Analysis of the Optimisation Potential of an Industrial Boiler System

by

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Abstract

Energy efficiency has been identified in a recent report to government in the UK as one of the methods that future energy policy will be most cost effectively served by. Combined with the well-documented financial return that efforts towards greater energy efficiency can bring, the implementation of techniques and technologies in this field are of increasing importance and relevance to industry.

Within a strategic energy management programme, or in an isolated environment, investigation of energy systems and processes allows determination of the nature, extent and financial burden of any under-performing technologies. With knowledge of losses, the potential exists to explore optimisation of these systems at various levels of investment.

This thesis demonstrates the value of exploring such optimisation options. This is done by investigation of a recognised problematic energy system at a sawmill operation in Scotland. The extent of wasted energy is examined, and the various levels of savings that could be made in both energy and economic terms are explored. It has then been shown that several low cost, short payback investments could be made to enhance performance of this system and deliver the operator significant financial savings.

This has been done through a process of analyzing the energy system and constructing a representative virtual model. Changes were then made to model to reflect potential upgrades to the system, and determine the outcomes of any modifications that could be made. In so doing, the thesis also demonstrates the value and relevance of this low cost analytical technique.

Chapter 1 - Introduction

1.1 Sustainable Development and Energy

General assessments of progress and development are generally performed using a small number of key measures, one of which is industrial activity. In post-industrialized countries, life expectancy, standard of living and most other measures of quality of life have increased in relation to industrial and related financial or enhanced-agricultural activities. The technological advances made in the period from the industrial revolution, in comparison with any equally short period in history, have been amazing, and the foundation of this evolution has been the progressive exploitation of energy services. Energy use has always been at the heart of progress, ranging in scale and ingenuity of application from small solar water heating systems to electricity generation on a scale necessary to keep cities running. Characterized in the developed world by the burning of fossil fuels and the use of nuclear energy, consumption levels of raw fuels have increased steeply with development until the relatively recent emergence of large service based sectors. Progress now dictates that we assess development in a new context, that of Sustainable Development, aiming to create "a better quality if life for everyone, now and for generations to come"[1], and this encourages a new perspective on energy issues for governments, industry and civil society.

Sustainable development is a global framework for progress in which all countries must contribute and play their part. While it is a simple idea, it is a complex process, consisting of social, economic, environmental and resource use dimensions, and local considerations. Each nation faces its own challenges and more than ever, international partnerships must be strong to ensure the success of this development strategy. The relationships between third world and developed countries are particularly important, as an alarming percentage of the global population still lives in degrees of poverty, and to lift numbers of people out of this restrictive lifestyle will require efforts across borders as never attempted before. Against the backdrop of recently enhanced understanding that stability in the world will be principally aided by economic growth in presently deprived areas, we can expect that governments and leaders will focus on this issue more than at any previous time.

The role of energy in this type of development policy is fundamental, since it affects all of the development dimensions. Shortage of this vital ingredient presently constrains progress from agrarian to more diverse economies in many countries. The task of providing the energy services that will enable growth in the third world will require the creation of enterprise based policies, including finance mechanisms, regulatory environments and regional co-ordination, supported by technology infrastructure. This is a massive task for most developing countries, and ideally their energy systems should evolve following in a demand-led manner, rather than a supply dominated model as experienced in the first world. As the third world moves towards increased prosperity, the rates of growth will be similar to those already experienced in the west, and this process largely shapes the responsibilities of the developed countries as regards sustainable development. These responsibilities are mainly in the form of development assistance to the third world, and environmental and resource use issues.

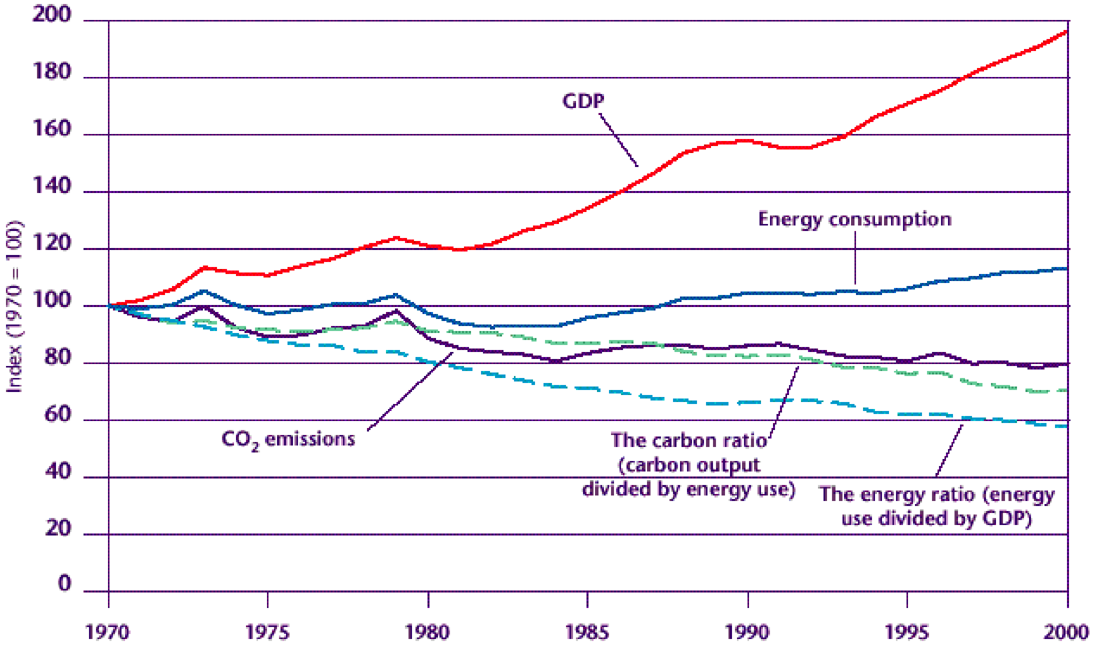
Debate is intense at this time as to whether the state of the world, as regards these issues, is actually getting better or worse. Are there impending social and environmental catastrophes or are we steadily increasing the lot of the world, with only a sustainable impact on our environment? These important questions increasingly set the framework of supra-national agreements and directives, such as environmental legislation, and influence the allocation of resources and efforts. This allocation of resources is extremely important. It is not desirable to invest heavily in preventative schemes such as pollution abatement, if they are not likely to be necessary in the long run, and are likely to be economically disruptive; even more so if international partners are not doing the same. This would constitute what could eventually be a massive waste. Decisions regarding these issues need to be based on informed choices, which clearly define the package of benefits against other options. As with all investments, the most desirable, and those which should be made first, are those that can stimulate maximum rewards, both financial and environmental, for minimum expense.

As it affects all aspects of development, energy is a central issue in government thinking, often affecting, if not largely integrated into, foreign policy. The UK government is presently formulating its first energy policy, responding to the new pressures of resources depletion and climate change. The policy is expected to be shaped by a recent report to Government entitled 'The Energy Review', from a think tank called the Policy and Innovation Unit, which exists to inform and direct future policy. The report recommends that the priorities of the UK's future energy strategy "are likely to be most cost-effectively served by promoting energy efficiency and expanding the role of renewables"[2]. The report recommends that the potential for energy efficiency in all sectors needs to be explored. Since industry is one of the largest users of energy in the UK, greater energy efficiency in industrial processes represents a major potential source of energy and economic savings, with these savings often accompanying improved environmental performance.

1.2 Energy and Industry

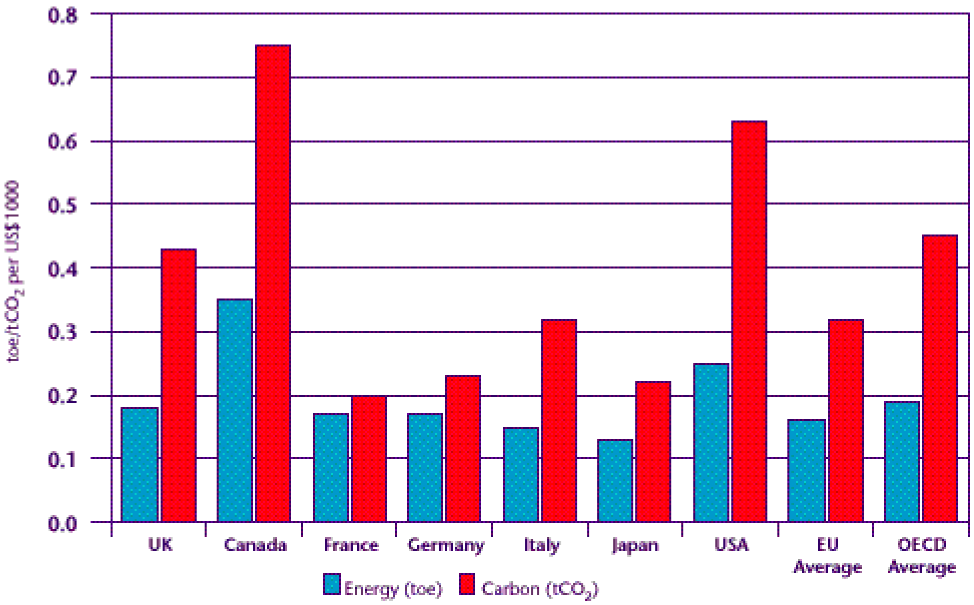
Industrial productivity is one measure of development, but it is a key one which affects an important measure of government reporting, Gross Domestic Product or GDP. Since governments will always strive to grow their country's GDP annually, a minimum level of demand in developed countries can be expected. Figure 1 shows the relationship between energy consumption and GDP in the UK for the past 30 years - GDP growth is diverging from energy consumption but both measures follow a rising trend.

Demand for energy in OECD countries presently accounts for approximately half of world consumption, though has remained constant or risen slowly over the past 15 years, reflecting the shift away from energy-intensive industries and an increasing awareness of energy conservation issues. Figure 2 shows the quantities of energy in tonnes-of-oil-equivalent (toe) per unit of GDP for the EU and OECD countries in the year 2000, and also the equivalent CO_2 emissions.



Source: DTI (2001a), ONS (2001), DEFRA (2001b).

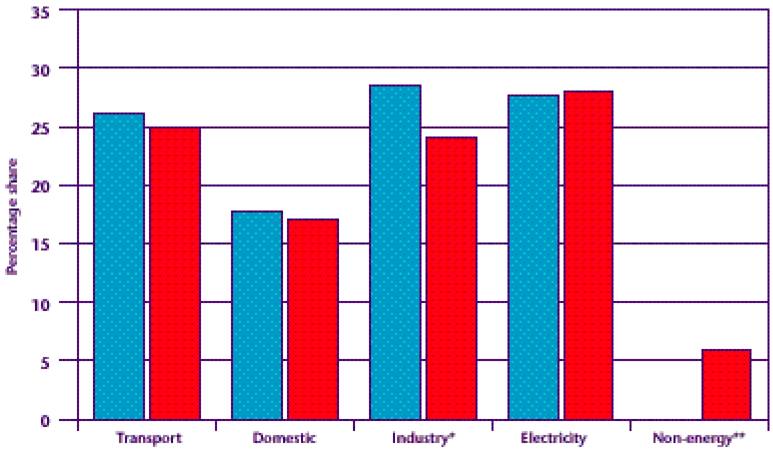
Figure 1 - GDP and Energy Consumption in the UK 1970 - 2000



Source: IEA (2001a).

Figure 2 - Energy Consumption and Carbon Emissions per unit of GDP for EU and OECD countries in the year 2000

Industry is one of the largest users of energy in these countries, accounting for approximately 25-30% of total consumption, a figure that is reflected in the UK. Figure 3 shows the consumption of fossil fuels by sector in the UK for the year 2000, showing industry consuming slightly more than electricity generation, although this represents a drop of consumption in real terms over the past 30 years. While the figure has dropped, reflecting the move away from large, energy intensive industries such as shipbuilding, it will not naturally drop any further. This means a continuing minimum level of energy and fossil fuel consumption unless drastic amounts of renewable energy are introduced. Although the UK government has set ambitious plans for integration of renewable energy at national / grid-integrated and distributed levels, any plans to reduce energy consumption and related environmental degradation indicate a need for extensive demand side action as well.



*Includes commerce, public sector and refineries
**emissions from land use changes

Source: DTI (2001d).

Figure 3 - Fossil Fuel Consumption by Sector in the UK in the year 2000

The country's international commitments to sustainable development and pollution control will be met in large proportion by industry, since the grouping is responsible for such a high level of resource use and emissions. It is also one that is easier to affect by legislation and is also driven by inherent values of continuous improvement.

Some of the priorities of the UK government's strategy for sustainable development are as follows:

- Achieving major long-term cuts in greenhouse gas emissions whilst ensuring secure, diverse supplies of energy at competitive prices in environmentally acceptable ways;
- Reducing the spread of persistent or diffuse pollutants and improving management of waste, and;
- Working with others to combat global climate challenges such as climate change and threats to biodiversity, oceans and forests[3].

Examining these priorities prompts the question of what is the present state in the UK of promoting energy efficiency, environmental performance and awareness of the need for action in industry. What do we stand to gain by acting, on micro and macro levels? What do we stand to lose? Who is responsible and what aids exist to assist those who are charged with action?

Presently there are some fiscal and legislative measures in the UK and the EU that serve to increase energy and environmental performance, though more so environmental, such as the climate change levy, fossil fuel taxation, and the IPPC directive. While these instruments do stimulate compliance levels of action, the onus is on companies to engage in voluntary measures, recognizing the potential benefits and acting within the context of improving profitability. The energy conservation field is generally known as Energy Management and is not a new subject. Much literature has been written on the techniques available for energy performance improvement in industrial processes, since the field began in the 1970's. A UK government scheme called the Energy Efficiency Best Practice Programme operates to disseminate information on generalized best practice, technology development and case study examples.

In the current world of instant information access, the information needed to assist improvements in energy and environmental performance is readily available. Furthermore, environmental performance can now be recognized under environmental management systems such as International Standard ISO 14001 and Eco-Management and Audit Schemes (EMAS), generally held to improve business through the appearance of running an environmentally responsible company.

So there have been some efforts towards greater energy efficiency in industrial processes, but there is room for much more. It is suggested that if today's best practices are adopted, the efficiency of overall energy use could improve by 10-25%[4]. Assuming that an organization is in principal interested in improving its energy and environmental performance, the next level of issues become those of management commitment, awareness, responsibility, and the influence of company culture. This presents challenges for originations of all sizes. Large companies with extensive premises will benefit from an existing information infrastructure and the availability of investment capital, though they will face a challenge in changing inefficient energy behaviour. SME's will not have to invest as much to make similar percentage savings, and will have an easier process to educate and change behaviour, but will lack the availability of resources to allocate solely to improvement of these systems. The issues are unique to individual organizations, which are required to take the initiative, though mechanisms of knowledge sharing will support both specific and general industry.

Almost all business activities now currently rely on use of software tools, and energy and environmental systems are also benefiting from increasing levels of research and commercial development. Using these tools can provide justification for energy projects, turning them from speculative ventures into dependable investments. Energy systems performance modelling for design and decision support, active systems control and optimisation, and investment appraisal tools all exist in mature states, and could eventually be integrated into standard business processes, once energy and environmental thinking becomes a priority in business values.

1.3 Summary

As we move towards sustainable development, energy issues are increasingly important, affecting all dimensions of this vision. The issues related to the developed world are primarily those of increased supply from technologies with good environmental performance, and the application of demand side management techniques across the board. Nowhere is this more important than in industry, which is a large sector-user of energy throughout the world. Information technology and the availability of software tools will provide a powerful tool in the increasing influence of this subject in business thinking.

1.4 Objectives

Having identified industry as a major consumer of energy, and argued the case for improvement of energy performance in industrial processes (Chapter 2), this thesis will present the value of, and demonstrate a methodology for optimisation analysis of energy systems.

In investigating the optimisation potential, the value of quantitative analysis by software modelling, to support decision-making, will be proved to operators of energy technologies and energy intensive processes.

This will be done through the use of a case study that was undertaken to investigate the potential for improvement of a heat-delivery energy system in a drying process, at a sawmill operation in Scotland. The results of this investigation give the operator choices to consider in their own energy performance improvement efforts.

References

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Chapter 2 – Energy in Industry

2.1 Energy in Industrial Processes

Energy demands in industry account for approximately 25%[1] of UK national energy demand, at a total cost of £7,000 million per annum. Individual industries and businesses have different demands, which are met from various combinations of on-site heat and power generation from delivered fuels, and electricity and gas consumption from mains supplies. Fuel and energy consumption rates and energy processes depend on the type of product produced.

The main energy needs of industry are for process uses, such as low temp (<500°C) and high temp (>500°C) furnace, drying and other heating operations; motive power, refrigeration, compressed air, and cooling water; and production and office building services such as space conditioning, lighting, domestic hot water (DHW), and general power.

A US study showed that six energy intensive industries dominate industrial energy consumption in that country. These are, in order of consumption; chemicals and allied products; primary metals; petroleum and coal products; stone, clay and glass products; paper and allied products; and food and allied products. A similar situation exists in the UK where, from an average annual consumption (in industry) of 448,443 million kWh, 84,999 million kWh (19%) is consumed in the iron and steel industry. Despite these large amounts of energy being consumed in a few energy intensive industries, the majority is consumed in diverse manufacturing units and large office complexes. This represents a barrier in the address of energy conservation issues. Many businesses are not aware of the issues, or do not prioritize them, making it a difficult area to stimulate action.

From a technical point of view, the common trait between these sectors and businesses are energy consumption patterns that generally apply. It is possible to categorize energy consumption patterns by the type of energy processes involved, and by forming them, basic categories of energy conservation can be related and their potential can be generally appreciated.

In approximate order of energy consumption, these categories are:

- Boiler fuel – energy to produce steam / pressurised hot water for process energy and space heating.
- Direct process heat – energy supplied to kilns, dryers, ovens etc.
- Feedstock – equivalent energy of materials consumed as feedstock to produce goods.
- Mechanical drive – energy supplied to electric motors for pumping, conveying etc.
- Space conditioning – energy expended to directly heat, cool or ventilate space.
- Lighting.

These categories bear a relationship to size of plant and the levels of production the facility operates at. However, this is not a linear relationship since efficiency drops when plant utilization decreases and energy consumption does not (there will be a minimum rate necessary to operate equipment). This means that the cost of energy per unit of production rises. It is often under these conditions that the benefits of energy conservation measures become clear.

2.2 Energy Efficiency and the Potential for Savings

Improving energy efficiency can provide industry with increased profitability and improved environmental performance. The systemic relationship between energy and environment will be the driving force behind improvements in the field, though as previously discussed, the responsibility of improving performance currently lies within the sector. As yet, no drastic legislative or fiscal measures are forcing companies to act; only the recognition of cost effective opportunities for savings.

The estimated potential for energy savings in the UK is 31.4%[2] across all sectors. In industry, this translates to an estimate of 23.8%[3] potential savings, which would drop its share of UK energy consumption to around 22%, with an annual saving of a staggering

£1,380 million. The main factors that will affect the levels of realization are economic, which are usually cost effective, and technological, which is mature. Maximizing these levels will likely be best served by specific energy efficiency sections in the energy policy - a proposal which could induce more action in energy efficiency is that the cost of climate change is linked to the price of fossil fuels, ultimately driving them up. Another method is to promote increased innovation in energy efficiency.

There are however, some potential barriers to increased energy efficiency. A significant potential effect of increased measures is that of the ‘rebound effect’. In industry this means that the increase in energy efficiency will lead to an increase in productivity, and ultimately an increase in demand. A similar effect is possible in the domestic sector, reducing estimated cross-sector savings to around 10%. However, any savings in the 10-31% bracket would play a significant part in reaching reduced emissions targets. Although these are not presently set, they should be in line with a strategy (which includes other energy issues such as expanding the role of renewable energy) for a 60% reduction of CO_2 emissions by the year 2050. Pace of improvement will need to be increased if these targets are to be reached

Yet in the short term acting in an energy efficient manner in industry will be mostly performed in the pursuit of in-house benefit, a worthy cause in its own right. This invites a brief discussion on the topic of Energy Management.

2.2.1 Energy Management

Energy Management originated during the oil crises of 1974 as a reaction to the prospect of insecure fossil fuel supplies, and has developed ever since as a result of concern over environmental issues. The subject is concerned with industrial energy auditing and conservation activities, aiming to apply engineering skills to the optimal use of energy resources within a business, thus increasing revenue for the organization. As such, it is a subject that crosses several disciplines, such as thermodynamics, heat transfer and fluid mechanics; electrical and control systems; and management and economics.

Within a particular site, energy management will address all energy consuming processes and devices in a search for opportunities for improvement and conservation. Success of the programme is best assured by a strategic approach, led from the top down, with commitment and resources guaranteed. This will be generally in three phases:

Phase 1 – Gaining control over energy consumption
Phase 2 – Investing in energy saving measures
Phase 3 – Maintaining control over consumption

To gain control over energy consumption requires knowledge of the existing periodic (usually annual) consumption patterns. This is done through *energy monitoring and auditing*. An energy audit gives a formal account of consumption and costs over the period. The data for the audit will come from a continuous programme of monitoring energy consumption. With this data at hand analyses can be made to identify inefficiencies in the system, and the potential for conservation measures. The initial phase will also consist of a review of fuel purchasing and operating practices.

Investment strategies can then be investigated, with the aim of ranking and implementing them in order of rate of return.

From the first investment made and continuously thereafter, a system of ensuring return on investment is secure should be in place, by maintaining new practices and information monitoring. Decisions can then be made on the future of the energy strategy. Several techniques of information analysis exist for the energy manager to do this, such as the use of an energy management matrix, which identifies the level of sophistication that the company has reached at any one time in six key energy management issues. These are: Energy Policy, Organization, Motivation, Information Systems, Marketing and Investment.

Other, more specific techniques are the use of Normalized Performance Indicators (NPI), which rate performance against industry standards, and CUSUM (CUMulative SUM deviation) analysis; a statistical technique which identifies trend in sequential data, such as consumption data.

2.2.2 Energy Use Profiles

An interesting way to examine the total energy consumption in industrial processes is to examine *energy use profiles*. All industrial processes have individual energy use profiles, which will be similar for like processes but will vary from one facility to another. An energy use profile is a description of all energy converted from one form to another, including the amount and losses, within an isolated industrial process. Energy use profiles are useful for examining the total energy inputs and outputs in an entire industrial process, and assist in identifying the potential for energy conservation. An example of a general energy use profile for steelmaking is shown in Figure 2.

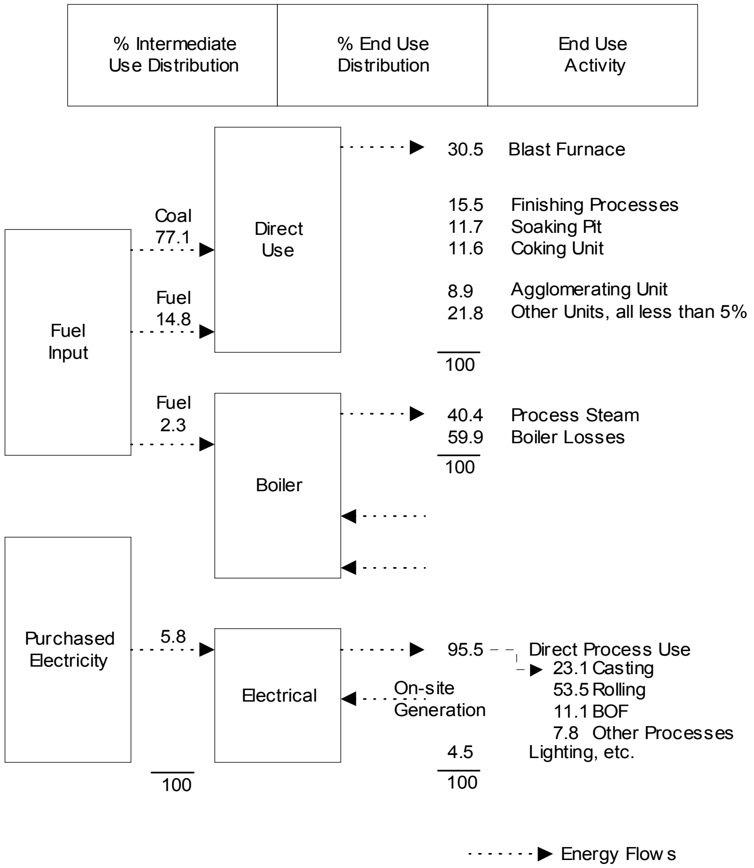

Figure 5 - Energy Use Profile for Steelmaking

The energy use profile for steelmaking in figure 2 is a simplistic representation of what is in fact a complex energy process, giving only an immediate indication of where all the energy in the process is used. The dashed lines in the diagram represent the energy flows, indicating percentage of total energy being used at each stage being of a specific process. This diagrammatic form can be drawn in more detail to include every energy process and its efficiency. This can be extremely useful for multi-stage processes with many energy inputs. Stage efficiencies can be calculated and the overall performance evaluated against the design specifications, by correlating the design efficiencies against those observed. This can indicate where problems exist, if any, in the process *as found*, before any energy conservation measures are applied to the system.

2.3 Energy Issues in Process Drying

Drying is an energy intensive process and ideal to isolate and investigate on account of its expensive nature. Chapter 3 gives a detailed account of a drying process that has been selected for an in-depth study of its energy issues; however, the following section will provide an introduction to the energy issues involved in process drying industries, such as heat delivery and techniques for optimisation.

2.3.1 Process Drying Industries

Drying is a technique used in industry to remove or reduce moisture content from materials, or preserve their dryness state. These materials may be themselves a finished product; dried foods for example, or be a component level part of a product or which drying is an isolated process, such as chemical compounds. A typical drying process will involve the transfer of heat from a heat-exchanging device such as a radiator, which may be assisted by air movement. Temperatures used in drying processes can reach up to several hundred degrees in the textile industry.

Process drying is an energy intensive operation used in many industries. In the UK, an estimated £365 million/year is spent on drying in textiles, food and drink, chemicals and paper industries[4]. It is therefore a process in which good design and operation of new equipment is necessary if energy performance is to be optimum, and which intervention into existing operations can yield significant savings.

2.3.2 Heat Delivery

Heated air has been used as a source of power since the days of the early Greeks. In the 19th century a hot air engine was created and greater understanding was achieved in the field of Engineering Thermodynamics, concerned with heat and work relationships using a working substance. The industrial revolution seen the continued development of machines and thermodynamics in a complimentary role, and this has continued to present. From steam engines to internal combustion engines to nuclear powered generating stations, thermodynamics and machinery have had a reciprocal growth.

Controlled delivery of heat remains an important engineering process upon which much of modern industry depends. It is also the foundation of all drying processes, where the heat is used directly and not for conversion to work. The technological heart of heat delivery systems in which a fluid is used as the heat transfer mechanism is the boiler. The working substance is usually water, which can be heated to steam or pressurized hot water. The heated fluid then needs to be transported to the location of its end use, which is done through a system of distribution pipework, which eventually feeds the working fluid back into the boiler at a lower temperature for reheating.

2.3.3 Process Inefficiencies and Optimisation

As with all industrial processes, inefficiencies can occur as a result of bad design, incorrect operation, and poor maintenance or neglect. A likely cause of inefficiency in drying processes is in the heat delivery systems, where heat is lost in the system before it can be used for its intended application. Heat loss will occur from all hot surfaces surrounded by lower ambient temperature, such as hot pipes and boiler surfaces. Other significant causes of inefficiency are poor combustion performance, caused by conditions such as excess air and excessive moisture in the fuel, resulting in low heat transfer to the working fluid; and poor control.

There are a number of techniques available to optimise performance under such conditions of large inefficiencies in the system. System insulation, improved control and heat recovery a few that are often cost effective. The potential for heat recovery alone in the UK is estimated at 5.6 PJ/year[5], with possible savings of around £10 million. Analysis of the existing conditions is necessary to quantify the inefficiencies and losses, so that cost effective courses of action can be determined.

2.4 Summary

Much of the energy consumed in industry is in a few energy-intensive industries, but the majority spread out over many diverse industrial units. A common trait between these diverse manufacturing processes is the energy processes involved.

Improving energy efficiency in industry is a direct method of increasing profit and environmental performance, and is consistent with government desires and obligations to international environmental agreements, though not presently regulated by government. Energy management and energy process optimisation are strategic and tactical methods of realizing improved energy efficiency, and have relevance to, amongst other industrial processes, drying operations where heat is used directly.

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Chapter 3 - An Optimisation Study

The relationship between energy and the current, global issues of Sustainable Development (SD) has been discussed, and also how industry has an important role to play in meeting SD targets in the developed world. Strategic approaches to energy efficient behaviour have been highlighted as viable investments for organizations of many sizes, and within this, the use of optimisation and best practice techniques. The potential for optimisation can then be demonstrated through analysis of a real energy related industrial problem.

To do this, an investigation was made at a sawmill operation in Scotland that produces sawn and treated wood products, employing a drying process. The investigation was instigated as a more detailed study to a general energy survey that was performed on the site, which highlighted that the system boiler, which provides the heat for the drying process, was not operating very efficiently.

The following section will provide an introduction to the company and a general discussion on the wood drying process.

3.1 BSW Sawmills

BSW (Brownlie Sawed Woods) are the largest specialist sawmilling business in the UK. The company has 6 sawmilling operations in the country at locations indicated in figure 5, employing over 500 people, and has recently set up an operation in Latvia. In total, the company accounts for 20% of sawn wood production from British coniferous forests.

The company processes recently felled and stripped trees into sections of wood that are of use in mainly construction, decking and fencing applications. For use in construction, timber must be processed to standards of quality determined by industry regulation. These customer demands have led to BSW becoming a leader in the production of kiln-dried, strength graded and chemically treated timber for load bearing and exposed use applications.

Figure 5 - BSW Operations in the UK

Kilmallie sawmill is based in Corpach, near Fort William in the western highlands area of Scotland. It is a 7-hectare site, and has an annual input of 142,000 cubic meters of felled wood; producing around 82,500 cubic meters of sawn timber.

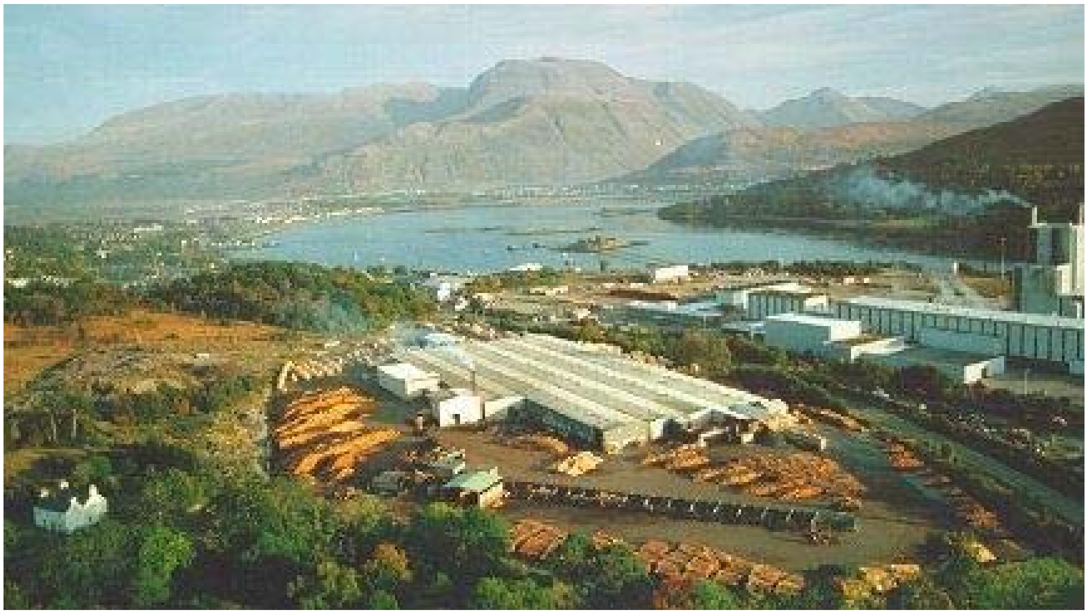

Figure 6 - Kilmallie Sawmill. The site is scenically located next to Ben Nevis, the highest mountain in the UK.

3.1.1 Kilmallie Sawmill Products

The Kilmallie sawmill line produces centre core and board sections of sawed wood, which are then dried in Kilns. Some batches are also chemically treated. Wood sections are produced from the site in the following sizes (depth x width (in mm)), in lengths between 2.4 and 4.8m:

38 x 100	47 x 75	50 x 100	63 x 100	75 x 100
38 x 125	47 x 100	50 x 125	62 x 125	75 x 125
38 x 150	47 x 125	50 x 150	63 x 150	75 x 150
38 x 175	47 x 150	50 x 175	63 x 175	75 x 175
38 x 200	47 x 175	50 x 200	63 x 200	75 x 200
	47 x 200		63 x 225	75 x 225
	47 x 225			
	47 x 250			

Table 1 - Board Sizes produced at Kilmallie Sawmill

Once the boards come off the sawmill line, they undergo the drying process, for which they are loaded onto ‘bogies’ for insertion into kilns. The boards are manually piled, then loaded onto a bogey by forklift truck, in a perpendicular orientation to the direction of travel in the kilns so that maximum exposure is given to the hot air. Each bogie usually consists of 4 packs, with each pack consisting of a quantity of same depth boards (e.g. 47mm). The 4 packs are spaced by 22mm x 45mm x 1.4m boards, parallel to direction of travel, at 900mm intervals and 200mm from the ends. Figure 5 shows loaded bogies waiting to enter the kilns at Kilmallie.

***Figure** 7* - Kilns 1, near, and 2, far, at the Kilmallie site, with loaded bogies waiting to enter.

3.2 Kilmallie Sawmill Wood Drying Process

3.2.1 Why and How the Wood is Dried

Drying is performed to remove moisture from the sawn timber, as required to achieve specification levels of moisture content (MC) required for use in construction and pallets. Drying is achieved by passing heated air over the wood in a controlled environment. In addition to removing moisture from the wood, this process brings several other benefits:

- dimensional stability and less risk of distortion
- fungi and moulds cannot survive on dry timber
- improved penetration of preservatives
- a smoother finish after machining
- improved performance of finishes such as paints and stains
- improved insulation
- improved strength
- lighter weight

There are two kilns at the Kilmallie site, with Kiln 2 slightly bigger than Kiln 1. They are progressive stage types. This means that during the complete drying cycle for a particular bogie, it moves progressively along inside the kiln from the infeed, colder side to the outfeed side, which is the hottest side since this is where the heating coils are located. The sequence of movement in the kiln is called a schedule, and varies for different species of wood being dried. Each of the 20 stages in the progression lasts approx. 6 hours, with one dried bogey being extracted from the kiln and one new bogie inserted in every time, for a total of around 120 hours of drying time for each bogie. In order for the kilns to receive and dispatch bogeys, the doors are opened and the bogies enter and exit the kiln on a mechanical rail device, which is manually controlled. The kilns run continuously 24 hours a day and 7 days a week, shutting down only for one week in the summer for maintenance and the same in the winter.

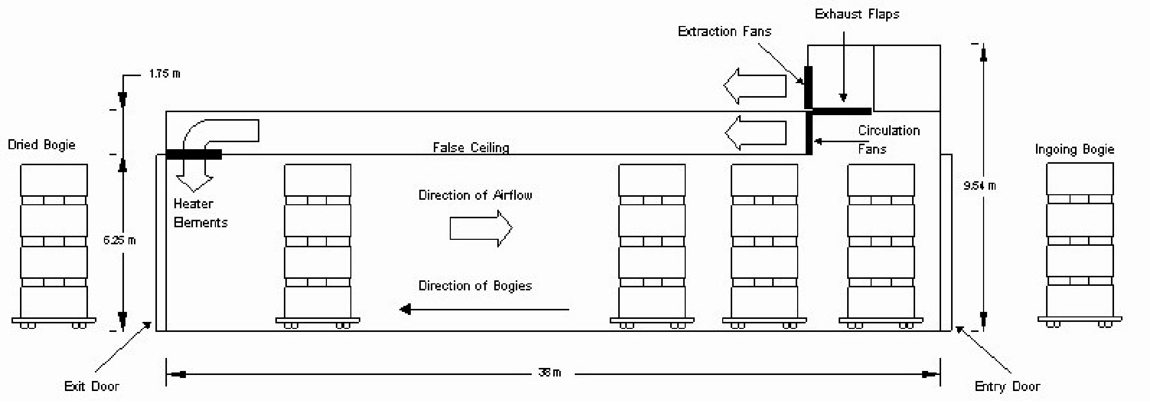

Figure 8 - Air and Material Flows in the Kilns

Figure 8 presents a schematic of the air and material flows in the kilns. The bogies enter the kilns and travel in the opposite direction from the hot air that dries the wood. Cold air from atmosphere is drawn into the kiln by a set of circulation fans (3 in kiln 1 and 4 in kiln 2), and travels along a corridor formed by a false ceiling and the actual ceiling. At the end of the corridor the air is passed over banks of heating coils (780m^2 in kiln 1 and 1170m^2 in kiln 2) at 115°C before entering the kilns' main chamber to dry the wood. Two extraction fans in each kiln carry the moistened air from the kilns back to atmosphere.

3.2.2 Quality Assurance

The main factor affecting failure rates of the finished product is moisture content. Inspection of the packs and MC testing is carried out both prior to and post drying. At the outfeed side of the kilns there is a large canopy under which dried timber cools down before its MC is checked and the product is verified. Allowing the product to cool ensures a higher pass rate, as the MC tests have proven inaccurate when the wood is still warm.

3.2.3 Kiln Control

Kiln conditions are maintained by a simple negative feedback control system, monitoring dry-bulb temperature and relative humidity (RH). These two variables are set to the following seasonal values:

Summer		Winter	
Dry bulb temp	50°C	Dry bulb temp	55°C
RH	45%	RH	40%

The only other variable that can be affected to ensure quality in the drying process is the cycle time. In summer this around 5-6 hrs/stage, for a total of ~120 hrs in the kiln, and in winter it is increased to around 7 hrs/stage, for a total of ~140 hrs in the kiln.

3.3 The Boiler System & Distribution Pipework

Employing wood-fuel boilers is a cost effective strategy for sawmill-based wood drying operations, since the fuel is provided in the form of residues from the sawing process. This is the case at Kilmallie. The boiler produces pressurized hot water (PHW) that is distributed to the kiln heating coils via a series of pipework.

The process residues that fuel the boiler are bark, woodchips and sawdust. Bark is only used during the summer, when MC is lower (bark stripping is the first process that arriving timber is subjected to, and is only performed in the summer). Woodchips are produced from passing sawn residues through a chipper. The chips are then automatically sorted from the sawdust and re-chipped if found to be too large - ideal size is around

25mm square. The sawdust is sold as a by-product and the chips and bark are used as fuel for the boiler.

3.3.1 Boiler Design and Operation Features

This investigation is aiming to determine to what level the boiler is operating outside of its design parameters. Therefore, this section describes the design characteristics and specifications as given in the documentation provided by the manufacturer, KARA Energy Systems.

The boiler was installed in May 1997, and is a laying triple-pass, fire-tube, wet-wood design, with a designed combustion efficiency of approximately 75% (defined as net energy output in hot water divided by energy input from wood, x 100% - based on net/lower heating value).

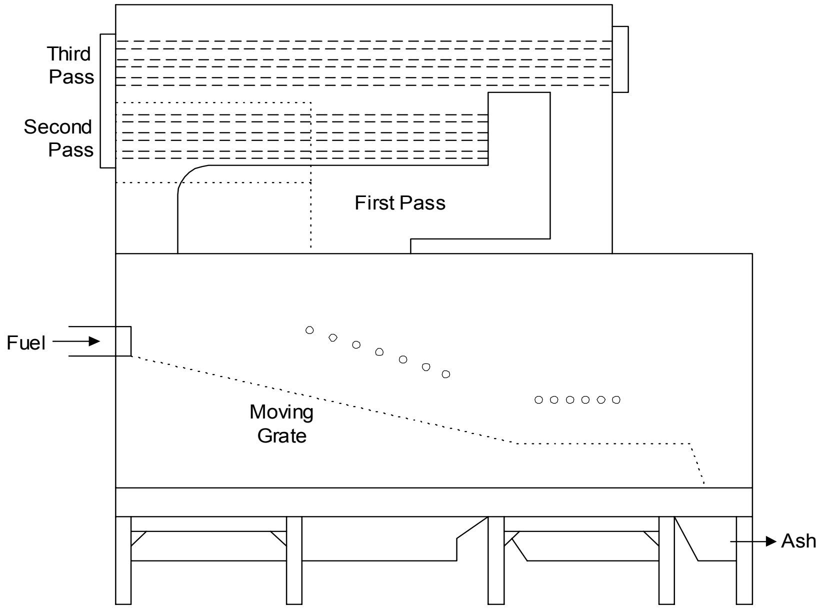

Figure 9 - Schematic of Boiler and Furnace

The following technical specifications[1] define the system design:

Capacity	2,326 kW	Fuel Consumption Rate	2,768.5 kg/hr
Max. Water Temp	110°C	Fuel Calorific Value	3,780 kJ/kg
Operating Pressure	3 bar	Fuel MC (up to)	70%
Test Pressure	5 bar	Combustion Air Rate	12,690 m^3/hr
Heating Surface Area	120 m^2	Combustion Air Oxygen %	11%
Water Content	7.5 m^3	Air Excess Factor	3.0168
Length	6m	Furnace Temp	1,000°C
Dia (Rounded Section)	2.7m	Flue Gas Temp	180°C
Height	6m	Flue Gas Rate	24650.1 m^3/hr

Table 2 – Main Boiler Design Specifications

Fuel is delivered to the furnace from a moving-floor hopper via a chain conveyor and a hydraulic feeding ram. The fuel moves along inside the furnace by means of hydraulic moving grate.

Combustion air rate should be split into primary and secondary air. The design intake rates are 4,230 m^3/hr for primary air and 8,460 m^3/hr for secondary air. Heat exchangers, tapping from the main hot water feed, are situated on both the air intakes and designed to increase the air temp from ambient (~20°C) to around 63°C. A tertiary air intake was added in an attempt to improve performance, but discontinued after it failed to do so (along with primary air which also does not operate). Air intake should also be regulated for batches of fuel with lower MC, for which a MC sensor should be located next to the fuel drying system. Motorized dampers should also be located on the flue ducting to modulate furnace pressure. A recirculation channel is present for under-pressure control, which should be enabled by an automatic damper system.

Modulated control is specified to optimise combustion, especially required to address the variations in moisture content of the fuel - quantity of fuel should be reduced when desired water temperature is reached, and air intake rate also reduced shortly thereafter.

Combustion gases are channelled from the boiler, through a filter installation, to the flue. An induced draught fan provides the negative pressure necessary for this effect. The filter is constructed from three cyclone devices that separate particulates from the gas. Removed particulates drop into a funnel and are removed in the first instance by an ash transport screw, and then transported by a conveyor chain to an ash pit. Modifications were made to branch off second-pass combustion gases and route them to the air intake to assist in the air pre-heat, but this was later isolated having been found to not produce the desired effect.

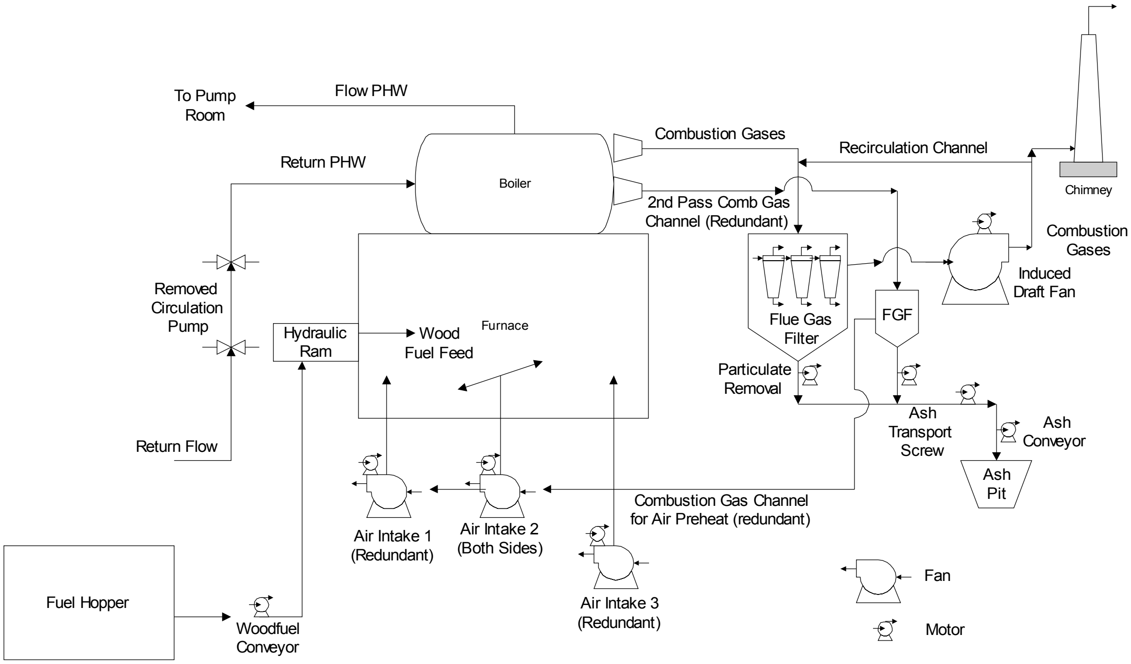

Figure 10 - Fuel, Gas & Water Flows in the Boilerhouse, including those designed in, added, and those that are now redundant

The system is closed loop, circulating water to the heating coils in the kilns and back again to the boiler. The fluid losses from this loop are small. There are two main pipes for the flow and return of water in the boilerhouse, from which several other smaller pipes branch off for various reasons. A flow and return pipe are branched off the main flow for the primary and secondary air intake heat exchanger, though the primary air is redundant and the heat exchanger isolated, and another branch provides cooling water to the hydraulic fuel ram, where buckling of the casing was being caused by heat from the furnace.

3.3.2 Heat Distribution

Pressurized hot water is distributed to the kiln heating coils by pipes. The main flow pipe runs from the boilerhouse, through the hopper room, outside, and along inside the main sawmill warehouse to a pumproom adjacent to the kilns. The main flow and return pipes split into two separate flow and return pipes for each kiln at this juncture. This constitutes a total of approximately 100m of piping from the boiler to the heating coils and the same on the return side. The system is designed to provide continuous flow from the boiler to the pumproom. The kiln controller is in the pumproom, and is designed to operate by opening an actuator valve to allow PHW to flow to and from the heating coils when the temperature in the kilns falls to the lower set point. When the upper set point has been reached, the actuator valves (one for each kiln) close and the PHW flow bypasses the kiln junctions and returns straight to the boiler. Two pumps, one for each kiln, are located on the return line for each kiln, to assist the flow from the pump room to the heating coils, as this involves a vertical climb of approximately 2.5m.

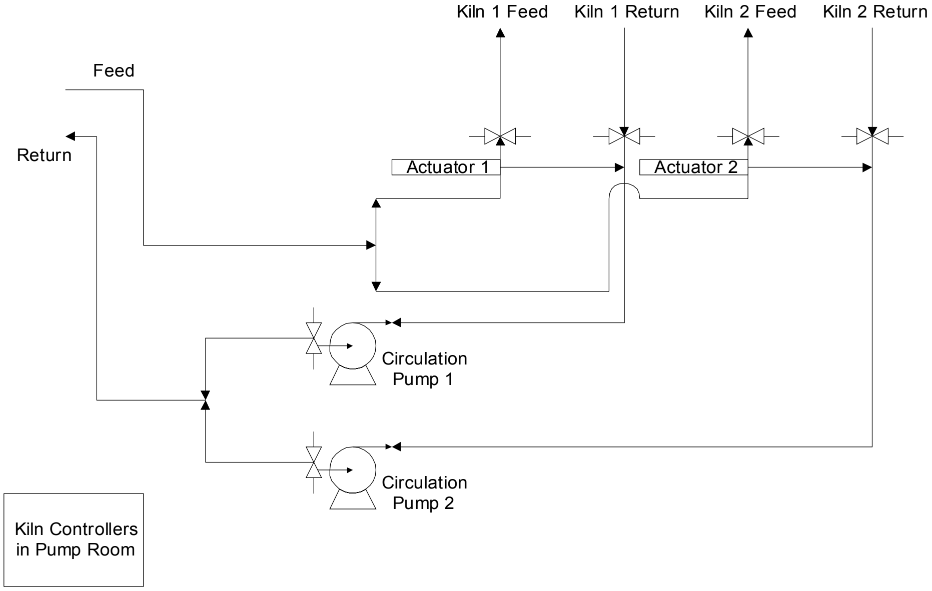

Figure 12 - Water Flows in the Kiln Pumproom

3.4 Design & Operational Characteristics and Problems

The previous section described the boiler and distribution system as it has been specified and designed. This investigation has arisen from the fact that the installation and operational characteristics, including progressive changes to the system that have been made, are not totally consistent with the documentation and expected performance, leading to speculation about the cost of these problems. This section will present these operational deficiencies.

3.4.1 Design and Installation Issues

Several issues have been observed with the design and installation of the boiler and the PHW distribution system. These are:

- ⇒ The boiler was a prototype for the manufacturer, not constructed with the benefit of analysing performance of previous models.
- ⇒ The boiler was sized with the scope of handling load from a planned additional batch kiln, which was subsequently not constructed. (Batch kilns process quantities of wood in one cycle, as opposed to progressive stages).
- ⇒ Several of the specified design/installation features are either not present, poorly installed, or not functioning. These are:
  1. The boiler surfaces and all of the pipework in the boilerhouse are not insulated.
  2. The distribution pipework, which was installed some 20 years previously with the previous boiler, is insulated in some sections and either not insulated or poorly insulated in others.
  3. The proposed fuel MC sensor is not installed, thus retarding the possibility of modulated fuel feed based on that variable.
  4. A specified heat exchanger in the flue gas ducting to provide heat for combustion air pre-heat is not installed.

The reasons for the state of the installation are unclear, though one probable explanation is that both the manufacturer and the operator made compromises over the issue of cost, with no appreciation of the future difficulties this would cause.

3.4.2 Operating Issues

The boiler system has a number of unspecified and undesired operating conditions that have resulted both from the initial design deficiencies and from progressive measures to get the system working (this investigation is concerned only with improvements to the boiler and distribution system, but these are inextricably linked to any end use conditions that vary from optimal. Hence, some reference is made to the kiln systems). These are:

- ⇒ Significant heat loss from the kilns, dropping the temperature to around 15°C, takes place when the doors are opened for the bogie insertion/extraction operation. This results in a demand increase every 6 hrs as the kilns heat up after the loss and return to their desired heating load, which can take around 15 minutes. The problem is exacerbated during winter. Considerable heat loss also occurs from the extraction fans.
- ⇒ The kilns are designed to accommodate 5.4m lengths of sawn boards, and the maximum produced board length is 4.8m. Thus the kilns are being under utilized, since a substantial amount of heat flows along the least-resistance path at the sides of the bogies, and is lost to atmosphere (through the extraction fans). The bogies have had to be entered in a staggered fashion in an attempt to address this loss.
- ⇒ There are several small leaks in the seals between the kiln doors and the lower seal.
- ⇒ Make-up water into the loop is not treated, indicating the possibility of scale formation along the length of the pipework and in the boiler.
- ⇒ The main PHW circulating pump, which is located on the return side near the boiler to induce PHW flow from the boiler through to the pumproom and back again, has been removed. The originally installed pump was found to be too small for the application and it repeatedly cut out. It was later removed and, with the

system then operating without operator intervention - a priority at the time regardless of efficiency, never replaced.

⇒ For optimal efficiency boilers should operate continuously at maximum load. The KARA system does not do this, due to the un-scaled relationship and unrelated control of demand and supply, and also the control of the boiler operating on a simple on/off basis.

Because the main circulation pump has been removed, circulation only takes place when the kiln temperature reaches its lower set point and the pumps in the pumproom are activated by the kiln controller (also in the pumproom and not connected to the boiler controls). At all other times the PHW is static in the loop and losing heat – a problem exacerbated by some poor / non-existent insulation on the pipework. The boiler activates when its control system observes that the flow temperature has dropped to its lower set point, usually 100°C, and switches off again when it reaches the upper set point, usually 115°C. This happens regardless of whether the PHW is circulating. Thus, the boiler temperature is rarely related the temperature at the end use (accounting for design losses); only so when the PHW has been recently circulated. If the PHW has not been circulated for some time and heat is being lost from the un-insulated flow pipe, the boiler will activate and heat water, which may not circulate to the end use for a further, undetermined amount of time. This indicates that excessive fuel is being consumed to provide an amount of heat that is not delivered to the end use. Also, the cyclic loading of the boiler means that the efficiency is reduced.

⇒ Moisture content in the fuel is very high and variable, and often higher than the maximum design limit of 70%, especially in the winter (the location is the wettest in the UK). This results in incomplete combustion of the fuel and significant heat loss through the flue in the form of steam, and also increased fuel consumption. The woodfuel is not dried.

⇒ To accommodate for the poor combustion due to high MC in the fuel, an oil burner has been added into the system. While this is an acceptable technique for wood burning boilers, assuming low use and therefore cost, this oil burner operates almost continuously during the winter months and consumes an expensive amount of fuel oil, rendering the reasoning for a free / site produced fuel fired system redundant.

⇒ Early operating difficulties with the system resulted in, among other measures, alterations to the air intakes. A tertiary air system was added to the original design then, along with the primary air intake, isolated. There is now only one air intake, the secondary air that, along with the exhaust flow, is unregulated despite this having been a specified condition. Automatic dampers (as specified) for these gas flows are in fact simple manual setting dampers, which have been fixed at settings that have allowed unassisted boiler operation. In operation, the gas flows only match the boiler load at full load because the motors driving their fans are fixed speed. Furthermore, the induced draught (ID) fan consumes excessive amounts of electricity.

⇒ The flue gas oxygen sensor is not operational.

The operational difficulties have emerged as a result of both the design issues and step changes to the system that have taken place in a non-integrated way. The primary factor driving this has been to get the system operational as quickly as possible to meet production needs, and it is only with the system operating unassisted that the operator can take full account of the problems and search for an integrated method to address them. Excessive annual spending on fuel oil has also been a motivating issue in having the system analysed.

3.5 The Need for Analysis

BSW considered an isolated examination of the boiler and distribution system as the most useful direction to take, on whose outcome decisions could be made regarding any changes, upgrades or even a full replacement. While investigations of this nature should begin with an appraisal of the demand side issues, the kiln systems are thought to be operating to an acceptable standard and no need exists to upgrade or replace them.
Identifying optimisation potential of the boiler system therefore needs a comprehensive analysis of the system as it stands.

3.6 Summary

Within an energy management strategy, or because of recognised poor performance, individual technologies and equipment may need isolated investigations so that their performance can be assessed. This will first require an investigation of the manufacturing process to determine where and how much energy is needed, and then assess the actual energy consumption against the requirements. The whole system and its components can then be assessed against best available technologies and optimisation methods, and appraised on a cost basis to determine courses of action that may be desirable.

In this optimisation study the energy using process (drying) has been described, as has the equipment used to provide the useful energy (the boiler). The technical deficiencies and the reasons for them have been described, and the operators' need for the system to be comprehensively analysed has been justified.

References

1. KARA Technical Manual

Chapter 4 - System Analysis

The energy issues of the wood drying process that are the subject of this investigation have been described, as has the equipment that provides the energy, and the design and operational deficiencies that have been reported by the operator and observed in the course of the study. This chapter deals with the analysis of these issues, aiming to construct a quantified representation of the system and assess courses of action to inform and support the operator's decision making.

4.1 Approach

The previous chapter highlighted the many problems that are apparent with the boiler-kiln system. While there are many problems, they are all largely related to each other in one form or another, and if not then it may simply be a case of replacing a failed component. This investigation aims to take a structured approach to quantify the losses and estimate the optimisation potential for the most pressing of these issues.

Reference to literature on the subject has revealed that, while developments in the technologies are continuous, fundamental operational principles must be adhered to, and only with the satisfaction of these fundamentals should more advanced, and expensive, methods of optimisation be considered. It is satisfaction of the original, designed-in efficiency that provides the direction of this analysis.

The analysis has proceeded based on data acquired for the financial year 2001-02, which is assumed to act as a base case. While annual variation is expected, all losses and savings calculated are expressed in relation to this year's figures.

4.1.1 Boiler Testing

The main focus of optimisation in end use and distribution for heat transfer systems is the most efficient use of the delivered heat. An investigation would seek to make sure that there is no preventable (at reasonable cost) heat loss was occurring from the equipment. When addressing optimisation of boilers however, specific issues need to be addressed, such as combustion efficiency. Therefore instrumented investigations need to be made to determine the as-found thermal efficiency of the boiler. A standard thermal test would seek to provide a full 'Heat Account' for the boiler, i.e. a description of all the heat inputs, outputs and losses from the system. Taking measurements allows these factors to be checked against the design expectations and any abnormalities immediately identified. This is done in large part through analysis of flue gases, but measurements need to be taken from a number of places on the system, as an extensive amount of data is necessary to determine exact quantities required if the test is to be worthwhile, such as the following;

- Gaseous content of the flue gas by percentage (Oxygen, Carbon Dioxide, Carbon Monoxide etc).
- Unburnt fuel by weight, as found in several depositions (solid fuels only).
- Elemental fuel content.
- Exact mass flow rates and properties, such as air intake and humidity.

It should be highlighted at this stage that this investigation did not include any instrumented content. Given the expensive and skilled nature of the necessary equipment use, this was decided to be impractical. Instead, the investigation has been based on a theoretical footing, using standard heat transfer relationships and assuming values where none are known (both known and assumed quantities are highlighted).

4.1.2 Specific Energy Issues to be Examined

Literature suggests that the best way to proceed with this type of investigation is to begin at the demand end of the system, and work backwards towards the boiler, only investigating its performance when all of the previous system effects have been addressed. However, while there are issues with the operation of the kilns that have already been identified as affecting the boiler system, such as heat loss through the periodic opening of the doors and through the extraction fans and some small leaks, the demand end of the system is assumed to be operating to an acceptable standard, and not in need of in-depth investigation. Observing the rest of the system and discussing the operational difficulties with BSW, led to the identification of two main areas that are the most in-need of attention, which are functionally related, comprise many of the individual problems mentioned, and easy to appreciate returns from any system changes (i.e. to the model). These are:

- Heat Loss
- Operational Efficiency and Fuel Cost Reduction

The structured approach to assessing these two parameters, working from the demand side backwards, is therefore as follows:

1. Estimate the heat loss from the distribution system, as found.
2. Assess the correctness of the match of boiler size to application.
3. Estimate the heat loss from boiler system, as found.
4. Determine the overall operational efficiency and costs, as found.

This will provide a quantified description of the system, as found. Only then can any variation in the system, reflecting any modifications or upgrades, be assessed.

4.1.3 Analysis by Modelling

The technique that has been used to assess the system is to model it. Mathematical modelling is a well-established technique in industry for analysis in design and decision support. The extension of modelling techniques into simulation, where inter-dependant variables can be assessed over time, is also gaining utilization as a valuable method in the designer's tool kit. Many software packages are already commercially available for a variety of applications, and progress is continuous as software developers exploit now-available significant computing power.

This model was created using the Microsoft Excel software; a suitable package for this type of application (though it is worth noting that dedicated software can be purchased for this type of analysis). This has been done by developing a spreadsheet, encompassing all the design and operational values and relationships of relevance, to form the required description. Then, by subjecting this model to numerical changes that reflect real, achievable modifications or upgrades to the system as suggested by best practice literature, the value of optimisation can be appreciated.

This raises the question of validity of the results. How can they be depended upon if certain quantities of the system are unknown? It is under these conditions that the strength of modelling techniques is to be found, since both the worst case and best case scenarios can be appreciated with simple numerical changes to the model. In addition, the *most likely* case can be developed based on operator knowledge of the system, and decisions based on the cost of both action and inaction with regards to all possible scenarios. Providing the model is constructed with the most accurate information that can be obtained, it is a cheap and effective way to support decision making.

4.1.4 Model Verification

The nature of the model, and the reason for using the technique, is that it contains many interdependent variables that are related by equations. This raises the possibility of error in the system in the event of an operator input mistake. Verification has therefore been employed to check the model is valid and the results correct and useful.

To do this the model was created using a system of continuously checking the correctness of all entered relationships by either:

1. Hand calculation checks, or
2. Comparison with other values in the system that depend on the same equations (and already checked by hand), by entering equal inputs.

Furthermore, upon completion, several randomly selected values that result from a series of calculations that are dependant on key variables have been hand calculated for comparison.

4.1.5 Approach to Creating the Model

To create the model, the progressive stages were as follows:

1. Gain an understanding of the system under investigation.
2. Collect as much data as possible on the system.
3. Determine standard, or expected, data to substitute for unknown parameters.
4. Determine the relationships that govern the system.
5. Enter the data and relationships into a spreadsheet in a form which allows editing of variables that are, in reality, under operator control (i.e. within the scope of optimisation techniques).

4.2 Annual Fuel Consumption & Costs

To illustrate the operation of the system, and analyse it, it is informative to look first at the annual fuel consumption, to determine the annual costs of operation. Data was acquired for the period of the financial year from April 2001 - March 2002 (week 1 = 1st April), and is as follows.

4.2.1 Annual Operating Fuel Consumption

The first element to consider is the amount of kiln-hours, or chamber-hours as they are known, that operate at the site. From figure 13 it can be see that there is significant variability in the amount of hours that the kilns operate from week to week. The maximum is 7x24=168hrs, x 2 kilns=336 chamber-hrs/week. Maintenance shutdown periods are indicated by gaps.

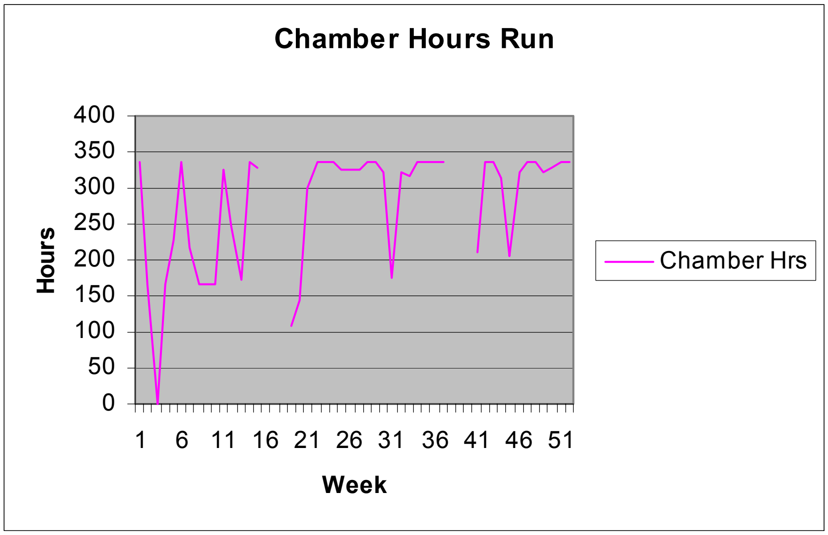

Figure 13 - Chamber Hours, accounting for both kilns, operated in the financial year 2001-2002.

The amount of fuel consumed can now be considered in relation to the chamber hours run. Woodfuel is produced on site as process residues. Kilmallie also takes delivery of wood-chippings from the Boat of Garten site as addition fuel. There is no internal cost for this fuel delivery, but there is a charge of £78 per delivery (included).

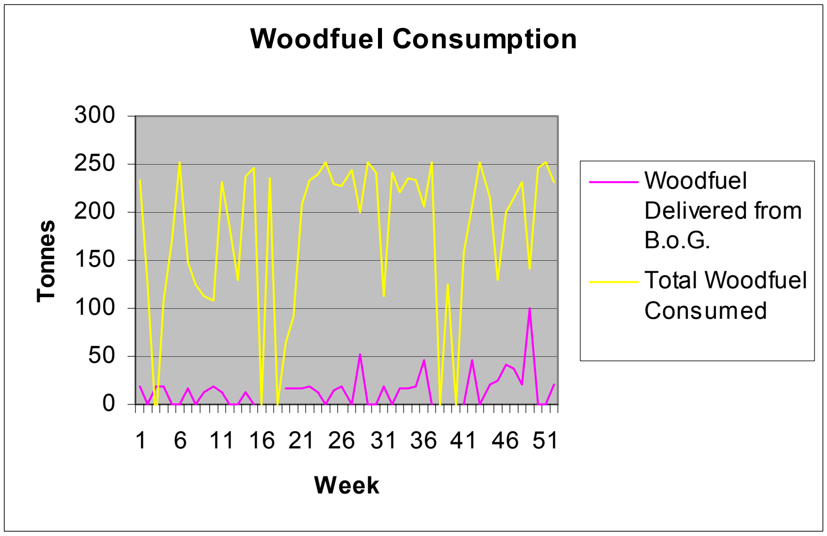

Figure 14 - Weekly Woodfuel Consumption, including that which was delivered form the Boat of Garten Site

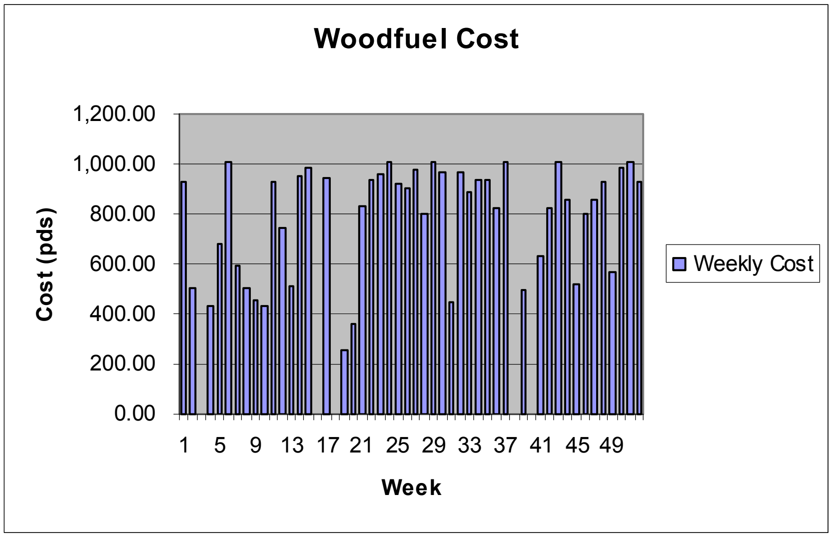

Figure 15 - Weekly Cost of the Woodfuel at £4/tonne.

It can be seen from figures 13 and 14 that solid fuel consumption is directly related to the amount of chamber hours run. However, as previously mentioned, the use of additional fuel in the form of fuel oil is used in this system. Figure 16 shows that the majority of this fuel oil is consumed during the winter and transitional seasons, when MC of the solid fuel is highest due to the high rainfall during those seasons. Figure 17 shows the weekly expenditure for this additional fuel.

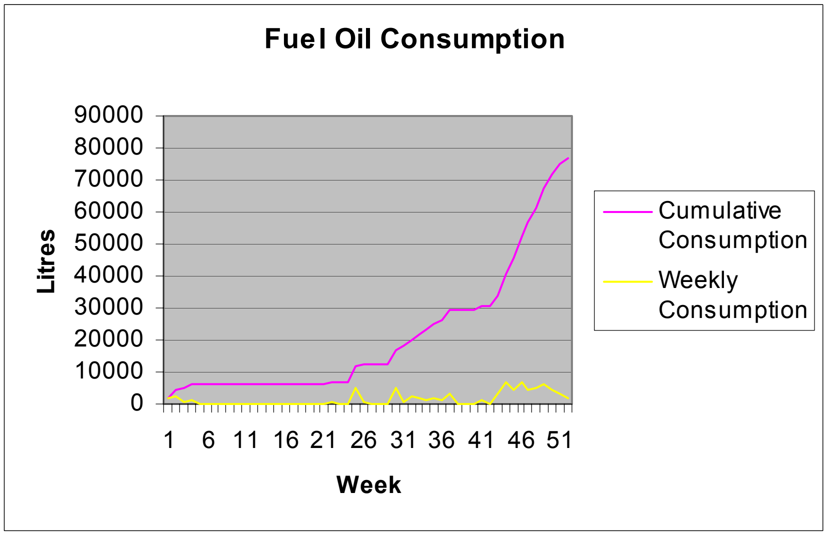

Figure 16 - Weekly & Cumulative Fuel Oil Consumption

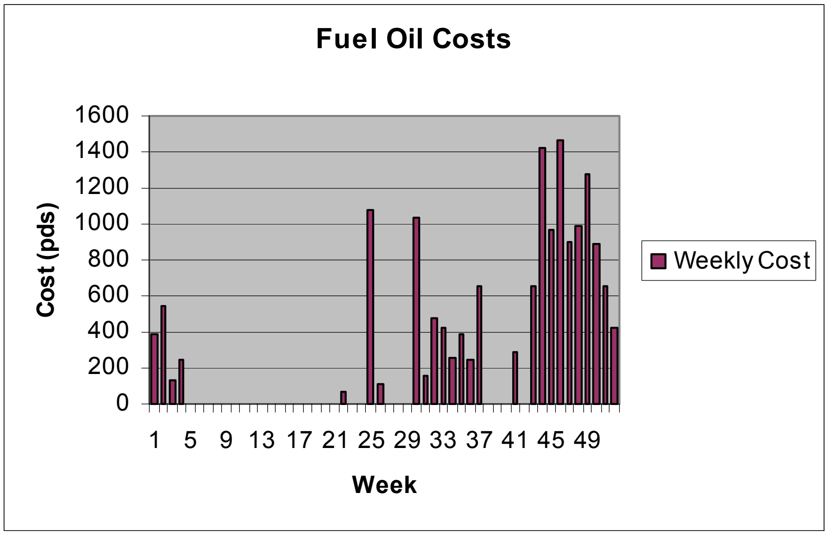

Figure 17 - Weekly Cost of Fuel Oil at £0.21/litre

The annual data that is represented in the above graphs can be summated as follows:

April 2002 to March 2003	**Annual Data**		
Consumption Totals	Total	Weekly Avg	Op Avg
Chamber Hours Run	13307	255.9038	283.1277
Fuel Oil Units (litres)	76804.00	1477.00	2954.00
Woodfuel – Delivered (Tonnes)	764.62	14.70	15.93
Woodfuel - Site (Tonnes)	8489.41	163.26	176.86
Woodfuel – Total (Tonnes)	9254.03	177.96	192.79
Average Consumption Rates			
Fuel Oil Consumption (litre/hr)	8.791667	N/A	17.58333
Wood Consumption (tonne/hr)	1.04	N/A	1.15
Costs			
Fuel Oil (£) at £0.21/litre	16128.84	310.17	620.34
Woodfuel – Delivered (£) at £4/T	2808.00	54.00	58.50
Woodfuel - Total (£) at £4/T	36862.52	708.89	767.97

Table 3 - Annual Consumption Data

The operating averages (Op Avg) are the average figures for the amount of productive chamber-hours run, as opposed to the average for the year, during which fuel will be consumed when the boiler is operational and the kilns are not, and when the kilns are operating but no product is being processed, such as during maintenance. The figures highlighted in red indicate the operating averages for fuel oil consumption, which is further defined as the only (productive) periods when fuel oil was being consumed, mostly during the winter and transitional seasons as mentioned. In order to appreciate further the seasonal variations in consumption, particularly with respect to the fuel oil, it is useful to examine them. Note that the seasons vary in length for operational days, accounting for the shutdown periods. This has been accounted for in all seasonal calculations.

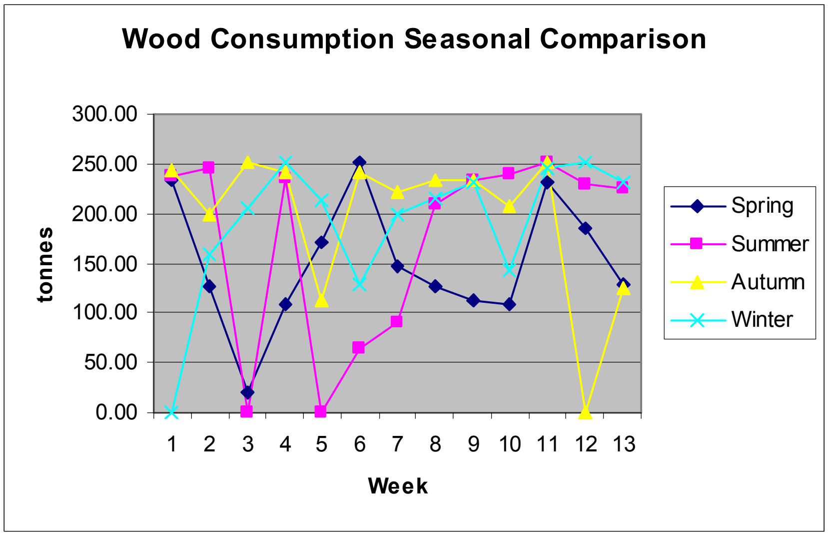

Figure 18 - Seasonal Comparison of Woodfuel Consumption

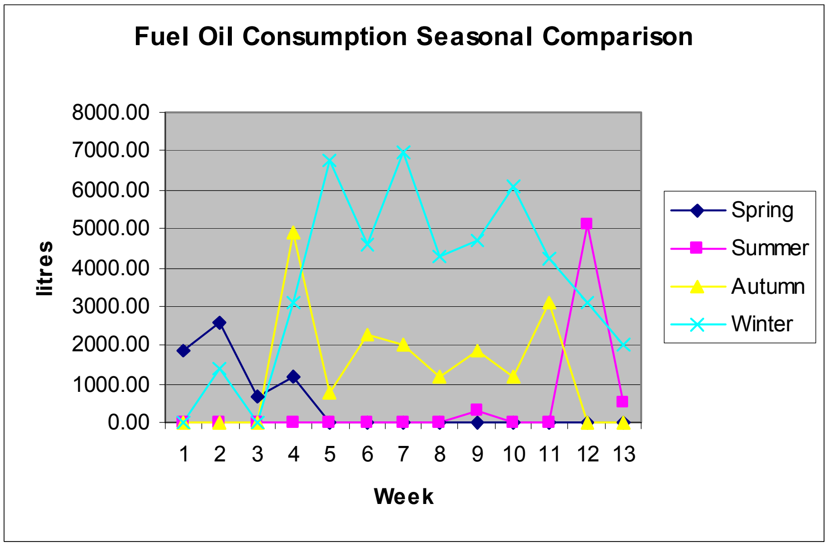

Figure 19 - Seasonal Comparison of Fuel Oil Consumption

An important point that is highlighted in the seasonal comparisons is that solid fuel consumption drops with the introduction of fuel oil. The drop is not a drastic one, but does describe a dependence on the fuel oil to achieve adequate heat input to the system.

Table 4 summates the seasonal data:

April 2002 to March 2003	Seasonal Data					
	Spring			Summer		
Consumption Totals	Total	Weekly Avg	Op Avg	Total	Weekly Avg	Op Avg
Chamber Hours Run	2703	207.92	225.25	3212	247.08	292
Fuel Oil Units (litres)	6231	479.31	1557.75	5985	460.38	1995
Woodfuel – Delivered (tonnes)	116.78	8.98	8.98	145.1	11.16	13.19
Woodfuel - Site (tonnes)	1832.09	140.93	140.93	2118.8	162.98	192.62
Woodfuel – Total (tonnes)	1948.87	149.91	149.91	2263.9	174.15	205.81
Average Consumption Rates						
Fuel Oil Consumption (litre/hr)	2.85	N/A	9.27	2.74	N/A	11.88
Wood Consumption (tonne/hr)	0.89	N/A	0.89	1.04	N/A	1.23
Costs						
Fuel Oil (£) at £0.21/litre	1308.51	100.65	327.13	1256.85	96.68	418.95
Woodfuel – Delivered (£) at £4/T	546	42	42	702	54	63.82
Woodfuel - Total (£) at £4/T	7641.88	587.84	587.84	9055.6	696.58	823.24

April 2002 to March 2003	Seasonal Data					
	Autumn			Winter		
Consumption Totals	Total	Weekly Avg	Op Avg	Total	Weekly Avg	Op Avg
Chamber Hours Run	3672	282.46	306	3720	286.15	310
6'Fuel Oil Units (litres)	17270	1328.46	2158.75	47318	3639.85	4301.64
Woodfuel – Delivered (tonnes)	188.62	14.51	15.72	314.12	24.16	26.18
Woodfuel - Site (tonnes)	2376.76	182.83	198.06	2161.76	166.29	180.15
Woodfuel – Total (tonnes)	2565.38	197.34	213.78	2475.88	190.45	206.32
Average Consumption Rates						
Fuel Oil Consumption (litre/hr)	7.91	N/A	12.85	21.67	N/A	25.6
Wood Consumption (tonne/hr)	1.17	N/A	1.27	1.13	N/A	1.23
Costs						
Fuel Oil (£) at £0.21/litre	3626.7	278.98	453.34	9936.78	764.37	903.34
Woodfuel – Delivered (£) at £4/T	702	54	58.5	858	66	71.5
Woodfuel - Total (£) at £4/T	10261.5	789.35	855.13	9903.52	761.81	825.29

Table 4 – Seasonal Data for Fuel Consumption

4.2.2 Annual Operating Costs

The above tables give:

- The consumption totals, seasonally and for the year, for primary and supplementary fuels, including weekly and operating averages.
- The average consumption rates, seasonally and for the year, for primary and supplementary fuels, including the operating averages, which are different for wood and fuel oil since fuel oil is not used continuously.
- The cost of consumption, seasonally and for the year, for primary and supplementary fuels, including weekly and operating averages.

This allows the extraction of some key figures regarding cost of operation of the boiler:

The main values of interest are the annual cost of the solid fuel and the fuel oil; £36,862.52 & £16,128.84 for the year respectively (the cost of the solid fuel will be higher than the planned cost (though not actually specified), because of the excessive MC causing incomplete combustion of the fuel, and the fuel oil cost is entirely an unplanned and excessive cost desired to be removed). Both annual (24/7/365) and annual-operating (chamber-hours) averages will be used to analyse the costs for one year, though since it can be observed that seasonal variation is a factor for this system, seasonal figures have also been analysed.

Site produced woodfuel is costed at £4/tonne, and fuel oil costs £0.21/litre, as indicated in the tables. Annual consumption averages are 1.04 T/hr of woodfuel and 8.79 l/hr of fuel oil;

1. £4/Tonne x 1.04 T/hr = £4.16/hr
2. £0.21/litre x 8.79 l/hr = £1.85/hr

Therefore the annual average (fuel) cost of operation is:

£4.16 + £1.85 = <u>£6.01/hr</u>

Operating averages are 1.15 T/hr of woodfuel and 17.58 l/hr of fuel oil (remembering that fuel oil is not constantly used, and the average rate only applies to when it is);

3. £4/Tonne x 1.15T/hr = £4.60/hr
4. £0.21/litre x 17.58l/hr = £3.69/hr

Therefore the operating average (fuel) cost is:

£4.60/hr

rising to:

£4.60 + £3.69 = £8.29/hr

when fuel oil is being used.

The same basic calculations can be made to determine the seasonal rates, which are:

Annual	Spring	Summer	Autumn	Winter
Woodfuel (£/hr)	3.56	4.16	4.68	4.52
Fuel Oil (£/hr)	0.6	0.58	1.66	4.55
Total (£/hr)	4.16	4.74	6.34	9.07

Operating	Spring	Summer	Autumn	Winter
Woodfuel (£/hr)	3.56	4.92	5.08	4.92
Fuel Oil (£/hr)	1.95	2.49	2.70	5.38
Total (£/hr)	5.51	7.41	7.78	10.3

Table 5 – Annual and Operating Seasonal Fuel Cost Rates

Again, the operating totals only apply when the fuel oil is actually being used, which is not consistently, so at all other times in the season, only the woodfuel cost applies.

Providing that operations are not in breach of environmental limitations (i.e. legally allowed to operate), reduction of these cost forms the best basis for action to improve performance, though these two fields are often related. These costs provide a datum from which to estimate annual savings in the appraisal of course of action options.

These figures indicate the actual costs of operation, averaged hourly both for over-the-year and for each chamber hour. Normal procedure would be to calculate the cost of useful output from the boiler. However, the boiler does not operate continuously, the PHW does not circulate continuously, and these two operations are not synchronised. Observing this, and the heat loss that occurs from both the distribution system and the boiler, makes it impossible to determine the cost of actual useful energy output in energy terms from the boiler at this stage. This then requires analysis of the system as-found situation.

4.3 The As-Found Situation

With the operating problems now described, and the annual costs defined, a quantified examination can now be made of the *as-found* situation. The first issue to be investigated is the heat loss in the distribution system.

4.3.1 Distribution System Heat Loss

The distribution system consists of a series of pipework in the boilerhouse, outdoors, and in the main production warehouse, including the pumproom. It was observed that the insulation on this pipework ranged from properly applied, to poorly or never applied, and in some sections it had even been removed. Heat loss from the pipes was therefore expected to be significant, and varied depending on insulation at each stage.

A survey of the pipework was made to gain knowledge of the lengths and outside diameters of pipe with PHW flow in them. Then the percentage cover, thickness and condition of the insulation on each section were surveyed. A quantitative description of this system was then made and the heat loss from the system determined.

For the purposes of determining heat loss by zone, the description of the entire pipework was achieved by numbering the pipes. Where a pipe crossed a zonal boundary, e.g. from the boilerhouse to outdoors, the pipe was then renumbered in the new zone. The numbering sequence runs continuously from 1, the main feed pipe from the boiler in the boilerhouse, to 19b, the return pipe from kiln no.1, which is outdoors. No data was available on the length of pipe sections, so this was approximately measured by hand, and the measurement inserted into the model for the individual sections, including orientation (horizontal or vertical), to obtain a total length for the pipe. The operating temperature for each pipe was assumed to be that of the either the feed or return temperature as indicated by the system control, based on whether the pipe was feeding or returning to the kilns, or a branch from these pipes. The pipe thicknesses were best estimates from standard pipe thickness tables (see Appendix 1). The zones, pipe numbers and descriptions of the pipework are as follows:

1. Boilerhouse Pipework

Pipe No.	Description	Dia (in)	Length (m)	Insulation %
1	Main Feed Pipe	10	18.3	0
2	Main Return Pipe	10	20.8	0
3	Hydraulic Ram Cooling Feed a	3	2.2	0
4	Hydraulic Ram Cooling Feed b	3	1.6	0
5	Hydraulic Ram Cooling Rtn a	3	2.3	0
6	Hydraulic Ram Cooling Rtn b	3	2.9	0
7	Secondary Air Heat Exchanger Pipe	3	13	0
8	Primary Air Heat Exchanger Pipe	3	8.6	0

2. External Pipework A

Pipe No.	Description	Dia (in)	Length (m)	Insulation %
9	Main Feed Pipe	12	2	33
10	Main Return Pipe	12	2	33

3. Warehouse Pipework

Pipe No.	Description	Dia (in)	Length (m)	Insulation %
11	Main Feed Pipe	12	70	65
12	Main Return Pipe	12	70	74
13	Main Feed Pipe	12-8	21	36
14	Main Return Pipe	12-8	14.7	19
15	Junction from Feed – Return Pipes	12	1.8	0
16	Junction from Feed – Return Pipes	5	1.5	0
17	Junction from Feed – Return Pipes	8	0.8	0

4. External Pipework B

Pipe No.	Description	Dia (in)	Length (m)	Insulation %
18a	Main Feed Pipe – Kiln 1	8	3	100
18b	Main Return Pipe – Kiln 1	8	3	100
19a	Main Feed Pipe – Kiln 2	8	3	100
19b	Main Return Pipe – Kiln 2	8	3	100

Table 6 – Distribution Pipework Description

(Note that the diameters given here are nominal diameters. Actual diameters vary and are usually slightly larger – see Appendix 1)

4.3.1.1 Calculation of Heat Loss from Pipes

Heat Loss from the distribution system was calculated using standard heat transfer formulae. Heat is transferred from the PHW to the pipe by *convection*, then through the pipe (and insulation if present) by *conduction*, and then to atmosphere by *convection* and *radiation*.

The rates of heat transfer through pipes can be described by the following equations for heat transfer through cylindrical layers:

1. Convection H.T. from the PHW to the pipe:

$$Q = h_1 (2 \pi r_1) (T_{fl} - T_1)$$

2. Conduction H.T. through pipe and insulation:

$$Q = (T_1 - T_2) / ((\ln r_2/r_1) / 2 \pi k L)$$ if pipe is not insulated, or;

$$Q = (T_1 - T_3) / ((\ln r_2/r_1) / 2 \pi k_a L) + ((\ln r_3/r_2) / 2 \pi k_b L)$$ if pipe is insulated

3. H.T. by Convection and Radiation to atmosphere:

$$Q = (h_2 + h_{R2}) (2 \pi r_3 L) (T_3 - T_{f2})$$ assuming the pipe is insulated (see below)

where:

Q = Heat Transfer Rate (kW)

h_1 = Convection H.T. Coefficient (W/m^2K)

r_1 = Inner Radius of Pipe (m)

T_{f1} = Temperature of PHW (°C)

T_1 = Temp. of Inner Pipe Surface (°C)

T_2 = Temp. of Outer Pipe Surface (°C)

r_2 = Outer Radius of Pipe (m)

k = Material H.T. Coefficient (a = Pipe, b = Insulation) (W/m K)

T_3 = Temperature of Outer Insulation Surface (°C)

h_2 = Convection H.T. Coefficient (W/m^2K)

h_{R2} = Radiation H.T. Coefficient (W/m^2K)

r_3 = Outer Radius of Insulation (m)

T_{f2} = Temperature of air (°C)

The following component values then had to be calculated:

1. $h_1 = (Nu \,.\, k_w) / r_1{*}2$ assuming Nu = 4.36 for forced convection, laminar flow.

2. $h_2 = 1.34\ ((T_2 - T_{f2}) / d)^{0.25}$

3. $h_{R2} = \sigma\ \varepsilon\ (T_2 + T_{f2})\ (T_2^2 + t_{f2}^2)$

where: Nu = Nusselt Number

k_w = k value of water

d = Outer diameter

σ = Stefan's Constant = 5.67×10^{-8} W/m^2 K^4

ε = Surface Emissivity

The following k values were used in the calculations:

k value of water @ 115 deg C (W/m K)	0.686
k value of water @ 110 deg C (W/m K)	0.684
k value of water @ 105 deg C (W/m K)	0.683
k value of water @ 100 deg C (W/m K)	0.681
k value of water @ 35 deg C (W/m K)	0.625
k value of mild steel pipes (W/m K)	45
k value of insulation (W/m K)	0.043

Table 7– k Values used in Analysis[1]

The k value of insulation is that for Rock Mineral Wool at ~100°C.

The pipe and insulation emissivity values have been taken as 0.7[2] and 0.2[3] respectively.

The rates of H.T. from the pipes to atmosphere is also dependant flow and return PHW temperatures, which are taken to be the set-point temperatures of 115°C and 100°C, and upon ambient temperatures, which vary seasonally. The average seasonal temperatures used[1] for the heat loss determinations were:

Season	Ambient Temp (BH)	Ambient Temp (Ext)	Ambient Temp (WH)
Spring (A/M/J)	25.3	10.3	15.3
Summer (J/A/S)	28.6	13.6	18.6
Autumn (O/N/D)	22	7	12
Winter (J/F/M)	19.3	4.3	9.3

Table 8 – Temperatures used in Analysis[4]

4.3.1.2 Heat Loss from the Boilerhouse Pipework

None of the pipework in the boilerhouse is insulated.

The heat loss rates and seasonal energy losses were found to be as follows:

	Spring		**Summer**		**Autumn**		**Winter**	
Pipe No.	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)
1	10.58	8317.9	10.2	70507.4	10.96	86187.7	11.27	77916.1
2	9.8	77074.9	9.37	64803.7	10.23	80429.5	10.58	73154.8
3+4	1.36	10678.99	1.31	9026.3	1.41	11089.8	1.45	10044
5+6	1.6	12591	1.53	10580.9	1.67	131345.4	1.72	11954.6
7	4.65	34361.6	4.47	30879.5	4.83	37938.6	4.97	34361.6
8	0.19	1499.3	0.12	822.4	0.27	2089.2	0.33	2274.1
Total	**28.18**	**221575.6**	**27.0**	**186620.1**	**29.37**	**230880.3**	**30.34**	**209705.4**

Table 9 – Seasonal Heat Loss Rates and Energy Losses from Boilerhouse Pipes

Therefore the total annual loss from the boilerhouse pipes is 848,781.34 MJ.

4.3.1.3 Heat Loss from the External Pipework

The external / outdoor pipework is in two sections. The first section / pair (feed and return) run from the boilerhouse over to the warehouse, which is approximately one-third insulated, and the second pair run from the warehouse over to the kilns, where the feed and return pips are split into separates for each kiln. These pipes are 100% insulated. The heat loss rates and seasonal energy losses were found to be as follows:

	Spring		**Summer**		**Autumn**		**Winter**	
Pipe No.	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)
9	1.16	9139.6	1.13	7776.6	1.20	9432.6	1.24	8559.6
10	0.98	7694.3	0.94	6510.6	1.02	7982.1	1.05	7223.9
18a/19a	0.39	3067	0.38	2608.4	0.4	3166.7	0.41	2855
18b/19b	0.33	26276	0.32	2222.5	0.35	2726.9	0.37	2468.6
Total	**2.87**	**22528.5**	**2.77**	**19118.2**	**3.0**	**23308.3**	**3.05**	**21107.8**

Table 10 – Seasonal Heat Loss Rates and Energy Losses from External/Outdoor Pipework

Therefore the annual loss from the external pipes is 86,062.8 MJ.

4.3.1.4 Heat Loss from the Warehouse Pipework

The pipework in the warehouse includes two main pipes for feed and return, approximately 70m long. These two pipes run to the pumproom, where they split and scale down to smaller diameter for the feed and return to the two kilns. Insulation on the warehouse pipes is very varied. The heat loss rates and seasonal energy losses were found to be as follows:

	Spring		**Summer**		**Autumn**		**Winter**	
Pipe No.	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)	H.T. Rate (kW)	Energy Lost (MJ)
11	21.22	166856.1	20.52	141863.5	21.92	172329	22.49	155426
12	14.79	116264.6	14.21	98218	15.36	120796	15.83	109447.7
13	4.96	38986	4.79	33138	5.12	40273.7	5.26	36329.4
14	6.89	54134.2	6.62	45757.5	7.15	56215	7.34	50913.8
15	1.07	8438.2	1.03	7150.5	1.11	8742.1	1.14	7903.6
16	0.68	5365.8	0.65	4546.5	0.71	5559.6	0.73	5026.7
17	0.43	3355.4	0.41	2843.3	0.44	3476.3	0.45	3142.8
Total	**50.04**	**393400.3**	**48.25**	**333517.3**	**51.82**	**407391.5**	**53.27**	**368190.8**

Table 11 – Seasonal Heat Loss Rates and Energy Losses from Warehouse Pipework

Therefore the annual loss from the warehouse pipes is 1,502,499.9 MJ

4.3.1.5 Total Distribution System Heat Loss

Summation of the above totals provides with the following annual heat loss statistics from the distribution system as found:

- An average heat loss rate of 82.3 kW.
- A total of 2,437,344 MJ of energy lost every year

4.3.2 Boiler Performance

Determining the as-found performance of the boiler requires looking at several issues. As previously discussed, a full appraisal of the system is impossible without instrumented testing. However, some valuable information about the boiler can be determined by quantitative analysis. As with the distribution system, the heat losses from the boiler surfaces can be analyzed using standard heat transfer formulae.

4.3.2.1 Boiler Surface Heat Loss

Heat transfer from the boiler surfaces is by radiation and convection, though mainly radiation. Convective heat transfer is calculated as before. The following relationship describes radiative heat transfer from a convex object in a large enclosure:

$$Q = \sigma A \varepsilon (T_{sur}^4 - T_{air}^4)$$

where:

T_{sur} = Temperature of the surface of the boiler

T_{air} = Temperature of the surrounding air

This gives the following results for heat loss from the boiler:

	Spring	Summer	Autumn	Winter
Rate (kW)	70.1	68	72.2	73.8
Energy (MJ)	551350.3	470305.6	567464.6	510291.87

Table 12 – Seasonal Heat Loss Rates and Energy Losses from Boiler Surface

Summation of the above totals provides with the following annual heat loss statistics from the boiler surface as found:

- An average heat loss rate of 70.91 kW.
- A total of 2,099,412 MJ of energy lost every year

It is then interesting to consider whether the boiler is correctly matched to its load. To do this it is necessary to consider the load from the kilns, the design output of the boiler at full load, which is the most efficient operating condition for normal boilers, and the actual output from the boiler.

4.3.2.2 Kiln Load

Heat is transferred from the PHW to the heating-air by means of heat exchangers (see Chapter 3). The incoming air is passed over heating coils, which heat the air from ambient temperature (which varies seasonally), to 55°C. Therefore, given the variation in ambient temperature over the seasons, the load from the kilns will also vary. The PHW temperature drops from around 115°C to 100°C, to deliver this heat. To determine the heat load in terms of kW requires knowledge of two other variables:

- Specific Heat Capacity (C_p) of the water
- Air Flow Rate

The C_p of water has been taken as 4.2 kJ/kg K, and the Air Flow Rate has been estimated at 22 kg/s. The following equation can then be used to determine the load:

$$\textbf{Heat (kW)= Mass Flow (kg/s) x } C_p \textbf{ x Temp Diff of Air}$$

which gives the following seasonal loads, based on the ambient temperatures above:

Spring (kW)	Summer (kW)	Autumn (kW)	Winter (kW)
988.81	915.81	1061.81	1121.53

This can then be considered against the boiler output.

4.3.2.3 Theoretical & Actual Boiler Output

The boiler is rated at 2,326 kW, with a design efficiency of 70%. Therefore, assuming continuous and normal operation, obtaining a useful output of 1,628 kW (= 1,628 kJ/s) in the PHW, useful energy that could be delivered is given in the following time frames:

One Minute (MJ)	One Hour (MJ)	One Day (MJ)	One Week (MJ)	One Year (49 Wks) (GJ)
97.7	5860.8	140659	984614	48,111.356

However, the boiler does not operate continuously. A section taken from the boiler chart recorder shows the cyclic nature of the boiler's operation:

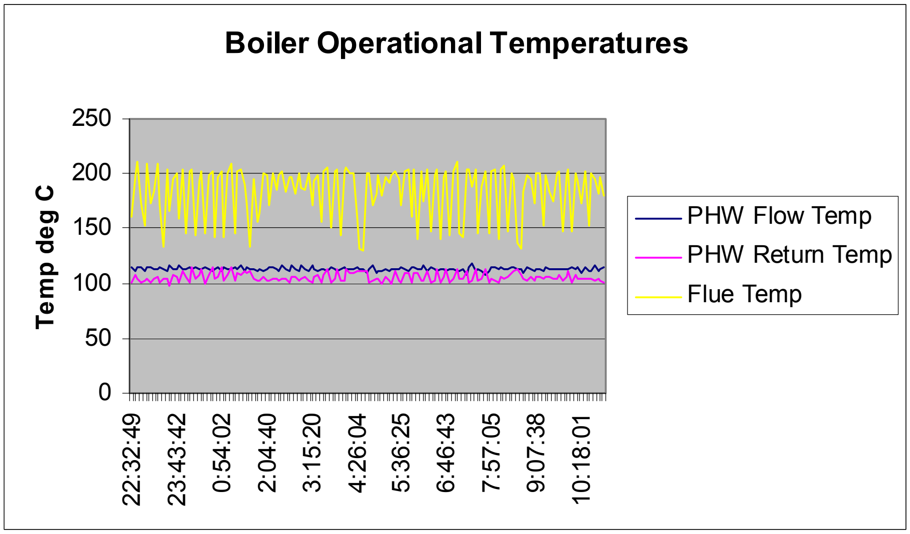

Figure 20 – Operating Flow & Return PHW, and Flue gas Temperatures

The section shown is over a period 12 hours. The system samples the data at 5-minute intervals. It can be seen, even without knowing the exact ON/OFF points, that the system temperatures fluctuate significantly, indicating the short periods of operation. This can be further clarified by the following chart, which shows actual ON and OFF periods taken in a sample (hand timed).

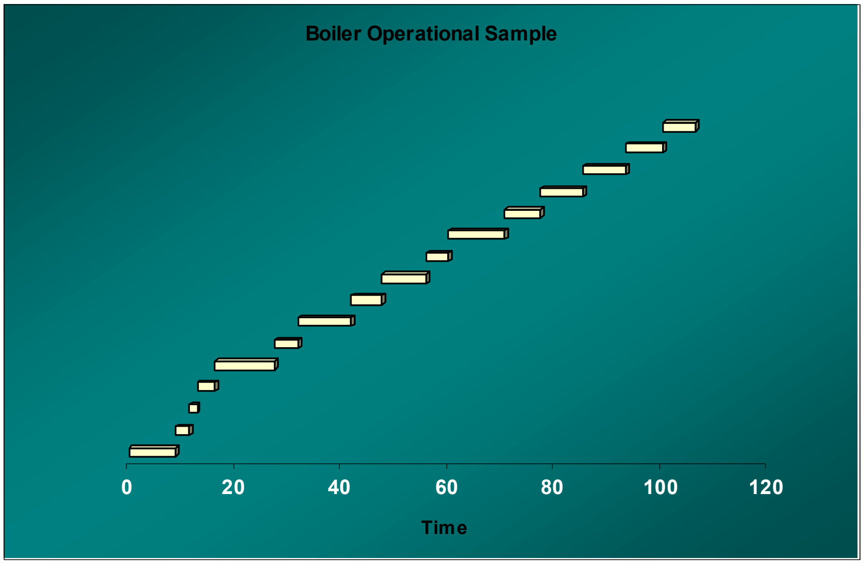

Figure 21 – ON & OFF Period Durations over a period of 2 hrs (The first, bottom period is ON, the next one up is OFF and so on)

The data used to create this chart shows the operational period is 61.7% against the slumber period of 38.3%. This sample was taken in the spring season, and of course seasonal variation can be expected, but will be assumed as a baseline in the absence of confirmative data. Other spring samples also show on average that the system operates for about 60% of the time.

Assuming the system is operating at 70% thermal efficiency, with a useful output of 1628 kW when operating 60% of the time, and 600 kW for the remainder, the average useful output would be 1216.8 kW. This translates to the following useful energy amounts:

One Hour	One Day	One Week	One Month (30 Days)	One Year (49 Wks)
4380.48 MJ	105131.52 MJ	735920.64 MJ	22077619.2 MJ	36,060.111 GJ

It is then necessary to calculate the actual thermal efficiency of the boiler to determine what output is indeed being achieved. This cannot be done without knowing the specific amount of losses that are occurring from the system. However, approximate values can be derived for the thermal efficiency based on the known quantities.

Thermal efficiency is based on the ratio of heat input to the system to useful heat output. As mentioned, this system is severely affected by moisture content in the fuel, hence the introduction of fuel oil to obtain the necessary performance. To determine the influence of moisture on the boiler output, the moisture content of the fuel must be known.

Data was acquired on the moisture contents of the fuel that were being experienced, and several samples were taken to confirm this (see Appendix 2 for details). Typically, the fuel is composed of several different wood types / sections, which have different MC's, thus affecting the overall MC. The following data was used:

Seasonal Moisture Content	Fuel Moisture Content (%)			
	Bark	Butt Reduced	Mixed Chips	Larch Chips
Spring (M/A/M)	53	50	54	40
Summer (J/J/A)	53	50	54	40
Autumn (S/O/N)	72	60	63	48
Winter (D/J/F)	72	60	63	48

Fuel Mix			
	Bark	Butt Red	Chips
Summer / Autumn	2	2	1
Winter /Spring		2	1

Table 13 – Seasonal Fuel Moisture Content and Fuel Mixtures

Heat input to the system is based on the calorific value of the fuel. Moisture content has the following effect on calorific value of wood fuels:

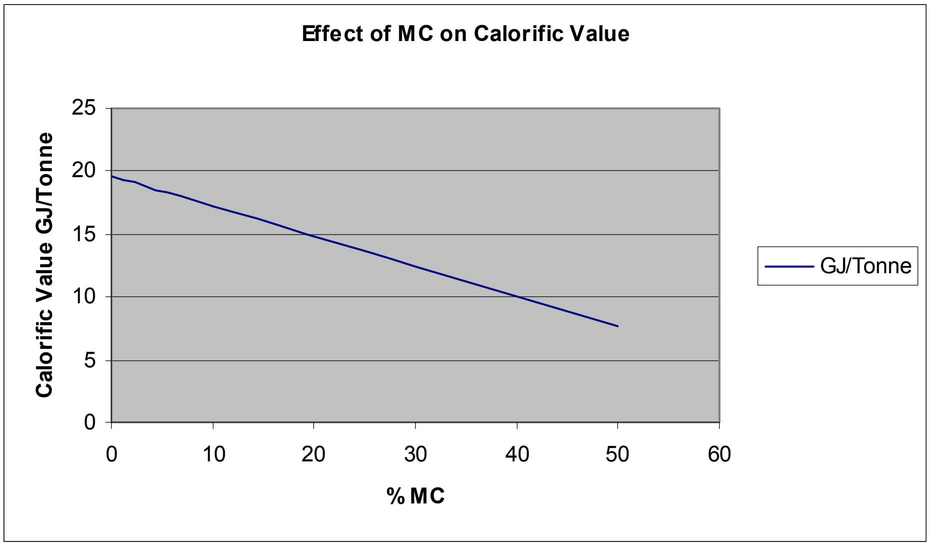

Figure 22 – Effect of Moisture Content on Calorific Value of Woodfuels

Given by the following relationship:

Net Calorific Value = Gross Calorific Value – (0.0114 x Gross Calorific Value x MC)

The net, or useful calorific value of the woodfuels being used, based on a gross calorific value of 16,000 kJ/kg, was therefore calculated to be as follows:

Spring	Summer	Autumn	Winter
7060.58 kJ/kg	6770.56 kJ/kg	5326.86 kJ/kg	4344.63 kJ/kg

It can be seen that the calorific value of the fuel is very low. A decrease of the moisture content to e.g. 30% would increase the calorific value of the wood to 10,528 kJ/kg. This low calorific indicates why the fuel oil is being used.

The total heat input based on these seasonal values, the fuel oil calorific value (which has been taken as 43,100 kJ/kg), and the fuel consumption rates, is therefore found to be as follows:

Seasonal Boiler Inputs	Spring	Summer	Autumn	Winter
Woodfuel Rate (kg/s)	0.24772	0.28889	0.3250	0.31944
Fuel Oil Rate (litre/s)	0.00258	0.00330	0.00357	0.00711
Heat Input from CV of Wood (kW)	**1745.53**	**1955.94**	**1731.23**	**1363.73**
Heat Input from CV of Fuel Oil (kW)	110.98	142.23	153.84	306.49
Total Heat Input from Fuels (kW)	**1856.51**	**2098.17**	**1885.07**	**1670.22**

Table 14 – Actual Seasonal Heat Inputs to the Boiler from Woodfuel and Fuel Oil. Fuel oil input, and therefore total input, only apply when fuel is being used, which is not continuously

The output of the boiler is then required to determine the thermal efficiency. This has been calculated using the following relationship:

Heat Delivered (kW) = (Flow Rate x (Specific Enthalpy of Main Water – Specific Enthalpy of Ambient Water)) – (Flow Rate x (Specific Enthalpy of Return Water – Specific Enthalpy of Ambient Water))

for which the following values were used:

1. Specific Enthalpy (h) of water at following temperatures:

Seasonal Ambient Temperatures		**Process Temperatures**	
Spring 10.3°C	42 kJ/kg	100°C	419.1 kJ/kg
Summer 13.6°C	56 kJ/kg	105°C	439 kJ/kg
Autumn 7°C	29.4 kJ/kg	110°C	460 kJ/kg
Winter 4.3°C	16.8 kJ/kg	115°C	483 kJ/kg

Table 15 – Specific Enthalpies of Saturated Water used in calculations

2. The PHW flow rate, 1700 l/min. Flow is not continuous however, only occurring when the kiln pumps activate. PHW is estimated to circulate, based on observation and timing, 60% of the time during the spring. Estimating a 5%

deviation in summer (decrease) and winter (increase), and the same amount in autumn, gives the following seasonal outputs:

Spring	Summer	Autumn	Winter
1005 kW	917 kW	1024 kW	1144 kW

Based on the annual inputs and output rates, the actual energy input and output to and from the boiler each are found to be 55,464,989 MJ and 33,043,682 MJ respectively. This gives an annual thermal efficiency, based on the heat input / output ratio, of:

59.5%

which breaks down into the following seasonal efficiencies:

Spring	Summer	Autumn	Winter
58.5%	47.5%	61.5%	73.7%

which shows that the greater demand from the kilns, and greater losses from the distribution system surfaces in the winter and transitional seasons means that more heat is absorbed into the PHW flow during those seasons. In the summer, when these losses are lower, the thermal efficiency drops as much of the heat produced in the furnace is lost to the flue.

However, these figures are misleading, since they show thermal efficiencies based on the heat ratios, and do not take account of:

1. The capacity of the system, and
2. The high woodfuel consumption rate, and also the undesired fact of fuel oil consumption, and their related costs.

and they cannot be verified by any other method than instrumented investigation.

Comparing the actual output against the possible output provides a more informative account of the efficiency of the system.

The theoretical output of the system (annual, operating for 49 weeks) is 48,111,356.2 MJ (based on 70% efficiency), which means that the operational efficiency of the system is approximately:

68.7%

indicating that it is oversized. This breaks down into seasonal operational efficiencies:

Spring	Summer	Autumn	Winter
66.7%	61.2%	73.2%	75.6%

Perhaps the most useful figure of the as-found operational analysis is the cost per MJ of heat (into the PHW) that the system provides. Presently the system has an energy output of 33,043,682 MJ/year. The total cost of this is £52,991.36, accounting for both the woodfuel and fuel oil. This means that the cost per MJ of output from the system is: £52,991.36 / 33,043,682 = £0.0016/MJ, or:

0.16p per MJ

It is therefore desirable to reduce this cost, which can be done by either:

1. Reducing the total annual fuel cost, by e.g. removing the fuel oil dependence; or
2. Increasing the amount of useful energy provided; or both.

Knowing these costs of operation and the overall operational efficiency provide a basis for exploring methods of optimisation for this system.

4.4 Methods of Optimisation

The high heat loss and low operational efficiency provide a justification for attempting optimisation of this system. However, this is only a worthwhile proposition if it is cost effective. Continuing with the theoretical analysis, modelling possible changes to the system allows determination of the worth of optimisation efforts on these main system problems. As with analysis of the system as-found, optimisation potential is best assessed at the demand-end and worked back towards the boiler.

4.4.1 Additional Heat End-Uses

Section 4.1 stated, and worked on, the assumption that no significant, alterable-at-reasonable-cost changes could be made to the kilns. Any optimisation that could take place on the kilns would further serve to reduce the load on the boiler, which has been shown to be rated above its demand. An interesting paradox exists here in that the oversized boiler should be searching for applications to distribute heat to, to justify its size and achieve optimal operating efficiency (ignoring fuel use issues for the moment). This then applies to all heat losses in the system. This however does not justify ignoring significant heat losses or lack of attention to any optimisation potential that exists or may arise at the demand side, since operation should be concerned with *useful* applications for heat generated. Otherwise, money is effectively being burned.

Unless another kiln is added to the system, as originally planned and subsequently changed, other uses for the heat need to be found. Possibilities are to use the heat in domestic applications, such as hot water, and for space heating in either the warehouse or office complex. However, the demand from such applications may outweigh the available output, and the capital and installation costs would also be high.

An interesting, process and problem specific method of optimisation is therefore to install a heat dump system, and use the heat to dry the excessively wet fuel, which could have in turn the positive effect of removing the need for supplementary fuel oil, reducing, or possibly eliminating that cost. This is further discussed in section 4.4.3.

4.4.2 Minimising Distribution System Losses

Heat loss in the distribution system has been shown to be significant, at 2,437,344 MJ/year. To appreciate this further, it is useful to consider in monetary terms. The costs of the distribution system losses, based on the cost of £0.0016/MJ, are:

£3,899 per year

Seasonally this equates to:

Spring	Summer	Autumn	Winter
£1020	£862	£1058	£959

Reduction of this cost can be achieved by either decreasing the cost per useful MJ, which does not address the problem but decreases its financial burden, or investing in insulation to reduce the heat loss, or both.

Insulation would need to be applied to all of the pipework in the boilerhouse, and some of the external and warehouse pipework, which would be both outright replacement of poor existing insulation and new application to 'open' sections.

Incorporating insulation into the model (with properties equivalent to that already modelled) shows that the following reduced heat transfer rates and energy loss reductions would be achieved:

	Spring		**Summer**		**Autumn**		**Winter**	
	H.T (kW)	Energy Lost (MJ)	H.T (kW)	Energy Lost (MJ)	H.T (kW)	Energy Lost (MJ)	H.T (kW)	Energy Lost (MJ)
Boilerhouse	2.91	22840.8	2.78	19227.3	3.03	23800.9	3.13	21610.5
Saving	*25.27*	*198734.9*	*24.22*	*167392.8*	*26.34*	*207079.4*	*27.21*	*188094.9*
Warehouse	12.73	100105.49	12.26	8749.9	13.2	103796.5	13.58	93898.9
Saving	*37.31*	*293294.8*	*35.99*	*324767.4*	*38.62*	*303595*	*39.69*	*274291.9*
External	1.03	8113.82	1.0	6883.3	1.07	8397.4	1.1	7585.98
Saving	*1.84*	*14414.7*	*1.77*	*12234.9*	*1.93*	*14907.9*	*1.95*	*13521.8*
New Total	**16.67**	**131060.1**	**16.04**	**34860.5**	**17.3**	**135994.8**	**17.81**	**123095.4**
Tot Savings	*64.42*	*506444.3*	*61.98*	*504395.1*	*66.89*	*525582.3*	*68.85*	*475908.6*

Table 16 – Seasonal Reduced Heat Loss Rates and Energy Losses, including savings, with the application of insulation to the distribution pipework

It can be therefore seen that the energy losses are reduced by 83% to 425,010.8 MJ/year, reducing the cost of these losses to £680 per year, a saving of:

£3,218 per year

This equates to the following seasonal savings:

Spring	Summer	Autumn	Winter
£810	£807	£840	£761

These figures only apply at the moment when the cost per MJ stands as it does. To put this insulation in place would actually have the effect of reducing the load on the boiler, effectively driving the price per output MJ up and negating the investment. This optimisation method, *in this case*, would only be worthwhile (assuming an adequate payback period), if accompanied by efforts to increase the operational efficiency.

4.4.3 Improving Boiler Performance

Improving the boiler's performance could make use of the application of several techniques. For instance, optimal combustion is desired as this prevents heat loss due to latent heat in the flue gases and fouling in the boiler tubes and surfaces, leading to reduced heat transfer and ultimately increased fuel use and cost. Combustion performance tends to degrade over time if not monitored and periodically tuned-up when necessary. Factors such as excess air and air intake temperature can be altered to find the most efficient combustion possible.

4.4.3.1 Minimising Surface Losses

While these are sensible courses of analysis for the operator, optimisation in this case can begin with assessing the value of insulating the boiler, thereby preventing definite, accountable losses.

Heat loss from the boiler surfaces is also significant, at 2,099,412 MJ/year. As with the distribution system, these losses are best appreciated in monetary terms. The total costs of the boiler surface losses, at £0.0016/ MJ, are:

£3,359 per year

Seasonally this equates to:

Spring	Summer	Autumn	Winter
£882	£752	£908	£817

As with the distribution system, incorporating insulation into the model allows assessment of annual energy savings and reduced loss rates, as follows:

	Spring		**Summer**		**Autumn**		**Winter**	
	H.T (kW)	Energy Lost (MJ)	H.T (kW)	Energy Lost (MJ)	H.T (kW)	Energy Lost (MJ)	H.T (kW)	Energy Lost (MJ)
Boiler	7.81	61448.9	7.39	51109.9	8.24	64760.4	8.58	59314.1
Saving	*62.31*	*489901.4*	*60.65*	*419195.7*	*63.93*	*502704.2*	*65.25*	*450977.8*

Table 17 – Seasonal Reduced Heat Loss Rates and Energy Losses, including savings, with the application of insulation to the boiler

It can therefore be seen that the energy losses are reduced by 89% to 236,633.23 MJ/year, reducing the cost of these losses to £379 per year, a saving of:

£2,980 per year

This equates to the following seasonal savings:

Spring	Summer	Autumn	Winter
£783	£670	£805	£722

As with savings from insulating the distribution pipework, these figures only apply as found when the cost per MJ stands as it does. Any measures to increase the operational efficiency and decrease the cost per MJ will decrease the savings, though it can be seen immediately the potential that this measure has.

4.4.3.2 Reducing the Cost per MJ

Perhaps the most significant performance increase and corresponding saving can be made from addressing the high moisture content in the fuel. Ideally, by reducing this high MC, the corresponding increase in calorific value will be enough to replace the calorific input gained from burning the fuel oil. This should have the immediate effect of removing the need for the fuel oil and its associated cost. Figure 23 shows how the presence of high moisture content necessitates the introduction of this supplementary fuel.

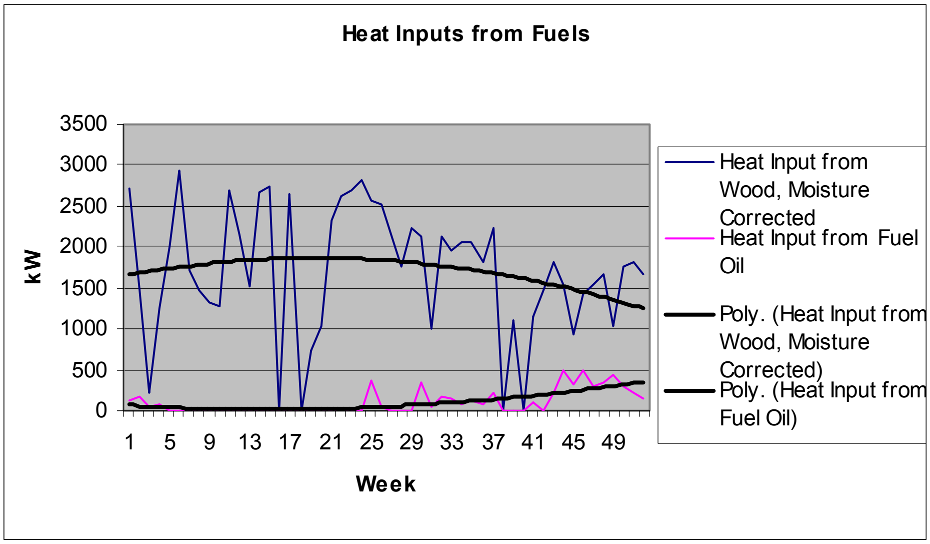

Figure 23 – Heat Input from Fuels for year 2001-2002. The trend-lines (black) highlight the seasonal effect that high moisture content has on the calorific value of the woodfuel, and the necessary addition of fuel oil

Reducing the moisture content of the fuel requires some source of heat to dry it. As mentioned in section 4.4.1, an option specific to this system, where the boiler rating outweighs the demand, is to install a heat dump mechanism and use the heat to dry the woodfuel, thus increasing overall operational efficiency of the system at the same time.

The as-found system consumes 9,254 tonnes (92,540 kg) of woodfuel and 76,804 litres of fuel oil per year. The cost of this, at £4/tonne and £0.21/litre, is £36,862.52 + £16,128.84 = £52,991.36/year. Wood moisture content is highest in winter and the transitional seasons. The moisture content has to be lowered to the point where every kW gained from burning fuel oil replaced by one from burning wood.

At present, the seasonal operating heat input averages from burning fuel oil are:

Spring	Summer	Autumn	Winter
111 kW	142 kW	154 kW	306 kW

(These averages only apply when the fuel oil is being used.)

In a case of simply replacing every kW of input from fuel oil with one from woodfuel, the model shows that a reduction of as little as 6% of average wood moisture content during the summer and transitional seasons and 9% during the winter provides the required calorific value to achieve this. Determination of the required heat input to dry the fuel then follows:

It takes 2.4 MJ/kg[5] to evaporate water, regardless of method and time taken. Based on seasonal fuel average consumption rates and moisture contents, the heating requirements to dry the MC from the fuel are:

	Spring	**Summer**	**Autumn**	**Winter**
Fuel Consumed (□ones)	1948.87	2263.9	2565.38	2475.88
Consumption Rate (kg/s)	0.24722	0.28889	0.325	0.31389
Moisture Content (%)	49	50.6	58.5	63.9
% MC to be dried for no Oil	6	6	5	9
Required Heat Input (kW)	17	21	23	44

Table 18 – Required heat inputs to dry woodfuel to level necessary to remove dependence on fuel oil input

(Note that % MC to be dried is percentage-of-moisture, not total weight)

The extra load on the boiler to achieve this is very small, though would vary on a weekly basis. A maximum of 70kW winter heat dump load would be necessary for the sole function of removing the fuel oil need. The reduced woodfuel moisture content could be achieved through a radiator type system directed at the fuel, most likely when it is in transit from the hopper to the furnace, since at this point the fuel is dispersed into small piles in conveyor baskets and adequate heat penetration of the fuel can be expected.

Rounding up the above drying loads to 30, 35, 35 and 60 kW respectively to allow for variation in weekly MC and therefore load, and also account for losses, gives the improvements in seasonal increases in operational efficiency:

	Spring	Summer	Autumn	Winter
Increase	1%	1.2%	1.3%	2.4%
New Efficiency	67.7%	62.4%	72.5%	78%

which is an annual operational efficiency increase of 1.46%. However, the significant achievement here is that the fuel oil dependence and also its associated annual cost of £16,128.84 has been removed. The same amount of wood is being burned, and the annual useful output (including drying) has increased by 1,167,696 MJ to 33,266,557 MJ, therefore the cost per MJ output drops to £36,862.52 / 33,266,557 =

<u>£0.0011</u> per MJ

or 0.11p per MJ, a drop of 0.49p per MJ, or 31%.

This allows re-evaluation of the savings made from the boiler and distribution surfaces:

Heat Loss Costs	New Cost Un-Insulated		New Cost if Insulated		*New Saving*	
	Dist Sys	Boiler	Dist Sys	Boiler	*Dist Sys*	*Boiler*
Spring	£701	£606	£144	£68	*£557*	*£538*
Summer	£593	£517	£122	£56	*£471*	*£461*
Autumn	£728	£624	£149	£71	*£579*	*£553*
Winter	£659	£517	£135	£65	*£524*	*£452*
Total	£2,681	£2,264	£550	£260	*£2,131*	*£2,004*

Table 19 – Revised Cost of Heat Losses from Surfaces, based on reduced cost per MJ

As can be seen from this table, the costs, and therefore savings have dropped, but there still exists a strong case for insulating the distribution system and boiler surfaces even with the removal of the fuel oil, since savings totalling:

<u>£4,135</u> per year

can be made by doing so.

It is also interesting to consider the potential for greater levels of heat dump, since this would have the effect of more continuous operation of the boiler. This increased level of heat dump could be used to achieve even lower levels of moisture content in the fuel. This would have the in-turn effect of lowering the woodfuel consumption, and driving down the cost per MJ further. However, another paradox exists here in that, while the cost per useful MJ would drop (insofar as that the output has increased) and also the total fuel consumption and therefore the annual cost of the woodfuel, the financial savings may not be as direct. This is because the fuel is not bought in, but site-produced as a by-product, which although costed internally at £4/tonne, may not have the same value if sold externally. Assuming then that a useful, cost-effective application can be found for the saved wood, such as a fuel for some of the other sawmills within the company (where the main cost would be transportation) or sold directly, the seasonal and annual savings in tonnes of fuel and the associated cost can be calculated.

Literature on wood burning suggests that 30% moisture content (percentage of total weight) is good for combustion. To achieve a consistent 30% MC throughout the year would require variable heat dump outputs in each season, and as such would have variable seasonal savings in woodfuel and cost, and seasonal thermal efficiency effects. Interrogating the model to determine the necessary heat dump outputs to achieve this level of moisture content consistently through the year, and the fuel and cost savings (from reduced spending on fuel) yields the following results:

	Spring	**Summer**	**Autumn**	**Winter**
New Moisture Content	30%	30%	30%	30%
Heat Input Needed	54 kW	57 kW	68 kW	74 kW
New Fuel Cons. Rate (T/hr)	0.6 T/hr	0.6 T/hr	0.6 T/hr	0.6 T/hr
New Tot. Consumption (□ones)	1310.4	1152	1310.4	1152
New Total Cost (£)	5,241.6	4,608	5,241.6	4,608
Fuel Rate Saving (T/hr)	*0.29 T/hr*	*0.44 T/hr*	*0.57 T/hr*	*0.53 T/r*
Total Fuel Saving (□ones)	*638.5*	*1111.9*	*1255*	*1323.8*
Total Cost Saving at £4/T (£)	*2,532*	*4,447.6*	*5,020*	*5,295*

Table 20 – Seasonal Heat Inputs needed to achieve 30% MC, and associated Fuel and Cost Savings from this reduction

The heat input needed is not much more than that needed to remove the dependence on fuel oil, since the consumption rate goes down and the amount of fuel to be dried at any one time is therefore less. As with the earlier example, weekly variation would exist and the radiator system would also experience losses. Rounding the seasonally added output from the boiler up to 70, 70, 90 and 100 kW respectively, gives an increase in seasonal operational efficiencies of:

	Spring	Summer	Autumn	Winter
Increase	3.4%	3.5%	2.2%	4.6%
New Efficiency	70.1%	64.7%	75.4%	80.2%

and as can be seen from Table 20, savings of:

4,329 tonnes of fuel, and

£17,295 (at internal rate)

can be made annually, from this lower level of moisture in the fuel.
Another financial perspective on this operating scenario is that, with the consumption rate now continuous, the hourly fuel cost becomes:

- £4/T x 0.6 T/hr =

£2.4/hr

- a significant drop, from the original operating costs of £4.60 per hour using woodfuel only and £8.29 per hour when using additional fuel oil.

Achieving this level of moisture content would give the operator the benefit of a consistent, and known, fuel intake rate. This could bring benefits in the planning of excess wood export / alternative-application ability, and the fuel requirements for any planned load additions to the boiler could also be more accurately determined.

Another interesting scenario to consider is that which would be necessary to have the boiler operating at its design maximum output. Assuming the reduced moisture content of 30%, the model shows that to have the system operating at its full potential would require the dumping of an additional 400 kW of heat (accounting for the increased heating demand due to the increased fuel consumption rate, which is 1 tonne/hr continuously throughout the year). This figure is valuable in that it allows exploration of any applications that may be able to use this level of high-grade heat. Assuming that an application could be found, the consumption rate of 1 tonne/hr would provide an annual woodfuel cost of:

£32,832 per year

It must be noted that the financial costs and savings that have been presented here relate only to fuel expenditure for operation of the boiler. If the boiler's output is to be increased then associated operational costs from other sources will have to be factored into the balance sheet to completely appraise the value of optimisation. Electrical costs in particular are expected to rise with the increased use of electrical motors on fans and pumps. One large motor that drives the induced-draught fan has already been highlighted as a large user of electricity, and any increased use of this fan may incur counterproductive costs.

However, assuming that any associated cost increases from the new operating conditions are either not too severe, or can be addressed with reasonable investment, this section has shown that there exists substantial value in optimisation in both energy and financial terms. Yet, as outlined in Chapter 2, there also exists an incentive to act in terms of the improved environmental performance from such action.

4.5 Environmental Performance

Emissions from combustion are well known as a major contributor to climate change. As indicated in Chapters 1 and 2, control of emissions is now a priority for developed and developing countries alike. Carbon dioxide (CO_2) in particular is a combustion by-product that has been recognised as requiring severe restrictions on emission levels over the coming years.

Burning quantities of various fuels allows the calculation of the amount of CO_2 emissions that will result. Therefore, the variation in fuel-type quantity in combustion in this study allows the determination of any associated change in CO_2 emissions, which may be of use to the operator under current and future environmental legislation.

As-found, the system is burning 76,804 kg of fuel oil and 9,254 tonnes of woodfuel, with variable moisture content, in one year. The emissions from this consumption can be calculated from the heat input (corrected for moisture for the wood), and an 'emissions factor'. Emissions factors exist for each fuel and provide a linear correlation between the amount of fuel consumed and the CO_2 emissions.

CO_2 emissions for fuel oil are given by (tonnes / year):

(0.26(5) x Annual Energy Consumption in kWh) / 1000

and calculated to be:

239 tonnes

CO_2 emissions for woodfuel are given by (tonnes / year):

(0.34)(6) x Annual Energy Consumption in kWh) / 1000

and calculated to be:

5,047 tonnes

Therefore, from the optimisation methods investigated it can be seen that reducing the woodfuel moisture content enough to replace the fuel oil results in an immediate saving of 239 tonnes of CO_2 emissions. In the base case year, this corresponds to the following seasonal savings:

Spring	Summer	Autumn	Winter
19,397 kg	18,631 kg	53,762 kg	147,302 kg

Further reducing consumption rate of woodfuel, by drying the wood to 30% MC, results in an increase in CO_2 emissions, since a greater net-amount of wood (as opposed to water) is flowing into the furnace. The new CO_s emission / yr are:

<u>5,211</u>tonnes

However, by implementing both of these optimisation measures, there is a net decrease in annual CO_2 emissions from (5047 + 239 =) 5286 tonnes to 5211 tonnes, which is a annual saving of:

<u>75</u> tonnes

Therefore, improved environmental performance provides a definite, measurable benefit from the optimisation methods.

4.6 Optimisation Capital Costs & Payback

The true financial value of the explored optimisation methods cannot be fully appreciated until the necessary investment costs have been accounted for. For the system under investigation, these costs would be for:

1. Insulation on the pipes, and;
2. A heat dump radiator and the necessary pipework.

These costs are estimated as follows:

4.6.1 Insulation Costs

Insulation would be required on both the boiler and distribution pipework surfaces.

A one-off cost for the boiler of:

£<u>200</u>[8]

is estimated.

The insulation quality in the distribution system as-found ranges from normal to severely degraded or removed. The amount of pipework that would require new insulation is:

<u>141.8</u>m

The results from the model were calculated assuming 2” thickness insulation, which is estimated to cost:

£8.40 per m[9]

which means the cost of pipework insulation would be:

£1,186

therefore the total cost of insulation for the system would be:

£1,386

4.6.2 Heat Dump/Fuel Drying System Costs

The cost of the radiator system would depend largely on the amount of heat that was to be dumped. An estimated cost of:

£20 per kW

allows determination of the total cost of the system based on the load. If the installed system is desired only to dry the fuel to the level where the fuel oil dependence is removed, the maximum winter load for the system is 70 kW. This brings the cost of the radiator to:

£1,400

However, if a larger system is required to dump heat to dry the fuel to a moisture content of 30%, the maximum winter load of 100 kW would mean the radiator cost rises to:

£2,000

The last situation examined was that where an additional 400 kW of heat was dumped to bring the operational efficiency of the system to its design specification. This large radiator system, which could be installed in a distributed form, would therefore cost:

£8,000

The cost of running pipe to and from the radiator would also need to be accounted for, and this would depend on the amount of heat that was being dumped. For the systems to dry the fuel only, the total length of pipe required would be low, since the distance to the fuel conveyor, where the radiator would dry the fuel, is only several metres. If a larger heat dump radiator was to be installed in addition to this drying system, the length of pipework would depend on the location of the heat dump system, and the cost of the installation would depend on the size of the pipe that runs to the radiator. Locating the dump system next to the boilerhouse, an estimated minimum of 20m of pipework in both feed and return directions would be necessary to locate the system at this nearest convenient external location.

Assuming only the drying system was to be installed, with an estimated requirement of 6m of 3” (nominal diameter) pipe, with a cost of £10 per meter of pipe installed, the capital cost would be:

£60

The system would also require insulation for the pipework, which would cost a further:

£50

If the larger heat dump system was to be installed, with the minimal length of pipe run of 40m, utilizing a 5” (nominal diameter) pipe, and a cost of £20 per meter of pipe installed, the capital cost would be:

£800

Insulation for this pipework would cost a further:

£336

The Total Cost to implement the various measures would therefore be:

1. To insulate the surfaces and install a fuel drying system enough to remove fuel oil dependence only (A):

   £2,896

2. To insulate the surfaces and install a fuel drying system enough to dry the fuel to 30% moisture content (B):

   £3,496

3. To insulate the surfaces and install fuel drying system A, and install the large heat dump system:

   £12,032

4. To insulate the surfaces and install fuel drying system B, and install the large heat dump system:

£12,632

4.6.3 Payback

The payback on these optimisation options is again dependent on what is implemented. However, it can be seen that by removing the fuel oil dependence, an annual saving of £16,128 is immediately made, which immediately covers the expenditure on any insulation and heat radiation systems within the first year. The Total Cost Options above would have approximate payback periods of 3 months for options 1 & 2, and 9 months for options 3 & 4.

4.7 Summary of Results

It has been attempted to show that optimisation potential exists for the boiler and distribution system at the Kilmallie sawmill. The method of determining this potential has been to construct a spreadsheet model of known and assumed values, and the relationships of the energy processes involved. The as-found situation of the system could then be more closely investigated to determine seasonal and annual performance characteristics.

The exploration of relevant optimisation methods were then discussed, and their value explored by subjecting the model to numerical changes that reflect the physical changes that would be made to the system if these methods were implemented. The value in energy, financial, and associated environmental performance was then described.

It is useful at this stage, to summarise the findings annually:

4.7.1 Annual Fuel Costs

The fuels are costed at £0.21 / litre for fuel oil and £4 / tonne for woodfuel (internal cost). For the base case year of 2001-02, the cost of consumption was:

£16,128 in fuel oil
£36,862 in woodfuel

£52,990 Total

4.7.2 Heat Loss in the System

As found, heat loss from the distribution system is extensive. The average annual heat loss rate, and total energy losses from these pipes, are:

82.3 kW

2,437,344 MJ

Given the expenditure on fuel, the financial cost of this energy loss runs to:

£3,899

which could be reduced by 83% to £608 by insulating the pipes; a saving of:

£3,218

The average annual heat loss rate and total energy losses would then drop to:

19.5 kW

578,897.7 MJ

Likewise, the heat loss from the uninsulated boiler surface is also extensive. The average annual heat loss rate, and total energy losses from the boiler surface, is:

70.9 kW

2,099,412 MJ

Given the expenditure on fuel, the financial cost of this energy loss runs to:

£3,359

which could be reduced by 89% to £379 by insulating the surface; a saving of:

£2,986

The average annual heat loss rate and total energy losses would then drop to:

8 kW

236,633.2 MJ

4.7.3 Operational Efficiency and Fuel Cost Reduction

The system appears to be oversized for the existing application. The actual output of system that meets the demand from the kilns is only:

60%

of the design output of the system at full load.

The fuel oil is presently used to achieve adequate heat input to the system, which is deficient due to high moisture content in the woodfuel. By reducing this moisture content in the woodfuel, it is possible to replace every kW of input from the fuel oil with one from wood. One method of doing this is by installing a heat dump system, which has the dual effect of increasing the load on the system, and drying the fuel to a state whereby the calorific value increases to the point that the fuel oil dependence can be removed. This immediately removes the £16,128 fuel oil expenditure. As a result, the cost per MJ of output drops from £0.0016 per MJ to £0.0011 per MJ, which decreases the savings from the insulating the heat losses to

£2,131 from the distribution system, and
£2,004 from the boiler surface
£4,135 Total

which is still a substantial saving.

Various levels of heat dump can be operated. The required amount of heat to dry the fuel to the point where the fuel oil use is removed is low, peaking at 70 kW in winter when the fuel moisture is highest. This increased load increases the operational efficiency of the system by 1.5%.

Improved combustion could be achieved by dropping the moisture content of the fuel even further, to 30%, consistently through the year. This would have a beneficial effect of predictable and diminished fuel consumption. Savings of:

4,329 tonnes of fuel, and
£17,295 (at the internal woodfuel rate)

can be made with this improved fuel characteristic.

In order to increase the overall operational efficiency, it is possible to dump greater levels of heat. This can possibly be used for an application, and the annual average amount that would need to dumped is 400 kW. The fuel consumption would increase to a total annual cost of:

£32,832

4.7.4 Environmental Performance

The removal of fuel oil dependence would have the immediate beneficial effect of removing the CO_2 emissions that result from that fuels combustion. By drying the fuel only to the level necessary where the fuel oil dependence is removed, the reduced CO_2 emissions would be:

239 tonnes

However, further increased levels of woodfuel consumption due to the heat dump system to dry the fuel would result in an increase of CO_2 emissions from that fuel, from 5,047 to 5,211 tonnes, though a net decrease of:

75 tonnes

of CO_2 per year would be made.

4.7.5 Financial Assessment

The costs of implementing the optimisation measures are attractive. All of the explored measures would pay for themselves within the first year due to the savings in fuel expenditure

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Chapter 5 – Conclusions & Recommendations

5.1 Review

The objective of this thesis has been to demonstrate, through example, the value in isolating an energy system, or elements of an energy system, for in-depth investigation to determine its potential for performance improvement and optimisation. Furthermore, the role of such activities within energy efficiency priorities in a Sustainable Development context, has been outlined. The need for analysis to provide decision support information has been shown, and that by performing the analysis in a virtual experimentation environment, no operational interruption occurs and a variety of optimisation scenarios can be evaluated.

The reason for such an investigation may be in reaction to reports of under-performance, or because of an increase in fuel consumption, but the modelling method of analysis incorporates no cost, and can therefore be used at any time to provide a perspective on performance. Optimisation studies can be undertaken as part of an overall Energy Management Strategy, either periodically or at the prompt of a problem, or in isolation if, for example, there are few energy-intensive systems on site and energy performance is otherwise known to be under control.

To obtain the maximum benefit from a modelling study, as much information as possible should be collected on the physical nature of the system, its material and energy flows and operating costs, and deviant characteristics within the system should be quantified where possible. The relationships of operational parameters must be understood so that a representative model of the system as-found can be constructed, to which changes that reflect real optimisation options will yield realistic and valuable results. These results can then be considered in their economic or environmental implications, or both, whichever is the most relevant to the operator, in the support of decisions with respect to their options.

Dedicated software is commercially available for this type of analysis for many technologies. Where absent or unobtainable due to, for example, financial constraints, spreadsheets provide a cheap yet powerful analytical tool with which to proceed, providing adequate data and information is available.

The first objective of improvement of an under-performing system should be to achieve the designed-in efficiency of the system, and any modelled parameters should reflect potential actions to achieve this. Given the degrading-over-time performance nature of some technologies, such as boilers, periodic evaluation of performance against design specification is recommended, especially if maintenance is known to be weak.

Further options to improve performance and optimise can be determined by examining literature on best practice, which, due to the prioritisation and true financial value of energy efficiency in modern industry, is abundant and easily obtainable through communications media such as the Internet.

The value of modelling as an analytical tool in an optimisation study has been demonstrated in a case study of a real energy problem, concerning a wood waste boiler that provides heat for wood product drying at a sawmill plant in Scotland. A general site energy survey highlighted several operational issues with the boiler, and the analysis of fuel consumption and condition data for a base case year allowed the determination of optimisation options in the scope of heat loss, fuel conditioning and overall operational efficiency.

5.2 Analysis Conclusions

Modelling the as found situation of the boiler confirmed and quantified expectations of high levels of heat loss in the system, and the severe effect that high moisture in the woodfuel is having on heat input and therefore fuel consumption.

The model showed that the losses from the surfaces of the pipes and the boiler currently run to 4,536,756 MJ per year, with an average rate of 153 kW. The cost of these losses given the current fuel expenditure is £7,258 per year. If this expenditure on fuel is reduced by removing the fuel oil dependence, then the cost per year in losses is still substantial, at £4,135 per year. Insulating these pipes is therefore recommended, and the payback for the investment is less than one year.

Modelling the affect of reducing the moisture content of the fuel shows that as little as a 6% decrease (9% in winter) will provide the increased calorific value of the woodfuel necessary to remove the fuel oil dependence. This results in an immediate saving of £16,128 per year. The cost of an installation to do this is very low, at £1,400, and pays for itself within a month.

Further decreasing the moisture content to a consistent level of 30%, which would require variable levels of heat input throughout the year, would only cost a further £600 of installation, from which savings of £17,295 in woodfuel cost (at the internally costed rate) would occur.

A final option is to employ extensive levels of heat dump to bring the system up to its design output. The cost of this installation is low, at £12,136, but it is only recommended provided a useful application for the heat can be found since a significant level of fuel consumption would accompany this increase in output.

In conclusion, it is recommended that the operator install insulation on the distribution system and boiler surfaces, and a fuel drying system to bring the moisture content down to 30%, since the financial return from these investments are highest. The reduced annual emission of 75 tonnes of CO_2 that would accompany this investment provides a further incentive. Installation of a large heat dump system is only recommended if a useful application for the heat can be found, which justifies the expense.

5.3 Further Work

Literature on boiler performance suggests that a complete analysis can only be made with a fully instrumented test of the boiler. It is therefore recommended to the operator that such a test be employed to determine the exact thermal efficiency of the system. This knowledge will allow the operator to quantify the system losses and evaluate in them in terms of total operating expenditure.

Other options such as integrated control and modulation are also worth considering given the many separate high-load and variable-use components. However, with a re-evaluated fuel expenditure based on savings from the recommended optimisation efforts, these options must be evaluated on their cost-benefit ratio.

Appendix A – Standard Pipe Thicknesses

The following standard pipe thicknesses table was used to estimate the pipe thicknesses in the distribution system. The thicknesses assumed are highlighted in red.

	Nominal O.D. (in)	**Nominal O.D. (mm)**	Actual O.D. (in)	**Actual O.D. (mm)**	Wall Th (in)	**Wall Th (mm)**	I.D. (in)	**I.D. (mm)**	X-Sect Area (in^2)	**X-Sect Area (mm^2)**
A	12	**304.8**	12.75	**323.85**	0.25	**6.35**	12.25	**311.15**	9.82	**633.5864**
B	12	**304.8**	12.75	**323.85**	0.33	**8.382**	12.09	**307.086**	12.87	**830.3724**
C	12	**304.8**	12.75	**323.85**	0.406	**10.3124**	11.938	**303.2252**	15.77	**1017.4804**
D	12	**304.8**	12.75	**323.85**	0.562	**14.2748**	11.626	**295.3004**	21.52	**1388.4704**
E	12	**304.8**	12.75	**323.85**	0.687	**17.4498**	11.376	**288.9504**	26.03	**1679.4556**
F	12	**304.8**	12.75	**323.85**	0.843	**21.4122**	11.064	**281.0256**	31.53	**2034.3156**
G	12	**304.8**	12.75	**323.85**	1	**25.4**	10.75	**273.05**	36.91	**2381.4332**
H	12	**304.8**	12.75	**323.85**	1.125	**28.575**	10.5	**266.7**	41.08	**2650.4816**
J	12	**304.8**	12.75	**323.85**	1.312	**33.3248**	10.126	**257.2004**	47.14	**3041.4728**
A	10	**254**	10.75	**273.05**	0.25	**6.35**	10.25	**260.35**	8.24	**531.6448**
B	10	**254**	10.75	**273.05**	0.307	**7.7978**	10.136	**257.4544**	10.07	**649.7164**
C	10	**254**	10.75	**273.05**	0.365	**9.271**	10.02	**254.508**	11.9	**767.788**
D	10	**254**	10.75	**273.05**	0.5	**12.7**	9.75	**247.65**	16.1	**1038.772**
E	10	**254**	10.75	**273.05**	0.593	**15.0622**	9.564	**242.9256**	18.92	**1220.7184**
F	10	**254**	10.75	**273.05**	0.718	**18.2372**	9.314	**236.5756**	22.63	**1460.0876**
G	10	**254**	10.75	**273.05**	0.843	**21.4122**	9.064	**230.2256**	26.24	**1693.0048**
H	10	**254**	10.75	**273.05**	1	**25.4**	8.75	**222.25**	30.63	**1976.2476**
J	10	**254**	10.75	**273.05**	1.125	**28.575**	8.5	**215.9**	34.02	**2194.9704**
A	8	**203.2**	8.625	**219.075**	0.25	**6.35**	8.125	**206.375**	6.57	**423.8964**
B	8	**203.2**	8.625	**219.075**	0.277	**7.0358**	8.071	**205.0034**	7.26	**468.4152**
C	8	**203.2**	8.625	**219.075**	0.322	**8.1788**	7.981	**202.7174**	8.396	**541.70992**
D	8	**203.2**	8.625	**219.075**	0.406	**10.3124**	7.813	**198.4502**	10.48	**676.1696**
E	8	**203.2**	8.625	**219.075**	0.5	**12.7**	7.625	**193.675**	12.76	**823.2752**
F	8	**203.2**	8.625	**219.075**	0.593	**15.0622**	7.439	**188.9506**	14.96	**965.2192**
G	8	**203.2**	8.625	**219.075**	0.718	**18.2372**	7.189	**182.6006**	17.84	**1151.0368**
H	8	**203.2**	8.625	**219.075**	0.812	**20.6248**	7.001	**177.8254**	19.93	**1285.8836**
J	8	**203.2**	8.625	**219.075**	0.906	**23.0124**	6.813	**173.0502**	21.97	**1417.5044**
A	5	**127**	5.5	**139.7**	0.258	**6.5532**	4.984	**126.5936**	4.304	**277.69408**
B	5	**127**	5.5	**139.7**	0.375	**9.525**	4.75	**120.65**	6.112	**394.34624**
C	5	**127**	5.5	**139.7**	0.5	**12.7**	4.5	**114.3**	7.953	**513.12756**
D	5	**127**	5.5	**139.7**	0.625	**15.875**	4.25	**107.95**	9.696	**625.58592**
A	3	**76.2**	3.5	**88.9**	0.216	**5.4864**	3.068	**77.9272**	2.228	**143.75056**
B	3	**76.2**	3.5	**88.9**	0.3	**7.62**	2.9	**73.66**	3.016	**194.59232**
C	3	**76.2**	3.5	**88.9**	0.437	**11.0998**	2.626	**66.7004**	4.205	**271.3066**

Table 21 – Standard Pipe Thicknesses (Source – 'Industrial Energy Management and Utilization' – L. Witte, P. Schmidt, D. Brown. 1988)

Appendix B – Woodfuel Moisture Content Testing

Two samples of wood chipping were taken at a 1-month interval to test moisture content. This was done by heating the material for a suitably long enough period to completely remove all moisture from the sample. The procedure to test them was as follows:

1. Insert 200g of material into a container and weigh contents to 1 decimal place.
2. Place container into preheated, fan assisted oven at 105°C.
3. Leave for 16 hrs.
4. After 16 hrs, remove container and re-weigh sample to 1 decimal place.
5. Perform following calculation to determine original moisture content:

((Original Sample Weight – Final Sample Weight) / Original Sample Weight) x 100%

The following results were found for the samples:

1. Sample 1 = 50% Moisture Content
2. Sample 2 = 60% Moisture Content

This confirms the data provided by the operator.

Appendix C – Kilmallie Sawmill Photographs

Figure 24 – The Boilerhouse

Figure 25 – Furnace (Red) with Boiler on top. The woodfuel conveyor is at the bottom left and some of the ducting is shown.

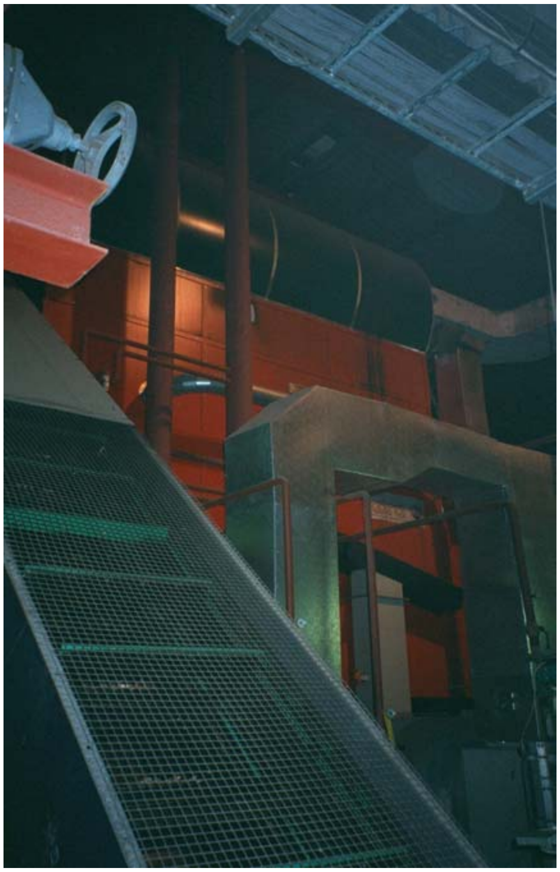

Figure 26 – Closer view of Furnace, Boiler and Woodfuel Conveyor

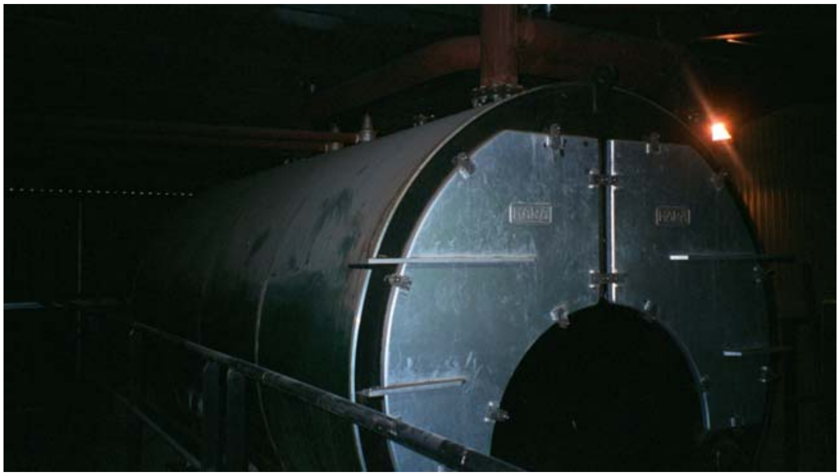

Figure 27 – The Boiler

Figure 28 – The Kiln Pumps in the pump room

Figure 29 – Woodchip stores. The woodchips will eventually be used as fuel.