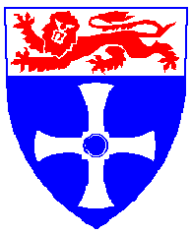

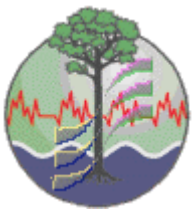

University of Newcastle upon Tyne & Third Generation Ltd.

PRELIMINARY ENVIRONMENTAL PERFORMANCE ANALYSIS OF A SMALL-SCALE COMBINED HEAT AND POWER SYSTEM ATTACHED TO A WOOD CHIPS GASIFICATION UNIT

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A thesis submitted for the degree of

Master of Science in Clean Technology,

Department of Chemical and Process Engineering

August, 1997

1. Abstract

Current trends in legislation and other forms of environmental public pressure have brought about the necessity of developing technologies for producing clean, renewable and economically feasible energy. Electricity and heat from biomass gasification is one of the alternatives.

Although much emphasis has been placed on the economical feasibility analysis, less progress has been achieved in the assessment of issues such as environmental burdens of small scale systems.

As a part of the development of a commercial small-scale downdraft fixed-bed gasifier, an approach has been devised for the analysis of the products and emissions. After a review of concerning issues and a definition of the boundaries for the study, the performance from different runs is assessed by comparison.

Assumptions and extrapolations from information compiled from literature aim to overcome deficiencies from a non-extensive preliminary monitoring. Recommendations from such schemes may be used as the basis of experimental files for gasification reactions which would permit studies of relationships to be carried out with greater facility than is possible at present.

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4. Acknowledgements

Getting information for the project was made much easier due to many very helpful people. I would like to thank Dr Sue Haile, Dr. Abdullah Malik, Dr. Colin Howarth, Mr. Murat Dogru, Mr. Rob Dixon and the staff at Third Generation, especially Mr. Gavin Goodall for their support. May I cheerfully acknowledge the sponsorship of the British Council and CETESB, without which this work would never be possible. Finally, I would like to thank my wife and family for their encouragement.

5. Abbreviations

AES	Analytical Environmental Systems
atm	Atmosphere
BATNEEC	Best Available Technology Not Entailing Excessive Cost
BOD	Biochemical Oxygen Demand (five days)
BPEO	Best Practicable Environmental Option
C	Carbon
Cd	Cadmium
CHP	Combined heat and power
CHPA	Combined Heat and Power Association
CIMAH	Control of Industrial Major Hazards Regulations 1984
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
COMAH	Control of Major Accident Hazards
CV	Calorific value
dBA	Decibels (acoustics)
EA	Environmental Agency
EC	European Community
EPA	Environmental Protection Act
g	Gram
GCV	Gross calorific value
H&S	Health and Safety
H.O.	Heat-only
H_2O	Water
HC	Hydrocarbon
Hg	Mercury
IPC	Integrated Pollution Control
kg	Kilogram
kWh	Kilowatt-hour
LHV	Low heating value
LPG	Liquefied petroleum gas (propane)
m^3/h	Cubic meter per hour
MJ	Megajoules
MSW	Municipal solid wastes
MWe	Megawatts electric
N_2	Nitrogen
NCU	University of Newcastle
ng	Nanogram = 10^{-9} g
NO_x	Nitric oxides
O_2	Oxygen
PAH	Polyaromatic hydrocarbons
Pb	Lead
PCB	Polychlorinated biphenyl
PCDD	Polychlorinated dibenzo-*para*-dioxin
PCDF	Polychlorinated dibenzofuran
POM	Polycyclic organic matter
ppm	Parts per million
R&D	Research and development
RDF	Refuse-derived fuel
SO_2	Sulphur dioxide
SP-1	Sampling Port 1
SP-2	Sampling Port 2

TEQ	Toxic equivalent
TOC	Total Organic Carbon
ton	Tonne
USA	United States of America
U.S.EPA	United States Environment Protection Agency
UHC	Unburned hydrocarbons
v/v	Volume by volume
VOC	Volatile Organic Compounds
w/w	Weight by weight
Zn	Tin

6. Disclaimer

The opinions and estimates in this report are part of an MSc student project. As such, the University of Newcastle or the author cannot be held responsible for any adverse consequences that may arise from following the recommendations in this work.

7. Summary

The following dissertation is based on an EC funded pilot project currently in its' preliminary stage, at Border Biofuels/Third Generation, at Newtown-St.Boswells, Scotish Borders, UK. The project involves the development of a biomass gasification system attached to a combined heat and power scheme, to generate heat and electric power from wood chips. The performance in terms of energy efficiency and pollution resulting from the process was assessed. A commercially efficient product in compliance with the environmental legislation is what this project aims to help achieving.

Initially, the cleaned wood gas is being combusted in a furnace, until a suitable quality for the fuel to be used in a spark engine generator is obtained. It was decided that the system would provisorily run using a boiler instead of the gas engine.

System boundaries were delimited for the monitoring. However, relevant issues outside these limits such as alternative fuels and processes, legislation, life cycle assessment and marketing aspects were mentioned from bibliography. An overview of the existing systems in literature took place in order to compare the system with others under demonstration phase.

The allowed time for monitoring was, unfortunately, quite restricted, affecting the reproducibility of performance results. Batch runs were conducted in order to optimise the air/fuel ratio to the gasifier. Samples of gases were collected before and after the cleanup system. Samples of condensate produced were also collected. Other parameters influencing the process - like temperatures, humidity and pressures - were measured in order to assess the experimental conditions.

From rates of consumption or production and analysis of the composition of wood chips, producer and fuel gases, condensate and ashes, the energetic performance was preliminary assessed.

Since the main objective from the studies is to improve the commerciability of a new product, some related issues were covered - without the intention of a deep analysis- such as economic and marketing factors, legislation, alternative types of fuel and life cycle assessment.

The best choice of air intake seems to be in the range between 6 and 12 m^3/h for the given conditions.

Startup and shutdown producer gas and releases have different characteristics from the steady state. The effect of these procedures are recommended to be minimised by less interruption of the cycle.

7.1 Aim

The aim of this study is - as a part of a R&D commercial project -to improve the efficiency of a small scale (50kW) energy production system incorporating biomass gasification technology, with energy recovered by a combined heat and power (CHP) scheme.

Two stages of this system to be specially focused are the determination of the optimum air/fuel ratio to the gasifier and the gas cleaning prior to combustion.

The resulting performance numbers - complemented by others obtained in an extensive literature review - give subsides for the determination of the commercial potential for the system and define areas for continued and focused research.

7.2 Objectives

The objectives of this project are:

- to study a methodology for optimising the performance of a wood chips fuelled, downdraft, fixed-bed, small scale gasification system in terms of air/fuel ratio;
- to assess the efficiency of the gas cleanup system, in order to provide a suitable fuel for a spark engine and minimise the environmental impact of the facility;
- to provide some preliminary results for the combined heat and power (CHP) system, in terms of energetic efficiency;
- to provide informations about the system running under batch conditions;
- to develop a monitoring apparatus to achieve these targets;
- to suggest ways to improve the overall efficiency and environmental performance, as well as the commercial acceptance of the technology, by referring to the current state of the art of the biomass thermochemical conversion systems, for different fuels.

8. Introduction

The present project involves a joint effort between Third Generation's plant at Newtown-St.Boswells, Scotland and the University of Newcastle-upon-Tyne to improve the performance of the system.

Third Generation was first approached by Dr. Abdullah Malik, a Newcastle University's visiting lecturer, to help investigating possibilities to improve the CHP system's performance, as a master level project.

Due to other priorities in the plant, one week was allowed by Third Generation for the practical experimentation.

The following text describes this study.

9. Literature Review

Pyrolysis of wood to make charcoal is over ten thousand years old. Gasification of the solid fuels wood and coal was discovered about 200 years ago. During the World War II, small gasifiers were used for power generation and for small vehicles, applications that nearly disappeared after oil became again available. Nowadays, this alternative is being reconsidered for it has very little sulphur and nitrogen compounds to foul the atmosphere, keeps the carbon balance (greenhouse effects) and is renewable.[53]

9.1 Biomass thermochemical conversion technologies

The energy in biomass - which potential to substitute the currently used fossil fuels is widely recognised but restrictedly used throughout the world - may be realised either by direct use as in combustion, or by upgrading into a more valuable and usable fuel or higher value products for the chemical industry. This may be achieved by physical, biological, chemical or thermal methods. Thermochemical processing has possibilities from relatively simple conversion technology to produce low heating value gas and basic liquid fuels to upgrading to higher value products such as gaseous and liquid hydrocarbon fuels, petrochemicals, bulk organics and chemical specialities. There are four thermochemical methods of converting biomass: gasification, pyrolysis, liquefaction and direct combustion, each giving a different range of products and employing different equipment configurations operating in different modes, as summarised in Table **16** . presented in Appendix **1**.

Combustion is the most mature technique, but with a still great challenge to develop new and more efficient and environmental acceptable systems. In a small-scale gasifier, one kilogram of air-dry wood gives an output of 2-3 Nm^3 of gas, this producing 0.8 kWh of electricity. Modular gasification plants of 50-100kWe can achieve installations of up to 10 MWe. [71]. Some[1] operational plants in generating electricity from biomass that could be mentioned are: Varnamo[59], Sweden; Tampere[55], Finland; Greve[3], Italy; Ochhra[56], India and Sao Paulo[18], Brazil. In the USA, projects are referred at Columbus, Ohio [50], Hawaii, Iowa, Kansas, Puerto Rico, New York, Minnesota, North Carolina, Florida and California [21].

Gasification is the partial combustion under substoichiometric conditions to generate a combustible producer gas containing carbon monoxide, hydrogen and gaseous hydrocarbons, a method to transfer the heating value of solid biomass into the heating value of the producer gas (and some sensible heat) while in combustion the heating value of the solids is completely transferred into sensible heat. [62]. Relatively to solids combustion, a gas burning process is easier to control, needs less excess air, allows for simpler burner construction, causes no particle emissions (if clean), less air pollution and less fouling of the heat exchange equipment. Gases, after cooled and cleaned, can be burned in internal combustion engines (gas turbines or reciprocating engines) and can be applied easily in combined cycles. [43]

Pyrolysis may be described as partial gasification, but highly endothermic, requiring an external heat source; it is not self sustaining and does not use air or oxygen for the partial combustion. There is quite of confusion in literature: many so-called pyrolysis systems are actually gasification systems. [62]. Fast or flash pyrolysis is used to maximise either gas or liquid products according to the temperature employed. The increased energy density - from 8 up to

[1] More are found in the websites <http://www.ecn.nl/eii/misc/list.html> and <http://www.pic.net/~stevie2/pages/contacts.html>

30 GJ/m^3 in wood chips to liquid - have advantages in transport, storage, combustion, retrofitting and flexibility in production and marketing, bearing seasonal variations on demand. Disadvantages can arise from the chemical and physical instabilities, needing improvements in product yield, quality, upgrading methods, product testing and utilisation and resolution of environmental problems. The liquid, referred as oil but more like tar, when formed, approximates to biomass in elemental composition, and is composed of a very complex mixture of oxygenated hydrocarbons, arising from the degradation of lignin and the broad spectrum of phenolic compounds that result from uncontrolled degradation. Char is the solid product, with limited application in developed countries for metallurgical and leisure industries. Water is also produced from moisture in the biomass feed and as a reaction product.[6]

Liquefaction is usually done with a high hydrogen partial pressure and a catalyst to enhance the rate of reaction and/or to improve the selectivity of the process, giving a more stable, marketable hydrocarbon product. Heat transfer to a liquid phase which is more effective than to a gas phase, the liquid phase reduces the reactor and ancillary equipment volume requirements. However, high pressure requirements are costly and potentially more hazardous. Higher costs arise from complex catalyst recovery systems or catalyst losses. A solvent is also necessary as a solid carrier which requires separation and recovery, increasing process complexity and cost. The result from these disadvantages is a comparatively little activity, related to other technologies and use of conventional fuels. [6]

9.2 Types of fuel

Feedstocks generally considered for thermochemical conversion are agricultural waste, wood and wood waste, energy crops, and refuse (MSW). The main criteria for the development of thermochemical processing are low moisture and ash contents in feedstock, cost, quantity available, feedstock variations, environmental legislation and increased energy recovery through development of new equipment and processes. The main functions of a biomass combustion system and the respective requirements are: complete combustion of the carbon (by appropriate design of the combustion chamber, homogeneous mixing of air and combustible gases, stable operation of the furnace at optimum excess air and accurate combustion control system); separation of ash and gases (ash removal on moving grate firings and low furnace exit gas temperatures for burning high alkali fuels); energy recovery (flue gas condensation for biofuels with high water content and new electricity generation systems) and; reduction of nitrogen oxide emissions (by air and fuel staged combustion and, if necessary, de-NO_x techniques).[6] [49]

9.2.1 Forestry wood

Wood biomass is a natural "plastic", a composite of lignin, cellulose and hemicellullose with a relatively constant ratio of $CH_{1.4}O_{0.6}$ varying slightly with species. Thermal conversion processes move the chemical composition of biomass to liquid or gaseous fuels by adding hydrogen and/or oxygen. In air gasification, this process is spontaneous. Ideally one would like to add the smallest amount of oxygen possible to achieve the formula:

$$CH_{1.4}O_{0.6} + 0.2.\ O_2 \rightarrow CO + 0.7\ H_2.$$

As there is more energy in the right hand side of this formula, in practice, some excess oxygen must be added, producing CO_2, H_2O and, typically, some methane. Approximately 30% of the biomass is burned to provide energy for gasification of the rest. The exact amount of excess O_2 required depends on the efficiency of the process. .[53]

Wood consists mainly of cellulose, which in its chemical composition includes over 43 per cent of oxygen. The calorific value of absolutely dry wood is of the order of 18-22 MJ/kg, but this is never available for ordinary use in industry. The value of wood as a fuel lies in its low ash content - 0.3-0.6 per cent - and in the clean long flame that can be obtained from it. Clean dry wood is a relatively consistent material having low fixed carbon, ash and sulphur contents and a high volatile matter content. However, wood harvested for energy purposes, e.g. forest residues or arable coppice, is a highly variable material with respect to moisture content and, to a lesser extent, ash content. In practice it is normally used in the air-dried condition. Fresh-felled wood may have from 25 to 50 per cent of moisture. The moisture content of forest residues can vary from around 25-30% for air dried material up to 60% for green material; this has significant effects on the value of the wood as a fuel and on the combustion technology required to burn it. The ash content of forest residues can vary with the harvesting method and depends on the amount of tramp material (e.g. soil, sand etc.) that is picked up during the process. The calorific value of these residues on a volume basis (energy density) can be between 9 and 12 times less than that of coal, depending on wood moisture content. The problems of handling and burning such material must, therefore, be appreciated. The specific gravity of most woods being less than 1, as contrasted with that of coal (up to 1.5), it is inconvenient to store it or transport large quantities by rail or road. [2] [65].

Since the fixed-carbon content of dry wood is about 17%; most of the combustion takes place in the gaseous state. The moisture content may vary up to 80% (with a typical net calorific value of 1.65 MJ/kg) depending on whether the logs are floated; in most conversion plants moisture varies from 25 to 50% (CV of 15.8 MJ/kg for 20%), whereas kilned wood and its derived waste moisture varies from 10 (CV 18.2 MJ/kg) to 15%. Dry wood has a CV of 20.6 MJ/kg.[25]

Experiments with various types of wood such as autumn olive, black alder, cottonwood and sycamore obtained, for a moisture content ranging from 8% to 10%, densities from 0.4 to 0.7 g/cm^3, a mean GCV of 19.8 MJ/kg and ash content mean of 1.029%, both with very little deviation. [14]. Comparisons between different types of forestry wood (Oak and Spruce) in terms of combustion effluents showed approximate characteristics. [47]

Moisture content is the most important aspect of wood fuel quality to the consumer, once the combustion technology employed at any particular site will normally only operate satisfactorily up to a certain moisture content. This characteristics also determine the value of the fuel (in Sweden, wood fuel is purchased by energy content, function of moisture assuming an agreed typical ash content, for district heating). Depending on the complexity of the fuel handling system in use, chip quality will also be important. For users employing only simple fuel handling systems, oversize material can cause problems, blocking conveyors and feed screws. Simple screening by the fuel supplier to remove oversize material will eliminate these problems. Fines removal during this operation also reduces tramp ash. .[2]

There are many applications for wood as a fuel, from space and water heating through combined heat and power systems, to power generation only. Definitive thresholds for the type of application, e.g. based on combustion plant output are almost impossible to specify, with the exception of the extremes of application, i.e. domestic space heating and plant solely generating electricity. The numerous variables affecting choice of system include geographical location in relation to wood fuel supplies; in-house heat and power demand profiles; proximity of electricity distribution lines; existing plant conversion or new plant and existing and possible future relative prices of wood, conventional fuels and electricity. [2]

9.2.2 Wood waste

Wood waste is an important source of energy, being a principal raw material in many industries where considerable waste is generally unavoidable. In the conversion plant or sawmill where the logs are first treated, wet bark, edgings and sawdust are produced from the green timber. Wet wood-waste from mills used to be disposed of by incineration in external furnaces but the tendency is toward dryers to reduce moisture to about 40% to facilitate steam raising; green-wood waste plants are normally dual fired, with oil or coal as auxiliary fuel. [25]

Problems peculiar to wood-waste are: handling storage and conveying of mixed materials; relatively large combustion chamber; great risk of smoke emission and high cost of refractory maintenance (external furnaces). Modern techniques overcome these satisfactorily, and often comprise a mixture of mechanical handling, drag-link, screw or belt, and pneumatic handling. Handling and burning of off-cuts etc. may be facilitated by automatic pulveriser or shredder. Wet wood-waste is best dealt with by the hopper, dry materials often by the pulverising mill. Power consumption of hogging or pulverising mills depends on size of waste and mill and can vary from 10 to 75 kWh /ton[2]. [25]

Dust from sanding machines, mixed with air, can be very explosive and at one time this was almost always separately collected and disposed of. But it can be quite successfully and safely burned in suspension at suitable concentration in a manner similar to pulverised coal, using precautions to prevent flaming back, and flame-failure control. [65].

Sawdust and pulverised wood-waste can also be manufactured as hard briquettes, with CV about 17.5 MJ/kg; using commercially available machines applying high pressures, after preliminary drying. Briquettes can also be produced at medium pressure using a binding agent such as coal-tar pitch, molasses or petroleum residues. [25]

Loose materials such as straw and MSW are difficult to gasify at a small scale; pelletisation can be applied but increases costs of the feedstock. [6] Handling of baled or bulky materials is also costly, and shredding or hogging produces a material more suitable for mechanical handling and combustion; but power costs for pulverising or hogging can be high. [25]

9.2.3 Waste and reject fuels

Waste materials have numerous sources and considerable potential. Some idea of the characteristics of waste fuels available is given in Table **17** and Table **18** in the Appendix **1**. As a comparison to wood, common MSW has a GCV of 6-15 MJ/kg, coal has 23 MJ/kg and sewage sludge, 12-19 MJ/kg. [64].

Common problems with most solid wastes are variability of moisture content and size or bulk; storage to coincide supply with demand and necessity of supplementary fuels to boost waste-heat output when waste material is deficient. Many solid waste materials are cellulose-based and high volatility can be a problem, usually calling for generous combustion chamber design and carefully designed secondary combustion air arrangements to ensure compliance with smoke-control ordinances. [25] Amongst other problems there are organic pollutants in MSW, including chlorinated benzols and phenols, polychlorinated biphenyls (PCBs), polychlorinated dibenzo-*para*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). The two latter

[2] These numbers were used in further calculations of energetic inputs for the system

have generated most concern, due to their generally high level of toxicity and persistence in the environment. [70]

The simple use of wastes in an energy production system - even if releases are controlled - does not guarantee a more “environmentally friendly” option. Sometimes, the environmental burden caused by the pre-treatment and transport make it unfeasible, more than in the economic aspect, in the associated processes. This issue will be later discussed, in the subject Life Cycle Assessment.

Many biomass wastes can be utilised for production of heat. Those of vegetable origin are chemically allied to wood (cellulose) and the CV mostly depends on moisture content. Examples are bagasse or residual crushed sugar cane, spent coffee bean and paddy husk. [25] Most commercial systems operate on wood chips while maize cops and coconut shells can also be successfully gasified. [6]

9.2.4 Mixed-firing and alternative fuels

The basic reason for using dual-fuel systems is in general to use some combustible material which is a by-product of a process on a particular plant. Problems in these systems - largely those of design - lie in the variable calorific values of the fuels and their unreliable supply which may vary with plant processes. Other problems are moisture and tar content of gas, affected by the method of cleaning. Soot - produced when insufficient oxygen is present to convert all the carbon to oxides - have quantities usually greater than those predicted from equilibrium data. Dilution of flame gases with recirculated combustion products reduces soot formation. [25]

Difficult materials eventually present in mixed waste fuels, e.g. with bitumen-coated papers, may demand after-burners to prevent smoke emission. The method of combustion depends greatly on the quantity and nature of the waste, but it may be burned in a baled, in a loosely compacted or in shredded form. [25]. Small quantities of wood waste can be burnt along with coal or coke, provided the firing technique is suitably adjusted. The high volatile matter content makes it necessary to provide about 90 per cent of the air for combustion as secondary air.[65].

Equipment necessary for handling, storage, sizing, and conveying other types of wastes may need separation at source, e.g. a magnetic separator.

9.2.5 Wood Gasification

Downdraft gasifiers in the 5 - 100 kW level were widely used in World War II for operating vehicles and trucks because of the relatively low tar levels. Producer gas technology is relatively cheap and simple. Wood gasifiers can be classified as fixed bed - updraft and downdraft - and fluidised bed. In downdraft operation - the technology present at the experimental site - air is drawn down through a bed of burning wood consuming the volatiles; the resulting gas then passes over the resulting charcoal and is reduced to a low energy fuel gas. However, since hot gases naturally rise, it is necessary to supply power to draw the gases down through the gasifier. This is achieved at the site by the use of a compressor, after a cleanup system. Compared to this system, fluidised bed gasifiers require high power input and exact controls and are suitable only for large installations. Updraft gasifiers produce large amounts of tar while consuming the char residue.[43]

Downdraft gasifiers show little flexibility with respect to feedstock moisture content (15-20%) and feedstock size. Well defined chips or pellets with a moisture content not exceeding 25% are necessary to produce a gas that has a really low tar content. [6].

The system monitored in the experiment was designed to operate only with dry wood chips (moistures below 10% w/w), according to Third Generation.

The vertical, fixed bed gasifier is simple and cheaper in terms of capital costs; however, requires a uniform, homogeneous fuel. [62]. This can be a problem for RDFs.

About half of the wood producer gas is made up of nitrogen, the remainder being divided between carbon monoxide, carbon dioxide, hydrogen, and methane. Air gasification produces a low heating value gas (of 5 MJ/Nm^3); medium heating value gas (20 MJ/Nm^3) can also be produced if oxygen instead of air is used as the gasifying agent. Alternatively, steam can also be used as the gasifying agent but then some provision has to be made to supply sufficient heat to the gasifier because steam gasification is an endothermic process.[6]

9.2.6 Fuel gas utilisation

Generally, combustion of the fuel gas from gasification can be expected to have less impact on the environment than in direct combustion. Basically, there are three main routes for combustion of the fuel gas produced: external combustion; heating or drying purposes or; for electricity generation. The direct use of the gas in a furnace or boiler is the simplest application and this generally requires little or no gas treatment except for dust removal. For efficiency reasons it is important to preserve the sensible heat of the product gas which requires close coupling of the gasifier and the furnace. [6]

Turbines are attractive for use in combination with a gasifier, due to long running periods between overhaul, low cost of maintenance, potential high inlet temperatures favouring high thermodynamic efficiencies and the possibility of using the exhaust gas in a steam generation cycle (combined cycle). Problems are corrosion by alkaline metal vapours, trace amounts of dust and in control technology of the gasifier-engine system.[6]

Gas can be used in ordinary diesel engines with modifications - and for these reasons is at present the favoured technology for small scale conversion of wood to electricity. However, there are drawbacks: the emerging producer gas from the gasifier is hot and contains dust and tars - depending on characteristics of fuel and gasifier. Tar removal is a major problem, particularly at the small scale where secondary gasification is not economical. Under specific conditions, downdraft gasifiers can produce a relatively tar free gas. However, irregular solids or open core gasifiers still require further additional R&D.[6] [43]

Energy can be recovered by using CHP schemes. These are usually comprised of Otto cycle engines, ranging from modified car engines through converted automotive diesel engines to purpose built industrial gas engines [51].

9.2.7 Equipments for biomass combustion

Traditional coal combustion technologies are largely inappropriate for burning low quality wood fuels. Appropriate equipment to burn high moisture content chipped wood fuels cleanly and efficiently is readily available, the majority emanating from Scandinavia.[2]

The most common commercial biomass combustion systems with low ash content in the range from 0.2- 5 MW are underfeed stokers, grate firing and cyclone combustor . New designs for wood log boilers wood stoves and fireplaces (< 20 kW) include catalytic combustors, downdraft combustion systems and air staging, which improve the combustion efficiency and reduce pollutant emissions. For small scale (<20 kW) systems, wood stoves and fireplaces are used. Traditional stoves and fireplaces have quite high emissions of CO and particles. To reduce these emissions, various new techniques have been investigated like downdraft combustion systems, catalytic afterburners, 2 stage combustion (air staging), and flue gas recirculation. Best results have been obtained with the first two examples. [49]

Small-scale (up to 400 kW) gasifier stoves, comprised of fixed bed gasifiers followed by a combustion chamber are world-wide spread. They have low cost and simple operation, their biomass fuel is usually a waste product. The particulate emissions are quite low, without need for frequent cleanup. However, in batch conditions - usually of 1 to 2 hours - the quantity and calorific value of the fuel gas varies considerably throughout the cycle.[4] This assumption was verified in practice during the experiment.

Many types of commercially available burners for low heating value gases have been tested, but none were found entirely satisfactory, mainly because of susceptibility to clogging or erosion and corrosion with dirty tar laden gases.[6]

Sufficient combustion chamber residence time, temperature and turbulence must be applied when considering the design of wood combustion systems. Because of the high volatile matter content of wood fuels, careful attention must be paid to the combustion air supply system, both in terms of the location, quantities and method of admission.[2]

The non-uniform nature of the fuel shape can bring problems with bridging and clogging. Sloping sides to the hopper and gasification chamber cause material to slowly and irregularly feed down. When it happens, indrawn primary air no longer passes over the active fuel and the gasification rate is too low to sustain secondary combustion. This can be verified by falling temperatures. Compacting the remaining fuel by pushing it down to the grate breaks the bridges and revitalises gasification. However, doing this by opening a door to introduce a pushing implement causes an uncontrolled ingress of air to the gasification chamber. In a heat-only secondary combustion chamber, this brings problems of high CO emissions - an area where careful control of the process is needed.[4]

Power engines require a gas temperature as low as possible,, very low permissible tars and particulates, low acids (H_2S, HCl etc.) and a low flame temperature. In other hand, for boilers are preferable high gas temperatures low to moderate acids, particulates and flame temperatures and moderate tars. [7]. Thus, the optimisation of a heat-only process is different than one to electric power generation from an engine.

9.2.8 Combustion control systems

Combustion control systems are necessary to ensure a high combustion quality and high efficiency. The most important control systems used today are combustion temperature control; excess air ratio (λ control); and control with a sensor which detects unburned gases. [49]

Since emissions of CO, HC, tar and soot are caused by incomplete combustion of the gases, a certain furnace specific correlation between these parameters can be found in different wood firing systems and with different biomass fuels. [49]

Minimum gas quality requirements for engines vary. For dust, values vary from <0.5 to <20 mg/m^3 whilst for tar a maximum value of 100 mg/m^3 is quoted. .[6]

Sudden movements of material in the bed region can cause fluctuations in the gasification rate, requiring any controller to have robust algorithms. The gasification of the system needs to be reduced when the unit is refuelled. An overload of air to the gasification chamber can cause a more complete combustion, raising the temperatures and decreasing the efficiency. Reference [4] suggests that air supply control may be feasible on the basis of combustor exit temperature.

9.3 Biomass combustion mechanisms and emissions

The production of any form of waste indicates inefficient use of energy. The provision of special means for removing waste products from effluent streams without any effective recovery of materials for further use is clearly a secondary waste of energy[25]

After presenting the main environmental issues concerning biomass combustion, the mechanism of waste production must be clearly understood for a convenient reduction at source.

Wood combustion can be described as a two-stage process: devolatilisation-gasification (dependent of the fuel/air ratio) of the solid substance and; subsequent oxidation of the gases and charcoal. Two main groups of pollutants the combustion of native wood can be distinguished: unburned pollutants (CO, HC-tar, PAH-polynuclear aromatic hydrocarbons, soot) and oxidised pollutants NO_x and CO_2.. Further, additional pollutants can be emitted if biomass containing Cl, metals etc. are burnt. Depending on the fuel composition, the design of the combustion equipment and the operation of the system, the combustion of biomass can lead to emissions of CO, HC, (VOC, UHC), PAH, tar, soot, particles, NO_x, N_20, HCl, SO_2, salts, PCDD/F and heavy metals (Pb, Zn, Cd and others). [49]

The raw gas from a gasifier can contain a number of contaminants. The condensable fraction includes both water soluble organics (such as acetic acid) and immiscible organics (e.g. tars). Particulates include ash, char and sand. [7]

The emissions depend on the rate of production, mostly in a batch process, the wood fuel specie and contamination and the process. [47]

Thermal processing has potential to generate wastewaters more difficult to treat than those from biological processing. Inadequate data are available on gas quality and wastewater composition in a commercial environment for thermal gasification of biomass. There is a current need for accurate analyses to be undertaken during the bench and pilot scale testing of most biomass conversion options. [30]

9.3.1 Air pollution

The pollutants which most need to be considered from burning contamined wood wastes are black smoke, the oxides of sulphur, the oxides of nitrogen and ash in the form of fine particles[25]

For comparison, emission from small-scale combustors are presented in Table **21** in Appendix **1**.

"Wood and biomass rarely contain sulphur. Some studies, however, have noted the presence of SO_x in wood smoke. As to NO_x substances which are only formed at high temperatures, tests carried out at temperatures below 600°C showed only traces just over the sensitivity threshold of the measuring apparatus used." [47] This assumption was confirmed by the experimental results, as further shown.

VOC levels in small-scale biomass combustors are in the range of 200-400 mg/MJ. The most abundant species are methane, ethylene, propane, benzene, methanol and acetic acid, with a correlation with CO emissions, as well as to wood fuel load. [33]

Recommended methods of reducing pollution of the atmosphere are to select fuels of low pollutant characteristics, remove the pollutant from the fuel before or from the gases after combustion. The use of tall chimneys, although not a solution, reduces the local impacts.[25]

The emissions from biomass combustion[3] can be distinguished between those which are mainly influenced by the combustion equipment and process (design and operation of firing systems; unburned pollutants which can be avoided by complete combustion: CO, HC, PAH etc.); and emissions which are mainly influenced by the fuel properties (emissions which are formed from elements found in the biomass: NO_x from N, HCl from Cl etc.). [49] In **Appendix 1**, **Table 19** shows typical emissions which are mainly influenced by the fuel (NO_x, HCl, particles, Pb, Zn, Cd, PCDD/F. These emissions have in recent years been more focused because of the new feedstocks utilised in biomass combustion. **Table 20** shows typical data for emissions from automatic wood furnaces (under stoker furnaces grate firings, dust firings) which are mainly influenced by the combustion (CO, HC, PAH).

Emissions of PCDDs ('dioxins') from non-contamined wood are usually from zero to below 0.1 ng TEQ/Nm^3 at 11% volume O_2 whereas urban waste wood can reach values of 18 ng TEQ/Nm^3. To avoid dioxin emissions, a complete burnout of the fly ash is required and the combustion should be operated at low excess air level (<11% O_2). [48] To meet emission controls for PCDDs ('dioxins') of 0.1 ng TEQ/Nm^3, the flue gases need to be treated either by adsorption onto activated carbon filters or by catalytic destruction. [70]

Polycyclic organic matter (POM) are specially toxic compounds, with considerable emissions (50mg/Nm^3 of gas) reported in biomass conversion processes.

With planned maintenance, a small-scale CHP achieves a 35% reduction in primary energy usage, over 50% reductions in emissions of CO_2 and virtually eliminates emissions of SO_2. Increases in overall NO_x emissions occur with standard gas engines, but can be minimised by incorporating catalytic converters or by lean-burn engines. Overall, CHP reduces the release of harmful emissions into the atmosphere. [5] At the plant site, this is expected when the system is fully operating, recovering the exhaust heat from the gas engine.

[3] For Carbon and Greenhouse effects, see <http://www.ornl.gov/ORNLReview/rev28_2/text/bio.htm> Biomass Fuels, Energy, Carbon, and Global Climate Change. J.H. Cushman, G. Marland, and B. Schlamadinger. 1995. ORNL Review: 28(2&3)

9.3.1.1 Gas Sampling

Air pollution monitoring needs a structured manner in order to determine the levels of particular contaminants and to allow comparisons to be made between data over a period of time or at different places; correct technique is vital to enable relationships to be investigated between specified pollutants and possible effects. Selection from a wide range of survey equipment should consider the nature of the pollutant, the necessary accuracy, time and resources available.

Sampling usually has three objectives: to take a small portion of gas to represent a larger bulk quantity; to place that small portion in a container suitable for transportation and storage, and to change the physical condition of the gas, e.g. temperature and pressure, into a state suitable for analysis. Samples can be: snap (taken quickly at an instant in time); a period sample (a special analysis system is necessary, unless the method is by its nature continuous); or flow-weighted period sample (represents the total gas which flows past the point of sampling). In practice, a period sample or a series of snap samples is satisfactory. Special treatment may be necessary to remove tar, moisture or other nongaseous materials during sampling. Low-pressure gases are normally taken and stored in glass gas pipettes. [25][47].

To provide reliable results, gas collection must be done as much as possible under isokinetic conditions. The sampling probe must be placed at a convenient distance from regions in the pipe system where discontinuities in the flux occur, such as curves and changes in diameter. Theoretically, the pipe section should be divided in regions and samples collected in each one of those. The extremity of the gas collector must collect gas in parallel lines of flux.[22]

9.3.1.2 Analysis of Gases

Methods of gas analysis fall into two categories: those which produce a general description of the gas (general methods) and those which give an analysis for one component or one class of components (special methods). Some methods can be used to a certain extent within either category. Gas chromatography is the most widely used of the general methods. The analysis for minor components in gases can easily be ruined by losses from reaction or by enhancement from contamination. The major contaminants of a gas sample are likely to be air and previous samples for which the system has been used. All analyses should include oxygen as a check on air contamination. [25]

9.3.1.3 Measuring grit and dust emissions, tar and condensates.

The most widely used apparatus is the British Coke Utilisation Research Association (BCURA) cyclone probe, referenced to the British Standard BS 3405. Other available standard methods for measuring particulates are the Italian (Unichim N402 and N422), German (VDI2066-1-2), French (NF X 44052) and American (U.S. EPA Method 5 Sampling System). [22] [38]. The latter, used in other references [50], is the most similar device to the apparatus used in this experiment.

Sampling periods for a significant mass of dust are largely determined by experience. Ideally sampling should be carried out during steady conditions of operation but this is difficult to achieve in many types of plant. [22]. This was verified during site experimental work.

Tar and condensate production rates, relatively to dry gases can be measured by purging a small side draw from the main gas stream and sending it through a series of filters and condensers. The filters trapped the tarry mist while the condensers removed the water contained in the gas stream. This methodology, used in the present experiment, is available in literature [68] and reported small yields of tar (0.13%) in a wood chip fuelled downdraft gasifier of 1,600 MJ/h of working capacity (up to 104.5 kg/h dry weight of wood chips). Condensate mass divided by the mass of the dry side draw stream gives the ratio R (condensate to dry gas mass ratio).

Regarding dust and particles, tests carried out on different charcoal-making processes were not able to include specific measurements of dust and particles, since these agglomerate with the tar.[47]

There are many difficulties in separating tars from moisture in gas sampling. Tars are arbitrarily defined to be a complex mixture of organic compounds which are non-soluble in water but soluble in acetone. Experimental work [28] on a 1.06 GJ/h (293 kW) downdraft gasifier using Poplar wood chips reported that 20% of the tars were collected at a temperature of approximately 200^{o}C, while the other 80% condensed out at a temperature between 20^{o}C and 200^{o}C. The C:H ratio of these two fractions was similar. Major polycyclic aromatic compounds, determined from an experimental work by gas chromatography, are listed in **Appendix 1**, Table 22, showing the proximity of the boiling points to the water. An approach to mapping the components of pyrolysis oils by using acid-base separation and steric exclusion chromatography, effectively analysing 60% of these components. Conventional gasification (700-800^{o}C) is reported to produce compounds like phenols, benzaldehydes and naphtofurans [24]

The tars produced in biomass gasification are primarily polynuclear aromatic hydrocarbons generally difficult to destroy by any other process other than combustion. Conventional scrubbing systems are generally the technology of choice for removal of these tars from the product gas, by cooling. This results in a waste water stream that must ultimately be disposed of. Even in the advanced Batelle process [50], up to 1% of the dry wood weight exit the gasifier as condensable tar material (typical values of 1.6 x10^{-2}kg/m^{3} for wood chips). The scrubbing system can, additionally, leave up to 30% of this original fraction as a fine aerosol mist, difficult to remove and liable to create problems in downstream equipment such as compressors and turbines. Researches are being conducted to develop a low-cost catalyst system to eliminate these hydrocarbons from the producer gas. Tar yields from partial combustion of oak and spruce wood chips showed similar values, close to 34 kg/t of dry wood. [47]

9.3.2 Water pollution

The best method of minimising water pollution is to employ a production process which generates the smallest possible quantity of harmless wastes.

Recycling the high hydrocarbons present in the condensate may represent an interesting option in terms of heat recovery, to be compared with traditional end-of-pipe solutions. The destiny could be similar to those of wet scrubber effluents, in a smaller scale: dewatered in a filter and dried in evaporators.[62] or by using (small scale) sludge lagoons or centrifugation [45]. However, some drawbacks may occur, such as the proximity of the boiling point of the water and most of the tars [28], the energy balance perhaps not favourable to these operations (more consumption than recovery), the separated supernatant is still a wastewater [62] and increased costs and other difficulties in operation and maintenance.

The level of treatment of wastewaters from gasification systems is dependent on the limits imposed on discharges. Compounds of environmental concern in the wastewaters are ammonia, cyanide, phenolics, benzene, thiocyanate and polyaromatics, with levels varying according to the fuel, process and treatment. [30]

There are many options for end-of-pipe solutions, in a vast bibliography, from which is specially recommended the references [46] and [63] for choosing and designing the appropriate treatment. Amongst these solutions, presented in the **Appendix 1**, Table 23., could be mentioned for the wood chips condensate the anaerobic biological treatment, which has a relative low cost. Nevertheless, this option is rather sensitive to effects of toxic substances (such as phenols) and temperature; the first may need a pretreatment while the last can be overcome by a convenient storage and possible recovery of heat from the process. If requirements are strict (which is not the case to the scale and type of project, but may be for alternative fuels) adsorption is recommended for removal of trace organics.

If requirements are strict (which is not the case to the scale and type of project, but may be for alternative fuels) adsorption is recommended for removal of trace organics.

According to reference .[7], "tars are readily separable from water by simple flotation and should be recycled to the reactor". This seem not to be the case observed from the samples taken. Two weeks after collection, the liquid in the bottle remained with the same immiscible appearance.

Waste water treatment is conventional, although oxygenated organics such as phenols may create problems. This aspect - with significant effects - is often omitted from technology and economic assessments of gasification and pyrolysis. Alternatives for treatment is to crack tars by limestone, dolomite or catalysts and a better reactor design to avoid particle carryover.[7]

Reference [30] suggests that "the transfer of technology from the treatment of coal gasification wastewaters to the treatment of biomass gasification is justified on the basis that they contain similar compounds only in different ratios." Centrifugation or filtration pre-treatment may be necessary to remove solids; flotation removes the oils. Before a biological treatment, steam stripping reduces ammonia (to at least 500 mg/L) and other volatile inorganic compounds while solvent extraction reduces phenol levels (maximum recommended 200 mg/L). Tertiary treatment includes activated carbon filtration, ion exchange or ozonation. The same author shows values for a small-scale, wood chips fuelled, fixed-bed downdraft gasification condensate of 7,116 mg/L of phenols. However, ammonia is not mentioned for this fuel, but only for peat. This is specially important in the case of switching the gasifier from wood chips to other alternative fuels.

In a work under similar conditions to the present experiment, reference [28] suggests that in the condensates there is a constant correlation between the values of TOC and COD. The composition of the condensates, essentially constant during the runs showed that most of the TOC values has been accounted for relatively few organic compounds, providing data for the carbon balance. Water content in the condensate was 35% w/w. The ratio COD/TOC had a constant value of 2.38. Tar analyses in the experiments presented 68.4% (w/w) of carbon in a dry basis. For the measured 35% (w/w) of water content, there was 55.66% (w/w) of carbon in the tars, under wet basis. This experiment will be further referred - in the practical part - for estimation of tar content in the condensate.

9.3.3 Solid Wastes from Wood

Solid wastes produced from wood combustion are basically ash and particles. These can be contamined from source with, for example, creosote or pentachlorophenol. Both in **Appendix 1**, **Table 24** presents common composition of wood ash and **Table 25** shows values of metals present in ash from treated wood. From these tables, can be derived that ashes from wood chips have an extremely variable metal concentration, according to the contamination. However, forestry wood fuels have contaminants much below threshold levels.[25] [29] Char was found to have absorptive characteristics similar to commercial activated carbon and may be useful for the advanced treatment of wastewater. Other uses are for construction. [62]

Good engineering practice for the management of combustion ash requires a proper control of fugitive dust emissions (by wetting or covering) and, for contamined ash other special procedures. Because fly ash is composed of micron and submicron particulates, it must be handled very carefully to prevent harm to workers and the surrounding environment. [62]

9.3.4 Hazards and Noise

Hazards involved in thermochemical conversion processes include toxic gases, explosive mixtures and the noxious chemicals in the tar fraction. As long as their potential is recognised, none is a problem..[7]. The presence of carbon monoxide in the gas is a potential safety hazard [43], as well as spontaneous ignition. The latter occurs by self-heating and is dependant on factors such as material characteristics, volume and shape of material storage bin and ambient temperature. Pressurised processes are more subjected to this risk.[69]

The condensable substances contains water and a substantial acid fraction, predominately acetic, propionic and formic, but together with the toxic and non-biodegradable phenolic group. The most toxic by-products are the POM group and the nitrogenous organic substances in tar, all of which with mutagenic and carcinogenic activity. A high degree of mutagenic activity has been detected in charcoal tar and attributed to the presence of primary aromatic carbohydrates. Similarly, carcinogenic activity has been detected and attributed to the polycyclic nitrogenous derivatives (aza-arenes) found in these forms of tar. Of the 671 organic pollutants listed in EMIC (Environmental Mutagen Information Centre) data, known to be present in the atmosphere, 77 are biologically active. These are classified into four main groups: 25 known carcinogens; 20 probable carcinogens; 15 substances favourable to the appearance of tumours or co-carcinogens and; 50 mutagens. In the different compounds identified in pyrolysis tar, 7 are in the first group, 2 in the second, 9 in the third and 12 in the last.[47]

Noise is another form of pollution. A noise source radiates at a given sound power, but the sound pressure level received by the ear depends primarily on the distance from the source and the acoustic environmental conditions. Sound power are independent of the acoustic condition and therefore comparable; they can be calculated from the measurable sound pressure level, given by manufacturers of equipment. Industrial noise is basically associated with impact or vibration. To reduce or treat noise after eliminating mechanical faults the following actions should be considered: replace (usually impracticable and uneconomic); redesign and modify (may be expensive but should be first consideration); enclose (have to consider problems of access and ventilation); provide hearing protection (an easy way out that does not cure problem and; isolate process in one area (if one type of machine in many is the problem).[22]

With mechanical services, plant rooms and associated distribution systems are the main noise problems. The major noise sources are fans, boilers and associated burner equipment,

compressors, cooling plant and pumps. Manufacturers will supply the sound-power levels of their equipment, but in order to ensure that it remains within the specification all equipment must be kept in good mechanical condition. Particular problems arise from worn bearings, loose panels and guards, unbalanced fan motors and badly mounted plant. With air-distribution systems, noise is due to high air velocities, turbulence, obstruction in duets, panel drumming and vibration. In the main, fan noise is transmitted along the ductwork. In plant rooms, breakout can be a problem and care must be taken to provide seals at all points where ducts and pipes pass through walls etc. If the plant-room noise is particularly high and likely to cause complaints in adjacent areas, then consideration may have to be given to enclosing noisy machines, treating the structure walls, replacing plant with quieter type, use of local attenuators, and anti-vibration mountings. With duet systems, attenuators may have to be fitted and ductwork lined. All pumps should be fitted with flexible connections and anti-vibration mountings.[25]

A typical boiler house has a noise level of 90 dBA. A CHP unit is relatively noisy when compared to other plant usually found in buildings. Noise originates from the exhaust system and the engine. Acoustic enclosure, a silencer, anti-vibration mountings and couplings are necessary. [5]

9.3.5 Mechanisms in wood combustion

When heated to temperatures above 300^{o}C, wood chips decompose into volatile components (CO, H_2, CH_4 and others) and char. At 500^{o}C, about 85% by weight of the wood substance is converted into gaseous compounds. There is only a small variation in the decomposition temperature between the various types of biomass However, the ash content and the ash behaviour (ash softening, melting point and sintering) of different biomass vary in a wide range. [49]

The combustion of wood can be described as a two-stage process employing air excess level (λ) less than 1 (gasification) in the first step and final oxidation of the gases ($\lambda \geq 1$)in the second step. A low NO_x concept can be achieved in a two-stage combustion; unburned pollutants can further be reduced effectively especially if the secondary air is mixed homogeneously with the combustible gases and the burnout takes place in a hot combustion chamber. An optimum excess air ratio is necessary to guarantee a high primary combustion temperature (λ as low as possible) and a complete secondary combustion ($\lambda > 1$; usually 1.5 -2) to avoid unburned pollutants. The optimum λ ratio is influenced by the grate and the boiler construction, the load and the quality of the fuel. If λ is too low, high CO emissions can be found due a local lack of oxygen. If λ is too high, burnout of the gases is restricted because the combustion temperature is too low. Therefore an optimum of the excess air ratio can he found. Each wood furnace shows a typical correlation between the CO emissions and λ, depending on the design. [49]

PAHs are formed during the devolatilisation/combustion, with a maximum at certain combustion temperature. If the temperature is low, and the combustion temperature is high enough, the formed PAHs are oxidised in the flame. For batch fired wood stoves and fireplaces, the CO emissions decrease with increasing average wood consumption. [49]

A high fuel moisture content can delay the startup - with dry fuel it can take 10-20 minutes to reach the gasifier chamber steady state and up to 30 minutes for the boiler - which is a secondary combustion chamber. Delayed ignition causes a serious level of smoke and some waste of potential heat output; a premium fuel backup - or, at least, a first load of dry (moisture less than 20%) wood chips - is recommended at this stage. Heat-only systems operations are

usually optimised for one condition, arising high smoke emissions. At the end of gasification cycle, CO emissions can arise when the secondary combustion chamber is quenched by excess air.[4]

There are five basic stages for the pyrolysis process in gasification: drying (at up to 200^{o}C, with losses of some volatile compounds); breakdown of less thermally stable hemicellullose (200-280^{o}C , with release of water, acetic acid, formic acid and furfural, CO, CO_2 and methanol); exothermic (a rapid temperature raise to 280-350^{o}C, producing more CO, CO_2, low hydrocarbons, appearing lighter tars); endothermic (350-500^{o}C, breaking down cellulose into water, CO_2, charcoal, those mentioned products from hemicellullose plus phenol compounds and some heavier tars) and; dissociation (500^{o}C and over, less abundant gases becoming enriched in hydrogen plus other reactions and recombination, increasing process complexity). These effects are affected by parameters such as moisture content, nature and size of raw material, final reaction temperature, reaction rate, pressure and atmosphere in which reaction takes place and; effects of catalysts.[47]

Emissions from a partial combustion batch carbonisation kiln vary during the cycle according to the average temperature of pyrolysis. A general rule cannot be defined; however, maximum emission levels occur during the exothermic stage when the wood undergoes most transformation.[47]

Nitric oxide emissions from biomass combustion originate mainly from the fuel bound nitrogen (thermal NO_x emissions are only of minor importance). To minimise NO_x emissions by primary measures, the fuel nitrogen must be reduced to molecular nitrogen in zones with $\lambda<1$. If it is not sufficient, secondary measures can be employed, such as injection of ammonia or urea (for reduction of up to 95%. [49] [70]

During the gasification, H, C, N and NH_i radicals (i = 0 ... 3) are formed. These components can react in different reactions to form molecular nitrogen, as in Figure 1 below. Reaction (1) is supposed to be most important for fixed bed combustion of wood. Reaction (2) might be of importance together with catalytic effects on ash. The primary excess air ratio in the gasification chamber influences the NO_x emissions to a great extent. During the gasification (< 0.7), only NH components are formed (no); these are oxidised in the combustion chamber, resulting in high NO emissions, typical for conventional wood furnaces. At $\lambda > 1$, the pyrolysis gases are burnt immediately, the concentration of NH components to reduce NO in the reduction chamber is close to zero. [49]

$NO + NH_2$	$\rightarrow$	$N_2 + H_2O$ (1)
$NO + CO$	$\rightarrow$	$CO_2 + 0.5\ N_2$ (2)
$NO + CH_4$	$\rightarrow$	$CO + 2H_2 + 0.5\ N_2$ (3)
$NO + H_2$	$\rightarrow$	$H_20 + 0.5N_2$ (4)
$NO + C$	$\rightarrow$	$CO + 0.5\ N_2$ (5)

Figure 1. Nitrogen reactions during gasification

In a 25 kW test furnace a NO reduction of 50% compared to conventional fixed bed combustion (from 200 mg/mL to 100 mg/mL for native wood) could he reached by a staged combustion with a heated reduction chamber between the gasification and the combustion. Fuel staging showed a comparable or even higher potential than air staging. However, this can be used only for larger plants. Flue gas recirculation was of minor influence on NO_x emissions in these experiments. [49]

9.3.6 Gas cleaning

The main development necessary in power generation designs is in minimising the need for gas cleaning. However, even where gas cleaning is now not necessary, the limits to efficiency will continue to be important constraints on the use of producer gas systems.[49]

When the wood gas is used as a furnace fuel, tars are burnt and conventional dust collection can readily meet the necessary standards. For use as a fuel in diesel engines, producer gas must be efficiently cooled and cleaned, otherwise engine life and efficiency can be dramatically reduced. Technically it is not very difficult, but makes the system more complex, increases capital and operating costs and risks of breakdown. Effective cleaning requires consistency of fuel size, and relatively dry fuels, with 10-20% on a wet basis. If the wood is harvested at much higher moisture contents, it must be dried, naturally or using a conventional dryer. The former is uncertain and means additional handling costs- the latter entails higher capital and operational costs, and lower systems efficiency. [43]

Native wood are biofuels with low ash content. Separation between ash and gas takes place in the combustion chamber. However, a dust separator in the flue gas (multi-cyclone) is used to guarantee low dust concentrations (< 150 mg/Nm^3). Other biofuels need more specific equipments. Biofuels with high ash content require moving grates. An efficient design guarantees a good transport of the fuel and removal of the ash. Air distribution is another issue, not to be instabilised by moving parts such as doors and grates. [49]

The gasification rate is very sensitive to the air intake. A desirable condition for a better cracking of heavy hydrocarbons is drawing the gas from under the bed and cross-mixing with the gas flow.[4]

Two methods of gas cleaning are dry and wet. Dry dust removal can be carried out by cyclones, filtration with high temperature resistant fabrics and a cooler-condenser for tar and water removal. The wet method also uses cyclones followed by a wet scrubber, either of conventional or venturi type design. [70]

The disadvantages of wet methods are: difficulty to handle, treat and dispose of effluent and possible formation of exhaust plume. Dry methods have operating temperature and humidity limitations and formation of dust and cakes, deterioring the plant and fouling the catalyst. [38]. Cooling the gas with water also presents toxic residue disposal problems. [43].

Cyclone, cheap and compact, are suitable for collecting particles > 10μm at efficiencies ranging from low (50-80%) to high (95-99%), increasing with: density of particulate material; inlet velocity; cyclone length; number of gas revolution; ratio body/outlet diameter; particle diameter; amount of dust and smoothness of cyclone wall. Usually operated at a pressure drop of 0.75-1.5 kPa (known up to 5), the maximum temperature limit is generally 540°C. Rigid ceramic cartridge filters are used for high temperature applications, with efficiencies up to 99% for particles >1 μm. [38]

There is much uncertainty on the efficiency of the gas cleaning methods. Primary cyclones were found to be not effective for particles below 5 micrometer, barrel filters not effective for diameters in the range 0.3-3 micrometer and bag house filters not efficient for particles between 0.3 and 1.0 micrometer. However, two stage or two sleeve fibre glass filters were found to be effective for any particle size. .[6]

9.4 Energy recovery and efficiency

Identification, evaluation and implementation of options for energy recovery are a significant part of integrated solid waste management systems because burning reduces the volume of wastes by up to 90%, significantly affecting life cycle burdens. [62]

In a typical power station, 65% of the energy content of the input fuel is discharged to the environment; the energy rejected from a single 2000 MW station would be enough to meet heating requirements of one million people. These losses can be reduced by using CHP and modern combustion techniques, raising overall efficiencies up to 80%. [52]

Energy can be recovered in the form of electricity and/or heat. Amongst systems for electricity generation from biomass combustion, the following may be mentioned: steam turbine (the most commonly used, although with efficiency usually in the range of 20%); steam engines (efficiencies from 7 to 22%, or 4-15% if considered the boiler); stirling engines (efficiencies up to 44%, but requiring dried wood to below 20%); indirectly fired gas turbines (hot air turbine) and pressurised combustion (fixed bed or fluidised bed) equipped to a directly fired gas turbine. Comparative cost studies of such systems with combined heat and power have showed favourable results to the stirling engine. [49] [43]. Simple arrangement of a gasifier/engine system provide relatively high overall efficiency in producing shaft power at different loads (with diesel engines up to 30%) and possibility of immediate use of other fuels.[6]

In gasification, the ratio CO/CO_2 or H_2/H_2O is indicative of the gas energy content and can be improved in practice with insulation, by drying or by preheating the reactants. The O_2 consumed in the process determines the products and temperature of reaction. A fraction required for complete combustion - called equivalence ratio (ϕ) - has an optimal typical value of 0.25 for gasification, in order to maximise conversion of energy from the wood and char to gas (if less, char is not converted; if more, gas is burnt and temperature rises rapidly). .[53] A sufficiently high temperature is necessary to guarantee the cracking of all the heavy hydrocarbons such as phenols and tars [71].

To achieve a high yield of heat recovery the flue gas temperature must be as low as possible; in practice, about 120^{o}C - 150^{o}C without having condensation problems in the chimney. Particle depositions in the heat exchanger may lead to a higher flue gas temperature and require cleaning of the equipment. If biofuels with high water content are burnt, flue gas condensation can be used to increase efficiency of approximately 20% and to a reduce particle emissions and certain gas phase emissions.. However, low temperature heating systems must be used (cold side approximately 45^{o}C). [49]

The maximum possible amount of heat which can be salvaged in a boiler system is normally considered to be the flue-gas enthalpy. In practice, heat is lost from the boiler to the surroundings and the flue gases cannot be cooled below the local water temperature or below the gas dew point.[25] The thermal efficiency of modern boilers is around 80%. If wet feedstocks are used, much of the gross calorific content of the waste is used up in evaporating this moisture. Recent energy recovery techniques such as flue gas condensation processes allow part of this latent heat to be recovered. [70]

In a boiler, five sources of loss are usually taken into account: hydrogen and moisture content in fuel; dry flue-gas loss; unburned gases; carbon in residue and radiation and unaccounted losses. The first two are the most significant, the other three account for about 1% of the losses. The only losses under direct control of the operator are dry flue-gas composition and unburned gas. Other losses are dependent on the fuel burnt and the boiler design. Thus the efficient operation of the boiler is mainly dependent upon minimising the excess air supplied

(lowering the air/fuel ratio) but also maintaining sufficient excess air to ensure the complete combustion of carbon monoxide. .[25]

An adequate supply of water for condenser cooling prevents higher parasitic power usage and reduces the output of the plant from air cooled condensers. [49]

Energy production systems from wood gasification have usually low efficiency, especially if drying is included. The efficiency of drying is about 80%, and that of gas production - i.e. fuel in to cooled gas out - is about 70%. If a diesel engine operates at 33% efficiency - only possible with very clean gas - the overall systems efficiency will be no more than 16%. While this is high enough to make a reasonable case for small scale wood-based electricity generation, it is not likely to be high enough to generate the returns needed for widespread dissemination of the concept. [43]

Yields for mass balances are reported in biomass production (50 to 100%), transport (~100%), size reduction (80-100%), drying (90-100%) and pyrolysis processes (20-70%). [8]

9.5 Issues concerned with product development

Although it is not the intention of the present work specifically to develop marketing, economic or life cycle studies in energy production from wood chips, these important aspects may not be disconsidered in an overview of the subject, principally when commercial purposes are involved. Legislation is another crucially involved subject.

9.5.1 LCA of a biomass power generating system

The environmental control problems associated with the production and use of energy are concerned with gaseous and particulate combustion products (carbon dioxide and monoxide; sulphur oxides; nitrogen oxides; smoke, dust and fumes); liquid effluents (washery effluents; oily waste; cooling water, effluents from gas treatment plants, oil spills and seepages); solid wastes (ash from combustion plants; sludges from water treatment); waste heat (cooling water; cooling tower plumes); noise (from operation of all types of plant); damage to visual amenity (chimneys; cooling towers; spoil heaps; storage and handling installations; electric power transmission lines and equipment, road transport of solids, liquids and gases). [50]

Nowadays, environmental impacts can not be dissociated to the concept of Life Cycle Assessment (LCA), an analytical tool for quantifying the environmental impacts of all processes used in converting a raw material to a final product. Performed in conjunction with a technoeconomic feasibility study, the total economic and environmental benefits and drawbacks of a process can be quantified. Material and energy balances are used to quantify the emissions, resource depletion and energy consumption of all processes between transformation of raw materials into useful products and the final disposal of all products and by-products. The results of this inventory are then used to evaluate the environmental impacts of the process so that efforts can be focused on mitigating these effects.[70] To date, most work in LCA has been focused on inventory, although the amount of available literature indicates that efforts to advance impact assessment and improvement are significant.

One of the most talked-about aspects of biomass energy is the potential reduction of atmospheric carbon dioxide (CO_2) per unit of energy produced. Biomass power is not a zero net CO_2 process, although a positive CO_2 production from the system is certainly less than the

contribution from a power plant of similar size using fossil fuels. The environmental loadings expected from a biomass gasification and combustion system are summarised in the Table 1. Table 2 presents stressor categories associated with biomass power production.[45]

Table 1 Environmental loadings from a gasification system

Feedstock Production	gaseous emissions	• CO_2, CO, NO_x, SO_2, NH_3, nitric acid, sulphuric acid, terpenes from biogenic sources, fluorine and fluoride compounds from phosphate rock processing
	solids	• catalysts requiring disposal • gypsum from production of phosphate fertilisers • dust and particulates from upstream processes and biomass storage
	liquid effluents	• nitrogen, phosphate and potassium fertiliser runoff
	other	• micro-organisms, spores, fungi
Transportation		• CO, CO_2, CH_4, other hydrocarbons, NO_x, N_2O, SO_x, particulate matter, O_3
		• spillages and leakages of fuels, oils and lubricants • evaporative and fugitive emissions • accidental releases
Biomass Power / Energy Production	gaseous emissions	• VOC's, PAH's, terpenes, CO, CO_2, NO_x, NH_3, SO_x, H_2S, Cl compounds, unburned hydrocarbons • fugitive emissions and accidental releases
	solids	• sand and ash mixture (with alkalis and heavy metals), char, catalysts, particulates including aerosols, wood dust
	liquid effluents	• wastewater, organics (e.g. tars) • leachate of pollutants from feedstock, ash and char piles, wastewater system
	other	• micro-organisms, spores, fungi • emissions associated with transpiration and biomass handling equipment

Table 2 Stressor categories associated with biomass power production.

Category	**Stressors associated**	**Major Impact Category * Area Impacted ****
toxicants	pesticides, herbicides, fertilisers tars, diesel fuel, other hydrocarbons SO_2, SO_3, H_2S, NH_3 fluorine, fluorides	H, E, L H, E, L H, E, L, R, G H, E, L, R
photochemical oxidants and precursors	hydrocarbons, O_3 VOCs	H, E, L, R H, E, L
particulates	wood dust micro-organisms, spores, fungi	H, E, L H, E, L, R
air pollutants	CO, O_3, SO_2, H_2S, HC, NH_3 chlorinated compounds wood and sand dusts micro-organisms, spores, fungi	H, E, L H, L H, L H, E, L, R
solid waste	catalysts, sand, ash, char, gypsum	H, E, L, R
physical trauma	accidents, noise odour	H, L L
climate change	CO_2, CH_4, nitrates, sulphates changes in plant growth	E, G E, L, G
acidification precursors	SO_2 (H_2SO_4), NO_2 (HNO_3), CO_2 (HCO_4-)	E, R
nutrients	nitrates, sulphates	H, E, L R
habitat effects	monoculture, non-native species, flora & animal kill	E, L, R
resource depletion	fossil fuel use, minerals, ores groundwater topsoil	E, R, G E, L, R E, L

* H= human health ; E= ecological health
** L = local (county); R= regional (state); G= global

9.5.2 Economic and Marketing Aspects

The relatively high capital costs of wood burning systems, compared with conventional fossil fuel fired plant, is perceived as a barrier to wood fuel use, except in those countries where tax and investment incentives positively discriminate in favour of biomass. Capital costs of wood fuel fired plant and condensing sets vary with plant capacity, location etc. but, as a rule of thumb, will be in the region of £1000/kWh of installed electricity generation capability. Capital requirements depend on the complexity and sophistication of the equipment and controls employed in fuel handling and storage, combustion system and steam/heat/power (either in CHP or stand-alone projects) generation plant.[2]

Biomass systems can be specially competitive in existing niche markets, such as projects with economically attractive co-products, areas with non-fossil mandates, areas with high fossil fuel costs, areas with rural development concerns, areas with waste or residue disposal concerns and areas with very low biomass costs. The challenge is in identifying and targeting these niches. [21]

There is a need in the world wide market for biomass power plants with: size in units from 1 to 20MWe, capable of using a large variety of biomass fuels without extensive pre-processing; simple, reliable, durable and easily maintained; producing electricity at low capital and operating costs; with just ash as by-product, few or no waste water to treat; exhaust gases meeting all air quality requirements and readily available and affordable parts and service [19].

Such systems may have access to low cost feedstocks or favourable treatment by regulatory bodies. It is important to continue development and demonstration of current technology and dedicated feedstock supply systems to be positioned to take advantage of these advances. Deregulation avoids head-to-head competition with large central station fossil-fuelled plants. [20]

The Non-Fossil Fuel Obligation (NFFO) introduced by the UK government has spawned a number of power generation projects, based on the burning of 'waste' fuels, e.g. used tyres, poultry liner, refuse derived fuels. These projects are unlikely to have been progressed .without preferential prices given for the electricity produced. Prices of around 6 p/kWh are not uncommon, while electricity exported current pool prices average approximately 3 p/kWh.[2][52]

As a subside for further studies, according to informations provided by Third Generation, the current market price of the chipped forest brash utilised is approximately £50 per oven dry tonne (£40 per tonne at 20% of moisture content). The cost of this type of timber is not expected to vary significantly. Capital costs for the system are estimated around £50,000. Border Biofuels leaflet states for the Arable Energy Coppice scheme a gross margin of £320/ha, in a 30 years life span.

9.5.2.1 Gasification Systems

A potentially very large market exists for small scale gasification, but problems are still found, such as: poor gas flow due to low density and swelling of wood in the pyrolysis zone; poor oxygen distribution due to small particle size; sintering arising from poor oxygen distribution and lack of a well designed continuous ash removal system. On an hour by hour basis, meeting peak loads for electricity production is probably feasible but longer term storage of a low heating value gas is considered not to be economic. [6]

Low Joule gasification of wood for shaft power in units below 0.5 MWe have promising economic potential in developing countries; in some of these, biomass supplies up to 60% of the energy. The economics of retrofitting diesel fuel generator sets with a biomass fuelled gasifier can also be attractive in the industrialised world in site specific situations. The most likely short term markets for industrial use of fuel gas from biomass and wastes are where gas quality specifications are undemanding such as in boiler retrofitting and direct firing (in the production of lime, cement, bricks and unglazed pottery). Current and short term economic applications lie in utilising wastes and residues to produce power and fuel gas where quality requirements are less demanding. There is potential for the production of transport fuels and chemicals in the longer term, particularly in less developed countries and those with few indigenous conventional energy resources. Rational use of biomass energy can be less polluting than conventional fuels and allocate set aside agricultural land, contributing to the improvement of the balance of trade in Europe .[43] [47]

The choice of direct burning MSW or converting it to fuel is influenced by the strength of public reaction to a waste-fired energy plant, the landfill saving economics and by revenues to the facility from the sale of energy.[62]

9.5.2.2 Marketing Informations for Combined Heat and Power

Even if are only considered acceptable paybacks under five years, there are still a large number of establishments where micro CHP can be very successfully employed. A modern CHP unit can be 90% efficient in terms of primary energy, compared to its combined conventional counterparts, with an efficiency of around 55%. Maintenance costs, a key factor, absorb about 20% of the gross energy savings. A desired feature of any CHP installation is that it should operate in parallel with the energy supply grid. [51]. For a cogeneration scheme to provide a viable alternative to conventional purchase and local heat generation, electrical and heat from a CHP plant must be nearly fully utilised for a high number of hours each year. [32]

The UK Government figures show that for each kWh generated by CHP, CO_2 emissions are reduced to 1.2 kg, compared to conventional, low efficiency forms of power generation.[34]. CHP provides 20% of heat in the Swedish economy [67]. There are nearly 1,000 wood fired plants in the USA, typically ranging from 10 to 25 MWe, only a third offering electricity for sale, the rest are owned and operated by the paper and wood industry for their own use; this sector is 70% self sufficient in energy. Wood fired systems account for 88% of the biomass power generation in this country; 70 % of biomass power is cogenerated with process heat. This was estimulated by federal tax policy and state regulation actions. [21]

9.5.3 Legislation

Although the study focuses a Scottish countryside based, pure wood-fuelled, small scaled system, the development of a marketable product must also take into consideration the legal and regulatory aspects concerning the use of alternative fuels (like wood contamined by solvents or other wastes, liable to be under the Integrated Pollution Control - IPC); the site-specificity (e.g. nuisances in the proximity of a densely occupied residential area); and the possibility of a larger scale of energy production (placing the system into another category). The applicable legislation varies, according to these characteristics.

9.5.3.1 Integrated Pollution Control and Health and Safety at Work

The Environmental Protection Act 1990 (EPA 1990)[27] lays down new procedures for the application of integrated pollution control (IPC) to a range of processes which have considerable pollution potential, and a new approach to air pollution control to be implemented by local authorities. The objectives of IPC are to prevent or minimise the release of prescribed substances, to render harmless any such substances which are released and to develop an approach to pollution control that considers discharges from industrial processes to all media in the context of the effect on the environment as a whole. Plant subject to IPC are required to apply the Best Available Technique Not Entailing Excessive Cost (BATNEEC) to control emissions.

Schedules 1 and 2 of the Environmental Protection (Prescribed Processes and Substances) Regulations 1991 provides separate lists of those processes and substances which are under IPC (Part A list) and those which come under local authority air pollution control (Part B list). The regulations also prescribe substances whose release into the environment is controlled. [41]

An extract of the consolidated version of this legislation, covering combustion, gasification and waste incineration processes is presented in the **Appendix 4**. The pilot Third Generation's

plant is not subject to IPC control. The closest category is Part B's Waste Burners of more than 0.4 MW capacity (in the event of switching fuel to MSW and increasing by 8 times the capacity of the plant).

A series of guidance notes sets out the SEPA's view of what are considered to be the BATNEEC for a particular process and indicate emission levels which BATNEEC should be expected to deliver. Clear information is given on emissions limits and controls; monitoring[37] [40]; sampling and measurement of emissions [39]; material handling and storage; flue gas treatment[38]; disposal of residues [63] [64]; chimney design [36] and general operation.

The provisions of the EPA 1990 apply equally in Scotland as in England and Wales except that in Scotland responsibility for enforcing the integrated pollution control provisions of the Act is undertaken by the Scottish Environment Protection Agency (SEPA), under the Environmental Protection (Determination of Enforcing Authority etc.) (Scotland) Regulations 1992 (SI 1992/530). There are arrangements between the SEPA and the Health and Safety Executive (HSE) in respect of discharges, primarily those to air and issues arising from the protection of persons at work and the public under the provisions of the Health and Safety at Work, etc. Act 1974. Important differences in procedures arise when it comes to enforcement, due to the requirement for corroboration of evidence in Scottish courts, influencing how sampling and other evidence must be gathered and presented in court when prosecutions are considered.[22]

9.5.3.2 Emission Limits and Quality Objectives

Section 3 of the EPA 1990 enables the Secretary of State for the Environment to make regulations establishing standards, objectives or requirements in relation to particular prescribed processes or particular substances. Regulations may prescribe: limits for the concentration or amount of any emission; standard requirements for the measurement or analysis of substances and; standards or requirements for any aspect of a process. These plans may establish: limits for the total amount, or total amount in any period, of any substance which may be released into the environment in the UK; quotas with regard to the release of substances; limits to progressively reduce environmental pollution and; progressively improve quality objectives. .[22]

9.5.3.3 Local Authority Control

Those prescribed processes which come under Part B must obtain an authorisation from the local authority for the area in which they are located. These authorities are responsible for the control of air pollution from small factories. Specific guidance is determined, in the form of BATNEEC provided on a process basis. Emissions from factories not subject to specific control come under the jurisdiction of the local authority if it can be established that a nuisance is being caused. The local authorities are also responsible for the control of smoke from industrial and commercial premises and the general implementation and monitoring of smoke control areas. They are as well empowered, on application, to exempt specific furnaces if it is satisfied that the emission will not be prejudicial to health or a nuisance.[22]

9.5.3.4 Smoke Emissions

Clean air legislation [15] imposes limits on the emission of smoke by prescribing limits for dark and black smoke and establishing a procedure for smoke control based on defined geographic

areas. Section 1 of the Clean Air Act 1993 prohibits, subject to conditions, emissions of dark and black smoke from chimneys serving boilers and industrial plant. Details are determined by the Dark Smoke (Permitted Periods) Regulations 1958 [23]. Two separate circumstances are considered: continuous and intermittent emissions. The limit for a continuous emission of dark smoke, caused otherwise than soot-blowing, is four minutes. The determination of intermittent emissions is based on aggregate emissions for a period of up to eight hours. For one furnace served by a chimney, the period is 10 minutes. The maximum aggregate emission of black smoke is two minutes in any period of 30 minutes. Aggregate emissions are considered by carrying out an observation over a period of time and accumulating incremental emissions.

In any proceedings brought under this legislation account must be taken of the statutory defences contained in s.1 of the 1993 Act. Cases cover startup, unforeseenable failures, use of unsuitable fuel or a combination of these causes. Section 4 of the same Act requires all new furnaces (other than domestic) to be capable, so far as is practicable, of operating continuously without emitting smoke when burning the fuel for which they were designed. “Furnace” is not defined in the Act but can be interpreted as any enclosed or partially enclosed space in which solid, liquid or gaseous fuel is burned, or in which heat is produced. [22]. Section 4 also requires that the local authority is advised of proposals to install new furnaces, other than domestic furnaces. If requested, the local authority can be required to consider whether the unit is capable of substantially smokeless combustion; there are few circumstances when an application cannot be approved. Section 2 prohibits emissions of dark smoke from trade or industrial premises. Subject to specific exemptions for prescribed matter, the prohibition is absolute; no permitted periods are provided. "Industrial or trade premises" are defined as “premises used for any industrial or trade purpose or premises not so used on which matter is burnt in connection with any trade or industrial process”. This legislation is used to control smoke emissions from bonfires.

9.5.3.5 Nuisances

Section 79 of the EPA 1990 includes the following within the definition of statutory nuisances: smoke emitted from premises so as to be prejudicial to health or a nuisance; fumes or gases emitted from premises so as to be prejudicial to health or a nuisance and; any dust, steam, smell or other effluvia arising on industrial, trade or business premises and being prejudicial to health or a nuisance. It does not apply to: smoke emitted from a chimney of a private dwelling within a smoke control area; dark smoke emitted from a chimney of a building or a chimney serving the furnace of a boiler or industrial plant attached to a building or for the time being fixed to or installed on any land and; dark smoke emitted otherwise than as previously mentioned, from industrial or trade premises. [27]

9.5.3.6 Grit and Dust Emissions and Chimney Height

The need to control grit and dust emissions from combustion plant is most necessary in the case of coal. The regulations eventually passed were applied to boilers and furnaces from which the only emission was fuel associated. Draft regulations for cupolas and incinerators were never laid before Parliament. Control is now based on the application of BATNEEC to authorised prescribed processes.[22]

Section 6 of the Clean Air Act 1993 requires that new furnaces are provided with plant for the arresting of grit and dust and that such plant should be approved by the local authority. The plant to which this provision applies is: furnaces which burn pulverised fuel; furnaces which

burn solid matter at a rate of more than 45 kg an hour and; furnaces which burn liquid or gaseous fuel at a rate of 366.4 kW or more. The same cases are subjected to control of chimney height, under Sections 14 and 15.

Section 5 provides for regulations to be made limiting emission of grit and dust from furnaces. Regulations for Emission of Grit and Dust from Furnaces [17] apply to: boilers; indirect heating appliances (in which combustion products are not in contact with the material being heated) and ; furnaces in which the combustion gases are in contact with the material being heated but the material does not contribute to grit and dust emissions. The regulations lay down the permitted limits based on heat output and heat input depending on the type of furnace under consideration. Section 7 of the 1993 Act allows certain exemptions to the general requirements, such as mobile plants and temporary sources of heat and power and a range of mechanically fired furnaces which burn less than one tonne an hour (with the exception of incinerators). [16]

9.5.3.7 Limits for atmospheric pollutants

The Air Quality Standards Regulations 1989, as amended by the 1995 Regulations [1] put a duty on the Secretary of State for the Environment to ensure that certain measures are taken for specific atmospheric pollutants. The EC does not have mechanisms to carry out the enforcement of legislation in Member States. Basis of its action is the development of policies which will form the foundations of a legal framework throughout the Community. [22] Although there are no regulatory achievable releases for small scale combustion processes, as a guideline, for larger processes (> 50 MWth) levels are: 50mg/m^3 for particulates, 200 mg/m^3 for NO_x, 850 mg/m^3 for SO_2, 20mg/m^3 for VOCs, optimised combustion of CO and invisible smoke. [35]

9.5.3.8 Legal Limits on Emissions from Small-scale CHP Plant

At present small-scale CHP in the UK is not subject to any limits on levels of emissions. The only constraints that apply are the general provisions of 'statutory nuisance' contained in the Environmental Protection Act. These provisions do not hinder the use of a gas engine provided it is correctly installed and operated. At present there are no plans to implement legislative limits in the UK for gas engine emissions. As a result the selection of engines has usually been based on meeting the heat and power needs of a building, while keeping the capital and operating costs as low as possible. Some European countries apply limits on emissions of NO_x, CO and UHC from gas engines. These limits generally require the use of catalytic converters to achieve them. This technology is proven and available, and its increased use within the UK is expected over the next few years. It can easily be fitted as an add-on to existing gas engines. [5]

10. Experimental Results and Analysis

10.1 Materials and Methods - System Studied

Performance data were obtained through test runs developed in July 1997 and presented hereafter. Just part of the system was under operation: producer gases were provisorily by-passed and flared in a boiler combustor instead of sent to the generator engine. Since the priorities of Third Generation were this other system (here called "Gasifier B" and Heat Only - H.O.), few test runs were allowed for the monitoring. Experimental results, where available, provided the basis for system performance assessment.

The issues tackled in the experiment were:

1. the production of a clean fuel (producer gas) from wood, suitable to be used in an ignition engine/electric power generator; and
2. an efficient recovery of energy released to the environment, for district heating

Issue number 1 should be achieved by, first, optimising the air intake flow ratio to the gasifier, then by cleaning the fuel gas produced. Issue number 2 was more a consequence of number one, once the gas needed to be cooled.

The boundaries for the experimental monitoring were limited to the gasifier, cleanup system and a part of the CHP scheme, as further described. Nevertheless, gathering of theoretical information tried to cover the subject in a broad manner.

A total of 20 gas and 5 wastewater analysis aimed to assess the performance of the gasification system. In parallel, were taken measurements of local conditions, like temperature and humidity. The available feedstock was also analysed, as well as the solid waste produced.

The environmental performance in terms of releases to the atmosphere of this provisory scheme. Some spot measurements in the flue gases leaving the boiler combustor aimed to give an idea of the air emissions.

10.1.1 Site Conditions

Simulations were performed on a biomass system under development by Border Biofuels (BB) - Third Generation, in a pilot plant based at the European Funded Tweed Horizon Centre, Newtown-St Boswells, Scotland.

The Third Generation's experimental plant examined is located approximately 10 metres away from an existing office building, partially occupied. Additionally, the plant is in close proximity to roads adequate for delivery of the biomass. Initially, wood residues provide the main source of fuel, but a new scheme is proposed for another major source within four years. The Arable Energy Coppice is based in a crop husbandry, with mechanical plantation and harvesting of willow stems. The intention is to establish a wood fuel producer group.

10.1.1.1 The Designed Final Plant

The final plant design include the following basic features, as shown in Figure 2 , :

- the gasification island: gasifier and hopper
- the power island: spark engine, generator and LPG backup
- the heat-only unit: a gas-fuelled water boiler
- the feedstock drying and storage
- the CHP system: gas and engine coolers.

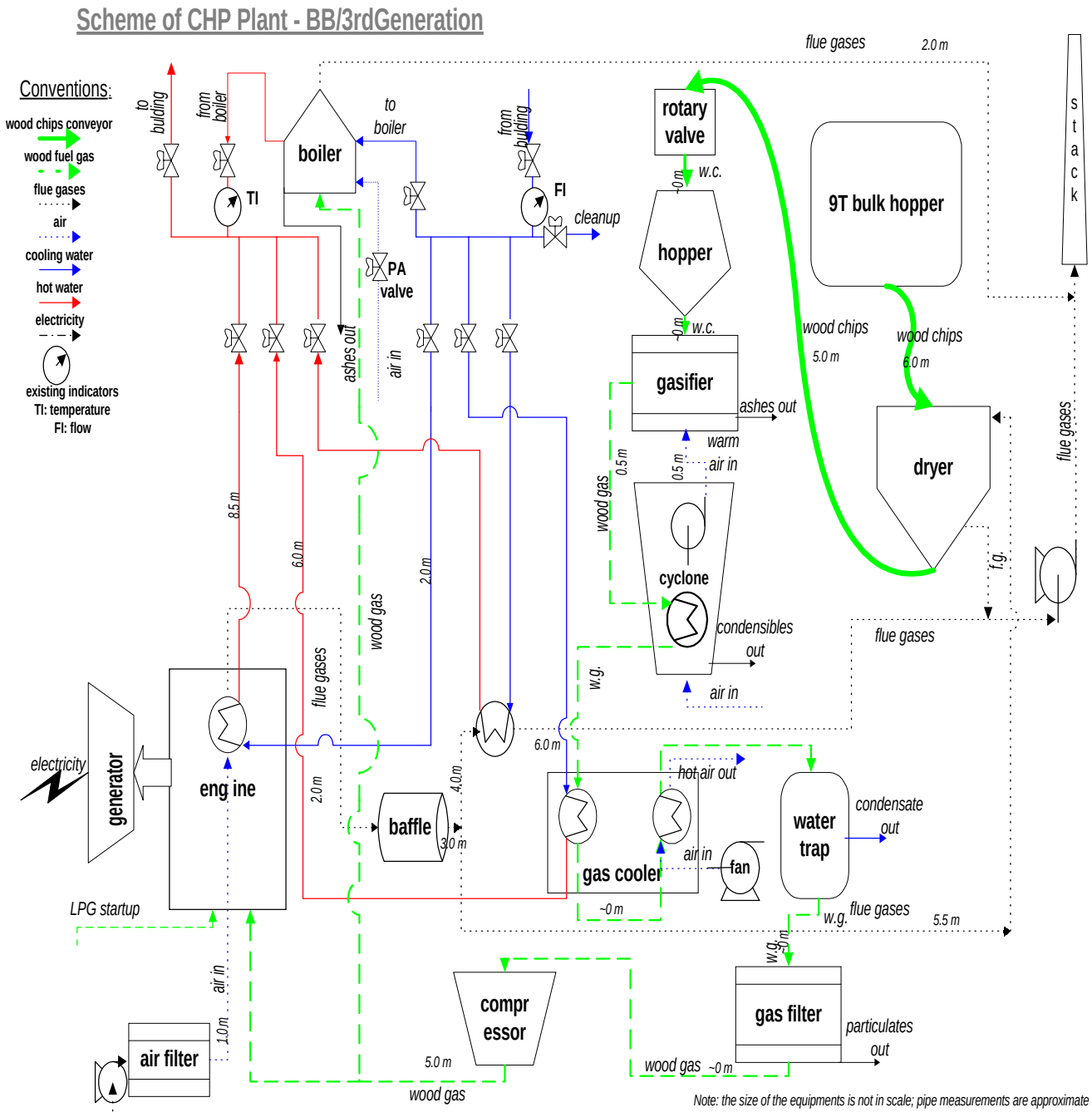

Figure 2. Schematic representation of the system to installed at the site.

A downdraft fixed bed catalytic gasifier is fed by wood chips and by an air stream coming from a cyclone-dust trap which exchanges heat from the hot gas leading to the rest of the cleaning system. The producer gas from the gasifier is sent to the cyclone, exchanging heat without direct contact with air. Some condensibles are removed at this stage.

The cyclone is followed by a two-stage gas cooler. First, there is a heat exchange - part of the CHP scheme - between producer gas from cyclone and warm water, returning from the building. Then, indirect quenching is designed between producer gas and cross-current air blown by a fan. This fan did not operate during the test runs.

Following, the gas passes through a condensate trap, basically an iron steel box with a purge manual pump.

Then, wood gas passes through a system with two polyethylene candle type filters in parallel. The gas flows at negative pressure from the suction of the gas engine and the compressor, located immediately after the filters.

In the final design, the clean, cooled producer gas is previewed to feed a dual fuel - with LPG backup - engine connected to a generator, to provide electricity for local use. However, during the experiment, the cleaned and cooled producer gas was by-passed to the boiler for flaring. The boiler's gas flaring needed also the use of propane to keep a sufficiently high temperature - wood producer gas only was not sufficient to stabilise the burnout -.and to prevent releases of CO to the plant.

The CHP scheme integrates plant sections. Its final design should cover three parts:

a) heat from the cooled producer gas, recovered in the hot water supply to the building;
b) heat from the engine exhaust gases, exchanged with cold water for building use and;
c) engine exhaust gases were also residually to be used in the internal wood chips dryer. The chips will act as a filter for air emissions, recovering hydrocarbons from the gas to be burnt in the gasifier

Problems need to be sorted out before the full system operates, such as :

- the engine adaptation to dual fuel of LPG and wood gas;
- the wood chips conveying system; and
- the assessment of the gasification and cleanup performance in order to provide a suitable fuel in terms of calorific value, purity and quantity.

10.1.1.2 System Boundaries

Due to the existing limitations - further described in the item 11.1, Limitations to the Experiment. (page 71) - the system boundaries were limited to the gasification and cleanup system. The initial biomass-to-energy scheme, primarily designed to be based on a gas engine, was investigated through bypassing the clean, cooled producer gas to the boiler to provide hot water to the office building.

Therefore, the system monitored was: the gasifier; and the gas cleanup system (gas coolers, condensate trap, gas filter and compressor).

The provisory boiler scheme performance was not assessed - although current the releases to the environment have their importance. To give an idea, some results from the monitored releases are presented; the literature review references may be useful for further work.

The following Table 3 presents items and systems assumed to be within the boundaries of the plant evaluated in this study.

Table 3. Process Boundaries

Process Section	Sub-section	Inside boundaries?
Fuel receiving, sizing, preparation, and drying	truck unloading system	no
	wood yard and storage	no
	chipping, sizing and conveying system	no*
	natural drying	no
	wood chips dryer integrated to the CHP	no*
Gasification and gas cleaning (Gasification Island)	wood feeding unit	no
	gasifier	yes
	cyclone-type air heater	yes
	gas cooler integrated to water heating	yes
	gas quench (fan)	no*
	condensate trap	yes
	gas filtering	yes
	gas compressor	yes
Fuel gas final combustion (Boiler Island)	gas boiler	no*
	pipe to stack	no*
	flue gas pumping	no*
Power Island	gas engine and generator	no*
	air pump to engine/to radiator inlet	no
	engine water cooling system	no*
	LPG backup	no*
CHP Scheme	water heating from gas cooler	yes
	water heating from engine cooler	no*
	heat from flue gases to water and dryer	no
General plant utilities and facilities	solid wastes produced	yes
	plant ventilation and instrument air	yes
	potable and utility water	no
	effluent water treatment and disposal	yes
	excess gas flare system	no
	fire-water system	no
	interconnecting piping	no*
	plant building	no
	office building	no
	lighting	yes
	computer control system and	yes
	electrical system.	yes

The boundaries are represented in the Figure 3. Some calculated extrapolations and other considerations cover partially the items marked with (*)

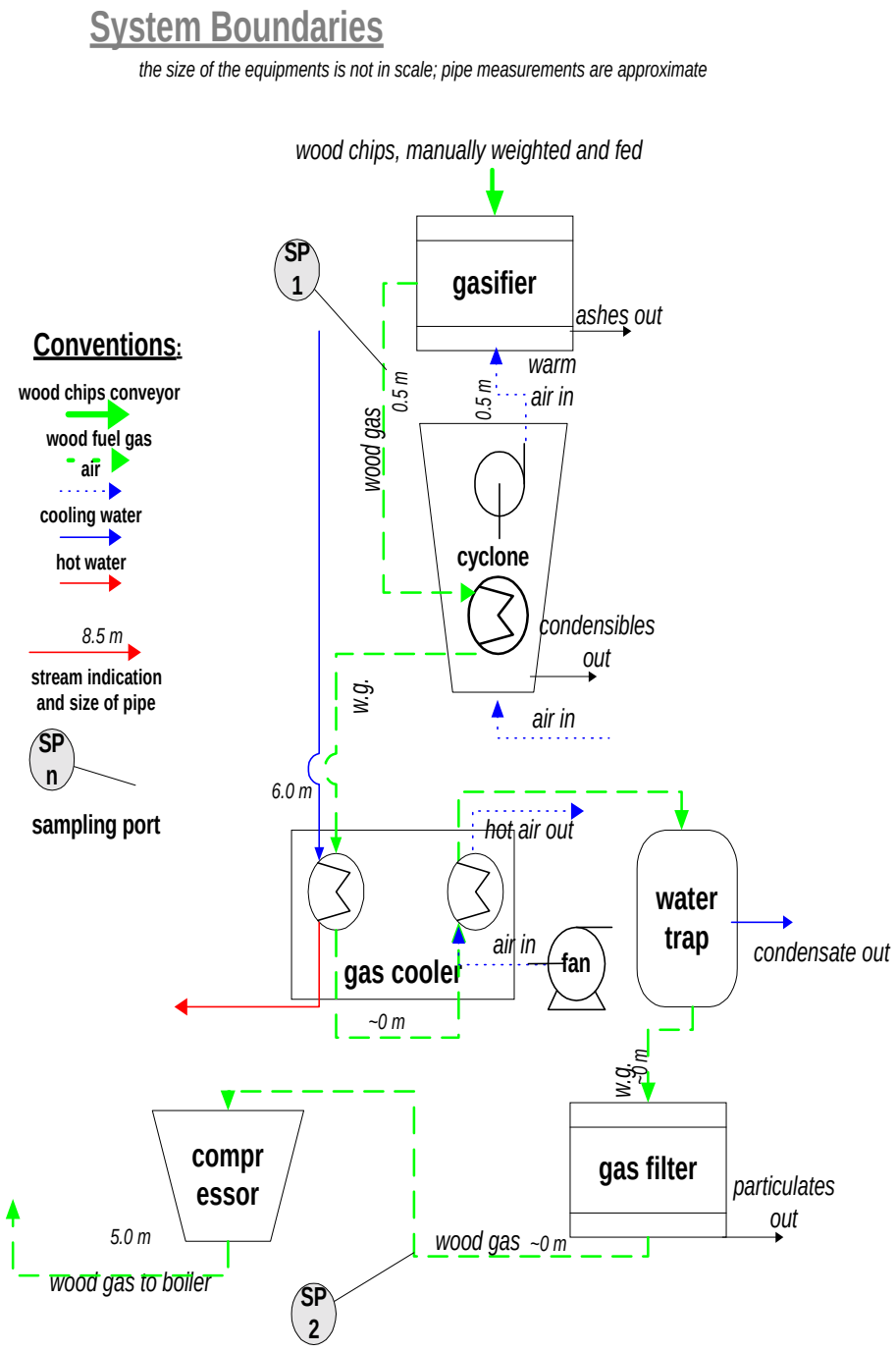

Figure 3. System boundaries considered in the experiment

Wood preparation was considered in the energy efficiency calculations with extended boundaries (Appendix 2 - Mass and Energy Balances, item e.1.), in terms of energy for chipping and transportation. Although not used during the experiment, the energy parasitically consumed in gas quenching by the fan was also considered in the same Appendix (d.1.). Other equipments using the energy (virtually) produced covered within the boundaries are the lighting, electrical and computer control systems. Some parts of the system were covered superficially, like the boiler combustor (monitored some emissions, item 10.2.10, page 68); LPG backup (calculated amount necessary, Appendix 2, item e.2.); energy recovered from engine

cooler (same item as previous) and part of the CHP recoveing heat from gases (same Appendix, d.2.).

10.1.1.3 Type of Biomass Utilised

The biomass used in this experiment was brash pine and spruce forestry residues in form of wood chips. Two types are available at present:

- type 1 (CHP) chips - utilised in this experiment -are approximately of 1" and smaller sizes. The supply available is of about 1 tonne, stored. Although informed by Third Generation that these chips should be at less than 5% moisture, proximate analysis verified a much higher value. Their analysis and other data comparing similar systems is presented in the item 10.2.7 - Comparative Results .
- type 2 (H.O. system) wood chips - sized in 2" and smaller, with approximately 22% of moisture.

They are delivered by truck to Tweed Horizons in 5 tonne batches from Woodend near Duns (20 miles distant) where there is a bulk store. These chips were obtained from forestry operations in the Berwickshire area.

The current wood chips requirements for the low-pressure gasifier "B" is about 20kg/h, to provide hot water to the building. Third Generation has given priorities for tests in this (H.O.) system, with development at a more advanced stage.

10.1.1.4 Wood Chips Drying

The wood chips are dried in an open-air area; moisture content varies according to the external conditions.

In the plant premises there is a wood dryer, not operating. Consisting of a gas tight insulated cabinet through which chips are conveyed from top to bottom by a series of augers, it was designed to use the exhaust gases from the power engine, after passing through a baffle and a heat exchanger (part of the CHP, to provide district heating).

According to Third Generation, the original feed system did not work due to:

- the location of the dryer is not convenient for the proposed feed system;
- the internal augers of the dryer can jam with chips;
- the hot gases contain tars and other substances which may contaminate the chips;
- the hot gases and high temperature may induce pyrolysis of the chips within the dryer which may lead to a risk of combustion in the dryer;
- the exhaust gases leak from the dryer causing a health hazard.

10.1.1.4.1 Gasification Equipment

The negative, low pressure gasifier system analysed in this study was a downdraft-fixed bed type. According to informations provided, the tested gasifier used nickel as a catalyst material to improve solid residence time and carbon conversion. The internal bed area measured approximately 35 x 35 cm^2.

Accurate gasifier design parameters and operating conditions are unfortunately not known. However, incomplete combustion of wood chips verified during experimental runs may indicate problems in internal design such as size of grate or slope of walls.

The internal temperatures could not be measured, just from the gas passing through the sampling port SP-1, located at a distance of 20 cm from the gasifier.

During the experiment, the automatic feeding system to the gasifier was not operating. The gasifier hopper was substituted by a closed top steel compartment, with a window through which a pre-weighted batch of wood chips was dropped.

Before each run, the window was closed and sealed with silicone. Only small batches (20 kg of wood chips for 1 hour of steady state) were allowed by this system.

Detailed procedures are further presented inAppendix 3. The system is shown in the Appendix 6.

10.1.1.4.2 Gas Cleanup and Cooling System

A cyclone (35 cm of diameter) is used to cool the gas. Although called as cyclone, when dismantled after the experiments this was shown to be an indirect heat exchanger rather than a particulate remover.

The fuel gas is cooled further in an indirect contact water heat exchanger and in a fan aerated indirect quencher. The latter was not used during the experiment.

Then, a steel drum acting as a condensate trap removes trace higher hydrocarbons and most of the water in the fuel gas stream. This operation also removes a significant amount of eventual alkali compounds from the fuel gas. Purge streams from condensate trap are to be sent to the public sewerage.

The fuel gas then enters a polyethylene (set of 2 candles, diameter 20 cm, height 80 cm) filter prior to the fuel gas compressors. The experimental results showed that the gas was sufficiently cooled to below 40^{o}C, without risk of burning the filters.

10.1.2 Monitoring Scheme

As previously described, the clean, cooled gases were by-passed to the heat-only system boiler combustor. Wood chips were manually fed to the gasifier, in small batches.

The monitoring covered:

- air intake flow rate
- the gases condensates: tar, particulates and moisture content
- the gas composition (%v/v)
- COD and TOC of condensate samples
- ash production rate
- a rough estimation of energy efficiency

10.1.2.1 Measurement techniques

10.1.2.1.1 Air intake

Ambient air characteristics were measured by using a dry and wet bulb humidimeter and a thermometer.

Air entering the gasifier via cyclone heat exchanger had it's flow rate measured by an anemometer connected to a flow meter (Euromatic/Eurototaliser).

Air was drawn through a flexible, corrugated pipe, linking the anemometer to the air inlet at the top of the cyclone. This pipe had approximately 2 metres of extension and 10 cm of diameter.

When the compressor was full pulling air to the system, the flow meter accused 60 m^3/h. There was no primary air (PA) valve controlling this flow. For the experiment, was used sealing tape in the cyclone inlet to reduce the flows to the range 2-12 m^3/h. This operation was not accurate and consumed 5 to 10 minutes to achieved the desired level.

It was not possible to start a batch run directly from reduced air flows. To achieve a sufficiently high temperature for startup, air flow was first set to 50-60 m^3/h, only reduced when gas temperature at the sampling port SP-1 was above 150^{o}C, closer to steady state temperatures, around 180^{o}C.

10.1.2.1.2 Temperature measurements

A thermocouple was used to measure directly the temperatures of the gas within the pipes at SP-1 and SP-2.

A thermocoupler linked to a thermometer measured the lower temperatures of the condensates in the third "U" tube.

The same equipment measured the external temperature of the water pipes in and out of the CHP gas cooler. The measurement was taken within the steady state period. Both water pipes (in and out) had a 6cm insulation. Nevertheless, there are still limitations in the measurement, for being subject to radiation from the gas cooler glowing surface.

10.1.2.1.3 Ash weighting

A door below the gasifier enabled the ash to be collected in plastic bags. Ash samples were taken after each run and weighted. The rate of ash production during the cycle could not be assessed: the ash box was closed and door sealed with silicon before each run.

This so-called "bottom ash" - but more like charcoal - was submitted to a proximate analysis at the Fuel Laboratory, NCU Chemical Engineering Department.

The current assembly of the system did not allow fines and particles to be removed from the cyclone and filter after each run. Only after the last trial, cyclone was dismantled and condensate accumulated collected..

10.1.2.1.4 Gas sampling

Twenty gas samples were taken during the four days of experiment. In order to eliminate the effect of moisture and tar condensation, were used the apparatus, further described.

During gas sampling, safety procedures had to be taken, as shown in **Appendix 3**. Was used a portable CO alarm for ambient levels above 50 ppm.

10.1.2.1.5 Monitoring Apparatus

The producer gas was monitored and collected for analysis using the apparatus shown in the Figure 4 and based in the methods described references [12], [13], [38], [44], [47] and [68].

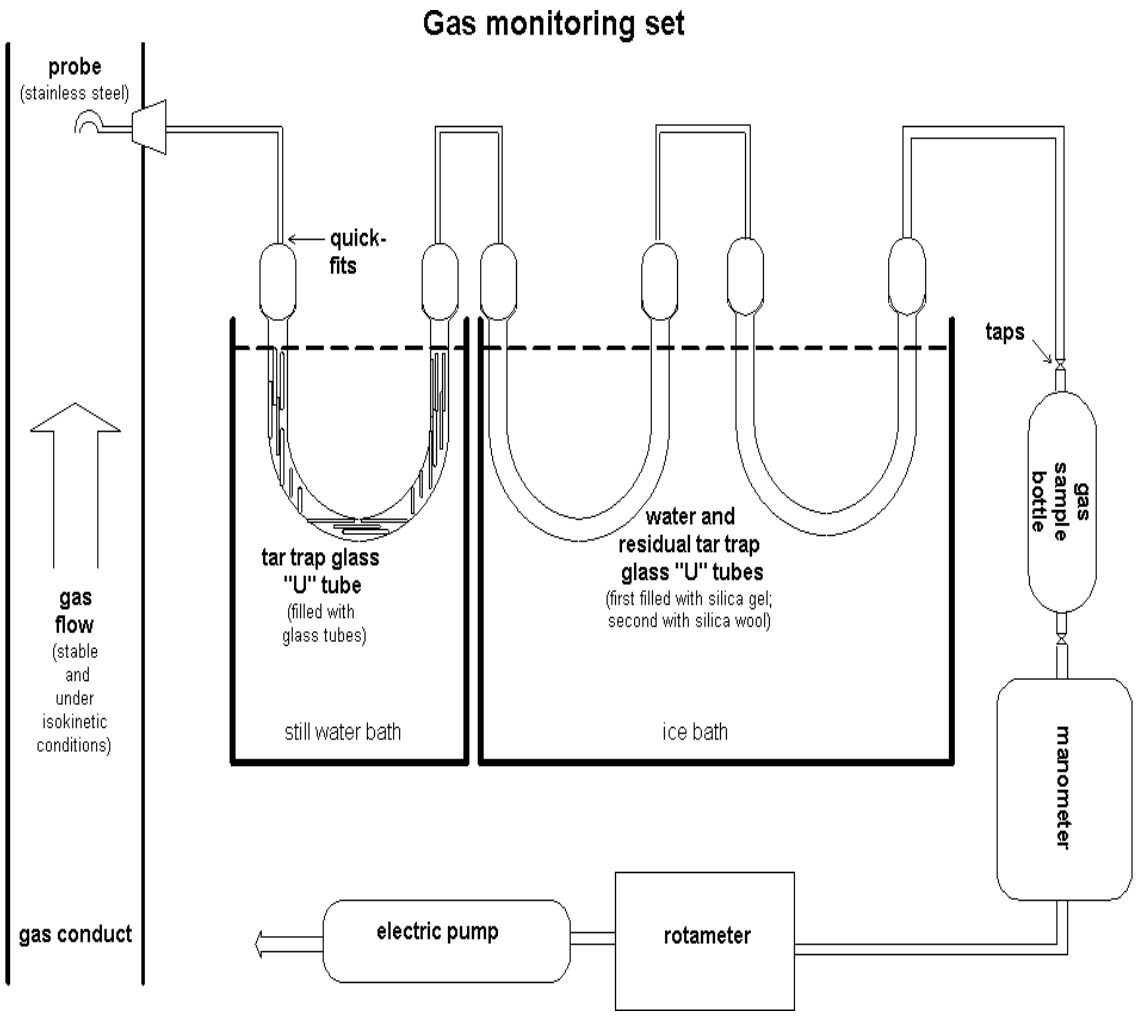

Figure 4. Gas collecting set

Basically, it consists of:

- a thermocoupler, designed to support temperatures of up to 800ºC, attached to a thermometer (Comark 2001, -60 to 1372ºC) , was used for the gases in the sampling port SP-1. This was inserted in the middle of the stream in a similar manner as the sampling probe.
- a stainless steel sampling probe (5mm diameter), with 3 pieces (50 cm each) attachable according to the necessary relative position of the sampling port (SP-1 or SP-2) and the rest of the gear. Long enough to quench the gases, the probe was not cooled by water. Two elbows permitted an "L" or "U" disposition of these parts. The extremity of the pipe to be inserted in the sampling port was curved (90º) to be set in the gas pipes and collect the gas under isokinetic conditions. An aluminium foil wrap was used to place the extremity of the probe in the centre of the section of the pipe to be monitored and to prevent excessive air from entering in the sampling port. The other extremity of the metal gas collecting pipes was attached by epoxy to a quick-fit glass adaptation for the "U" tubes
- following, three "U" tubes (Pyrex) were placed in series in two ice baths (buckets), for trapping tar and moisture. The first trap contained smaller diameter glass tubes between glass wool on both sides to provide a large surface area to flue gas. The second trap contained silica gel between two pieces of cotton wool. The third contained glass wool. The first trap was placed in an individual ice bath. Temperature was measured in the third tube by another thermocoupler (thermometer Solex ST 505, -50 to 800ºC)
- then, a gas bottle with two Teflon taps was used to collect the samples;
- a differential pressure mercury column manometer (Gallencamp) and a rotameter (MFG Fischer 10L/min) were placed between the gas bottle and the vacuum pump.
- an oil pump (AEI type BS 2406 0.25 hp) was used to draw the gases through the sampling bottle (a vacuum CO_2 pump was previewed to be used, but broke down days before the experiment);

Auxiliary equipment used in site were:

- an anemometer connected to a flow meter for the air intake, as mentioned in item 10.1.2.1.1 - Air intake
- a 2-digit scale mechanical balance, used for weighting the "U" before and after each sample collection;
- a chronometer, for measuring a time of 2 minutes in SP-1 and 4 minutes in SP-2, necessary to provide a sufficiently measurable quantity of condensate. The rate of production was averaged during this time.
- clamps and auxiliary supports kept the set in position;
- the second thermocoupler, previously mentioned, was also used for measuring CHP water pipes surface temperatures.
- plastic bags and closeable bottles were used for samples of the gasifier bottom ash and condensate purged from the trap.

10.1.2.1.6 Analyses of gases

Small samples (1 mL) were withdrawn from the gas bottles by syringe and analysed by gas chromatography, to detect the permanent gases and hydrocarbon levels. Reference [57] was used for the theoretical background.

The gas chromatograph used was a programmed, automatic Shimadzu GC-8A. The carrier gas was Helium.

The parameters for each column are presented in Table 4

Table 4. Gas chromatograph parameters

parameter	Column 1	Column 2
pressure (kPa)	95	85
gas velocity (mL/min)	39.6	35.5
molecular sieve for	H_2, O_2, CH_4, N_2, CO	CO_2
using	Aluminium silicate	Chromosorb 108

Column 2 defined also the concentrations of (O_2 + N_2). There were no higher hydrocarbons. The operating conditions were based upon the results of trial runs using a series of standard samples.

The method used was the Area Normalisation. The position of the peak along the line axis of the time chart measures the component retention time which identifies the component; the area under the peak is a measure of its concentration. Hydrogen is specially difficult to measure due to the small size of the molecules. The operation of inserting 1mL of sample into the GC also shows difficulties: first, there is always a residual gas in the seringe; second, there are leakages when pulling the gas from a bottom under negative pressure; third, an exact sample of 1 mL is difficult to measure in the seringe, in a rapid operation.

Composition of the gasifier product gas was thus measured and compared with experimental data from the other gasifier (available in the site and named "B"), tested with the same type of wood chips.

10.1.2.1.7 Condensate composition

For the optimum performance, two samples of condensate were be taken: one from the condensate trap and other immediately before the stack. These were analysed at NCU Civil Engineering Dept. and AES (a private laboratory, part of Northumbrian Water, based at Howdon, Newcastle), to assess the polluting potential of the waste waters. Other parameters were taken from bibliography.

For qualitative analysis, a sample was taken from the condensate trap to measure COD, TOC, pH and organic phenols. Another ample of the condensate leaving the boiler to the stack had the COD determined. Accurate condensate analysis were based in the literature[28].

10.1.2.1.8 Engine and Boiler Performances

Due to a lack of instrumentation available, the energy efficiency of the system was just roughly estimated, in terms of heat from wood effectively transferred to the water for district heating.

Gas engine performance was not assessed, just estimated based on the operating parameters (air flow, pressure ratio, firing temperature, outlet temperature) found in literature and few available specifications.

The major auxiliary equipment items (pumps, blowers etc.) are explicitly included in the simulation and their power requirements subtracted from the gross plant output.

10.1.3 Experimental procedure.

As mentioned, only 2 hours batch conditions were possible for the experiment.

The procedure adopted was the following:

1. start up the boiler with propane gas backup (these specific procedures are presented in the Appendix 3)
2. clean the gasifier bottom box and grate from the previous run ash and unburned wood
3. purge the condensates from the trap
4. fill the top compartment with the pre-weighted wood chips to maximum capacity
5. close gasifier window, using screws
6. seal the window and the bottom ash box with silicone
7. switch on the compressor, blowing air at negative pressure at full capacity (55-50m^3/h)
8. ignite wood fuel by blowing hot air (using a portable air blower) through a pipe in the bottom of gasifier
9. the desired level of air flow was set after 45 minutes of the startup procedure, by partially closing the entrance at the top of the cyclone with sealing tape
10. steady state conditions are attained in approximately one hour after startup.

10.1.3.1 Batch Runs

As mentioned, since the automatic feeding system was not operating, batch runs using up to 25 kg of wood chips were conducted. To attain the desirable self-sustainable combustion, the aperture at the top of the cyclone for primary air had first to be fully opened. After 45-60 minutes, this flow was reduced to the desired level of each experimental run, by blocking partially the entrance with sealing tape and reading the flow meter.

The steady state was attained in a short period. However, instant changes in the gasifier output and efficiency because of variations in the mass flow of wood chips and decreased efficiency of the cleaning system could not be measured. As a matter of record, the total time elapsed for each batch was taken, as well as the elapsed time of each sample collection. This relative proportion (elapsed/total batch times) is presented together with each result.

Therefore, it was not possible to have a whole batch run at a constant air in flow rate, neither a sufficiently long and representative steady state.

The monitoring started directly from hot runs. In each run, temperatures were measured and gas samples collected at SP-1 (gasifier producer gas outlet) and SP-2 (prior to compressor). Temperature measurements at SP-1 also gave an idea of what occurs during the batch time. However, this is just an idea, since there are no thermocouplers inside the gasifier. Temperature measurements at gasifier outlet cannot how effective is the gasification, or even if the gasifier is simply burning completely the wood., not producing fuel gas. This was observed in practice in the last runs, when a high temperature was measured at SP-1 - suggesting that gasification was occurring - while gas analysis results presented very low calorific values. The temperature measured in the boiler could not help, for it was using a propane backup together with the fuel gas.

End of startup was assumed after 1 hour, when the boiler internal reached relatively steady values (around 180ºC) and gas temperatures at SP-1 were also quite stable. Beginning of shutdown was assumed when started the orange light glow from charcoal burning, visible from the gasifier glass window. Typical conditions obtained are shown in the item 10.1.2.1.2 Temperature measurements (page 43).

The best run was determined in terms of calorific value produced (MJ/h), basically the percentage of combustible gases (CH_4, CO and H_2) times the calculated producer gas flow rate. Low tar production was another issue to be considered.

Since the first results showed air leakages, sampling was repeated for air flows of the low and medium values (2 and 6 m^3/h).

10.1.3.2 Effect of moisture in wood

The effect of wood moisture was to be assessed by adding water to the wood chips and measuring the differential weigh. Since this procedure would result in the system working out of specification, it was not authorised by Third Generation. After the proximate analysis results, it was verified that all the trials were conducted with wood chips with moisture above specification.

Informations about effect of the moisture are, therefore, referred in the literature review.

10.2 Results and Discussion

The obtained results from the monitoring are presented and discussed hereafter. For a better comprehension of the numbers, some observations are summarised in Table 5.

Table 5. Principal observations from each day of run

Date of sample	Observations
21/07/97	• a previous test run was done at full air intake, 3 days before, without filters; system had accumulation of condensates (tars + water) • filters were installed • run started from full air (flow of 55 m^3/h); after 30 minutes, dirty smoke from the stack showed that this was not the best range. Following a recommendation from Mr. John Seed, air was reduced to one fifth ($12m^3/h$) and monitoring started • installing the monitoring gear was not difficult, but problems came up when moving from SP-1 to SP-2 and vice-versa. More three persons were at the site, helping with this, as well as with measurements of temperatures, weighting tubes, controlling levels of CO etc. • end of batch occurred 2 hours after startup, a sample #2 was quickly taken, but leakage was not avoided • stainless steel probe/glass quick-fit connection broken and fixed at site with epoxy resin

Date of sample	Observations
22/07/97	• air flow reduced to the minimum value measurable by the meter: 5-6 m^3/h • 3 persons were in the plant for the work; sampling simultaneously before and after the pump required all the group • same difficulties with moving the gear and broken connections; an adaptation using plastic tube between the steel and glass proved to be effective, supporting the high gas temperatures • the amount of wood was too low: batch finished suddenly; samples #s 7 and 9 were collected after charcoal burning light glow appeared in gasifier's window • a large amount of char was collected from the bottom ash box, due to bridging in wood chips (see 9.2.7, page 16)
23/07/97	• 50% more wood was put into the gasifier (23 kg); the resulting steady state took longer to finish; however, a large amount of char was still found in the ash box • initial pressure boost from the air pump lead to some mercury spilling from the manometer; although it did not affect the results, time was consumed in the cleaning operation • instead of moving the gear from port to port before each sampling, it was decided to take two samples at SP-1, move the apparatus, then take two samples at SP-2 • 3 persons in the plant
24/07/97	• compressor pump broken down (due to tar accumulated) and repaired
25/07/97	• repeated trials at lower air intakes (2-7 m^3/h), using 21 kg of chips; air flow was changed 100 minutes after startup • temperatures took about one hour to reach values above 150^oC at SP-1; steady state was kept just for a short time • all the gas analysis results showed that only a very poor gasification occurred in this day

Ambient conditions and summarised results from the experiment are presented in Table 6.

Table 6. Significative results from each day of run

Date of sample	21/07/97	22/07/97	23/07/97	25/07/97	25/07/97
wood chips wet weight (kg)	14.5	14	23	21	21
wood chips moisture content (w/w)	13.72%	13.72%	13.72%	13.72%	13.72%
wood chips dry weight (kg)	12.5	12.1	19.8	18.1	18.1
total batch time (min), until burnout	120	103	180	120	120
steady state time (min)	60	43	120	60	60
wood chips consumption, dry(kg/h)	6.26	7.04	6.61	9.06	9.06
ambient temperature (oC)	22	22	22	21	21
air humidity (%)	62%	56%	69%	67%	67%
pressure (mmHg), assumed	760	760	760	760	760
air flow in (m3/h), nominal	12	6	2	2	7
fuel/air ratio (dry)	40%	90%	255%	350%	100%
gas produced (L/min)	263.53	140.37	42.38	34.26	113.77
gas produced (m3) in batch	15.81	6.04	5.09	2.06	6.83
gas produced (m3/kg of dry wood)	1.26	0.50	0.26	0.11	0.38
heat value of gas (MJ/m3)	3.56	3.94	3.09	0.83	0.03
heat produced (MJ) in batch	56.30	23.80	15.72	1.71	0.24
as representative samples #	1	5; 7	11,12	15,16	17,18
bottom ash/charcoal weighted (kg)	0.739	2.9	2.311	na	na
ash+charcoal/ dry wood (g/kg)	59	240	116	na	na
moisture + tars produced (g/L gas)	0.34	0.41	0.19	0.02	0.02
moisture + tars (kg/kg dry wood)	42.39%	20.47%	4.78%	0.28%	0.60%
worst (tar+H_2O) removal efficiency (%)	92%	97%	97%	70%	37%
moisture + tars (kg) in batch	5.30	2.47	0.95	0.05	0.11

na: not available

Table 7. Overall Results

Sample #		1	2	3	4	5
Date of sample		21/07/97	21/07/97	21/07/97	21/07/97	22/07/97
minutes elapsed after startup		30	120	80	70	58
total batch time (min) until only charcoal		120	120	120	120	103
% of batch time elapsed		25	100	67	58	56
T oC of gas @ SP-1		160	180	190	180	166
T oC of gas @ SP-2		na	na	31	na	na
Port #		1	1	2	2	1
Concentration %(v/v)	H_2	11.19%	0.12%	5.07%	0.41%	13.64%
	O_2	0.63%	13.58%	7.97%	16.39%	0.31%
	N_2	59.95%	85.57%	70.68%	79.62%	52.94%
	CH_4	2.24%	0.02%	1.01%	0.08%	2.73%
	CO	11.39%	0.07%	5.25%	0.46%	13.66%
	CO_2	14.60%	0.62%	10.02%	3.03%	16.72%
LHV(MJ/m3)		3.56	0.03	1.62	0.14	4.31
considered representative?		yes	no	yes	no	yes
H2:CH4:CO:CO2		5:1:5:7	5:1:3:25	5:1:5:10	5:1:6:37	5:1:5:6
Monitoring flow, adjusted (L/min)		6.23	6.32	6.28	6.30	6.27
condensates (tar+ water)(g/L gas)		0.34	0.03	0.03	0.01	0.45
MW gas(g/L)		1.21	1.28	1.27	1.30	1.20
% condensates in gas (w/w)		4.43	0.41	0.32	0.07	6.00
Air flow (m3/h) measured		12	12	12	12	6
N balance (g/min), air: 79%		197.50	197.50	197.50	197.50	98.75
Producer gas flow (L/min)		263.53	184.64	223.53	198.44	149.21
Producer gas flow (m^3/h)		15.81	11.08	13.41	11.91	8.95
LHV of gas (MJ/h)		56.30	0.36	21.78	1.62	38.62

na: not available (cont.)

Table 7 (cont)

Sample #	**6**	**7**	**8**	**9**	**10**
Date of sample	22/07/97	22/07/97	22/07/97	22/07/97	23/07/97
minutes elapsed after startup	58	123	80	103	60
total batch time (min) until only charcoal	103	103	103	103	210
% of batch time elapsed	56	119	78	100	29
T oC of gas @ SP-1	166	190	213	190	147
T oC of gas @ SP-2	na	na	25	na	na
Port #	1, pump	1	2	2	1, pump
Concentration %(v/v) H_2	3.67%	10.59%	6.01%	6.09%	5.07%
O_2	13.14%	0.45%	9.14%	9.30%	7.97%
N_2	73.43%	60.06%	69.09%	68.84%	70.68%
CH_4	0.73%	2.12%	1.20%	1.22%	1.01%
CO	3.90%	12.47%	5.53%	6.23%	5.25%
CO_2	5.12%	14.32%	9.03%	8.31%	10.02%
LHV(MJ/m3)	1.19	3.57	1.84	1.94	1.62
considered representative?	yes	yes	yes	yes	yes
H2:CH4:CO:CO2	5:1:5:7	5:1:6:7	5:1:5:8	5:1:5:7	5:1:5:10
Monitoring flow, adjusted (L/min)	6.54	6.89	6.76	6.91	5.83
condensates (tar+ water)(g/L gas)	0.43	0.37	0.01	0.01	0.24
MW gas(g/L)	1.26	1.22	1.25	1.25	1.27
% condensates in gas (w/w)	5.22	4.39	0.17	0.10	3.18
Air flow (m3/h) measured	6	6	6	6	2
N balance (g/min), air: 79%	98.75	98.75	98.75	98.75	32.92
Producer gas flow (L/min)	107.58	131.54	114.34	114.76	37.25
Producer gas flow (m^3/h)	6.46	7.89	6.86	6.89	2.24
LHV of gas (MJ/h)	7.67	28.20	12.64	13.38	3.63

na: not available (cont.)

Table 7 (cont.)

Sample #		11	12	13	14	15
Date of sample		23/07/97	23/07/97	23/07/97	23/07/97	25/07/97
minutes elapsed after startup		60	77	90	98	76
total batch time (min) until only charcoal		210	210	210	210	120
% of batch time elapsed		29	37	43	47	63
T oC of gas @ SP-1		147	152	138	126	175
T oC of gas @ SP-2		na	na	na	28	na
Port #		1	1	2	2	1
Concentration %(v/v)	H_2	9.84%	9.88%	3.10%	1.06%	2.38%
	O_2	2.27%	1.58%	13.32%	17.03%	15.35%
	N_2	62.57%	61.72%	73.93%	78.33%	77.28%
	CH_4	1.97%	1.98%	0.62%	0.21%	0.48%
	CO	9.92%	9.36%	2.76%	0.99%	2.36%
	CO_2	13.43%	15.49%	6.28%	2.37%	2.16%
LHV(MJ/m3)		3.12	3.06	0.94	0.33	0.75
considered representative?		yes	yes	yes	no	yes
H2:CH4:CO:CO2		5:1:5:7	5:1:5:8	5:1:4:10	5:1:5:11	5:1:5:5
Monitoring flow, adjusted (L/min)		5.55	5.31	4.79	5.51	5.57
tar (g/L gas)	tar (g/L)	0.25	0.13	0.00	0.01	0.04
MW gas(g/L)		1.23	1.24	1.28	1.28	1.26
% tar in gas (w/w)		3.64	1.90	0.06	0.12	0.52
Air flow (m3/h) measured		2	2	2	2	2
N balance (g/min)	79.00%	32.92	32.92	32.92	32.92	32.92
Producer gas flow (L/min)		42.08	42.67	35.62	33.62	34.08
Producer gas flow (m^3/h)		2.53	2.56	2.14	2.02	2.04
LHV of gas (MJ/h)		7.88	7.84	2.01	0.66	1.53

na: not available (cont.)

Table 7 (cont.)

Sample #		**16**	**17**	**18**	**19**	**20**
Date of sample		25/07/97	25/07/97	25/07/97	25/07/97	25/07/97
minutes elapsed after startup		85	119	125	60	137
total batch time (min) until only charcoal		120	120	120	120	120
% of batch time elapsed		71	99	104	50	114
T oC of gas @ SP-1		175	165	160	180	153
T oC of gas @ SP-2		na	na	29	na	na
Port #		1	1	1	2	2
Concentration %(v/v)	H_2	2.89%	0.03%	0.19%	1.15%	0.00%
	O_2	14.32%	18.40%	18.71%	16.71%	21.04%
	N_2	76.45%	81.43%	80.60%	79.47%	78.24%
	CH_4	0.58%	0.00%	0.04%	0.23%	0.00%
	CO	2.88%	0.03%	0.20%	1.18%	0.00%
	CO_2	2.88%	0.11%	0.26%	1.26%	0.72%
LHV(MJ/m3)		0.91	0.01	0.06	0.37	0.00
considered representative?		yes	yes	yes	yes	yes
H2:CH4:CO:CO2		5:1:5:5	-	5:1:5:7	5:1:5:5	-
Monitoring flow, adjusted (L/min)		5.42	5.44	4.99	5.42	4.61
tar (g/L gas)	tar (g/L)	0.01	0.02	0.01	0.01	0.02
MW gas(g/L)		1.26	1.28	1.28	1.27	1.29
% tar in gas (w/w)		0.19	0.36	0.11	0.16	0.26
Air flow (m3/h) measured		2	7	7	2	7
N balance (g/min)	79.00%	32.92	115.21	115.21	32.92	115.21
Producer gas flow (L/min)		34.44	113.19	114.35	33.14	117.80
Producer gas flow (m^3/h)		2.07	6.79	6.86	1.99	7.07
LHV of gas (MJ/h)		1.88	0.05	0.43	0.73	0.00

na: not available

10.2.1 Temperature measurements

Figure 5 below shows the typcal rise in the gas temperature measured at SP-1. Some difficulties were found when measuring temperatures: tars accummulated in the thermocoupler, taking up to 5 minutes to the thermometer to give a steady result. The thermocoupler could not be placed in the sampling port continuously.

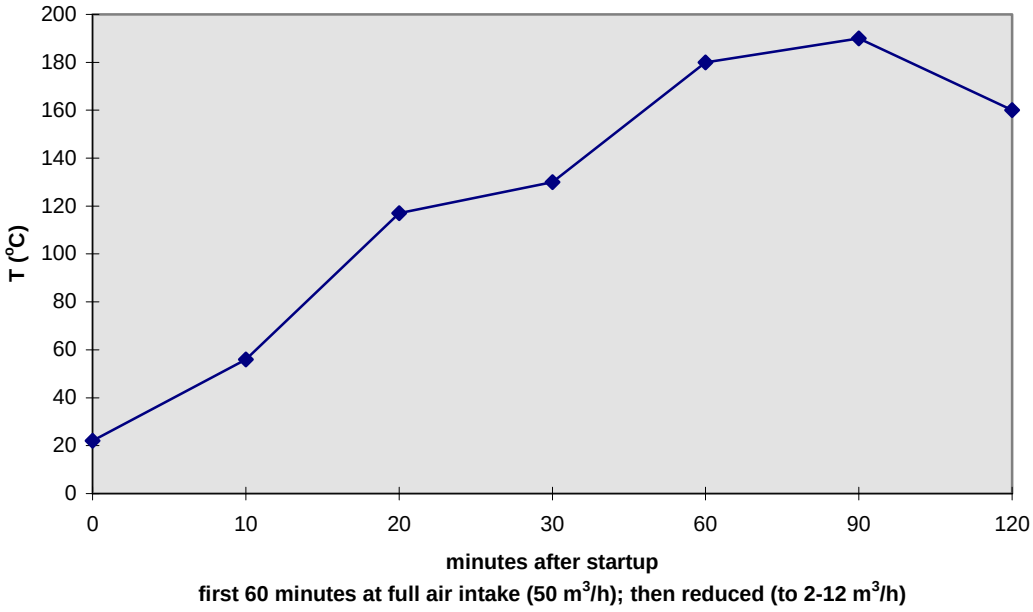

Figure 5 Typical temperatures measured for the producer gas at SP-1 (sample #1)

10.2.2 Production of Ash

The source of the (non-contamined) wood is known, as well as its elemental dry composition, from the experience with the gasifier "B" (H.O. system). Variations occur in the moisture content.

Although data from this gasifier suggested that better than 98% burnout was achieved and the amount of ashes should be quite low, the same effect was not verified in the CHP gasifier. Amounts up to 21% (2.9 kg of "bottom ash" for an input of 14 kg of wood chips) of charcoal were collected after each run, due to incomplete burnout within the gasifier. Some parts of this charcoal kept visibly the original colour of the wood. Table 8 shows the characteristics of the wood chips and two samples collected in the bottom ash box. Visually, the proportion between the partially burnt wood (char) with visible colour was below 5% of the total, the rest being charcoal and some ash.

Table 8 - Results from proximate analysis of samples of wood chips and two types of residues found in the bottom ash box of the gasifier

parameter	**wood**	**char**	**charcoal**
moisture	13.72%	6.55%	2.44%
ash	0.16%	1.23%	4.73%
volatile matter	69.52%	51.92%	7.46%
fixed carbon	16.60%	40.29%	85.38%
calorific value (MJ/kg)	16.76	29.05	33.53

The cyclone was - in theory - expected to remove fines and particles. In practice, when dismantled, an approximate amount of 3 litres of condensates was found in this indirect heat exchanger, according to informations by Third Generation.

10.2.3 Dry, clean producer gas composition

In the Figure 6 are represented the relative percentages of each constituent of the producer gas. For an easier view, Nitrogen is not included.

From the graph can be noticed the relatively high concentration - above 5% - of O_2 in most of the runs (except runs # 1, 5, 7, 11 and 12).Specially in the last batch (runs #15-20), high O2 levels, associated with low CO2 levels showed either:

- a failure in the monitoring, allowing air to leak in (not probable to happen in all samples); or
- all the wood was burnt during the long time of startup, then air short-circuited the gasifier bed during the short steady state

As mentioned in the review (item 9.2.8), the concentrations of O_2 in the gas can give an idea of the contamination from air in the system. A convenient gas sampling methodology was one of the main problems to be tackled in the experiment, Contamination was a special problem, caused by a number of factors.

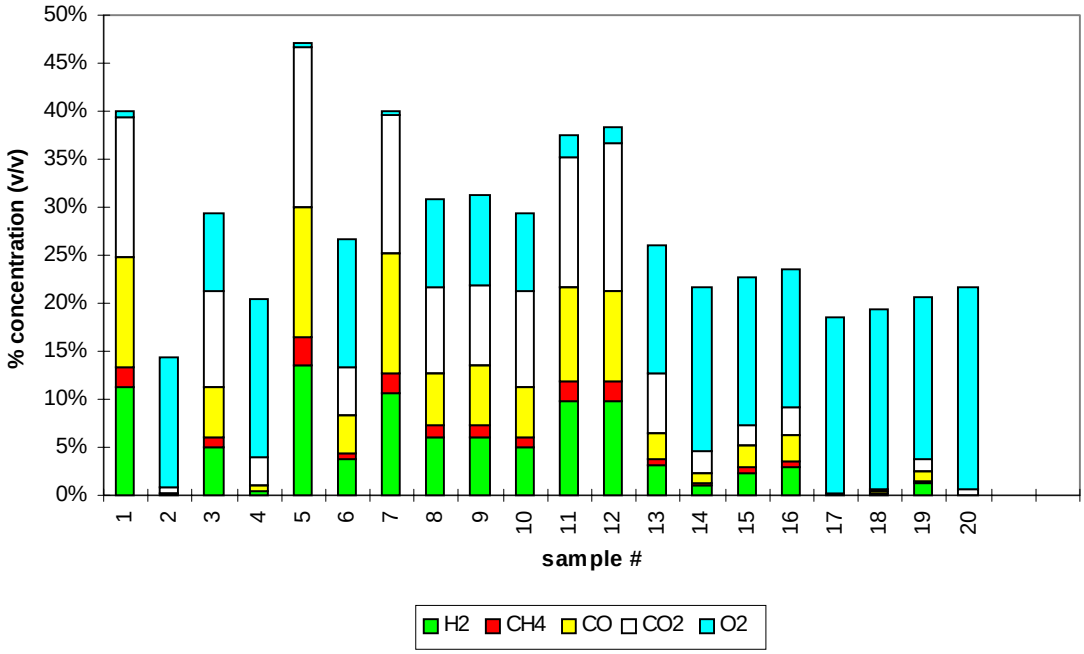

Figure 6. Producer gas concentrations, by volume(except N_2), in each sample.

10.2.4 Producer gas - definition of the steady-state best range

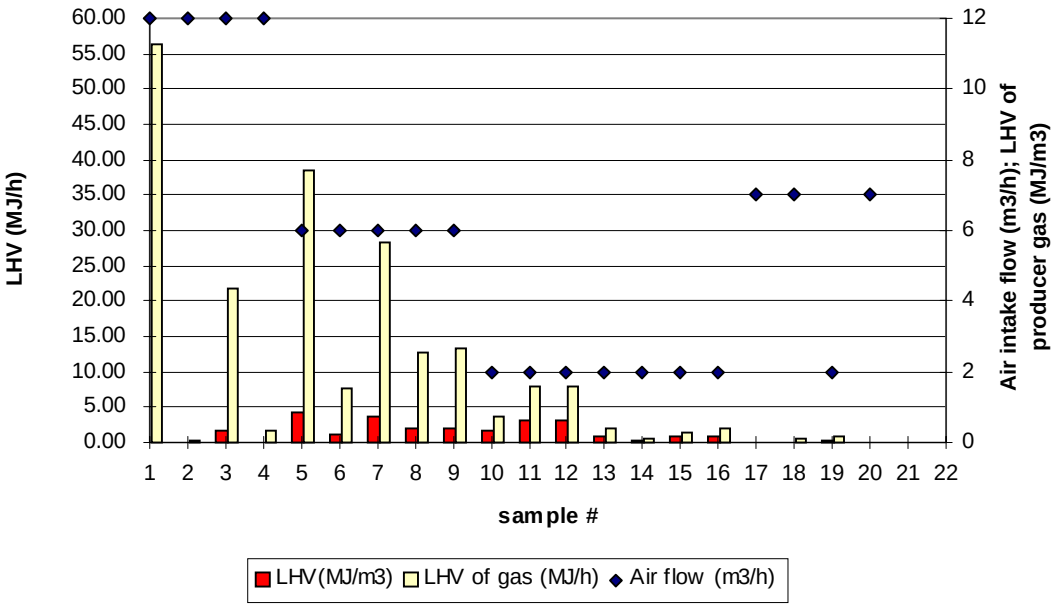

Figure 7. Lower heating values (LHV), in volume and time basis, obtained from the gas samples and producer gas flow rate calculated through mass balance

From the preliminary results from the 20 samples, previously presented, it is not absolutely clear the optimum air intake flow rate. The best gas quality, in terms of calorific value, was obtained from the samples # 1 and 5 (backed up by the values of samples taken at SP-2). The best air flow intake range, therefore, seems to be between 6-12 m^3/h.

The best LHV of fuel gas obtained was 56 MJ/h. However as shown in Figure 7, many poor results occurred, not only due to failures in monitoring. Unfortunately, repeated experiments did not give repeated results. Gas quality could be considered poor all through the batch conducted in the last day (samples # 15-20)

As mentioned in the literature review (item 9.2.7), quantity and calorific value of the fuel gas varies considerably during the batch.

A fraction of the O_2 consumed in the process required for complete combustion - called equivalence ratio (ϕ) - has an optimal typical value of 0.25 for gasification, in order to maximise conversion of energy from the wood and char to gas (if less, char is not converted; if more, gas is burnt and temperature rises rapidly). .[53]

A sufficiently high temperature is necessary to guarantee the cracking of all the heavy hydrocarbons such as phenols and tars [71].There was a high production of charcoal in the system, collected in the bottom ash box. Attention should be taken with the limitations in the experiment, as further described.

10.2.5 Gas cleanup

10.2.5.1 Comparison between gas samples, before and after cleanup

Figure 8 presents some views of the gas sampled before the cooling/cleanup system (at sampling port SP-1) and after (at SP-2). Samples could not be taken simultaneously, for operational limitations. The relative stage in the batch time elapsed (%) is therefore represented to give an idea of this gap. The temperature refers to gas at SP-1. To help visualisation, N_2 (an inert gas for these purposes) concentrations were omitted.

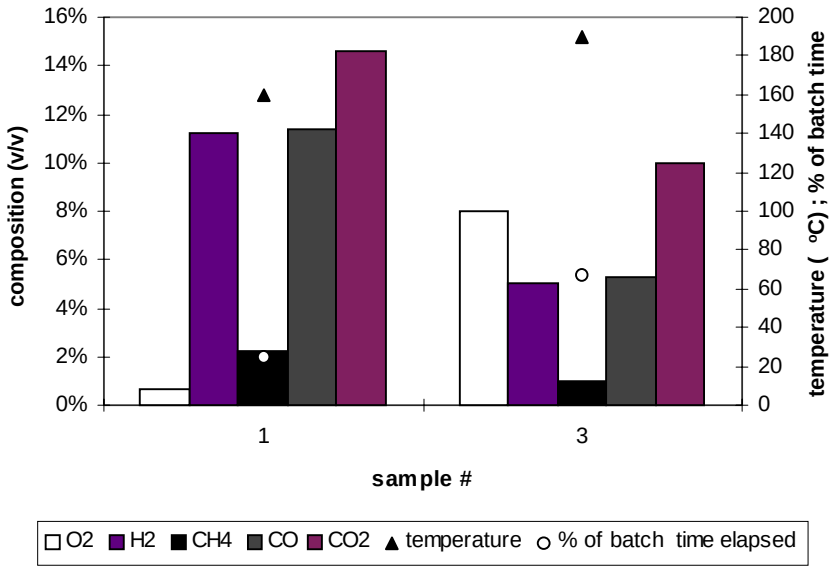

Figure 8- Comparison between samples #1 (SP-1) and 3 (SP-2), for an air flow rate of 12 m3/h (21/07/97).

As seen in the graph, the proportional decrease in the concentration of all gases but O_2 suggests air leaking into the system. Even after the cleanup equipment, gas concentration should theoretically be the same (if taken at the same time).

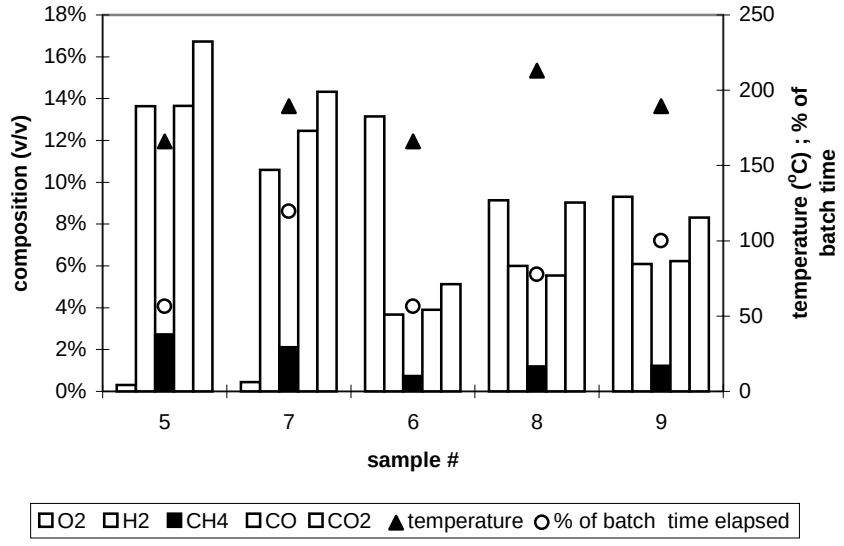

Figure 9 Comparison between samples # 5, 7 (SP-1), 6(SP-1, back of pump); 8 and 9 (SP-2); flow rate = 6 m^3/h (22/07/97)

Comparing samples #5 and #6, taken simultaneously, the effect of air leakages in the pump is clear. Differences may also occur due to the fact that the first is taken under negative and the second under positive pressure. Not by coincidence, O_2 concentrations - indicating air contamination - are higher at SP-2, as shown in samples #s 8 and 9.

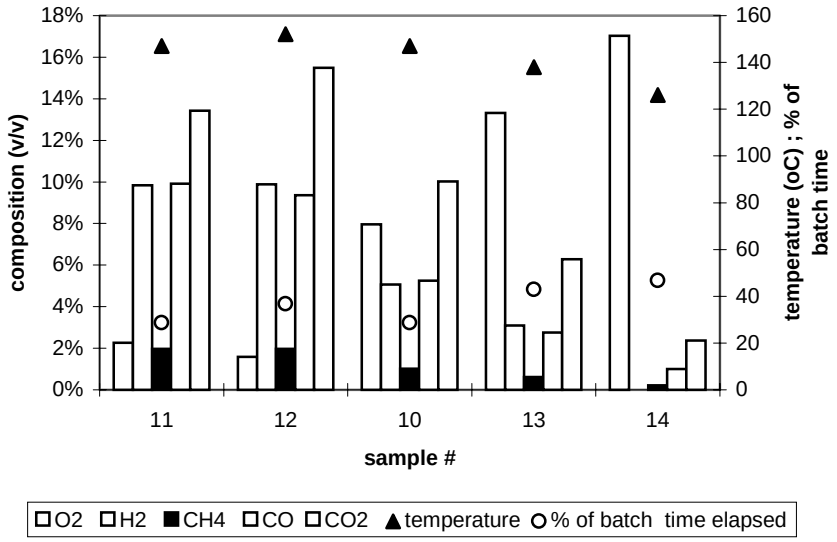

Figure 10. Comparison between samples # 11, 12 (SP-1), 10 (SP-1, back of pump); 13 and 14 (SP-2); flow rate = 2 m3/h (23/07/97)

Once again, the same observations are repeated: air leaking in the sample taken under positive pressure (#10) and at SP-2 (#s 13 and 14). A very strong contamination occurred in the #14.

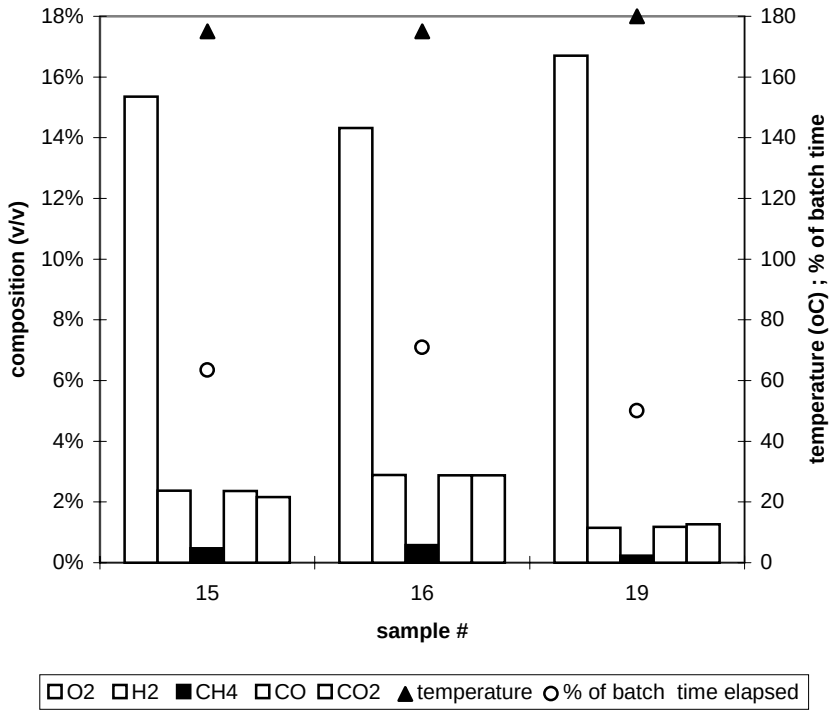

Figure 11. Comparison between samples # 15, 16 (SP-1) and 19 (SP-2); flow rate = 2 m3/h (25/07/97)

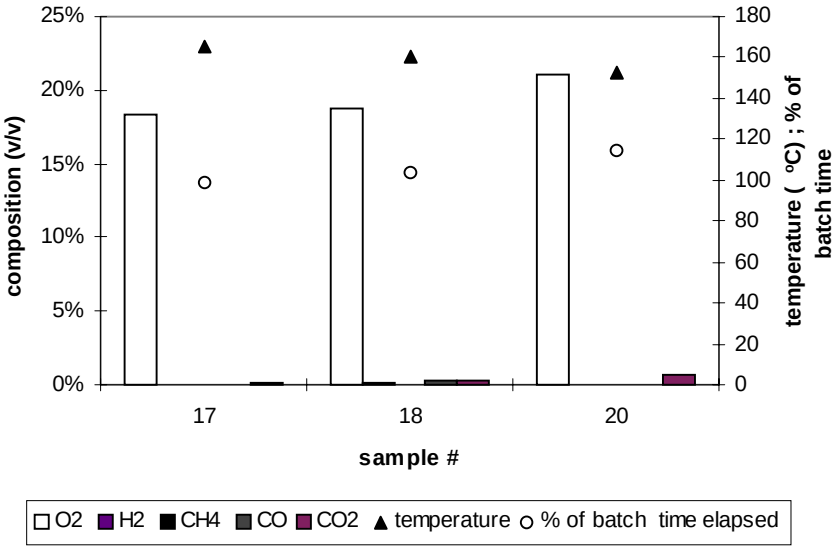

Figure 12. Comparison between samples # 17, 18 (SP-1) and 20 (SP-2); flow rate = 7 m3/h (25/07/97)

Strong contaminations or nearly no production of gas at all. Practically found only air in the samples Observations are the similar for both last graphs, for samples taken in the same day.

10.2.5.2 Production of condensates

The rate of production of tars, derived from the differential weighting of the set of three "U" tubes in each trial, is represented in the Figure 13 below.

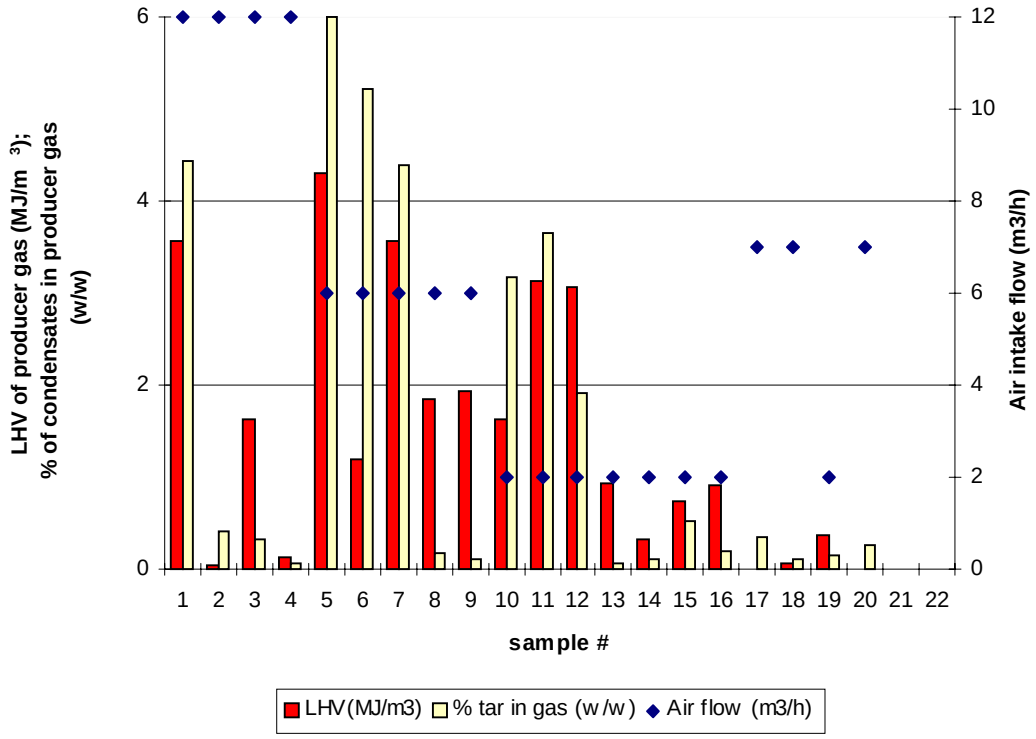

Figure 13. Production of condensates, compared to air flow intake and low heating value. "Tars", in the graph, represent the total amount of condensate, including water.

Quantities of approximately 2-4 litres of condensates were purged from the trap after each run. As mentioned, a considerable amount of condensate was also found in the cyclone.

In the stack gases there was another source of condensates. A sample was taken for analysis.

10.2.5.3 Tars in the condensate

There were two sources of condensate in the present provisory system: the gasifier and the boiler.

It is not possible to consider that all the tars were trapped in the first "U" tube and all the moisture kept in the other two. From boiling points, tars are not easy to separate from moisture in the condensate (as shown in Table 22 in Appendix 1).

10.2.5.3.1 Total amount of tars in condensate

In the experimental work at Third Generation, tars in the condensate were estimated based on reference [28]. A more extensive comparison between the conditions and results of the two systems is shown in Table 14, item 10.2.7 - Comparative Results at page 66. The results from each run were already presented together with the gas characteristics.

A sample of condensate was taken from the trap and analysed, giving the results presented in Table 9

Table 9. Results from condensate analysis

Parameter	3rd G (a)	Ref. [28] *(b)	(a/b)
COD (mg/L)	84,000	132,000	63.64%
TOC (mg/L)	36,000	55,450	64.92%
ratio COD/TOC	2.33	2.38	98.02%
pH	4.5	3.6	-

* for a water content of 35% (w/w) in the condensate

The ratios COD/TOC are very similar in both experiments, suggesting that the amount of tar can be derived from this correlation. Total conversion of carbon occurs at a ratio of 2.38 [28].

As an information, condensate generated from the boiler flue gases, fed without propane by producer gas from the Gasifier "B" (H.O.) collected from the stack and analysed had a COD of 124,000 mg/L.

The concentration of tars in the condensate depends on a number of factors: air humidity, air/fuel ratio, moisture content in wood, previous cleanup steps etc.

Reference [28].also suggests a correlation between the values of COD and TOC, in a constant ratio. Since accurate and repeated analyses of condensates are not always possible, under this assumption of constant ratio, estimations could be done by analysing the COD of a sample and applying the specific COD/TOC ratio to obtain the TOC, as in Equation 1.

$$TOC_{sample}\ (g/L) = COD_{sample}.\ (g/L)/(\text{ratio COD/TOC})\ .$$

Equation 1

From the TOC results and referenced water-free tar analysis (in Table 10), could be derived the Equation 2 from the carbon balance

Table 10 Elemental composition of tar [28].

Element	% (w/w) dry basis	% of TOC
C	69.2%	100 %
H	9.9%	-
N	20.6%	-
O	0.4%	-
Total	100.1% *	-

* round error

$$\text{tar (g/L)} = \text{TOC (g/L)} / 0.692 .$$

Equation 2

Therefore to estimate the values of the tar from the COD, both equations can be fused, as in Equation 3.

$$\text{tar (g/L)} = \text{COD (g/L)} / (0.692 . \text{ratio COD/TOC})$$

Equation 3

Applying this equation to the values from the analysed sample, there is an amount of 52.02 g/L of tars in the condensate.

As a rough estimation, as mentioned, condensates from reference [28] presented a water content of 35% (w/w) in the condensate, or approximately 0.35 L/L. Applying the Equation 3 to this example, an amount of 80.13 g of tars are obtained for each litre of condensate with, therefore, a tar density of 123g/L. If extrapolated, this number gives a water content of 36% w/w to the present experiment.

The proportion of water in the condensate could only be accurately defined if the composition of the tar was known in details. As will be further presented, it varies from experiment to experiment. This approach is useful for the total amount of tars, but not for its compounds.

10.2.5.3.2 Composition of tars

Guideline values for each of the components may come from previous analyses or, applying the same criterion from above to the values from the Table 11.

Table 11. Composition of condensates: major components and Carbon content [28]

compound	chemical formula[4]	molecular weight MW	g compound/ 100 mL condensate dry basis %	proportion of Carbon in the substance % (w/w) C/MW	proportion in TOC % (w/w) C/TOC
phenols	C_6H_6O	94	0.77	76.6	6.9
acetic acid	$C_2H_4O_3$	76	6.60	31.6	30.9
propionic acid	$C_3H_6O_2$	74	0.69	48.6	3.9
methanol	CH_4O	32	2.35	37.5	10.3
acetone	C_3H_6O	58	0.54	62.1	4.0
formaldehyde	CH_2O	30	2.72	40.0	12.8
tannin and lignin	-	-	1.08	-	6.6
unknown	-	-	-	-	24.5
tars	-	-	-	-	100.0

Assuming a direct correlation between COD, TOC and concentrations of each of the compounds in the tars, a comparison between the values obtained with the referenced could be tried - for cross-checking purposes - for phenols.

[4] Hazardous Chemical Database: <http://ull.chemistry.uakron.edu/erd/>

Applying Equation 1:

$$\text{phenols (mg/L)} = \text{TOC x } 6.9\% \,/\, 76.6\% = 0.09008 \,.\, COD_{sample}\ \text{(mg/L)} \,/\, \text{(ratio COD/TOC)}$$

Equation 4

For the COD value of 84,000 mg/L and ratio COD/TOC of 2.33, the calculated phenol concentration in the condensate is 3242 mg/L.

Table 12. Condensates cross-checking values between derived from reference [28] and sample result

compound	from analysys* (a)	calculated (b)	(a/b)
phenols (mg/L, water free basis)	1600	3242	49%

* phenols analysed were the monohydric ones, reference covers other types

This cross-checking suggests that this extrapolation for tar composition is not reliable. Different wood chips gasified under different conditions produce different relative proportions of organic compounds. Reference [30], for example, shows values for a small-scale, wood chips fuelled, fixed-bed downdraft gasification condensate of 7,116 mg/L of phenols.

10.2.6 Verification of the monitoring apparatus

To verify air leakages into the monitoring apparatus, conditions were assessed by installing two gas bottles, one after the pump and comparing the obtained gas compositions. These follow in Table 13 (also shown in Figure 11), extracted from the results.

Table 13. Verification of the monitoring system

Gas bottle, relative to the air pump			before, sample#11	after, sample#10
producer gas	composition	(v/v) H_2	9.84%	5.07%
		N_2	62.57%	70.68%
		O_2	2.27%	7.97%
		CH_4	2.24%	1.97%
		CO	9.92%	11.39%
		CO_2	13.34%	10.02%

The leakage of air is evident from the increased levels of O_2. An even higher difference can be observed from Figure 9, if compared samples # 5 (before pump) and 6 (after). This leakage was expected, since the type of pump used (oil) was not appropriate for the experiment. Even so, the reason for doing this cross-check was to suggest this methodology for next experimental work.

A vacuum pump was first intended to be taken to the site, but broke down days before and had to be replaced by this other type.

Gas samples taken before the pump are under negative pressure. This may induce air to enter into the bottle by leaking through the taps or when the gas chromatograph seringe is introduced. Samples under pressures above atmospheric are not subjected to this problem; this is the reason for recommending sampling after a conveniently sealed vacuum pump..

Gas analysis produced inaccurate results because of many air leakages during the process and monitoring. Some of them could be pointed out:

- the gas collection was done under negative pressure (of up to 40 mmHg, measured in the manometer). Both taps in each extremity of the bottle were closed at the same time. This induced air to leak in when purging with a seringe for chromatography. The Teflon taps of the bottles and the rubber cap for the needle also could not prevent air to contaminate the sample.
- in the monitoring apparatus, other parts were subjected to allow air to enter. The stainless steel probe, when inserted in the sampling ports, did not seal their entrance. Although the gasification was operating under negative pressure from a compressor pump, this could also pump air in through the port. Some of this air could then enter through the probe, inserted at a depth of just 4 cm inside the pipe. Other delicate parts which could allow air to enter were the two screw elbows in the probe and the six quick-fit tops of the "U" tubes.
- for the samples taken after the pump, at positive pressure, there were also connections between pipes and rotameter, manometer, pump, as well as leakages into the oil pump itself
- although were taken measures such as sealing doors with silicone, some leakages in the unit were clear: during the first days, condensate was visibly spilling from the gas cooling system (where water exits, air enters); also bridging effects in the chips allowed short-circuiting of air.

10.2.7 Comparative Results

As a guidance, Table 14 shows representative results obtained for the CHP gasifier (named "A"), compared with the Heat-Only system gasifier ("B"), available in the plant and to two other similar references.

Table 14 Comparison between the tested gasifier (A) with referred similar downdraft, wood chips fuelled gasifiers (C,D, E) and the other gasifier (updraft) available in the site (B)

System	**A (*1)**	**B**	**C**	**D**	**E**
site or reference	3rdG, "A"	3rdG, "B"	ref. [28]	ref. [71]	ref. [9]
finality	CHP	H.O.	heat-only	power	fuel gas
wood fuel **type**	spruce/ pine chips	spruce/ pine chips	poplar chips	"European " wood chips	wood chips
fuel/air ratio (dry)	44%-385%	61.39%	83.70%	na	84.38%
wood feed rate (dry) (kg/h)	6.7- 10.0	16.2	65.34	575	100-700
moisture (w/w) %	13.72%	19.10%	10.50%	20.00%	30-60%
dry composition .(%w/w) C	45.94%	46.10%	48.00%	na	51.6-56.2%
H	5.60%	5.60%	6.20%	na	5.9-6.3%
N	0.06%	0.06%	0.00%	na	0.0-0.1%
S	0.50%	0.50%	0.00%	na	0.0%
O	47.70%	47.70%	45.30%	na	36.7-41.5%
ash	0.16%	0.04%	0.50%	0.80%	0.6-1.2%
GCV (MJ/kg of wood, as fired)	18.52	15.67	19.05	14.70	20.00

Table 14 Comparison between the tested gasifier (A) with referred similar downdraft, wood chips fuelled gasifiers (C,D, E) and the other gasifier (updraft) available in the site (B) (cont)

System	A (*1)	B	C	D	E
site or reference	3rdG, "A"	3rdG, "B"	ref. [28]	ref. [71]	ref. [9]
fuel gas (m^3/kg dry wood)	0.10-1.15	2.60	1.53	na	2.18 (*2)
composition (v/v) H_2	0.1-13.6%	5.20%	16.90%	15-18%	17%
N_2	53-81%	67%	42.30%	47-52%	48%
O_2	0.3-14.7%	1.00%	0.90%	na	-
CH_4	0.0-2.7%	1.30%	3.20%	1.5-2.5%	1%
CO	0.1-13.6%	9.00%	24.00%	20-23%	21%
CO_2	0.1-15.5%	16.00%	11.40%	10-15%	13%
C_2H_6	0.0%	0.20%	0.10%	na	-
C_nH_n	0.0%	0.30%	1.20%	na	-
LHV (MJ/m^3)	0.00-3.56	2.63	6.94	4.83-5.46	5.7
temp.(outlet)(oC)	136-213	500	680	na	400-1000
condensate(w/w dry wood)	0%-38 %	na	21%	na	na
COD(mg/L)	84,000	na	131,900	na	na
pH	4.50	na	3.60	na	na
TOC (mg/L)	36,000	na	55,450	na	na
COD/TOC	2.33	na	2.38	na	na
phenols (mg/L)	1,600	na	4,990	na	na
organic acids(mg/L, acetic)	na	na	37,430	na	na
methanol (mg/L)	na	na	15,310	na	na
acetone (mg/L)	na	na	3,550	na	na
tars CV (MJ/kg dry)	na	na	25.63	na	na
water content (%w/w)	36%	na	35%	na	na
particulates (g/kg dry wood) (filter)	na	na	4.64	na	na
%C(fixed)	na	na	29.70%	na	na
CV (MJ/kg dry)	na	na	9.43	na	na
bottom char (g/kg dry wood)	54-218	na	74.25	na	na
%C(fixed)	85.38%	na	76.80%	na	na
CV (MJ/kg dry)	33.53	na	30.28	na	na
cyclone fines(g/kg dry wood)	na	na	4.64	na	na
%C(fixed)	na	na	55.88%	na	na
CV (MJ/kg dry)	na	na	24.22	na	na
gas temperature @ outlet (oC)	na	na	173	na	na
energy required(kg wood/kWh)	0.32	na	0.22	1.15	na

(*1) averaged values from sample #
(*2) kg/kg wood

10.2.8 Gas cooling

At steady state, the producer gas was cooled in the system from 180oC (SP-1) to 22oC (SP-2). The maximum gas temperature verified before cleanup was 213oC and after, 40oC. Commonly were found temperatures around 25oC at SP-2, during the steady state.

Temperatures of the water heated through the present CHP showed a rise from 40 to 52 oC.

According to the engine cooling system (Bowman heat exchanger) specifications the heat transferred to the CHP is equivalent to a rise from 45-60^{o}C to 60-75^{o}C in a water flow of 60 L/min (using a pump of 120 kW).

Results are further presented in the page 69, item 10.2.12, Energy Balance: Combined Cycle Energy Efficiency

10.2.9 Fuel Gas Compression

Compression of the fuel gas prior to the boiler combustor was accomplished in a single stage centrifugal compressor.

A batch run was conducted in the system by Third Generation, 3 days prior to the experiment In this run, the filters were removed and air intake was set to the maximum (55-60m^3/h). A large amount of condensate was produced (were purged from the condensate trap about 4 litres before the first run). Tars from this run and from the next 3 days of experiment accumulated in the body of the pump, giving it a squeaking noise, until it broke down (on 24/07/97). The next day, a last batch run was conducted.

10.2.10 Gas Flaring

Although the boiler is considered outside the boundaries, a measurement of flue gases was taken and analysed, as shown in Table 15. The boiler is also producing condensates, with COD results previously mentioned in this work.

Table 15. Typical boiler flue gas characteristics during the experiment

Flue gas data from continuous monitoring		Burning only producer gas	With propane flaring backup
component	CO (ppm)	5000	120
	CO_2 (%)	4	1.5
	O_2 (%)	19	19
	NO (ppm)	30	2
	NO_2 (ppm)	2-4	2
	NO_x **(ppm)	15-30	4
	SO_2 **(ppm)	40	1
temperature (^{o}C)		60 *	60

* during a short period; only producer gas could not sustain the fire in the boiler, there was a risk of accumulation of CO in the plant.

** since NO_X and SO_2 gases are soluble, there are some errors, particularly when condensate builds up in the filters.

As a guideline, typical emission criteria for pyrolysis plants in France require, for gas incineration, O_2 above 7%, CO content below 0.2% (2,000 ppm) and CO_2 below 12% [47]. Although this is not applicable to the site, improvements in the gas flaring could achieve a better heat recovery from the CO, rising the temperature of the boiler and producing less tars.

As referred in the literature review (9.3.1 - Air pollution - page 18), NO_x and SO_x levels were rather low. Immediately after the boiler, the flue gases temperature is low, causing production of condensibles at a high rate (as referred in literature review, item 9.4, page 27).

The volumetric production rate of flue gases is possible to be defined by Carbon/Nitrogen balances. However, for this purpose it is necessary to measure the air intake flow rate to the boiler, gasifier and eventual leakages into the system. This task was unfortunately impossible with the conditions available.

10.2.11 Mass Balance

In Appendix 2 is presented a detailed mass balance calculation for sample #1. Assuming correct the air flow intake, the closures were rather satisfactory.

10.2.12 Energy Balance: Combined Cycle Energy Efficiency

As a part of a questionnaire kindly answered by Third Generation, the power consumption requirements of the plant are:

- lighting, approximately 1 kW;
- extractor fan, 500W;
- cooling fan, 300W;
- CHP cooling water pump, 100W;
- boiler pump, 1kW; and
- control and monitoring system etc., a maximum of 1kW

The requirements within the boundaries were inserted in the energy balance, also presented in Appendix 2. The efficiency achieved was 74%.

Since the system is not fully operating, these calculations provide only a methodological framework, very preliminary.

For demonstration, an exercise of LCA extended the boundaries to the transport fuel inputs. Calculations are presented in Appendix 2. The energy lost during transportation, for the wood chips, is relatively low (less than 0.5 % of the system energetic output). Of course, there are many other environmental burdens, but there are also some myths about the unfeasibility of biomass-generated energy due to transportation of feedstock.

As another exercise, the same Appendix shows some extended calculations of efficiencies to the Power Island (gas engine and CHP water cooling system). Producer gas only provides 10% of the engine requirements (under the best verified conditions in the monitoring). LPG as a dual fuel is therefore necessary.

Relative to the Power Island (gas engine + CHP efficiency), an output/input ratio of 76% could be achieved, as calculated in this Appendix. Parameters were derived from the available engine specifications, related in Appendix 5 Characteristics of the Gas Engine.

In a preliminary calculation, CHP recovers 12 kW from 37kW of inputs from wood: a recovery of 32% of the energy.

These figures did not consider - due to lack of information - the recovery of flue gases from engine to dryer and heat exchanger for district heating. The efficiency of the Heat-Only system (boiler) was also not taken into account.

10.2.13 Cost savings - payback

With obtained energetic input and output numbers, an extremely preliminary calculation of saved costs, giving a quite short payback at the end (less than four years), is shown in the Appendix 2. Many factors were disconsidered, like maintenance, staff, LPG backup costs, electricity transmission and distribution costs, interests, opportunity costs[5] etc.

[5] Costs related to lost profits from other better economic options.

11. Conclusions

The conditions under which the trials were conducted were difficult: short time allowed, long distances to cover in the same day, scarse resources and available informations about the system.

Literature review was an useful tool in order to help overcoming difficulties from the test conditions. Extrapolations, however, must not be excessively used in further work. The development of a commercially acceptable product requires more assessment.

This project was first planned to have the monitoring phase in 4-6 weeks, time necessary for corrections of deviations of route. The system needs modifications prior to further research, such as better instrumentation and control, as well as a convenient sealing.

11.1 Limitations to the Experiment.

Since one week was given for all the measurements, data from literature and/or simplified mass and energy balance models were used to derive internal parameters, when necessary. Fortunately, data from other gasifier operation at the site was available for comparison.

The first intention of the experiment was to optimise the steady state air/fuel ratio of the gasifier, monitoring the producer gas at sampling port SP-1, immediately after the gasifier and; the producer gas quality after the overall clean up system, at SP-2. A batch run would assess the effect of startup and shutdown. After the optimisation phase, a whole more 2 runs were planned, in the same way, using the same type of wood with different moisture contents. This was limited by:

- the lack of time for a more extensive experiment
- the batch runs were too small, the short time of steady state could not be monitored simultaneously in the two SPs.
- there was a problem with moving the sampling apparatus from one sampling port to the other, up to three times an hour. Fragile parts like the connection epoxy/stainless steel/glass of the probe broke constantly. Movement could have loosen other connections, allowing air to contaminate the gas samples. Mercury spillages from the manometer and intoxication with CO are unsafe operation problems that need to be overcome by a more flexible system.
- the balance available was mechanical; gas collecting time had to be enough for trapping a measurable amount of condensates, but could not be extended too long due to excessive releases of carbon monoxide to the premises
- the gas was collected in the bottles by negative pressure, not securely supported y the Teflon taps without leakages
- the use of different moistures in the chips was not allowed by Third Generation, due to potential hazards (there would be no time for this, anyway)
- air leakages, principally detected those at the top of the cyclone and in the walls of the CHP water gas cooler (from which was leaking condensates out of the system as well)
- the lack of accurate controls and measuring equipment for the air flow intake, gasifier internal temperatures, CHP water flows and temperatures

- the pipe connected to the anemometer was not attached to the top of the cyclone , allowing air to leak through the system. The anemometer was as well not accurate sufficiently to measure low flows, below 6 m^3/h.
- a previous run without filters at full air intake overloaded the compressor pump with tars. During the first 3 days of experiment, it was squeaking, until breakage on 24/7. This day was also lost.
- the distance from the plant to NCU; gas samples were analysed at least 3 hours after collected

"One of the main problems in wood gasification systems is that, despite the commercial availability of the technology, only limited operating experience is available from the open literature". [6] The assumption is definitely correct.

11.2 Improvements to be recommended

11.2.1 Further Studies

With the present conditions, unfortunately it was not possible to achieve repeatable and reproducible results. When sampling, an extended monitoring should have statistical significance. After setting up more reliable measuring equipments, runs from the best air intake flow range could be repeated. It is advisable to consider representative median values, instead of averaged, for disconsidering extremities.

Although not targeted in this study, an accurate costs analysis can also be developed (reference [9] is specially recommended). Respecting operational and legal limitations, other studies considering site-specificity with alternative types of wood (or even other fuels) could be also conducted.

11.2.2 Suggestions for the Process

The primary suggestions for the process are:
- to provide a reliable air flow meter
- to seal the passages through which air leaks into the system; and
- to set up a wood feeding system that could keep a steady state for a more extended time

11.2.2.1 Monitoring and control

To develop a commercial prototype, efficient, preferably continuous measurements of parameters such as flows, temperatures and pressures are necessary.

As a pilot-scale experiment, continuous monitoring[37] of particulates and gaseous pollutants is recommended. If eventually contamined wood waste is used, this recommendation becomes even more essential.

As mentioned in item 9.2.8 (page 17), fluctuations in the gasification rate require robust control algorithms. It is necessary an automatic and rapid adjustment of the gas production to the operating conditions to avoid wastes, shortage or need for expensive additional gas storage. Suitable instrumentation and control devices guarantee a continuous and mainly automatic

operation. The control equipment could have an acoustic signal to indicate when the gas is available for use. Engine and compressor must be turned off if operation of the gasifier is terminated or interrupted.

11.2.2.2 Wood Drying

The mechanical dryer could have its' operation studied in another suitable (ventilated and with fire precautions) room. Ambient air could be mixed with the combustion products to reduce the gas temperature prior to introduction to the dryers. While this can result in a relatively high oxygen content, the temperature is believed to be sufficiently low to avoid the possibility of dryer fires. Gas leaving the dryers could enter a cyclone and then a baghouse filter to reduce particulate emissions. The temperature level at the baghouse is, again, believed to be sufficiently low to mitigate fire danger. Measurement of temperatures of the gas inlet and outlets, as well as the dried wood exiting the dryer are advisable.

11.2.2.3 Wood Feeding

As cited in item 9.2.7 (page 16), in batch conditions of 1-2 hours, the quantity and calorific value of the producer gas varies considerably throughout the cycle. A CHP plant must also be nearly fully utilised for a high number of hours each year (9.5.2.2, page 32). The problem should be overcome by using a continuous wood feeding system.

Two solutions are available: providing an automatic feeding mechanism and changing the geometry of the chamber - steeper sides around a lower grate. It is also recommended to have fuel size of less than 150 millimetres of dimension in any direction .[4] (see also item 9.2.7 - Equipments for biomass combustion, page 16)

The screw conveyor could be of the live bottom metering type, to meter and introduce the feed into the gasifier near the bottom of the bed. This could avoid wood bridging and clogging, improve controlling and also reduce air leakages, which affect the gasification and combustion reactions.

An intermediate, closed compartment - the "live" storage tank from which wood chips are is fed to the gasifier - could also be installed. Chips could be transported through a similar screw conveyor system, by automatic means to match the gasifier consumption to balance to the gas requirements of the engine.

11.2.2.4 Gasification

The air intake to the gasifier should be directly first calibrated in a cold run to give repeatable air measurement. A primary air diaphragm valve and a rotameter model could be used to provide accuracy. The rotameter must be checked against a gas flow measurement laboratory facility. From this calibration, percentages of the maximum possible air flow to the system, function of the aperture of the PA valve, could be defined.

From the experimental results, carbon conversion in the gasifier is not constantly high, due to factors such as the large size of the grate, clogging and bridging of the wood chips.

If a more controlled wood and air feed to the system and a smaller size of the grate does not achieve the necessary conversion, a separate char combustor may be required. Many commercial version of gasifiers are likely to have very high carbon conversion (99%).

To assess the feasibility of operating the gasifier without a drying system, different feedstock moisture levels should be tested, showing the relationship between moisture content of the feed versus gasifier temperature.

11.2.2.5 Gas Cleanup and Cooling

If the dryer operation is adjusted when the whole CHP system is under operation, re-using the exhaust gas from the engine, the wood chips could act like a filter, capturing particulates and higher unburned hydrocarbons and thus using the gasifier as a tar cracker.

Although the energy value contained in the tar can be used by the boiler without the need for cleaning, combustion engines may need additional equipments. Alternative fuels, producing higher emissions, may require a tar cracker or a char combustor, which can provide recoverable energy (char has a carbon content of approximately 87%).

Alkali species present in the fuel gas can cause corrosion and deposition if introduced into a gas engine. It is necessary to remove these species prior to combustion, to extremely low levels, typically less than one part per million. Fortunately, most alkali components present in biomass synthesis gas have relatively high condensation temperatures. Cooling to below 500^{o}C results in condensation of the bulk of these species, usually as fine particles that can be removed with the rest of the particulates.

Gas cooling can be accomplished by indirect cooling of the fuel gas, utilising the recovered heat, or by direct injection of water into the gas stream, diluting and reducing the gas heating value. Although it is the simplest and least expensive from an equipment standpoint, more wastewater is produced.

In the final design, in which the engine gases are recovered by the dryer, cleanup measures are still necessary. The gas flaring in the boiler also needs cleanup, as can be seen from the tar released. Although the energy overall efficiency of the system is regards saved heat from emissions, the exhaust temperature from the boiler must be sufficiently high to avoid any possible corrosion in the stack and to mitigate plume visibility issues.

11.2.2.6 Noise and Hazards

Noises arose principally from the compressor, increased by the effects of accummulated tars. The Power Island is isolated from the rest of the plant by walls, but was not operating at the time.

The natural ventilation in the plant is defficient, needing electric fans to prevent accummulation of toxic gases.

Of course, there are risks of fires and explosions. However, Third Generation provides protective equipment and trained personnel.

The wood chip dryer/CHP could be tested in an isolated room, designed for its purposes.

11.2.2.7 Plant design

The plant is overall well-designed for the experimental purposes. Some observations for the follow:

- when developing commercial systems, a good pipe design is crucial to minimise the pressure drop
- a more effective ventilation system, combined with larger external windows could prevent accumulation of gases in the plant
- in a separated room, with convenient ventilation and fire precautions, the wood chips dryer could be included in further experiments, as a tar cracker, as previously mentioned.

11.2.2.8 Suggestions from Third Generation

After completed this experimental phase, these are some modifications suggested by the staff of Third Generation, which must also be acknowledged:

- grate size matched to fuel… larger chips or smaller grate size;
- methods of reducing tar output and cleaning the cleanup system;
- disposal of these contaminants;
- air mixing of flare off;
- adjust primary air flow rate;
- drain pump fitted to first filter tank;
- fuel loading system allowing longer run time;
- fully clean compressor;
- addition of temperature sensors in key locations to monitor gasification performance;
- clean up filters; and
- check water and air coolers are clear and not blocked with tars.

11.3 Final Conclusions

From the first trials in the system, some conclusions obtained were:

- not withstanding the short period, it was sufficient for testing the system and monitoring apparatus; further collect of samples is advisable only after modifications are made;
- reproductibility of results are nor guaranteed by the present experimental conditions;
- there must be one set of monitoring apparatus for each sampling port; for moving is time consuming and liable to failures in sealing; attention must be specially paid to fragile parts, quick-fit connections and fixing probe to sampling port during collection to prevent air from leaking in;
- the cleanup system must be sealed against air contamination as well;
- air intake flow measurement must be accurate and reliable; air intake pipe securely attached to top of cyclone;
- the present wood feeding conditions allow batch runs with very short steady states; a continuous - or semi-continuous - system, protected against air leakages, allows a better reliability;
- exact definition of end of startup is difficult; internal, continuous temperature measurements in the gasifier could help;
- end of batch is determined visually, without problems;

- wood chips used have a moisture content above the maximum allowed;
- gasifier's internal design, combined to size and shape of wood chips cause bridging effects and relatively high amounts of char and charcoal, losing a considerable calorific value and producing more solid wastes;
- the solid wastes, according to literature, are quite inert;
- the rate of production of condensates is considerable; those contain toxic substances;
- tars accummulated in the system; runs must not be conducted without the filters;
- under the experienced conditions, emissions of pollutants to stack from boiler combustor are relatively low ; the low temperatures allow condensibles to accummulate;
- the CHP system effectively improves the efficiency in terms of energy recovery and gas cooling;

Problems like those are expected to occur at any experiment. The effort of Third Generation in improving this technology must be acknowledged.

As the preferred processing routes are identified and environmental concerns continues to grow, the focus of most research on thermal processing is expected to change from just quality and yield of the target product.

More than just any commercial product aiming for profits, renewable sources of energy - such as from biomass - are a necessity in terms of pollution prevention, maintenance of standards of living and job allocation.

The conclusions achieved - and mistakes observed - during the short period are a small step in this direction.

However, it is not without resources - economic, human and technological - that a new form of energy production will be developed. Efforts like those from Third Generation deserve public and private incentives for a continuous and consistent R&D.

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13. Appendices

13.1 Appendix 1 - Auxiliary Tables from Literature

Table 16. Typical values for thermal conversion technologies [6]

Characteristics	Slow Pyrolysis	Flash Pyrolysis	Liquefaction	Gasification
Products	fuel gas, oil or liquid fuel substitution, solid fuel or slurry fuel		oil or liquid fuel substitution	fuel gas
Feedstock				
feed size	any	small	small	mixed-large
moisture content	low	very low	very low	50% max
Parameters				
T (°C)	500 - 700	500 - 900	250 - 350	800 - 1500
pressure, bar	0.1 - 1	1	100 - 200	< 30
maximum throughput achieved, T/h	5	0.05	0.1	20
Yields for Products (%w/w); dry feed				
gas	< 40	<70	20	100 - 250
liquid	< 30	< 70	<50	<5
solid	30	<20	< 25	nil (ash)
Heating Value for Products				
gas (MJ/Nm^3)	5 - 10	22	2 - 6	5 - 15
liquid (MJ/kg)	22	22	27	22
solid (MJ/kg)	30	30	30	-

Table 17. Typical analyses of various trades wastes [25]

Type of waste	Moisture (%)	Gross CV MJ/kg)	Ash (%)
Joinery-shop refuse	12.0	18.0	2.0
Wood chips (cedar)	**28.4**	**14.2**	**0.3**
Wood briquettes	13.6	16.4	0.8
Hardboard offcuts	6.4	19.0	2.7
Cardboard and waste paper	8.2	15.8	7.9
Jute waste	9.9	17.6	2.7
Fibre waste	9.7	16.6	1.5
Curled hair waste	14.4	16.2	2.0
Oil cotton waste	4.6	23.6	0.8
Cotton-impregnated rubber	2.5	18.2	34.7
Bitumenised hessian	4.3	25.4	1.4
Bitumen-impregnated chipboard	2.0	27.8	7.2
Bitumen waste	0.2	38.5	2.8
Rubber waste	-	34.0	19.4
Print-works waste	29.9	20.4	14.4
Nitro-cellulose waste	0.9	8.5	.1
Bagasse	40.0	11.7	2.1
Spent coffee	65.0	8.1	1.5
PVC	-	22.8	2.0
Polyethylene	-	45.6	1.2
Polystyrene	-	36.8	0.5
Polyurethane	-	26.0	4.5

Table 18 Combustion properties of urban solid waste fuels.[58]

Type of waste	HHV MJ/kg	Vola-tiles (%)	Fixed Carbon (%)	Ash (%)	Mois-ture (%)	Sul-phur (%)
mixed urban wood waste (non-forestry	16.58	66.1	11.9	2.5	16.0	0.1
urban tree residue	10.46	41.1	10.6	1.2	47.0	0.1
tyre derived fuel	35.93	66.0	24.6	8.9	0.5	1.4
non-recycled plastic (ground polystyrene)	40.11	96.9	18.0	2.3	0.4	0.06
refuse derived fuels	13.36	58.5	6.9	12.4	21.8	0.2
densified non recycled paper fuel	19.59	76.9	5.5	6.8	10.8	0.1

Table 19 Emissions @ 11% O_2 for native wood and urban waste wood and demolition wood (UWDW) [49]

Typical values for	**Native wood**	**UWDW**
NO_x (mg/Nm³)	100-200	400-600
HCl (mg/Nm³)	< 5	100-1000
Particles (mg/Nm³)	50-150 after cyclone	<10, after filter
Pb + Zn + Cd + Cu (mg/Nm³)	< 1	20-100
PCDD/F(ng TE/Nm³)	< 0.1	0.1 - 20

Table 20 - Emissions from automatic wood furnaces [49]

Emissions @ 11% O_2 for excess ratio, λ=	**Poor standard of furnace (mg/Nm³)** 2-4	**High standard (mg/Nm³)** 1.5-2
CO	1000-5000	20-250
HC	100-500	<10
PAH	0.1-10	<0.01
Particles, after cyclone	150-500	50-150 (except dust firings usually>150)

Table 21. Emissions from small-scale combustors[1] [60]

Source	**Average Emissions (g/kg fuel)**				
	Particu-lates	**Organics**	**SO_x**	**CO**	**NO_x**
Fireplaces (wood)	13.8	20.7	0.46	55.3	0.05
Wood waste burners silos	1.8	0.4	0.46	24.4	0.92
Residential waste back yard incineration	11.1	116.1	0.46	276.5	0.05
Fuel oil fired boiler (small scale, under 4.9 MWe)	2.2	0.33	21.2	0.02	9,2
Coal-fired boiler	92.2	4.61	35.02	1.4	9,2

[1] Applied conversion rate 1lb/ton = 0.460858 g/kg; 1 hp= 9.809 kW . Source: <http://www.legacysy.com/~legacysy/convert2/convert2.html >

Table 22. Results from gas chromatography analysis of tar of a downdraft gasifier[28]

Compound	**Quantity (mg / g)**	**Boiling Point (°C)**
Toluene	*0.031*	*111*
m-,p-xylene	*6.10*	*139*
o-xylene	*6.93*	*144*
Cumene	*0.075*	*152*
Trimethyl benzene	*0.60*	-
p-cymene	*na*	-
Indene	*0.12*	*183*
Tetralin	*na*	-
Naphtalene	*0.47*	*218*
Biphenyl	*0.50*	*255*
Acenaphtene	*0.082*	*270*
Fluorene	*0.071*	*294*
9,10-dihydrophenanthrene	*0.43*	-
Phenanthrene	*0.048*	*338*
Anthracene	*0.027*	*340*
Fluoranthene	*0.036*	*383*
Pyrene	*0.031*	*393*
Benz(a) anthracene	*0.023*	*435*
Chrysene	*0.011*	*441*
Benzo(k) fluoranthene	*0.015*	*481*
Benzo(b) fluoranthene	*0.043*	*481*
Benzo (a)pyrene	*0.033*	*496*
Indeno (1,2,3-cd)pyrene	*0.037*	-
Benzo (ghi)perylene	*0.027*	-

Table 23. Optional techniques for treatment for the waste waters [63], applicable to the main pollutants found in the condensate from gasification system

Treatment for	**BOD**	**COD**	**SS**	**Ammonia**
Aerobic Biological Treatment	✓	S	I	✓
Anaerobic Biological Treatment	✓	S	I	✓
Bioaugmentation	✓	S	I	✓
Powdered Activated Carbon Treatment	✓	✓	I	I
Powdered Activated Carbon Treatment	I	✓	I	
Granular Activated Carbon	I	✓	I	
Zeolites	I	✓	I	✓
Chemical Coagulation	I	✓	✓	
Lime dosing	I	I	✓	
High Density Sludge Process	I	I	✓	
Steam Stripping	I	I	P	✓
Air Stripping	I	I	P	✓
Wet Air Oxidation	I	✓	I	
Ozone, Ozone + UV, Ozone + H_2O_2	I	✓	P	
Chemelec Cell Electro Deposition			P	
Membranes	I	✓	✓	

✓: designed for purpose
I: incidental
S: some of the chemicals represented in the group
P: poor

Table 24. Elemental concentrations from wood ash [54]

Analysis	**Median**	**Maximum**
dry solids (%)	99	100
pH	12.9	13
Ca (%)	1.8	36
K (%)	3.0	24
Sulphates (%)	0.6	26
Cl	176	1117
P (mg/kg)	4500	10000
Total Kjeldajl N (mg/kg)	340	5400
Ammonium N (mg/kg)	3.1	22
Nitrate N (mg/kg)	210	3300
Na (mg/kg)	1910	44533

Table 25. Elemental metals analyses for ash from treated wood [29].

Metal	**Regulatory limits (in the USA) (mg/L)**	**Normal Wood Fuel (mg/L)**	**Construc-tion/ demolition wood (mg/L)**	**penta-chloro-phenol treated (mg/L)**
Al	n.a.	4500	5800	4200
As	75	53	98	27.7
Ba	n.a.	300	590	270
Cd	85	6.1	8.1	10.1
Cr	3000	14	39	23
Cu	4300	46	93	61
Fe	n.a.	6100	7400	5100
Pb	840	35	1010	235
Mn	n.a.	2750	2230	2230
Hg	57	0.08	0.52	0.16
Mo	75	6.7	8.0	6.1
Ni	420	8	10	9
Se	100	0.69	0.97	0.65
Ag	n.a.	0.4	0.1	0.2
Zn	7500	420	1520	590

13.2 Appendix 2 - Mass and Energy Balances

In the next pages is presented the calculations, from which were obtained:

- the flow rate of producer gas, leaving the gasifier;
- the calorific value and density of this gas;
- values for elemental flow rates;
- energetic efficiencies, including those from the CHP
- as an exercise, some considerations on the energetic burden of transportation of wood to the plant
- an estimated quantity of LPG to be supplied to the engine and energy recovered by CHP from this engine
- some rough financial calculations about feedstock and energy

MASS AND ENERGY BALANCES for best run #1, 21/07/97, air flow nominal 12 m^3/h

Key to field background:

	were used for data input
	are final calculations, conclusions
	are intermediate calculation steps

a) **Mass inputs to the system**

a.1.) **Wood chips**

mass inputs from wood		**(w/w)**(*1)		**flow(kg/h)**
feed rate, total, as fired (kg)			14.50	-
batch time elapsed (min)			120	-
dry wood GCV (MJ/kg)			19.06	-
wood GCV (MJ/kg), as fired			16.76	-
feed rate, as fired (kg/h)				7.250
moisture content in wood		13.72%	-	0.995
from which,	H	1.54%	-	0.111
	O	12.18%	-	0.883
ash content in wood	C	0.16%	-	0.012
dry wood, ash free		86.12%	-	6.244
dry wood ash free composition	C	46.11%	-	2.879
	H	5.60%	-	0.350
	N	0.10%	-	0.006
	S	0.51%	-	0.032
	O	47.69%	-	2.977
	total	100.00%	-	6.244

(*1) composition analysed at the NCU Chemistry Dept. Laboratory

Intakes from wood, as fired	Flow rate (kg/h)	Atomic Weight (*2)
C	2.890	12.011
H	0.461	1.008
N	0.006	14.007
S	0.032	32.064
O	3.861	15.999
wood, total	7.250	

(*2) Himmelblau, 1989

a.2.) **Total air intake to the system (from cyclone, boiler and leakages, e.g. in wood feed)**

Moisture content in air: mc_{air} = (w/w)/{1+(w/w)} = 2.69%

air characteristics		
air intake flow rate from cyclone Fair1 (m3/h)	12.00	nominal value
air intake flow rate from leakages (m3/h)	0.00	estimation derived from calculation (see further)
total air intake flow rate Fair (m3/h)	12.00	derived (sum)
relative humidity	56%	measured
temperature °C	21	measured
water/dry air (w/w) (*1)	2.76%	
∴ Moisture content in air: mc_{air} =	2.69%	

(*1) air-water vapour diagram, Himmelblau, 1989

Molecular weight of dry, clean air: MW_{dair} = $\sum MW_i * x_i$ = 29.03 kg/kgmole

component	composition w/w_{air}(*1) kg/kg air	molecular weight MW (kg/kgmole)	(w/w)*MW	molar fraction xi	
N	76.83%	28.01	21.5227	74.4%	(*1) Himmelblau, 1989
O	23.17%	32.00	7.4141	25.6%	(*1) Himmelblau, 1989
air	100.00%	29.03	28.9368	100.0%	
density of dry air (kg/m3) =	1.296	(= MW_{dair} / 22.4)			

Molecular weight of wet, clean air: MW_{wair} = 28.84 kg/kgmole

component	com-position w/w_{air}(*1) kg/kg air	MW (kg/kgmole)	(w/w)*MW	molar fraction x_i
N	74.77%	28.00	20.9346	73.1%
O	22.55%	32.00	7.2153	25.2%
H_2O	2.69%	18.00	0.4835	1.7%
air	100.00%	28.84	28.6333	100.0%
density of wet air (kg/m3) =	1.287	(= MW_{wair} / 22.4)		

component from water	com-position w/w_{water}(*1) kg/kg water	com-position w/w_{air} kg/kg air	molecular weight MW (kg/kgmole)
H	11.19%	0.30%	2.00
O	88.81%	2.39%	16.00
H_2O	100.00%	2.69%	18.00

Air flow rate (calculated) =	12.00	m3/h
(x) density of wet air (kg/m3)	1.287	
(=) air feed rate =	15.45	kg/h

Intakes from wet air	com-position w/w_{air}(*1) kg/kg air	Flow rate (kg/h)	Atomic Weight (*2)
N	74.77%	11.55	14.007
O	24.93%	3.85	15.999
H	0.30%	0.05	1.008
air	100.00%	15.45	-

(*2) Himmelblau, 1989

a.3.) **Summary of inputs (wood + air + moisture) to the system (gasifier + cleanup), excluded heated water**

Element	from wood (kg/h)	from air (kg/h)	Flow rate (kg/h)	Atomic Weight (*2)
N	0.006	11.55	11.56	14.007
O	3.861	3.85	7.71	15.999
C	2.890	0.00	2.89	12.011
H	0.461	0.05	0.51	1.0080
S	0.032	0.00	0.03	32.0640
total	7.250	15.45	22.70	-

(*3) based in wood chips feed rate of 7.25 kg/h, as fired

b) **Mass Outputs**

b.1.) **Producer Gas**

b.3.1) **Calculation of flow rate for inlet air to gasifier, utilising the producer gas composition**

Molecular weight of dry fuel gas: MW_{dgas} = $\sum MW_i * x_i$ = 27.20 kg/kgmole

Gross Calorific Value of gas: GCV_{dgas} = $\sum CV_i * v_i / v_{gas}$ = 3.56 MJ/m^3

component, fuel gas condensate free	com-position v/v_{gas}(*2) = molar fraction X_i	molecular weight (*3) MW (kg/kgmole)	(v/v)*MW	composition w/w_{gas} kg/kg gas	calorific value (*4) CV MJ/m³	CV * v/v_{gas} MJ/m³
H_2	11.19%	2.016	0.2256	0.0083	12.10	1.35
O_2	0.63%	31.999	0.2016	0.0074	-	-
N_2	59.95%	28.013	16.7940	0.6175	-	-
CH_4	2.24%	16.043	0.3594	0.0132	37.71	0.84
CO	11.39%	28.011	3.1904	0.1173	11.97	1.36
CO_2	14.60%	44.010	6.4255	0.2363	-	-
C_2H_6	0.00%	30.070	0.0000	0.0000	66.07	0.00
C_nH_n	0.00%	220.050	0.0000	0.0000	100.00	0.00
producer gas	100.00%		27.1964	1.0000	-	3.56

(*2) dry gas chromatography analysis

(*3) and (*4) Himmelblau, 1989; assumed value for high hydrocarbons (C_nH_n)

Applying the values from the previous table to elemental composition by weight, producer gas has:

component, fuel gas	w/w kg/kg $_{gas}$	composition in **1.00** kg/h of producer gas (kg/h)				
		H MW= 1.0080	O MW= 15.9994	N MW= 14.0067	C MW= 12.0112	Total
H_2	0.0083	0.0083				0.0083
O_2	0.0074		0.0074			0.0074
N_2	0.6175			0.6175		0.6175
CH_4	0.0132	0.0033			0.0099	0.0132
CO	0.1173		0.0670		0.0503	0.1173
CO_2	0.2363		0.1718		0.0645	0.2363
C_2H_6	0.0000	0.0000			0.0000	0.0000
C_nH_n (*1)	0.0000	0.0000			0.0000	0.0000
producer gas	1.0000	0.0116	0.2462	0.6175	0.1247	1.0000

(*1) assumed a theoretical substance as C_5H_5

N balance: $N_{in} = N_{out}$ in gasifier

Nitrogen inputs to gasifier	**(kg/h)**
from wood, as fired	0.006
from clean air	11.551
N_{in} =	11.557

=

Nitrogen outputs:		**(kg/h)**	
from ashes		0.000	neglectible
from tar	0.59%	y	*1
from producer gas		x	
N_{out} =		11.557	

*1 condensate in producer gas (w/w) =	4.43%	(tars+ moisture), experimental result from this run	
from which	65.00%	tars	(Esplin, 1996)
from which	20.60%	N	(Esplin, 1996)
therefore, there is approximately	0.59%	N from gas (w/w) lost in tars	
		∴ neglectible	
N_{out} =	11.56	kg N/h	
divided by	0.6175	kg N/ kg of dry, clean producer gas	
=	18.72	kg of dry, clean producer gas/h	
divided by	27.1964	density of producer gas (kg/22.4 m^3)	
times	22.40	m3	
=	15.42	m^3 of producer gas/h, calculated flow rate	

The elements for the balances are obtained by multiplying this flow rate by each unitary value of mass flow

component, fuel gas	v/v gas	w/w gas	kg/h in **18.72** kg/h of dry producer gas				
			H MW= 1.0080	O MW= 15.9994	N MW= 14.0067	C MW= 12.0112	CV (MJ/h)
H_2	11.19%	0.83%	0.1552				20.87
O_2	0.63%	0.74%		0.1387			
N_2	59.95%	61.75%			11.5572		
CH_4	2.24%	1.32%	0.0622			0.1852	13.02
CO	11.39%	11.73%		1.2541		0.9415	21.02
CO_2	14.60%	23.63%		3.2150		1.2068	
producer gas	100.00%	100.00%	0.2174	4.6078	11.5572	2.3334	54.91

b.2.) **Ashes**

from a.1.)

Weighted ash Fash=	0.74	kg in batch, or		0.370	kg/h
completely burnt out (w/w)	80%	C, assumed		0.296	kg/h
remaining dry wood (w/w)	20%	or, C	46%	0.034	kg/h
		H	6%	0.004	kg/h
		N	0%	0.000	kg/h
		S	0%	0.000	kg/h
		O	48%	0.035	kg/h

b.3.) **Condensate: moisture, tar and**

char in producer (fuel) gas

condensate characteristics			**% w/w**	**flow rate (kg/h)**	
mass flow rate Fc (kg/h)			4.43%	0.829	
water content (w/w)			35.0%	0.290	Esplin, 1996
from which,	11.19%	H	3.92%	0.032	
	88.81%	O	31.08%	0.258	
insoluble matter and hydrocarbons (w/w): tar and char			65.0%	0.539	

tar and char composition	**% w/w**(*1)	**flow rate** (kg/h)
C	69.2%	0.373
H	9.9%	0.053
N	20.6%	0.111
O	0.4%	0.002
total	100.1%	0.539

(*1) from literature (Esplin, 1996)

Therefore:

condensate composition	**% w/w**	**flow rate** (kg/h)
C	51.9%	0.373
H	11.9%	0.086
O	36.2%	0.260
total	100.0%	0.719

c) **Mass overall balance**

Element	flow in (kg/h)	flow out (kg/h)	closure %
N	11.557	11.557	100%
O	7.713	4.903	64%
C	2.890	3.036	105%
H	0.507	0.307	61%
S	0.032	0.000	0%
total	22.700	19.804	87%

d) **Energy Efficiency Analysys, using the energy balance**

d.1.) **Basic inputs:**

energy inputs				**flow**	**(unit)**		
wood feed rate, as fired (kg/h)				7.25	kg/h		
gross calorific value of wood, H_{wood} (MJ/kg), as fired		16.76	x feed rate=	121.51	MJ/h =	33.75	kW
input electrical energy:	compressor					1.00	kW
	extractor fan					0.50	kW
	cooling fan					0.30	kW
	CHP cooling water circ.pump					0.10	kW
	control and monitoring system etc (future, previewed)					1.00	kW
	lighting					1.00	kW
total energy input						36.75	kW

d.2.) **Basic outputs:**

energy outputs							
Temperature of water	from building, T_o =	40.0	°C (returned hot water)				
	from gas cooler, $T_{f\ gas\ cooler}$ =	52.0	°C=>ΔT=	12.00	°C		
water flow rate from building, derived to the gas cooler		3.6	m^3/h => H=	43.20	MJ/h =	12.00	kW
Producer gas LHV sent to boiler				54.91	MJ/h =	15.25	kW
total energy output from system =						27.25	kW

d.3.) **Overall Energy Efficiency**

(Output/Input)= 27.25/36.75 **= η = 74%**

e.) **Expanding the boundaries**

e.1.) **Extending the boundaries with application of LCA concepts to assess the real energy consumption and subsidise cost analysys**

Additional information (extended inputs) outside boundaries:

energy inputs from wood chipping and transport of processed wood chips					
wood chips consumption:		7.25	kg/h =	0.00725	T/h
energy for chipping @	10 kWh/T (*1) =			0.07250	kW
loading capacity of wood chips in a truck:		5.00	T/journey		
distance from production to plant:		40.00	miles, including return (2 journeys)		
average truck fuel consumption (*2)		0.22	litres/mile=	1.78	litres fuel/T wood chips
gross calorific value of fuel (oil) (*3) :		9.98	kWh/litre		
energy input, transportation fuel:		17.79	kWh/T wood chips		
total energy input (transport fuel):		0.20	kW or	0.74%	of system output

(*1) Dryden, 1982. A conservative value, assuming the waste nature of the chips

(*2) <http://www.eren.doe.gov/feguide/fegselect.html> GMC K1500 Sierra, consumption 17mpg
although not the proper vehicle, figures are shown for an estimative

(*3) Eastop, 1996. According to <http://www.wps.com/LPG/WVU-review.html>

0.73 kg/L x 43.90 MJ/kg / 3.60 kWh/MJ 8.93 kWh/litre

e.2) **Boundaries extended to gas engine requirements and efficiency**

Energy required inputs:

Energy inputs required to the sub-system Power Island/CHP				
fuel/power ratio (MJ/kWh) =	10.50	from the engine schedule, for	50	kW of energy
the minimum energy input to the system is	525	MJ/h		
producer gas LHV (MJ/h)* =	55	(for air intake of 12 m^3/h), or just	10.48%	of the total required
				the rest needing to be backed up with LPG
given the LPG consumption =	242	g/kWh	from engine specifications (for simplification, without a margin of 20%)	
there is a requirement for the engine dual fuel of	10.83	kg/h of LPG **		

* an assumed (good) condition for the system. There are air leakages throughout the cleanup system, reducing the calorific value of the gas.

** Eastop (1996): LPG LHV = 51.67 MJ/kg => 559.67 MJ/h input

Energy outputs: electrical power + recovered heat from cooling water *						
temperature of water	from building, T_o =	40.0	°C (returned hot water)			
	from cooler, $T_{f\ cooler}$ =	65.0	°C => ΔT=	25.00	°C	
water flow rate from building, derived to the gas cooler	3.6	m^3/h => H=	90.00	MJ/h =	25.0	kW
electrical power (nominal) output:					50.0	kW
total energy output from sub-system Power Island/CHP =					75.0	kW

* there is also the heat from the flue gases, not considered due to lack of information

Considering the system from wood to electricity, the balance is:

kW from	Inputs	Outputs	Net
wood	33.8	-	-33.8
LPG	155.5	-	-155.5
electricity	3.0	50.0	47.0
heat to water, CHP gas & engine coolers	-	87.0	87.0
total	192.2	137.0	-55.2

The overall efficiency is: **(Output / Input) =** 137.0 / 192.2 **= η = 71%**

f) **Preliminary economic exercise**

Considering that the wood consumption of 7.25 kg/h
provides only 10.48% of the engine requirements,
would be necessary a theoretical wood equivalent load of 69.20 kg/h, without the propane backing up

to provide the energetic requirements of
electricity + CHP heat recovered 134.00 kWh, net

therefore, at a consumption of 69.20 kg/h of wood chips
at a price of £0.05 /kg (£50 per oven dry tonne)
results in £0.0258 /kWh (without considering other maintenance costs)

if the energy from the national grid is sold at £0.0360 /kWh
the net margin is £0.0102 /kWh

if the gasifier+chp system is sold in the marked at a price of, say £15,000
dividing by the margin of £0.0102 /kWh
then the energy that has to be produced for payback is equal to 1473853 kWh

if the system produces 1072.00 kWday; @ 8 hours/day shift,
then the payback time = 1375 days, or 3.77 years

13.3 Appendix 3 - Procedures

As required by Third Generation, these were the Health and Safety procedures proposed:

H&S Procedures

The following text shows the operating procedures during the programme of work to ensure the health and safety of personnel :

1. All the experiments must be conducted with, at least, two persons (preferably three), aware of the stages of the process and their potential hazards. Those are basically: escaping gases (mainly CO), overheat explosions and fires and hot surfaces.
2. Fire extinguishers must be available; the precinct must have its passages clear at all times
3. Appropriate safety clothing, gloves and glasses must be worn during collection of samples
4. Levels of carbon monoxide in the premises must be continuously monitored on site by an alarmed equipment
5. Temperature at gasifier outlet and gas cooling system must be monitored to prevent explosions and fires
6. Attention must be kept. Monitoring sessions must not exceed two hours without intervals of ten minutes.
7. Laboratory work must follow NCU procedures
8. Occurrences must be immediately reported

For the start up of Heat-Only unit (Boiler + Gasifier "B"), the procedures utilised at the site, as transcribed, were:

1. ensure adequate personal protection equipment is worn during start up routine.
2. keep boilerhouse door open and check that someone knows your location.
3. ensure that CO and methane detectors are switched on and working
4. switch on extractor.
5. check stack for draught and water in trough.
6. clean inspection window
7. check boiler for residue, clean the tubes
8. check the control and monitoring software is loaded and operational
9. check all valves are open and set
10. load hopper and level fuel.
11. light fuel, leave fire door open
12. when temperatures at points C1 and C2 are above 650^{o}C, switch on fan (60%) and close fire door slowly.
13. record energy produced on previous run.
14. monitor temperature and gradually close primary valve until steady state is reached. (30 min to 1hr from lighting).

13.4 Appendix 4 - Extract from IPC Schedules 1&4 Processes and Substances

SCHEDULE 1
DESCRIPTIONS OF PROCESSES
CHAPTER 1: FUEL PRODUCTION PROCESSES, COMBUSTION PROCESSES (INCLUDING POWER GENERATION) AND ASSOCIATEDPROCESSES

Section 1.1 Gasification and associated processes

PART A
(a) ...

(b)...

(c) Producing gas from coal, lignite, oil or other carbonaceous material or from mixtures thereof other than from sewage or the biological degradation of waste, **unless carried on as part of a process which is a combustion process** (whether or not that process falls within Section 1.3 of this Schedule).
(d) ...
In this Section, "carbonaceous material" includes such materials as charcoal, coke, peat and rubber.

PART B
...

Section 1.2 Carbonisation and associated processes

PART A

(a) The pyrolysis, carbonisation, distillation, liquefaction, partial oxidation or other heat treatment of coal (other than the drying of coal), lignite, oil, other carbonaceous material (as defined in Section 1. 1.) or mixtures thereof **otherwise than with a view to gasification** or making of charcoal.

(b) The purification or refining of any of the products of a process mentioned in paragraph (a) or its conversion into a different product.

Nothing in paragraph (a) or (b) refers to the use of any substance as a fuel or its incineration as a waste or to any process for the treatment of sewage. In paragraph (a), the heat treatment of oil does not include heat treatment of waste oil or waste emulsions containing oil in order to recover the oil.

PART B

Nil

Section 1.3 Combustion processes

PART A

(a) ...

(b) ...

Nothing in this Part of this Section applies to the burning of any fuel in a boiler, furnace or other appliance with a net rated thermal input of less than 3 megawatts.

PART B

The following processes unless carried on in relation to and as part of any Part A process

(a) ...

(b) ...

(c) burning as fuel, in an appliance with a net rated thermal input of less than 3 megawatts, waste oil or recovered oil;

(d) burning in an appliance with a net rated thermal input of less than 3 megawatts solid fuel which has been manufactured from waste by a process involving the application of heat;

(e) **burning**, in any appliance, **fuel manufactured from, or including, waste** (other than waste oil or recovered oil or such fuel as is mentioned in paragraph (d)) if the appliance has a net rated thermal input of less than 3 megawatts but **at least 0.4 megawatts** or is used together with (whether or not it is operated simultaneously with) other appliances which each have a net rated thermal input of less than 3 megawatts and the aggregate net rated thermal input of all the appliances is at least 0.4 megawatts.

In paragraph (c) of Part A and paragraph (e) of Part B, "fuel" does not include gas produced by biological degradation of waste; and for the purposes of this Section:

"net rated thermal input" is the rate at which fuel can be burned at the maximum continuous rating of the appliance multiplied by the net calorific value of the fuel and expressed as megawatts thermal; and

"waste oil" means any mineral based lubricating or industrial oil which has become unfit for the use for which it was intended and, in particular, used combustion engine oil, gearbox oil, mineral lubricating oil, oil for turbines and hydraulic oil; and

"recovered oil" means waste oil which has been processed before being used.

CHAPTER 5: WASTE DISPOSAL AND RECYCLING

Section 5.1 Incineration

PART A

(a) The destruction by burning in an incinerator of any waste chemicals or waste plastic arising from the manufacture of a chemical or the manufacture of a plastic.

(b) The destruction by burning in an incinerator, other then incidentally in the course of burning other waste, of any waste chemicals being, or comprising in elemental or compound form, any of the following: bromine, cadmium, chlorine, fluorine, iodine, lead, mercury, nitrogen, phosphorus, sulphur zinc.

(c) The destruction by burning of any other waste, (...) otherwise than by a process related to and carried on as part of a Part B process, on premises where there is plant designed to incinerate such waste at a rate of 1 tonne or more per hour.

(d) ...

PART B

(a) The destruction by burning in an incinerator other than an exempt incinerator of any waste (...), except where related to a Part A process.

(b) ...

"**exempt incinerator**" means any incinerator on premises where there is **plant designed to incinerate waste**, (...) **at a rate of not more than 50 kg per hour**, not being an incinerator employed to incinerate clinical waste, sewage sludge, sewage screenings or municipal waste (as defined in Article 1 of EC Directive 89/369/EEC); and for the purposes of this section, the weight of waste shall be determined by reference to its weight as fed into the incinerator; "waste" means solid or liquid wastes or gaseous wastes (other than gas produced by biological degradation of waste)

SCHEDULE 4
RELEASES INTO AIR: PRESCRIBED SUBSTANCES

- oxides of sulphur and other sulphur compounds
- oxides of nitrogen and other nitrogen compounds
- oxides of carbon
- organic compounds and partial oxidation products
- metals, metalloids and their compounds
- asbestos (suspended particulate matter and fibres), glass fibres and mineral fibres
- halogens and their compounds
- phosphorus and its compounds
- particulate matter

13.5 Appendix 5 Characteristics of the Gas Engine

The available information for the gas engine follows:

Gas engine Power Torque Iveco 7000G

The engine utilises as fuel commercial propane with liquid offtake, alternatively to butane and propane vapour supply. It can also operate using biogas, but reductions of 5-10% in power output compared to natural gas can be expected. The requirements for biogas operation are:

- *CH_4 in the range of 35-80% v/v (factor related to the total volume of gas; i.e. if CH4 factor in a particular gas is 50%, volume of gas needs to be doubled to restore engine power to near the advertised level)*
- *CO_2: 25-55%*
- *small amounts of other gases, including H_2S (below 0.05% v/v; attention should be paid to the fact that, doubling the gas volume, H_2S quantities could be outside the desired levels, increasing the possibility of corrosion of copper components. A recommended pre-treatment is scrubbing the gas with iron hydroxide. The dealer gives assistance, but no warranties to failures attributable to the gas quality)*
- *a suitable oil*
- *engine must run as continuously as possible at high temperature with a high load factor*

If the gas is of poor quality or low calorific value, engine can be started on LPG. Alternative gas source before shutdown is advantageous in dissipating impurities in engine.

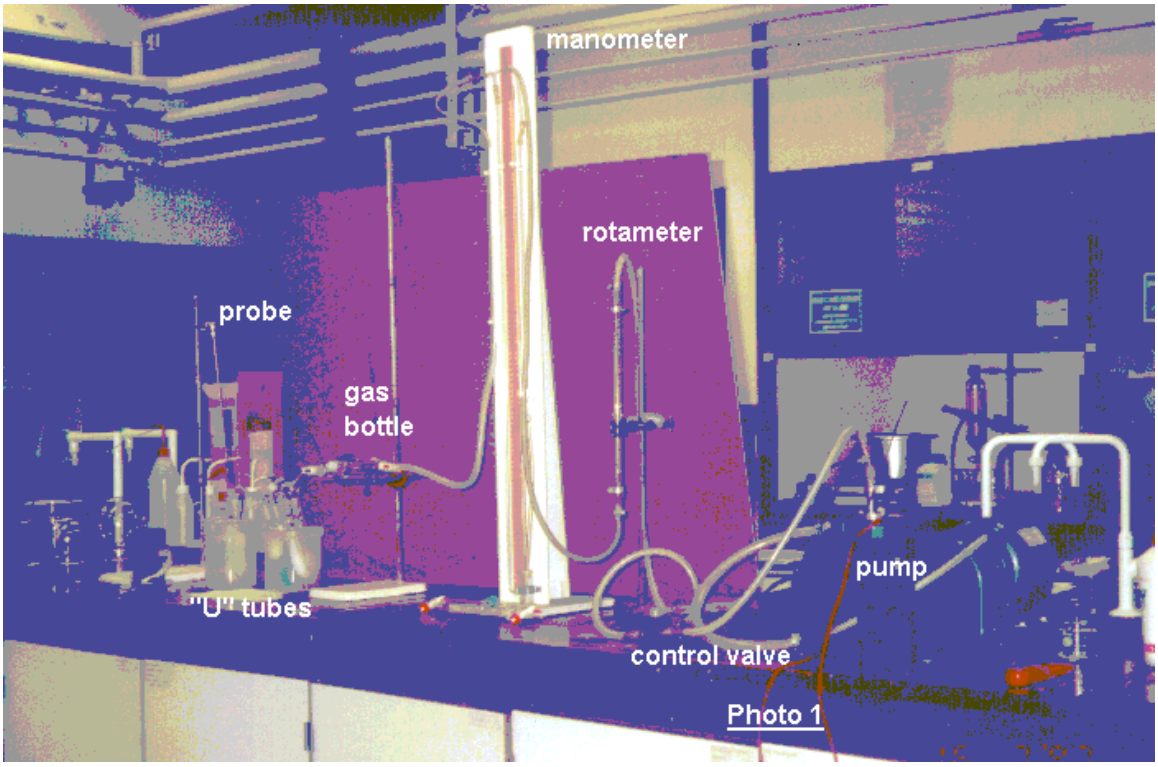
The engine service schedules are:

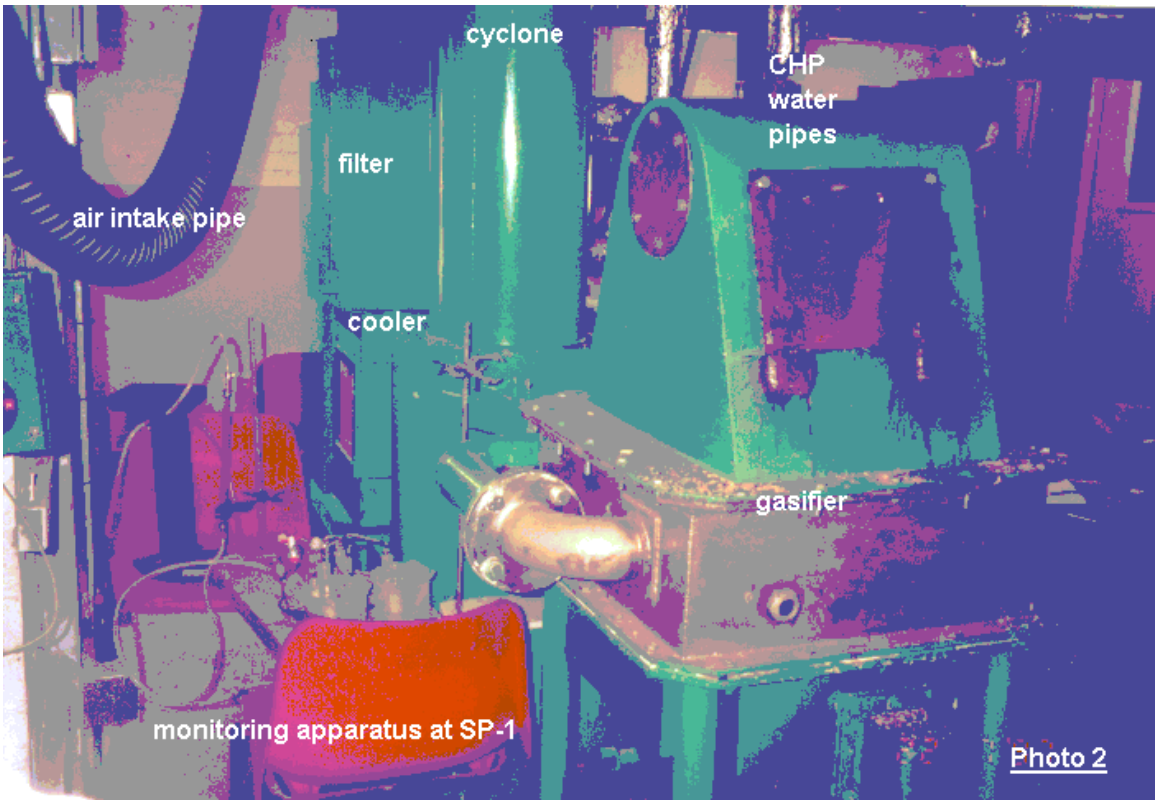
excess air ratio (λ)	NOx (ppm)	CO (ppm)	power (kW)	Fuel/power ratio * (MJ/kWh)
1.0	2400	-	75	10.6
1.2	4500	0	70	10.0
1.4	4000	100	60	10.2
1.6	1000	150	50	10.5

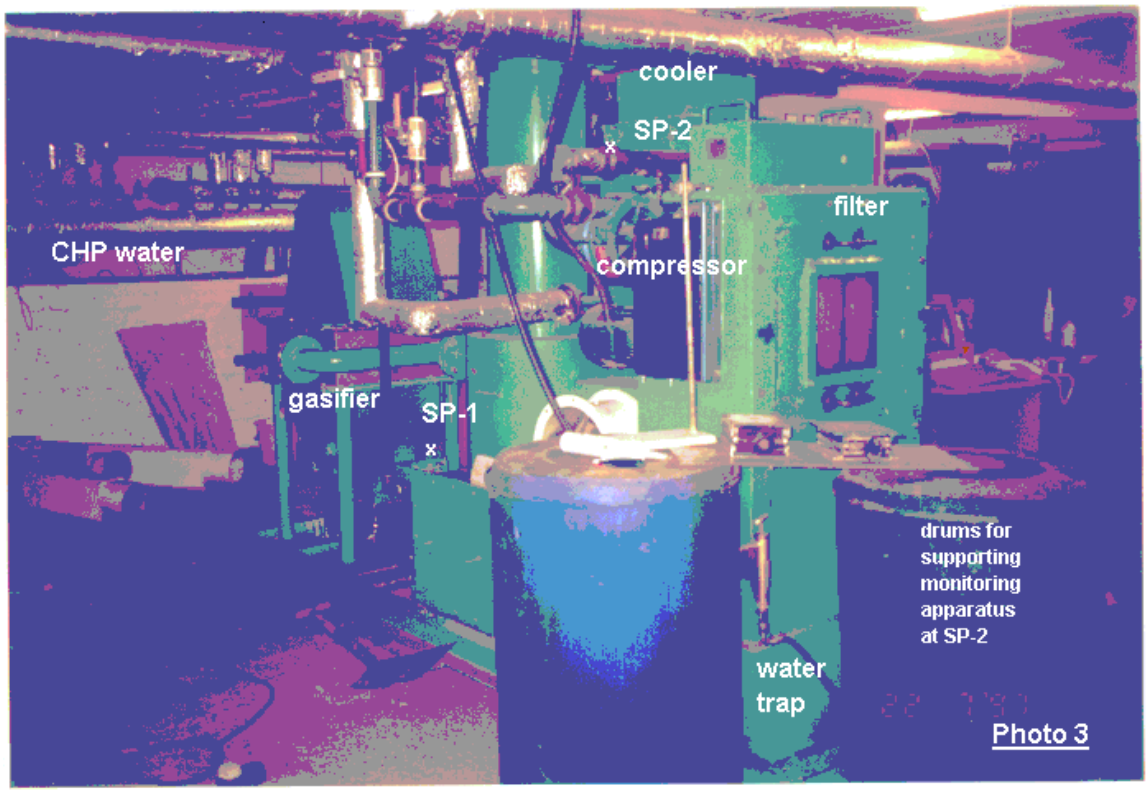
- *recommended a margin of 20%*

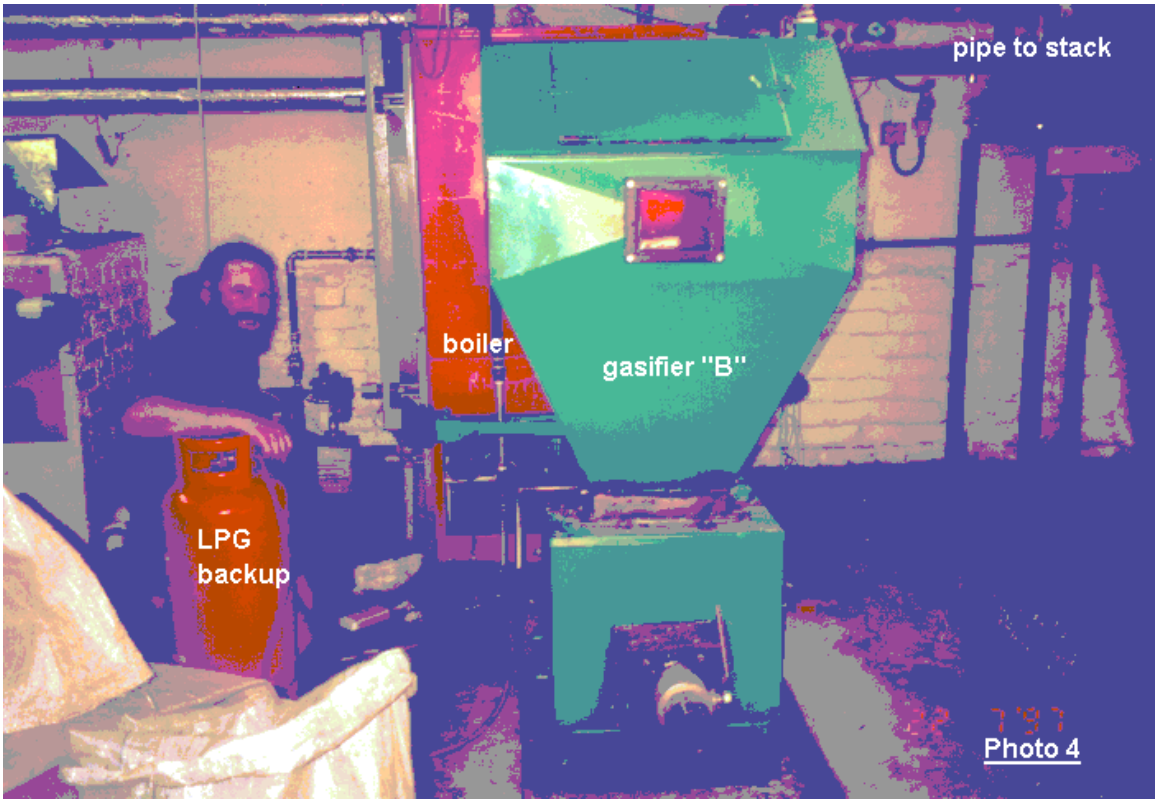
The engine cooling system (Bowman heat exchanger) requires a nominal pumped (120kW) water flow of 60 L/min, heated from 45-60 ^{o}C to 60-75^{o}C.

13.6 Appendix 6 : Pictures of the System






cooler
SP-2
filter
CHP water
compressor
gasifier
SP-1
drums for supporting monitoring apparatus at SP-2
water trap
Photo 3


pipe to stack
boiler
gasifier "B"
LPG backup
Photo 4

13.7 Appendix 7 : Related WWW Adresses

1. **<http://es.inel.gov/techinfo/facts/chmr/strtgy4.html>** Fact Sheet: Pollution Prevention: Strategies for Fossil Fuel Electric Power Generation. Center For Hazardous Materials Research (CHMR). Concepts applicable to power production from biofuels.
2. **<http://es.inel.gov/techinfo/facts/epa/p2-cost.html**> Pollution Prevention Financial Analysis and Cost Evaluation System. United States Environmental Protection Agency. Basically a software, but with detailed discription for cost analyses
3. **<http://es.inel.gov/techinfo/research/reduce/rrel446.html**> Waste Reduction Activities and Options for a Fossil Fuel Fired Electrical Generating Station. By Kevin Gashlin and Daniel J. Watts (New Jersey Institute of Technology) and the United States Environmental Protection Agency Research and Development Risk Reduction Engineering Laboratory. Concepts applicable to other systems.
4. **<http://www.ace.co.uk/energy/>** The Northern Energy Initiative; an European centre for energy technologies , based in Sunderland, UK
5. **<http://www.chem.ruu.nl/nws/www/research/e&e/biomas_a.htm#Publications**> Biomass and Waste - Research at the University of Utrecht
6. **<http://www.chem.ruu.nl/nws/www/research/e&e/e&e_link.htm>** University of Utrecht: www pages that cover energy and environmental related topics.
7. **<http://www.doe.gov/html/eren/erhelp.html**> Energy Efficiency and Renewable Energy Database - U.S. Department of Energy
8. **<http://www.ecn.nl/eii/misc/list.html>** Netherlands Energy Research Foundation (ECN). Energy Information on Internet
9. **<http://www.energy.rochester.edu/uk/chpa/**> U.K. Combined Heat and Power Association
10. **<http://www.epa.gov/docs/appcdwww/crb/aptb/index.html>** USEPA - Air Pollution Technology Branch. Fundamental and applied combustion research: control of oxides of nitrogen (NOx) via combustion; hazardous waste incineration; municipal waste combustion; destruction of CFCs and other ozone depleting substances; work in characterization and control of hazardous air pollutants and artificial intelligence-based controls.
11. **<http://www.epa.gov/docs/crb/aptb/mfc.html**> A multi-fuel stoker combustor, for MSW, RDF, biomass fuel and coal (USEPA)
12. **<http://www.epa.gov/docs/epacfr40/chapt-I.info/subch-C/40P0060/index.html>** USEPA - Standards of performance for new stationary sources (updated 1996). Several guidelines.
13. **<http://www.epa.gov/docs/oppeoee1/globalwarming/sub4/index.htm>** Global warming links
14. **<http://www.epri.com/energylinks.html**> The Electric Power Research Institute (USA) - Energy-related links.
15. **<http://www.eren.doe.gov/biopower/5088-2-4.html>** Promoted Commercialization of Biomass Power Through Joint Ventures- Increasing Efficiency Through Gasification. U.S. DoE
16. **<http://www.eren.doe.gov/biopower/all.html**> Biomass Power Industry Assessment Report. U.S. DoE
17. **<http://www.eren.doe.gov/biopower/biohawaii.html>** Hawaii Biomass Gasifier Project
18. **<http://www.eren.doe.gov/biopower/dynamics.html>** Dynamics of the marketplace for biomass power projects
19. **<http://www.eren.doe.gov/biopower/gascd.html**> Biomass Gasification—Commercialization and Development: The Combined Heat and Power (CHP) Option, by Richard L. Bain, Kevin C. Craig, and Ralph P. Overend National Renewable Energy Laboratory
20. **<http://www.eren.doe.gov/biopower/innovative.html>** Innovative Ways of Utilizing Biomass in a Cofiring Scenario with a Gas Turbine Integrated Combined Cycle System, by Pamela Spath, Kevin Craig, Richard Bain. National Renewable Energy Laboratory (USA)
21. **<http://www.eren.doe.gov/biopower/news.html**> Biopower news
22. **<http://www.eren.doe.gov/biopower/snowpapr.html>** Cost and Performance Analysis of Three Integrated Biomass Gasification Combined Cycle Power Systems, by Kevin R. Craig and Margaret K. Mann. National Renewable Energy Laboratory

23. **<http://www.eren.doe.gov/biopower/technical.html**> The Technical Side of BioPower, including a virtual tour of gasifier systems; demonstration projects; fact sheets and technical papers
24. **<http://www.eren.doe.gov/femp/greenfed/2.0/2_2_economic_analysis.htm>** Greening Federal Facilities - a resource guide in reducing energy consumption and costs (U.S. DoE) Reference to LCA analysis.
25. **<http://www.eren.doe.gov/menus/energyex.html**> Ask an Energy Expert. Answers to e-mail submitted questions on energy-efficient and renewable energy technologies. Energy Efficiency and Renewable Energy Clearinghouse (EREC), U.S. DoE
26. **<http://www.esd.ornl.gov/annual-reports/FY94/bfdp.html>** Biofuels Information Network - U.S. Department of Energy
27. **<http://www.ieagreen.org.uk/doc3a.htm**> Technical solutions for reducing global warming. IEA Greenhouse Gas R&D Programme
28. **<http://www.ornl.gov/ORNLReview/rev28_2/text/bio.htm>** Oak Ridge National Laboratory - Research on Biomass Fuels, Energy, Carbon, and Global Climate Change
29. **<http://www.osha.gov/**>U.S. Occupational Safety and Health Administration (OSHA)
30. **<http://www.pic.net/~stevie2/pages/contacts.html>** Who's who in Renewable Energy
31. **<http://www.scotborders.co.uk/horizons/**> Tweed Horizons webpage
32. **<http://www.sepa.org.uk/>** Scottish Environment Protection Agency's re-(SEPA)
33. **<http://www.eren.doe.gov/biopower/biovermt.html>** Vermont (Batelle) Gasifier Project. Fact Sheet.