0	296.8	255.4	552.3	82.5%
02-Jan	2.1	5.9	4.0	*-14.2*	0.0	**4.7**	0.0	373.7	255.4	629.2	72.4%
03-Jan	3.9	9.3	6.6	*-13.3*	0.0	**4.4**	0.0	337.3	255.4	592.7	76.8%
04-Jan	6.6	8.6	7.6	*-11.9*	0.0	**4.0**	0.0	284.0	255.4	539.4	84.4%
05-Jan	5.1	10.7	7.9	*-12.7*	0.0	**4.3**	0.0	314.6	255.4	570.0	79.9%
06-Jan	5.0	10.0	7.5	*-12.7*	0.0	**4.3**	0.0	315.6	255.4	571.0	79.8%
07-Jan	7.9	12.5	10.2	*-11.3*	0.0	**3.9**	0.0	258.4	255.4	513.8	88.6%
08-Jan	6.3	7.0	6.6	*-12.1*	0.0	**4.1**	0.0	289.9	255.4	545.4	83.5%
09-Jan	4.2	10.3	7.3	*-13.1*	0.0	**4.4**	0.0	331.3	255.4	586.8	77.6%
10-Jan	7.2	10.8	9.0	*-11.6*	0.0	**4.0**	0.0	272.2	255.4	527.6	86.3%
11-Jan	5.9	9.0	7.5	*-12.3*	0.0	**4.1**	0.0	297.8	255.4	553.3	82.3%
12-Jan	3.2	6.9	5.1	*-13.6*	0.0	**4.5**	0.0	351.1	255.4	606.5	75.1%
13-Jan	2.9	7.5	5.2	*-13.8*	0.0	**4.6**	0.0	358.0	255.4	613.4	74.2%
14-Jan	2.6	7.2	4.9	*-13.9*	0.0	**4.6**	0.0	362.9	255.4	618.3	73.7%
15-Jan	5.3	11.0	8.1	*-12.6*	0.0	**4.2**	0.0	310.6	255.4	566.1	80.5%
16-Jan	5.7	7.8	6.7	*-12.4*	0.0	**4.2**	0.0	302.7	255.4	558.2	81.6%
17-Jan	2.9	6.5	4.7	*-13.8*	0.0	**4.6**	0.0	357.0	255.4	612.4	74.4%
18-Jan	-0.9	6.7	2.9	*-15.7*	0.0	**5.2**	0.0	431.9	255.4	687.4	66.3%
19-Jan	4.8	11.0	7.9	*-12.8*	0.0	**4.3**	0.0	320.5	255.4	575.9	79.1%
20-Jan	8.6	10.1	9.3	*-10.9*	0.0	**3.8**	0.0	244.6	255.4	500.0	91.1%
21-Jan	5.3	7.7	6.5	*-12.6*	0.0	**4.2**	0.0	310.6	255.4	566.1	80.5%
22-Jan	5.2	8.5	6.9	*-12.6*	0.0	**4.3**	0.0	311.6	255.4	567.1	80.3%
23-Jan	1.9	7.6	4.8	*-14.3*	0.0	**4.7**	0.0	376.7	255.4	632.1	72.0%
24-Jan	1.8	6.6	4.2	*-14.3*	0.0	**4.8**	0.0	378.7	255.4	634.1	71.8%
25-Jan	1.5	7.1	4.3	*-14.5*	0.0	**4.8**	0.0	385.6	255.4	641.0	71.1%
26-Jan	2.3	7.3	4.8	*-14.1*	0.0	**4.7**	0.0	368.8	255.4	624.3	73.0%
27-Jan	2.1	4.9	3.5	*-14.2*	0.0	**4.7**	0.0	373.7	255.4	629.2	72.4%
28-Jan	1.5	6.7	4.1	*-14.5*	0.0	**4.8**	0.0	385.6	255.4	641.0	71.1%
29-Jan	0.6	6.0	3.3	*-14.9*	0.0	**4.9**	0.0	403.3	255.4	658.8	69.1%
30-Jan	3.5	8.7	6.1	*-13.5*	0.0	**4.5**	0.0	345.1	255.4	600.6	75.8%
31-Jan	6.9	11.3	9.1	*-11.8*	0.0	**4.0**	0.0	279.1	255.4	534.5	85.2%
01-Feb	5.9	9.6	7.7	*-12.3*	0.0	**4.2**	0.0	298.8	255.4	554.2	82.2%
02-Feb	5.9	11.5	8.7	*-12.3*	0.0	**4.1**	0.0	297.8	255.4	553.3	82.3%
03-Feb	9.4	11.4	10.4	*-10.5*	0.0	**3.6**	0.0	228.8	255.4	484.2	94.1%
04-Feb	6.7	12.5	9.6	*-11.9*	0.0	**4.0**	0.0	283.0	255.4	538.5	84.6%
05-Feb	5.2	10.2	7.7	*-12.6*	0.0	**4.3**	0.0	311.6	255.4	567.1	80.3%
06-Feb	3.8	7.6	5.7	*-13.3*	0.0	**4.5**	0.0	339.2	255.4	594.7	76.6%
07-Feb	1.4	8.0	4.7	*-14.5*	0.0	**4.8**	0.0	386.6	255.4	642.0	70.9%
08-Feb	4.2	7.5	5.8	*-13.1*	0.0	**4.4**	0.0	331.3	255.4	586.8	77.6%
09-Feb	1.2	9.1	5.1	*-14.6*	0.0	**4.9**	0.0	391.5	255.4	646.9	70.4%
10-Feb	6.0	10.1	8.0	*-12.2*	0.0	**4.1**	0.0	296.8	255.4	552.3	82.5%

Daily Heating Profile 41

0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	66.7%	66.7%	66.7%	66.7%	66.7%	66.7%	66.7%	66.7%	66.7%	66.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	31.9%	31.9%	0.0%	31.9%	0.0%	0.0%	0.0%	31.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	Total
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4
0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	63.9	63.9	0.0	63.9	0.0	0.0	0.0	63.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	455.4

	Temperatures 04/05 42			HDD Data 43			Heat Energy Required 44			45	46
Month	Min	Max	Mean	Base Temp	HDD	Heating	Preheat	HWS	Total Energy	%WC Avg.	Gas
Jan	-0.9	12.5	6.2	-13.2	0.0	0.0	7378.2	5656.3	13034.5	77.8%	2891.5
Feb	-2.0	12.5	5.3	-14.0	0.0	0.0	7314.1	5108.9	12423.0	74.0%	3234.3
Mar	-2.3	15.3	7.2	-13.3	0.0	0.0	7479.7	5656.3	13135.9	77.7%	2934.5
Apr	0.0	15.2	8.6	-12.8	0.0	0.0	6804.9	5473.8	12278.7	80.0%	2456.0
May	3.3	18.2	10.6	-12.1	0.0	0.0	6428.0	5656.3	12084.3	83.8%	1954.6
Jun	7.3	23.7	14.7	-9.9	0.0	0.0	4410.0	5473.8	9883.8	96.5%	348.7
Jul	7.1	22.2	15.1	-9.6	0.0	0.0	4279.7	5656.3	9936.0	98.2%	174.0
Aug	8.8	22.5	15.7	-9.4	0.0	0.0	4049.4	5656.3	9705.7	99.0%	97.9
Sep	3.7	22.0	14.1	-9.9	0.0	0.0	4360.7	5473.8	9834.5	96.5%	349.1
Oct	2.6	16.1	10.8	-11.2	0.0	0.0	5687.0	5656.3	11343.3	89.0%	1243.0
Nov	-0.5	15.1	7.5	-12.8	0.0	0.0	6842.9	5473.8	12316.7	80.0%	2467.9
Dec	-1.1	11.9	6.3	-13.2	0.0	0.0	7420.5	5656.3	13076.8	77.7%	2916.3
Total	-2.3	23.7	10.2	-11.8	0.0	0.0	72455.2	66598.0	139053.2	84.3%	21067.8



Total Energy and % Load by Wood Chip

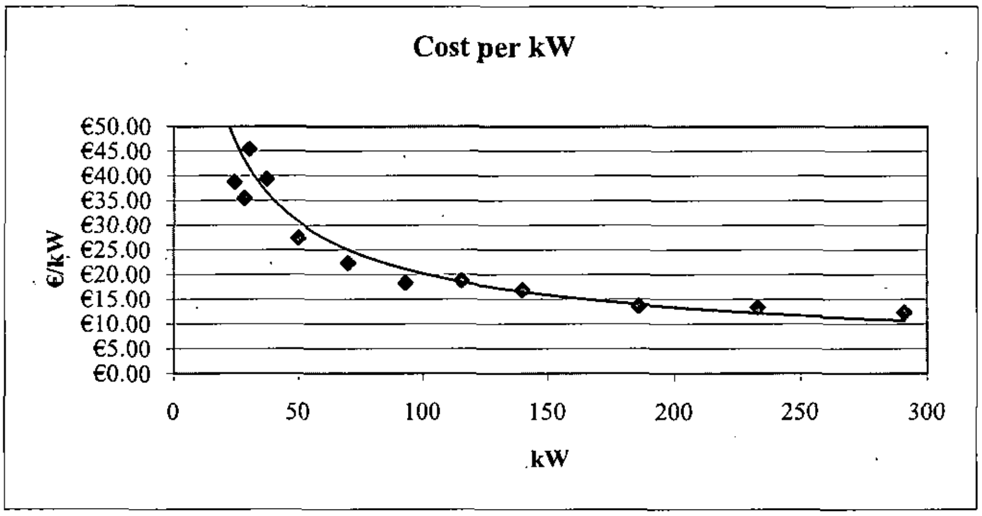
kW	Cost €	€/kW
12	€988.00	€82.33
15	€1,040.00	€69.33
18	€1,092.00	€60.67
24	€1,227.00	€51.13
30	€1,363.00	€45.43
37	€1,456.00	€39.35
24	€929.00	€38.71
28	€993.00	€35.46
93	€1,700.00	€18.28
116	€2,177.00	€18.77
140	€2,358.00	€16.84
186	€2,526.00	€13.58
233	*€3,114.00*	*€13.36*
291	€3,588.00	€12.33
50	€1,367.20	€27.34
70	€1,563.20	€22.33

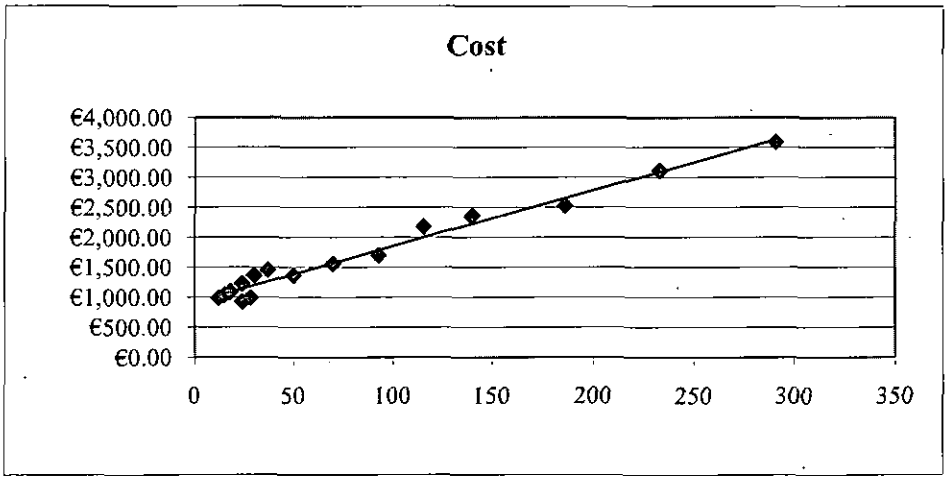
47

Slope	9.31
Intercept	*922.01*

Additional Costs

Flue, T	€
Standard	€81.50
Vertical	€107.00
Average	€94.25





Wood Chip Running Costs 48

Efficiency		
Efficiency	90.0%	

Wood Chip		
Fuel	115	€/T
%MC	35.0%	
Energy Cost, WC	€0.0354	€/kWh

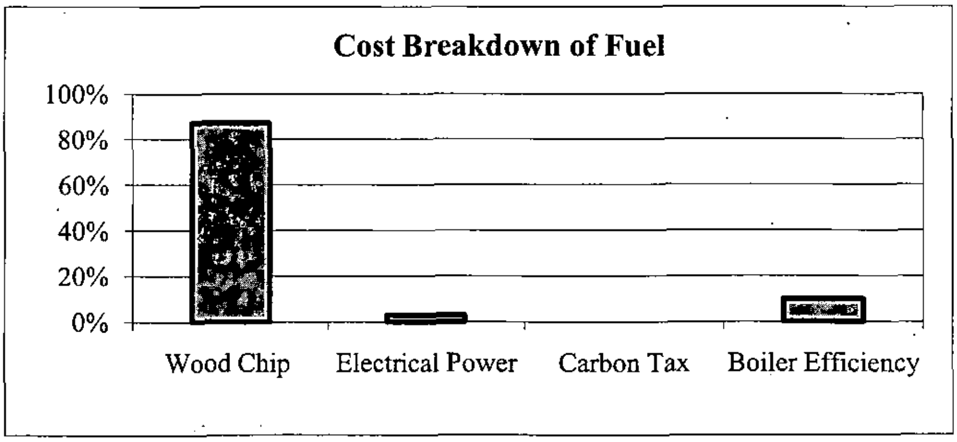
Additional Costs		
Maintenance	€500.00	per Year

Electrical Power 49		
Ratio of Elec	0.8%	% of kW
Energy Cost, E	€0.14	€/kWh, E
Energy Cost, WC	0.001177687	€/kWh

Carbon Tax			
Carbon Tax Rate	€0.00	€/TCO_2	
Wood Carbon	0.00	$kgCO_2/kWh$	(0.30)
Elec Carbon	0.60	$kgCO_2/kWh$	
Carbon Tax	€0.000	€/kWh	

Results 50		
Fuel Cost	€0.0406	€/kWh
Additional Costs	€500.00	per Year

Chart	
Wood Chip	87.1%
Electrical Power	2.9%
Carbon Tax	0.0%
Boiler Efficiency	10.0%



Scenario Conditions 51	% Peak	% Energy		
Wood Chip	50.0%	84.3%	**Fossil Fuel**	**Oil**
Fossil Fuel	50.0%	15.7%		

Inputs			
Size	200	kW	
Energy required	139053.2	kWh	
Capital			
Wood Chip	€28,471.73	(inclusive of storage and buffer)	
Fossil Fuel	€2,120.77	€1,947.44	€2,120.77
Total	€30,592.50		
100% Fossil Fuel	€2,790.93	€2,878.62	€2,790.93
Annual Cost			
Wood Chip	€5,260.83	€6,144.34	
Gas	€2,280.07	€2,898.72	€2,280.07
Total	€7,540.90		
100% Fossil Fuel	€14,028.51	€11,297.02	€14,028.51

		52	53	54			
PNV / IRR		CASHFLOW	CUSUM	1.0%	2.0%	3.0%	4.0%
Year 0	0	-€27,801.58	-€27,801.58	-€27,801.58	-€27,801.58	-€27,801.58	-€27,801.58
Year 1	1	€6,487.61	-€21,313.97	-€21,378.20	-€21,441.18	-€21,502.93	-€21,563.49
Year 2	2	€6,487.61	-€14,826.36	-€15,018.43	-€15,205.49	-€15,387.74	-€15,565.33
Year 3	3	€6,487.61	-€8,338.75	-€8,721.62	-€9,092.07	-€9,450.65	-€9,797.87
Year 4	4	€6,487.61	-€1,851.14	-€2,487.15	-€3,098.53	-€3,686.50	-€4,252.24
Year 5	5	€6,487.61	€4,636.46	€3,685.58	€2,777.50	€1,909.77	€1,080.10
Year 6	6	€6,487.61	€11,124.07	€9,797.20	€8,538.31	€7,343.04	€6,207.35
Year 7	7	€6,487.61	€17,611.68	€15,848.31	€14,186.16	€12,618.06	€11,137.40
Year 8	8	€6,487.61	€24,099.29	€21,839.51	€19,723.27	€17,739.43	€15,877.83
Year 9	9	€6,487.61	€30,586.89	€27,771.39	€25,151.81	€22,711.64	€20,435.94
Year 10	10	€6,487.61	€37,074.50	€33,644.53	€30,473.91	€27,539.03	€24,818.73
Year 11	11	€6,487.61	€43,562.11	€39,459.53	€35,691.66	€32,225.82	€29,032.96
Year 12	12	€6,487.61	€50,049.72	€45,216.95	€40,807.09	€36,776.10	€33,085.10
Year 13	13	€6,487.61	€56,537.33	€50,917.37	€45,822.22	€41,193.84	€36,981.39
Year 14	14	€6,487.61	€63,024.93	€56,561.35	€50,739.02	€45,482.92	€40,727.82
Year 15	15	€6,487.61	€69,512.54	€62,149.45	€55,559.41	€49,647.06	€44,330.16
Year 16	16	€6,487.61	€76,000.15	€67,682.22	€60,285.28	€53,689.93	€47,793.95
Year 17	17	€6,487.61	€82,487.76	€73,160.21	€64,918.48	€57,615.04	€51,124.51
Year 18	18	€6,487.61	€88,975.36	€78,583.96	€69,460.84	€61,425.82	€54,326.98
Year 19	19	€6,487.61	€95,462.97	€83,954.01	€73,914.14	€65,125.61	€57,406.27
Year 20 55	20	€6,487.61	€101,950.58	€89,270.89	€78,280.11	€68,717.65	€60,367.13
Total		**€101,950.58**	**€101,950.58**	**€89,270.89**	**€78,280.11**	**€68,717.65**	**€60,367.13**
Chart		X	NO DR	1.00%	2.00%	3.00%	4.00%
		Y	€101,950.58	€89,270.89	€78,280.11	€68,717.65	€60,367.13

RESULTS 56						
NPV	€101,950.58					
Simple Payback	4.3	years				
					EXP	POWER
NPV 10% DCR	€27,431.09		Discounted PB	4.29	5.8	5.9
Payback	34,947.81	35.9		57	30.0654	
					83.839%	
IRR	**15.795%**	€11,086.11	IRR			

Gas 58

% WC	150	200	250	300	400	
0%	€0.00	€0.00	€0.00	€0.00	€0.00	
5%	-€20,228.21	-€22,154.79	-€22,184.44	-€22,207.70	-€22,240.72	
10%	-€18,431.90	-€22,240.72	-€22,261.08	-€22,272.48	-€22,276.34	59
15%	-€16,588.51	-€14,720.88	-€22,277.32	-€22,271.22	-€22,235.98	
20%	-€14,720.88	-€12,207.55	-€9,676.46	-€7,132.79	-€22,156.50	
25%	-€13,160.24	-€10,118.16	-€7,057.46	-€3,983.58	€2,191.99	
30%	-€12,005.86	-€8,583.64	-€5,143.28	-€1,690.06	€5,243.48	
35%	-€10,873.03	-€7,076.29	-€3,261.71	€565.50	€8,246.58	
40%	-€9,771.23	-€5,609.70	-€1,430.58	€2,761.00	€11,170.44	
45%	-€8,715.02	-€4,203.99	€324.37	€4,865.00	€13,972.17	
50%	-€7,696.32	-€2,848.31	€2,016.76	€6,893.93	€16,673.77	
55%	-€6,713.47	-€1,540.52	€3,649.23	€8,850.88	€19,279.30	
60%	-€5,770.10	-€285.59	€5,215.44	€10,728.15	€21,778.26	
65%	-€4,870.51	€910.62	€6,707.94	€12,516.72	€24,158.47	
70%	-€4,018.12	€2,043.49	€8,120.92	€14,209.55	€26,410.45	
75%	-€3,734.01	€2,418.44	€8,586.31	€14,765.12	€27,145.80	
80%	-€3,657.10	€2,517.13	€8,706.40	€14,906.32	€27,328.65	
85%	-€3,606.88	€2,580.16	€8,781.85	€14,993.92	€27,439.95	
90%	-€3,579.10	€2,613.28	€8,819.91	€15,036.65	€27,491.41	60
95%	-€3,656.09	€2,506.84	€8,683.64	€14,870.27	€27,264.27	
100%	-€2,258.96	€3,741.26	€9,754.99	€15,778.30	€27,845.12	61
Min	-€20,228.21	-€22,240.72	-€22,277.32	-€22,272.48	-€22,276.34	
Max	-€2,258.96	€3,741.26	€9,754.99	€15,778.30	€27,845.12	
Max - 100%	€0.00	€2,613.28	€8,819.91	€15,036.65	€27,491.41	
%WC		100%	100%	100%	100%	

Oil

% WC	100	150	200	250	300	400
0%	€0.00	€0.00	€0.00	€0.00	€0.00	€0.00
5%	-€18,601.21	-€16,923.05	-€15,230.70	-€13,529.33	-€11,821.57	-€8,392.55
10%	-€15,230.70	-€11,821.57	-€8,392.55	-€4,950.86	-€1,500.21	€5,420.01
15%	-€11,821.57	-€6,673.01	-€1,500.21	€3,688.01	€8,887.17	€19,308.55
20%	-€8,392.55	-€1,500.21	€5,420.01	€12,357.99	€19,308.55	€33,236.21
25%	-€6,106.46	€1,939.70	€10,015.09	€18,109.09	€26,216.29	€42,458.49
30%	-€5,255.14	€3,210.80	€11,705.23	€20,217.81	€28,743.24	€45,821.23
35%	-€4,451.27	€4,412.70	€13,304.68	€22,214.50	€31,136.96	€49,008.52
40%	-€3,736.60	€5,481.58	€14,727.38	€23,990.77	€33,266.61	€51,844.59
45%	-€3,165.49	€6,334.99	€15,862.69	€25,407.73	€34,965.03	€54,105.55
50%	-€2,711.75	€7,012.33	€16,763.22	€26,531.18	€36,311.23	€55,896.84
55%	-€2,370.97	€7,520.12	€17,437.60	€27,371.89	€37,318.07	€57,235.54
60%	-€2,156.28	€7,838.50	€17,859.21	€27,896.43	€37,945.35	€58,067.85
65%	-€2,082.62	€7,944.89	€17,997.82	€28,066.94	€38,147.52	€58,332.87
70%	-€2,161.55	€7,821.88	€17,830.15	€27,854.24	€37,889.54	€57,983.77
75%	-€2,358.04	€7,522.27	€17,426.82	€27,346.79	€37,277.69	€57,162.56
80%	-€2,632.48	€7,105.73	€16,867.57	€26,644.44	€36,431.98	€56,029.52
85%	-€2,991.03	€6,562.95	€16,139.93	€25,731.57	€35,333.58	€54,559.50
90%	-€3,419.67	€5,915.03	€15,272.12	€24,643.46	€34,024.90	€52,809.09
95%	-€3,887.21	€5,208.94	€14,326.88	€23,458.69	€32,600.33	€50,904.35
100%	-€2,303.49	€6,545.95	€15,416.62	€24,300.80	€33,194.56	€51,002.27
Min	-€18,601.21	-€16,923.05	-€15,230.70	-€13,529.33	-€11,821.57	-€8,392.55
Max	€0.00	€7,944.89	€17,997.82	€28,066.94	€38,147.52	€58,332.87
Max - 100%	€0.00	€7,944.89	€17,997.82	€28,066.94	€38,147.52	€58,332.87
%WC	65%	65%	65%	65%	65%	65%
%FF	35%	35%	35%	35%	35%	35%

Ref. No.	Description
PAGE 01	
01	Drop down menu for changing between oil and gas
02	Percentage reduction of capital costs. (grant aid)
03	Drop down menu for single NPV or comparison NPV
04	Internal Design temperature used in sizing boiler
05	External design temperature used in sizing boiler
06	Occupancy hours linked from hours tab
07	Days of week system in operation. 5 day standard working week
08	Hours allowed to preheat building linked from hours tab
09	Thermal weight of building. Factor between 1-8
10	Internal Heat gains. Either from design manual or building simulation
11	Internal Heat Losses. Either from design manual or building simulation
12	Design system size. without any additional safety factors.
13	The percentage of wood chip power installed as fraction of system size
14	Boiler Efficiency
15	Cost of Wood chip per tonne
16	Moisture Content of Delivered Wood Chip
17	Gas boiler efficiency
18	Oil boiler efficiency
19	Basic Cost per kWh of Oil
20	Basic Cost per kWh of gas
21	Carbon Tax rate
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22	Calculates AU, AY and heating coefficients from inputs.
23	Calculates peak internal heat gain
24	Calculates energy required to preheat and hour profile.
25	Calculates rough area based on inputs
26	Calculates energy for hot water using inputs and hour profile.
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27	Peak design heating times
28	How water heating times.
29	Preheat times.
PAGE 04	
30	Heating Degree Days for stated day
31	Average temperature for stated day.
32	Average max temperature for stated day.
33	Energy for preheating
34	Energy for heating.
35	Total equivalent heating degree days including preheat and water heating
36	Calculated base temp for stated day.
37	Average min temperature for stated day.
38	Percentage of total energy supplied by installed wood chip boiler.
39	Total Energy for stated day.
40	Energy for hot water services
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41	Hour by Hour energy use based on Hour Profile and Inputs

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42	Monthly totals
43	Monthly totals of daily figures.
44	Monthly averages of Daily figures
45	Percentage of total monthly demand supplied by wood chip boiler.
46	Remaining load on gas boiler

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47	Sample of Capital Cost Calculations

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48	Sample of running cost calculations. Inputs for calculating Fuel Costs
49	Electrical load of boiler and feed systems
50	Final cost of fuel per kWh and annual fees.

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51	Net Present Value Calculations
52	annual non-discounted cashflow
53	Sum of cashflows
54	Discount Rate from 1%-35%
55	Investment Period
56	Initial results of inputs and set parameters.
57	Macros for obtaining quicker results.

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58	Sample results page.
59	Blue indicates lowest figure
60	Green indicates next best figure.
61	Red indicates highest figure