

Combustion of Solid Waste from Wood-Based Ethanol Production

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PREFACE

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ABSTRACT

The solid residue from wood-based ethanol production has a low ash content and high heating value, making it interesting for combustion applications, e.g. small-scale appliances and gas turbines.

Combustion and gasification properties have been studied using thermogravimetric analysis (TGA) and differential thermal analysis (DTA). Char combustion rate data obtained could be used in combustion simulations. TGA and DTA data are useful for comparison with other fuels where data are available for similar heating rates.

One possible use is direct-firing of gas turbines for Combined Heat and Power (CHP) at the site of the ethanol plant. Another possible use of the material is for the production of fuel pellets.

A combustion test with a 150 kW powder burner has been done. Fuel feeding and combustion were stable. The average concentration of CO in the stack gas was 8 mg/MJ, the average concentration of NO_x was 59 mg/MJ and the average total hydrocarbon concentration was below 1 ppm, at an average O₂ concentration of 4.6 per cent.

Process parameters, investments, costs and revenues for these two production options have been estimated. The conclusion is that CHP is the most profitable use, although the uncertainties in estimated costs are considerable. Reductions of greenhouse gas emissions are decidedly larger for the CHP option. It has been concluded that CHP production is an option worth pursuing further. The technical feasibility of using the material for direct-firing of a gas turbine remains to be established however.

THESIS

This licentiate thesis is based on the following papers:

- Paper A. G. Eriksson, B. Kjellström, B. Lundqvist and S. Paulrud, 2004: Combustion of wood hydrolysis residue in a 150 kW powder boiler, Fuel 83, 1635-1641
- Paper B. G. Eriksson, R. Backman and R. Hermansson, 2005: TGA/DTA measurements of hydrolysis/fermentation residues from softwood ethanol production. To be submitted.
- Paper C. G. Eriksson, R. Hermansson, 2005: Economic assessment of Combined Heat and Power (CHP) production integrated with ethanol production from softwood. To be submitted.

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Part I

Summary

1. Introduction

There is a virtual consensus among climate researchers that global warming does occur. According to the International Panel on Climate Change (IPCC) the global average surface temperature has risen by 0.4 to 0.8 °C since the late 19th century, and most of this temperature rise is due to impact from human activities. Natural variations do not explain all of this warming, while antropogenic greenhouse gas emissions are consistent with this warming. The atmospheric concentration of CO₂ has increased from about 275 to about 370 parts per million (ppm). (IPCC 2001)

The IPCC has set a target for stabilizing CO₂ concentrations at 550 ppm. (IPCC 2001). Other targets have also been proposed, usually ranging from 450 to 550 ppm CO₂. (Pacala and Socolow 2004)

Depletion of most easily accesible oil and gas resources may soon have economic consequences. Aleklett and Campbell (Aleklett and Campbell 2003) point out that the issue is not so much when the oil resources will be completely depleted, as how soon the peak in consumption will occur. They have argued that the IPCC scenarios are based on overestimated oil reserves, and that global oil use probably will peak even before 2020. The claim is controversial and the IPCC argues that such an early depletion of the oil resources, if it occurs, would be offset by increasing use of coal. There is no doubt however that replacing oil with coal would accelerate global warming, since the CO₂ emissions per unit of energy are higher.

About 25 per cent of the contribution to global energy-related carbon dioxide emissions were caused by the transport sector in the European Union. Renewable fuel production is a high priority sector in the Seventh Framework Programme, in particular liquid biofuels for the transport sector (Commission of the European Communities 2005)

1.1 Climate policy and the transportation sector

Emissions of greenhouse gases from road transport can be reduced either by increasing the efficiency of the conventional internal combustion engine vehicles (ICEVs) or by switching to other technologies. The efficiency of the ICEVs can be increased by about 50 percent by the use of variable valve timing, shut-off during idling, higher compression ratio, variable displacement and continuously variable transmission (Johansson and Åman 2002).

Several technologies have been suggested as replacements to the conventional petrol- or diesel fuelled internal combustion engine (ICE). In addition to biofuels, it is worthwhile to mention hybrid vehicles and fuel cell vehicles.

Hybrid vehicles use a battery-powered direct current electric motor, in parallel with a conventional ICE. Losses from idling and braking can be considerably reduced in the electric mode. Hybrid vehicles are now marketed by Toyota and Honda while Daimler-Chrysler, Ford and General Motors plan to introduce them on the market before 2007. Less than 1 per cent of new cars sold use hybrid technology.

Fuel cell cars use a fuel (like hydrogen) to produce direct current. Fuel cells are being developed for buses in the Clean Urban Transport for Europe (CUTE). (Cropper et al 2004). Hydrogen fuel cells would require a new infrastructure for hydrogen distribution. One possibility to avoid this could be to reform a different fuel to hydrogen on board the vehicle (Johansson and Åman 2002).

Biofuels include methanol, ethanol, di-methyl esters, pyrolytic oil, and Fischer-Tropsch gasoline. No attempt will be made here to evaluate the different options. A life-cycle analysis for different biofuels has been done by Blinge (Blinge 1998)

1.2 Production of wood-based ethanol

There is commercial production of ethanol in Brazil (from sugar cane) and in the US (from maize). In ethanol production from ligno-cellulosic material, sugars in the hemicellulose and cellulose are converted to ethanol. The polymers in the cellulose and hemicellulose are hydrolysed into sugars, either by acids or enzymes. The sugars are fermented into ethanol by bacteria or yeast.

Conceptually, the process can be divided into four steps: pre-treatment, hydrolysis, fermentation and distillation.

The raw material is pre-treated to make it more susceptible to hydrolysis, usually by exposing it to steam, sometimes also to sulphuric acid.

The hydrolysis and fermentation can take place either in separate process steps (SHF, separate hydrolysis and fermentation) or in the same process step (SSF, simultaneous saccharification and fermentation).

Hydrolysis of cellulose by acids has been done for more than 150 years. When concentrated acids are used, they are mainly halogen acids or sulphuric acid, and the process takes place more or less at room temperature. The hydrolysate from concentrated acid hydrolysis gives high ethanol yield when fermented but the process leads to problems with corrosion and acid recovery.

Dilute acid hydrolysis is a high temperature process. Sulphuric acid is used.

By enzymatic hydrolysis, the conversion can be more specific. Enzymatic hydrolysis of softwood is still in the development stage.

1.3 The Swedish programme for wood-based ethanol production

In the Swedish ethanol research and development programme for ethanol two technologies are considered.

The research is mainly devoted to enzymatic hydrolysis. Since 2001, processes have been tested at small scale at the process development unit at Lund University of Technology.

A pilot plant with a production capacity of 400 litres of ethanol per day has been commissioned in April 2005 at Örnsköldsvik in northern Sweden. Experiments with both dilute acid production processes and enzymatic production are scheduled. The designer of this plant has suggested ethanol production plants co-located with existing heat and power production in 'bioenergy refineries' (Lindstedt 2003).

Since the wood production is limited, and fuel production would have to compete with other uses, it is important that low-quality wood from logging residues can be used. In Sweden for instance, the current rate of felling at between 80 and 85 million cubic metres annually is somewhat above the sustainable rate (National Board of Forestry 2004). So far, feedstock for the PDU has been stemwood. Initially, the pilot plant will use stemwood.

When ethanol is produced from wood, most of the hemicellulose and some of the cellulose is converted into fermentable hexoses. A solid residue remains, consisting mainly of lignin with some cellulose. In addition, the slop from the hydrolysis/fermentation remains.

To be competitive in the motor fuel market, the production cost of ethanol must be low. The use of lignocellulosic materials like wood for production of ethanol results in large amounts of residues. It is crucial for the process economy that this material can be profitably used. Low ash and alkali content makes this residue an attractive fuel for gas turbines, making studies of its properties during combustion, pyrolysis and gasification worthwhile.

An obvious use of the solid residue is to combust it to generate process steam and electricity needed for the ethanol production process. High-pressure steam is needed for pre-treatment of the wood chips. There is more than enough solid residue to make the ethanol plant self-sufficient on steam and electricity. The surplus can either be sold as a fuel or used to produce additional heat and power for sale.

Some non-energy uses of the solid residue have been considered, for instance additives for motor fuels. While it may be worthwhile to explore such high-value uses further, the quantities produced will be huge in case ethanol becomes widely used as a motor fuel, and so it seems likely that much of it will be available as a fuel whatever the other uses.

1.4 Generation of heat and electric power from biofuels

CHP with gas turbines using biofuels have been demonstrated in the pressurised fluidised bed at Värnamo, Sweden. To avoid erosion, corrosion and fouling of the turbine blades by ash particles and alkali, a gas cleaning stage before the turbine inlet was used. If a clean biofuel could be used, the gas cleaning stage could be dispensed with and construction costs for the gas turbine system could be significantly reduced.

The turbine manufacturer ABB Stal (now Siemens Industrial Turbines) uses the following gas quality criteria:

Table 1. Gas quality criteria for GT35P gas turbine.

Parameter	Diluted burned gas into turbine expander
Total dust load (mg/kg gas)	Below 400
Particles above 8 μm (mg/kg gas)	Below 10
Potassium and sodium (mg/kg gas)	Below 10
Melting temperature of ash particles ($^{\circ}\text{C}$)	Above 850

As mentioned, the solid hydrolysis/fermentation residue, usually called 'lignin', has a very low ash and alkali content. If it could be used in a gas turbine, it is likely that separate gasification and gas cleaning steps would not be necessary. To keep the temperature at the turbine inlet below 850 $^{\circ}\text{C}$, an air factor of about 5.7 will be necessary, diluting particles and alkali in the gas. The resulting concentration of Na+K would be below 10 mg/kg gas.

Like renewable liquid fuels for transport, electricity production and heat production from indigenous renewable energy sources are both high priority sectors in the 7th Framework Programme (Commission of the European Communities 2005).

2. Properties of the solid residue from wood-based ethanol production

The properties of the lignin from ethanol production has been studied.

When ethanol is produced from wood, most of the hemicellulose and some of the cellulose is converted into fermentable hexoses. About 30 percent of the dry weight remains as a solid residue, consisting mainly of lignin with some cellulose. In addition, approximately 15 per cent of the dry mass ends up in the slop (liquid residue) from the distillation. For simplicity this residue will be referred to as 'lignin', although it contains some cellulose as well. The energy content in the lignin per tonne of raw material is 2.6 times the energy content of the ethanol. The energy content in the slop is roughly equal to the fuel value of the ethanol. It is clear that the use of these materials is important to the total process economy.

Some basic chemical and physical properties for this material are described in section 2.1. Measurements to determine devolatilisation kinetics are described in section 2.2.

2.1 General properties

Basic chemical and physical properties were determined for two materials, both solid residues from ethanol production based on softwood. The reason is that two different processes are being considered for future industrial production in Sweden.

The first process uses dilute-acid hydrolysis to release the saccharides before fermentation. In the second process, enzymes are used for the hydrolysis, and the hydrolysis and fermentation take place in a common reactor.

Material from the first process (1) was produced in the Rundvik reactor in Örnsköldsvik, Sweden, where spruce sawdust was hydrolysed in two stages using dilute sulphuric acid. The two-stage hydrolysis procedure has been described by Eklund and Pettersson (Eklund and Pettersson 2000).

Material from the second process (2) was from an enzymatic process. It was produced at the Process Development Unit, Lund University of Technology, Sweden from spruce stem wood. The process is called SSF (Simultaneous Saccharinification and Fermentation). The material is referred to as SSF material.

The yield of ethanol from the enzymatic process is 23 per cent, although this figure remains to be verified in industrial scale. The ethanol yield from the dilute-acid process is only 15 per cent. On the other hand, the latter process has been used for decades. Both processes will be tested at the pilot plant at Örnsköldsvik, Sweden, which was inaugurated May 2004.

Of the three main components in wood, hemicellulose is most readily converted to saccharides. As mentioned, cellulose can be converted into ethanol with a considerably higher efficiency in the SSF process, which means that a large part of the material remaining in the solid will be lignin, the third main component which is not converted.

Results of proximate and ultimate analyses of materials (1) and (2) are listed in Table 2.1. Data for a comparable wood powder are included for comparison.

Table 2.1 Elemental composition for the material

	Method	Residue, dilute acid hydrolysis (1)	Residue, hydrolysis and fermentation, SSF process (before washing) (2)	Wood powder (3)
C (per cent of dry substance)	LECO	55.7	59.4	49.8
O (per cent of dry substance)	By difference	38.5	31.2	43.7
N (per cent of dry substance)	LECO	<0.1	2.9	<0.1
H (per cent of dry substance)	LECO	5.8	5.0	6.2
S (per cent of dry substance)	SS18 71 77	0.03	0.28	0.01
Ash (per cent of dry substance)	SS18 71 71:1	<0.1	1.2	0.4
Volatile matter (per cent of dry substance)	ISO 562:1	78.4	63.8	84.5
Lower heating value (MJ/kg TS)	ISO 1928:1	21.57	25.86	19.0

After drying, the material consisted of solid lumps with typical diameters between a couple of millimetres and a couple of centimetres. It was ground manually in a cleaned 1 100 W Retsch SK1 electric mill so it could be used in a powder burner.

The average size of the particles of material (1) is small. This facilitates combustion, but could make handling more difficult, for instance care must be taken to avoid dust explosions.

2.2 Studies of combustion and gasification kinetics using thermogravimetric analysis (TGA) and differential thermal analysis (DTA)

When designing combustion and gasification systems, the kinetics of devolatilisation is an important parameter for ignition and flame stability. To develop equipment for combustion and gasification, computerised fluid dynamics (CFD) simulations is an important tool, and the rates of devolatilisation are needed as input parameters. Particle devolatilisation/gasification and combustion of volatiles in the gas phase are simulated separately. To quantify the devolatilisation properties, thermo-gravimetric analysis (TGA) and differential thermal analysis (DTA) of the sample material has been done. These measurements give information about the weight loss rate of the material measured, and about the heat of reaction for devolatilisation/gasification. They do not give any direct information about the composition of the volatiles.

An additional reason for the TGA/DTA tests was that during previous combustion tests, ignition was identified as a potential problem, either caused by slower release of volatiles

during pyrolysis, or by higher ignition temperatures or lower heating value of the volatiles initially released. (REF Use of hydrolysis residue as ... (2002)).

Thermo-Gravimetric Analysis (TGA), where a sample is weighted during pyrolysis/combustion in a furnace is a commonly used method to obtain kinetic data for fuels. Weight changes are related to devolatilisation and oxidising reactions and describe the overall kinetics of the event. It is often very difficult to completely exclude the influence of experimental conditions and equipment specific factors. Thus, obtained kinetic parameters are always to some extent method specific, and should preferably be used in comparison to other data obtained by the same technique rather than as generally valid entities.

Another commonly used procedure is Differential Thermal Analysis (DTA), in which a sample is heated, and its temperature is compared to the temperature of a thermally inert reference material. This temperature difference, which is recorded as a function of the furnace temperature, provides a quantitative measure of changes in internal enthalpy due to chemical reactions and phase transformations e.g. drying, devolatilisation, condensation or depolymerisation. Whether the reactions are endothermic or exothermic is shown by the sign of the temperature difference between the sample and the inert residence, where an upward peak corresponds to an exothermal reaction.

Experiments were performed using two different equipments owned and operated by the Combustion and Materials Chemistry group at Åbo Akademi University in Finland. Equipment and procedure is described in more detail in Paper 2.

The first was a pressurized thermogravimetric reactor (PTG). The sample was suspended in vertical tube furnace with a gas flow coming from below. The sample holder was a platinum cup. In this device, both atmospheric and pressurized samples were studied. The second device was a TA Instruments SDT2960 simultaneous TGA-DTA analyser, where both thermogravimetry and differential thermal analysis are made at the same time. It has a horizontal tube furnace with the sample and reference placed symmetrically in the middle of the furnace. This device operates only at atmospheric pressure.

Experiments were done at 1 bar and 12 bar total pressure.

Three materials were studied:

- 1) Hydrolysis residue from dilute acid process
- 2) Hydrolysis/fermentation residue from the SSF process (an enzymatic process)
- 3) Commercial wood powder

Three sets of experiments were made using three different atmospheres: 1) Air; 2) N₂ and 3) CO₂. The heating rate was 20 °C per minute. The temperature was increased gradually to 900 °C.

A particle undergoing devolatilisation in a combustor is surrounded by a layer of outward-moving gas, which prevents contact with oxygen from the air. During this phase, it is probable that a more inert atmosphere than air is a better approximation of the conditions in a combustor. Therefore, the results in N₂ are relevant.

At gasification conditions, where there is a deficit of oxygen in at least parts of the combustor/gasifier, the reaction of CO₂ with fixed carbon in the particle may have an

important influence over the particle mass loss rate. That is the main reason to include the test runs using CO₂ as the purge gas.

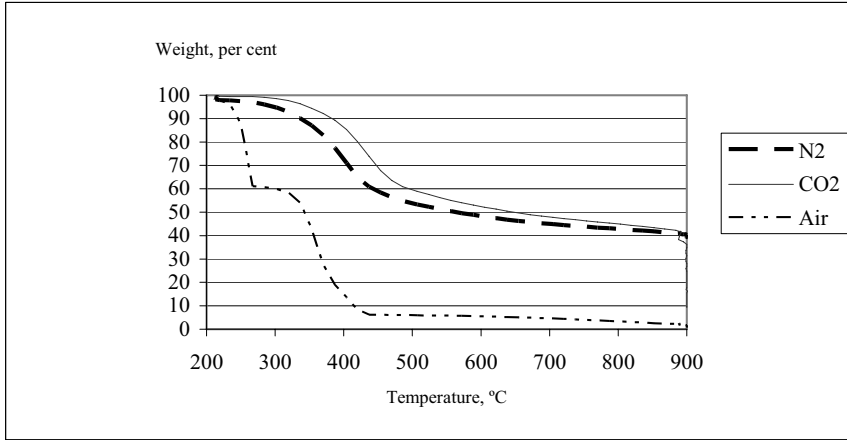


Figure 2.1. Weight loss as a function of temperature for material (2) at atmospheric pressure.

2.2.1 Char yield and char kinetics

Since char burnout is typically completed in time scales which are much longer than the devolatilisation, char burnout time determines the necessary particle residence time. Char properties are therefore important for the design of combustion equipment.

Table 2.2. Comparison between char yield in N₂ and CO₂ atmosphere

Purge gas	Total pressure, bar	Dilute-acid hydrolysis residue (1)	Enzymatic material (2)	Wood powder
N ₂	1	18.3 per cent	41.1 per cent	10.9 per cent
CO ₂	1	14.0 per cent	40.9 per cent	6.7 per cent
N ₂	12	29.1 per cent	46.4 per cent	24.6 per cent
CO ₂	12	32.6 per cent	44.2 per cent	17.5 per cent

Char yields for N₂ and CO₂ atmosphere are listed in Table 2.2.2. They are consistent with earlier results that larger char particles are produced under higher pressure, reported for instance by Cetin et al (Cetin 2004).

2.2.2 Determination of kinetic data for devolatilisation of hydrolysis residue

The kinetics of devolatilisation has been determined for the three purge gases used. First order kinetics has been assumed, with the rate of conversion following the expression:

$$(1) \quad k = A \cdot \exp(-E_a/RT)$$

where T is the temperature, R is the gas constant, the preexponential factor A has the dimension s^{-1} and E_a is the activation energy.

A model with three parallel and independent reactions has been used. It has been suggested that the three main components of wood, hemicellulose, cellulose and lignin are devolatilised independently, meaning that the total rate is simply a weighted sum of the rate for each material (Hanaoka 2005, Heikkinen 2004, Várhegyi 1997).

The time derivative of the measured weight curve was computed for each data point using the difference between the adjacent points. Only the part of the data with a constant heating rate of 20 °C per minute were used.

For the dilute-acid material (1) and the enzymatic material (2), analyses have shown that very little hemicellulose remains after the chemical treatment, and therefore only two parallel reactions were considered. The weight loss rate of wood was considered to be the sum of three parallel reactions.

The preexponential factors k and the activation energies E_a (as defined in equation (1) above) for the parallel reactions were determined numerically. In addition, the weight fraction of each material was computed. The non-linear optimisation algorithm in Matlab was used to make a least-square adaptation of the function.

An example of a computed weight loss rate for material (1) is shown in Figure 2.2.2. The measured weight loss rate is also shown.

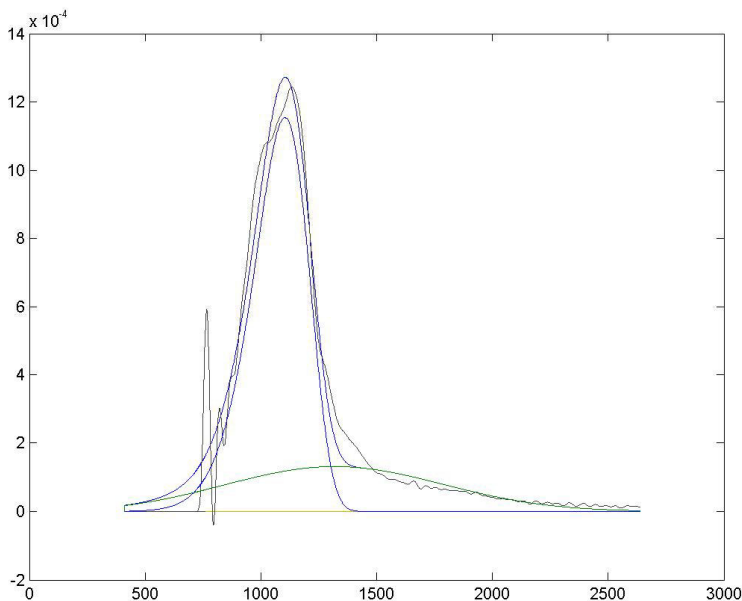


Figure 2.2. Normalised weight loss rate for material (1) (dilute-acid material) in N_2 atmosphere at 1 bar. The black curve is the measured mass loss ratio. The For this case, the

kinetic constants were A_1 (s^{-1}): $1.9 \cdot 10^4$ E_1 (kJ/mol) 82.31 A_2 (s^{-1}) $3.4 \cdot 10^{-2}$ E_2 (kJ/mol) 22.0. According to the curve-fitting, 70.8 per cent of the material was described by the first reaction (A_1 and E_1).

The heating rates in any combustor used in practice are several orders of magnitude higher than in the TGA/DTA runs, and the results must therefore be used with care. It is well known that the kinetic parameters are different for different heating rates. The data may of course be used for combustion simulations for want of anything better.

Still, the results may possibly be useful if data on combustion with other materials are available. The TGA data could be used for comparison, to see how similar the hydrolysis residue and the hydrolysis/fermentation residue are to the other materials, where the combustion behaviour is better known. This could give a hint which input parameters to use for the combustion simulations. The ultimate test of any simulation model is of course whether it produces results which can be verified through measurements.

3. Combustion test with a 150 kW powder burner

The Värnamo plant, where a wood-fired gas turbine was demonstrated, used a pressurised fluidised bed with gas cleaning. If the ash and alkali contents of the biofuel used are low enough, the fuel could be fed directly into the gas turbine combustor, through a powder burner. If feasible, this would simplify the process enormously.

A test of the lignin in a 150 kW powder burner was therefore performed. The main objective of the experiments was to confirm that stable combustion of the hydrolysis residue powder could be achieved with a standard wood powder burner. The test was carried out at the unit for Biomass Technology and Chemistry (BTC), Swedish University of Agricultural Sciences, Umeå, Sweden (BTC). A VTS powder burner (VTS, Nyköping, Sweden) with a capacity of approximately 150 kW was used for the tests. The test is described in detail in Paper 1.

Some conclusions:

- Feeding of the hydrolysis residues by a screw feeder and by pressurised air works at least as well as for wood powder. Improvements of the feeding system to reduce fluctuations in the fuel flow may however be necessary.
- The temperature and emission measurements show that the combustion of the hydrolysis residue in this particular powder burner is reasonably stable, at least as stable as when wood powder is used.

4. Economic viability of Combined Heat and Power (CHP) and pellet production

Even if combined heat and power production using lignin from wood-based ethanol production using direct-fired gas turbines turns out to be technically feasible, that is not sufficient. Whether it will actually be used is a matter of economics as well. A study of the economic viability of CHP and pellets production has therefore been done. It is described in detail in Paper 3.

The two most obvious ways to dispose of the solid residue from a production-scale ethanol plant is to either combust it or deposit in a landfill.

The lignin could be combusted in a gas turbine, as already described. To keep the temperature at the turbine inlet below 850 °C, the air fed into the combustor must be 5.7 times the stoichiometric rate. Therefore the flue gas will contain 17 per cent oxygen. To generate process steam for the ethanol production, slop could be combusted with flue gas from the gas turbine combustor used instead of air. There would be more than enough fuel for steam generation, and it could be used to generate additional pressurised steam for electricity generation in a steam turbine.

Another option would be to produce fuel pellets at the plant. They could either be used at existing heat and power plants, or they could be used for small-scale residential heating where the high heating value and low ash content would be useful. On the latter market the price is higher. A study of the combustion properties of fuel-pellets has been done at ETC, Piteå, Sweden (Öhman 2002). The conclusion was that soot-formation could be a problem for small-scale applications, although there is still a possibility that this could be overcome through appropriate design of the combustion equipment. Only large-scale applications are considered here.

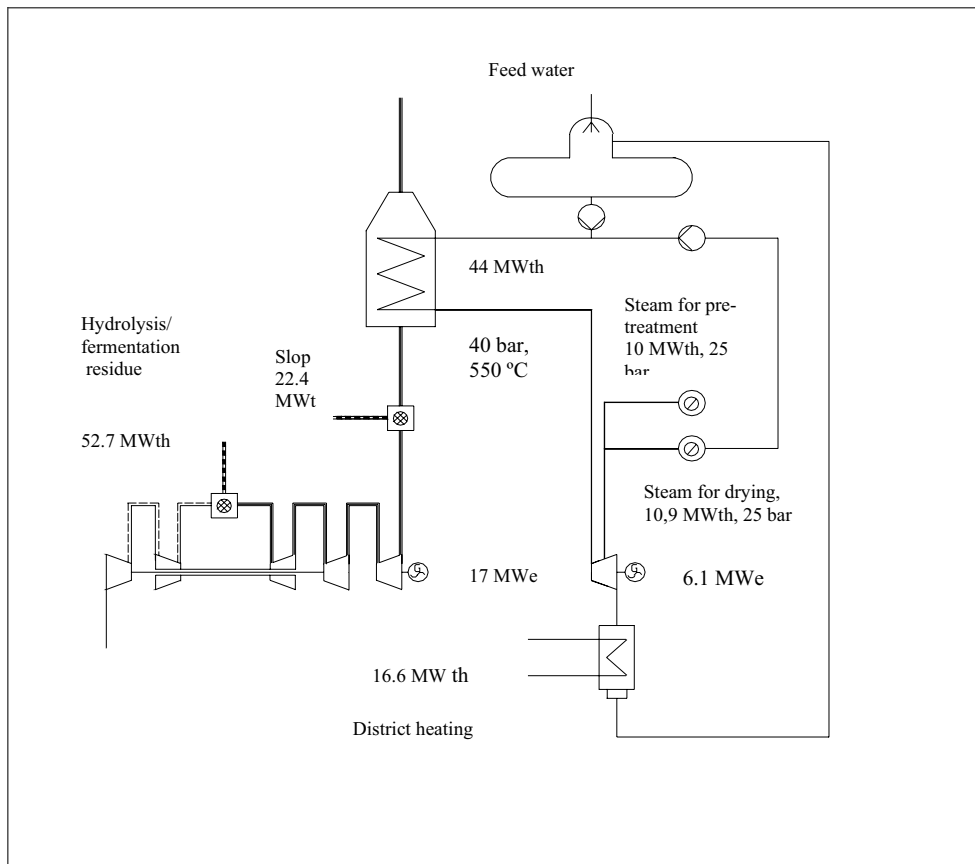


Figure 4.1. Process chart for process steam and CHP generation.

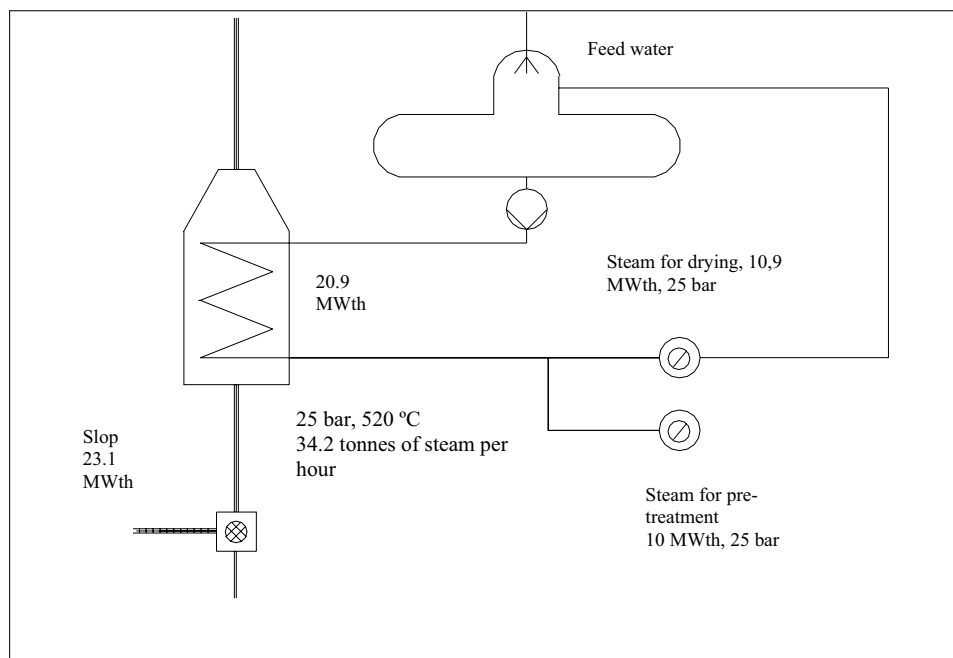


Figure 4.2. Process chart for process steam generation for the pellets production case.

In this study, two options for the production of combined heat and power (CHP) at a wood-based ethanol plant are being considered: 1) All solid residue is used for combined heat and power production at the site of the ethanol plant, 2) The lignin is used for fuel pellet manufacturing, and the slop is used for process steam generation.

Table 4.1. Summary of the two production alternatives considered

	Ethanol production and CHP (Combined Heat and Power)	Ethanol production and pellet production
Raw material used, tonnes of dry substance per year	200 000	200 000
Ethanol production, m ³ per year	58 800	58 800
Hydrolysis/fermentation residue, MWh per year	450 000	450 000
Slop, MWh per year	166 000	166 000
Process steam used, MWh per year	161 000	161 000
Electricity used, MWh per year	60 000	60 000
Electricity produced, MWh per year	184 000	0
Heat produced, surplus, MWh per year	133 000	0
Pellets produced, tonnes of dry substance per year	0	63 000
Pellets produced, MWh per year	0	450 000

It is assumed that the annual raw material use is 200 000 tonnes (dry substance) of logging residues.

The size of the plant has not been optimised, taking the possibilities of CHP production and pellet production into account. Such an optimisation would be a trade-off between economics of scale and transportation costs. For the CHP case, a larger plant also means that the plant location has to be chosen with more care to find use for the heat produced. The size used here was chosen to fit the process data provided by Lund University of Technology, who have worked mainly with the ethanol production process.

4.1 CHP production

It is assumed that the gas turbine GT35C is used to combust most of the lignin. Information was available from the manufacturer, Siemens Industrial Turbines, Finspång, Sweden. The electric efficiency for the turbine GT 35P which is similar is 33 per cent when coal is used. The efficiency should be roughly the same for the lignin powder, provided that excessive pressure losses in the combustion chamber can be avoided. The temperature at the turbine inlet is limited to 850 °C, which requires an air factor 5.7, and the outlet temperature is 400 °C (Strand 2005).

The oxygen content in the flue gas from the gas turbine is 17 per cent due to the high air factor. Supplementary firing of the remaining lignin and the slop is therefore possible. Here it is assumed that a steam boiler with a powder burner is used. The steam is produced at 40 bar and 550 °C.

The steam is expanded through a steam turbine, where process steam is extracted at 25 bar.

After the turbine the steam is condensed. The condensation heat can be used for district heating. This means that the plant will have to be located where there is sufficient heat demand. Several such locations are available in Sweden.

4.2 Fuel pellet production

While the lignin could have a considerable economic value as a fuel due to its high heating value and low ash content and could be worth transporting some distance, it is probable that the best use for the slop is to burn it on site. The slop would be sufficient to most of the process steam demand. All the lignin would be sold as pellets.

For the purpose of this study it is assumed that the pellets must be sold to bulk users (as mentioned it could be possible to use it for small-scale heating using certain suitable burners, but this requires further study).

4.3 Assumptions

The following main components of the combined heat and power process have been identified:

- 1) gas turbine with gear and generator;

- 2) fuel feeding and pressurisation system;
- 3) steam boiler;
- 4) steam turbine.

4.3.1 Investments for pellet production

For the investment for pellet production equipment, historical data have been used. (Hirsmark 2002). Investment costs reported vary widely, and the value chosen was 1 million SEK per 1000 tonnes of annual production capacity. To get a better estimate, it is necessary to look at the process in more detail.

4.3.2 Costs

It is assumed that the price for the raw material is 550 SEK per ton. This has been calculated from contacts with the forest industry (Söderström 2005, Olsson 2005), and is consistent with published figures (Swedish Energy Agency 2005)

According to official statistics, the price for electricity for larger industries is SEK 293 per MWh (industries with more than 50 000 customers, 3-year contract, 1 January 2004, see Statistics Sweden 2004).

For the CHP and process steam production, it is assumed that the costs for operation and maintenance are 2 percent of the total investment.

Operation and maintenance costs for the ethanol production process have been estimated in study from 1995 (NUTEK 1995).

4.3.3 Revenues

For electricity sold, it is assumed that the price is equal to the spot market price of Nordel, SEK 250 per MWh. In addition, electricity production using renewables will give the producer electricity certificates which can be sold at market price. It is assumed here that the price is SEK 200 per MWh (the average price between 24 November 2003 and 24 November 2004 was SEK 222.98).

The price for heat produced has been assumed to be 317 SEK per MWh which was the average for heat traded between producers and distributors in 2003 according to official statistics (Statistics Sweden 2005) It is assumed that the facility is located where there is a sufficient heat demand. Several such locations exist in Sweden.

It is assumed that any pellets produced are sold for SEK 184 per MWh, which is the price offered for bulk distribution (mainly to heat plants and other large-scale users) (Bioenergi Luleå 2004)

4.3.4 Financial assumptions

A five per cent rate of interest and a depreciation time of 25 years has been assumed for all investments, which gives an annuity factor of 7.1 per cent.

4.3.5 Greenhouse gas emissions

Only emissions of CO₂ are taken into account, contribution from other greenhouse gases is considered to be negligible in this context.

When ethanol produced from biomass replaces gasoline, net CO₂ emissions to the atmosphere are reduced, assuming that CO₂ fixated as the biomass is replaced compensates for the CO₂ emissions from the ethanol combustion.

Each MWh of ethanol produced is assumed to replace one MWh of gasoline. Differences in vehicle engine efficiency when different fuels are used are not taken into account. For each MWh of gasoline combusted it is assumed that 242.0 kg of CO₂ are released, this is simply a function of the lower heating value and the carbon to hydrogen ratio (figures published vary slightly but that is not important for the conclusion).

Marginal increases in the production of biomass fuelled CHP can be assumed to replace Danish coal-fired condensing power plants, given the current production in the Nordic countries. The figure 860,4 kg of CO₂ per MWh has been used by Wahlund et al (Wahlund 2004). For larger increases, this assumption will have to be reconsidered.

1 MWh pellets which replace coal will reduce CO₂ emissions by 327,6 kg per MWh according to Wahlund. For district heat, the figure used is 302.4 kg CO₂ per MWh (also from Wahlund).

4.4. Results and discussion

Production costs per litre of ethanol have been estimated. The production costs for the two options are shown in Figure 3. An interest rate of 5 per cent was assumed, with a depreciation time of 25 years, resulting in an annuity factor of 0.071. This was added to the estimated operating costs for the plant. Incomes from the sale of electricity, heat and fuel pellets were subtracted.

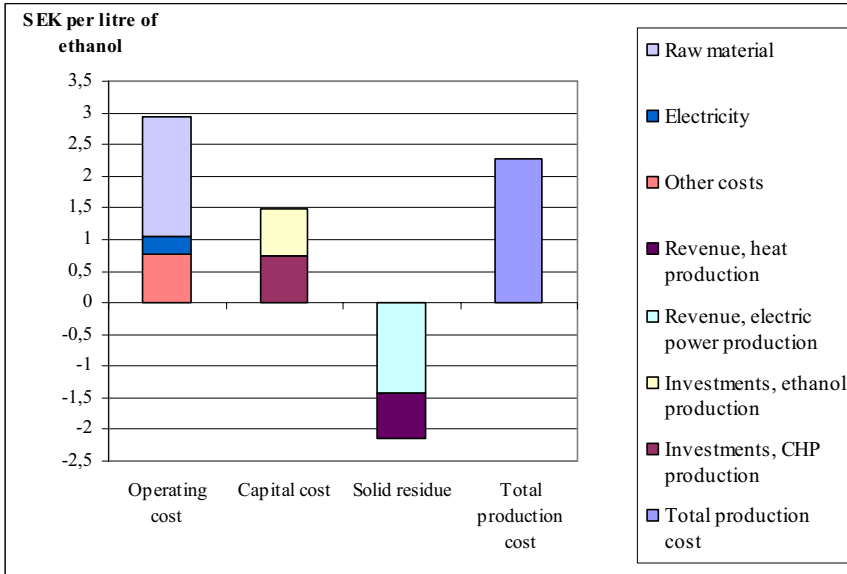


Figure 4.3. Production cost per litre of ethanol when the residue is used for CHP production

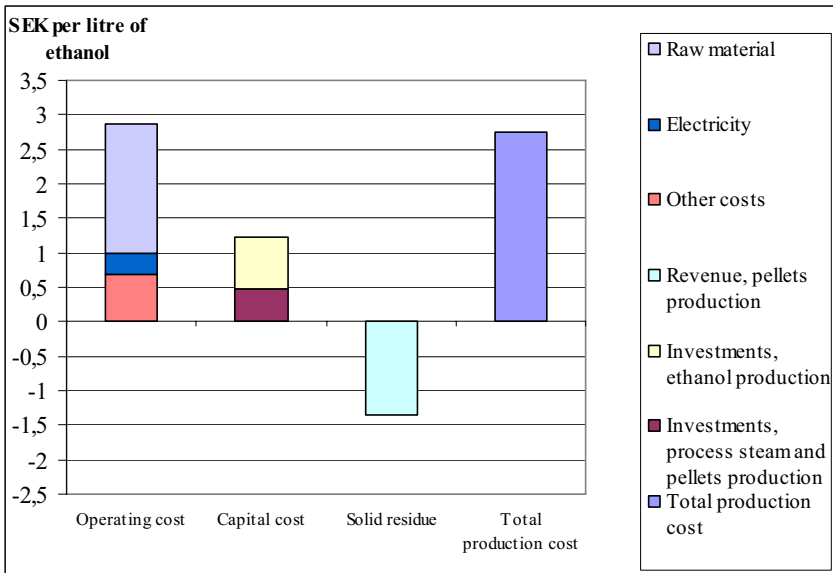


Figure 4.4. Production cost per litre of ethanol when the lignin is used for pellets production.

A sensitivity analysis has been done. The result is reported in Paper 3.

4.4.1 Impact on greenhouse gas emissions

The reductions in net CO₂ emissions when gasoline is replaced by ethanol and fossil fuel generated heat and electric power production is replaced by renewable CHP production have

been calculated, using the assumptions above. The result for the two production options is presented in Figure 4.5.

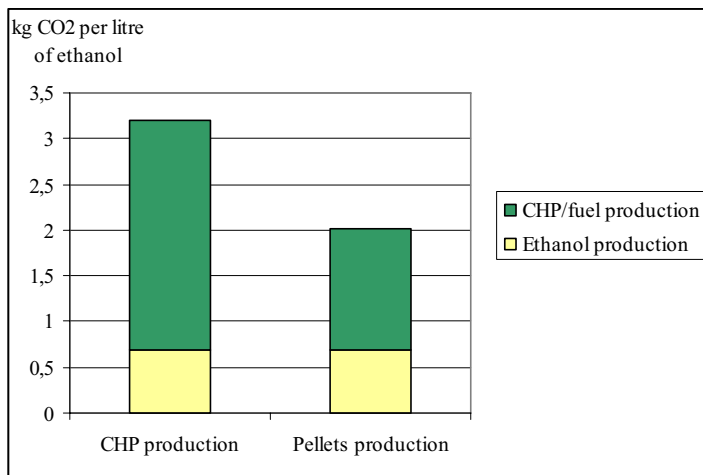


Figure 4.5. Reductions in anthropogenic CO₂ emissions for each litre of ethanol with the two production alternatives.

For public policy considerations, the respective costs for CO₂ reductions for the two production options have been calculated. The result is shown in Figure 4.6.

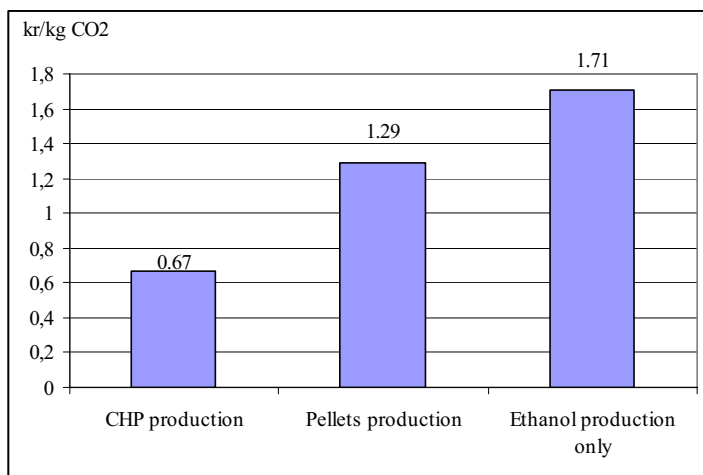


Figure 4.6. Net cost for substituting gasoline with ethanol, divided by the avoided quantity of CO₂ emissions from fossil fuels for the two production options. Ethanol production without fuel use of the lignin and slop as fuel was included for comparison.

5. Conclusions and suggestions for further work

Measurements of the devolatilisation properties of the lignin are available from atmospheric and pressurised conditions, and can be used for CFD simulations of combustion.

A combustion test of lignin with a powder burner at atmospheric conditions has been done, and it was demonstrated that the combustion properties were similar to wood powder. This suggests that direct combustion in a gas turbine combustion chamber could be feasible. Tests at pressurised conditions remains to be done, however.

CHP production and pellet production are both profitable uses of the by-products from wood-based ethanol production.

Given the assumptions described above, the economic result for the CHP option is better. However, the range of uncertainty for the investments are considerable, and the result must therefore be treated with caution.

From a climate policy point of view CHP production is a vastly better option. Since greenhouse gas reduction is one of the main reasons for developing ethanol production from wood in the first place, this should be relevant.

It is also obvious that if there are no major unforeseen discoveries of oil, energy prices in general will increase sooner or later. In the medium to long run it is therefore plausible that the economic result of CHP production will be considerably better.

It must be emphasised that the results above are only valid on the condition that gas cleaning equipment before the gas turbine inlet is not necessary. Further work must be devoted to verify that direct firing of the lignin under pressurised conditions is technically feasible.

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Paper A



Combustion of wood hydrolysis residue in a 150 kW powder burner

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Abstract

A combustion test has been made with residues from hydrolysis of wood for fuel ethanol production. A 150 kW powder burner was used. Fuel feeding and combustion were stable. The average concentration of CO in the stack gas was 8 mg/MJ, the average concentration of NO_x was 59 mg/MJ and the average total hydrocarbon concentration was below 1 ppm, at an average O₂-concentration of 4.6%. The low contents of potassium and sodium in the hydrolysis residue make the material attractive as a gas turbine fuel and the conclusion of this test is that direct combustion may be a feasible approach for gas turbine applications.

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Keywords: Biomass; Lignin; Combustion

1. Introduction

Ethanol has the potential to replace fossil gasoline as a motor fuel on a large scale. However, to be competitive with other fuels, production costs must be reduced. The process considered in Sweden for production of ethanol from wood includes pre-treatment of the feedstock by hydrolysis. Between 40 and 45% of the feedstock then ends up as a solid residue. For the overall process economy, a profitable use for this residue needs to be found.¹

One possible use of the hydrolysis residue is as a fuel for gas turbines. It appears as much more suitable for this application than wood. The low ash content of the hydrolysis residues and the low contents of potassium and sodium in the ash compared to other solid fuels would give

less risks for ash deposition in the turbine and erosion or corrosion damage. Using gas turbines adapted to operation with gas with some dust, like the PFBC-turbine designed by ABB-Stal, could then make it possible to eliminate the expensive gas cleaning that is included in the pilot plants with wood fuelled gas turbines in Värnamo and Arbre.

The simplest and cheapest approach to utilisation of hydrolysis residue gas turbine fuel would be to burn the residue in a specially designed combustion chamber. The objective of the experimental study presented here was to find out if this approach should be pursued or abandoned. Direct combustion of hydrolysis residue for gas turbine operation would be studied further if the results of the initial tests indicated that the combustion properties are acceptable and that the gas quality criteria developed by ABB [2] based on the experiences from coal fired PFBC-plants (Table 1) can be met.

Blunk and Jenkins have previously studied the combustion properties of the hydrolysis residues in detail [3]. They measured composition, density, heating value, ash volatility, ash fusibility and SO₂ release during heating for residues from hardwood and softwood. The material was very fine, in the case of softwood 50% of the particle mass fraction was not retained in a sieve with a mesh size of 420 μm. The initial deformation temperature for softwood ash was measured to 1120 °C. Applied combustion tests were outside the scope of their work.

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¹ According to von Sivers and Zacchi [1], in a weak-acid hydrolysis process, the production cost per litre of ethanol can be reduced by about 20% provided that 65% of the solid by-product can be pelletised and sold as a fuel (the rest is used to provide heat and steam for the process). The assumed prices are 80 SEK per MW h for the wood and 140 SEK per MW h for the solid by-product. For an enzymatic process, the reduction in cost is smaller, but still above 10%, because more of the cellulose can be converted to sugars (and subsequently to ethanol), and because the internal heat demand of the process is higher. It should be noted too, that also the internal heat and steam generation can be combined with electricity production, contributing to the overall process economy.

Table 1
Gas quality criteria for GT35P gas turbine [2]

Parameter	Diluted burned gas into turbine expander
Total dust load (mg/kg gas)	Below 400
Particles above 8 μm (mg/kg gas)	Below 10
Potassium and sodium (mg/kg gas)	Below 10
Melting temperature of ash particles ($^{\circ}\text{C}$)	Above 850

When sulphuric acid is used for the hydrolysis, the solid residue will contain some sulphur. For the proposed enzymatic ethanol production methods, the wood chips are pre-treated with either sulphuric acid or sulphur dioxide. When either of these methods are used, emissions of sulphur oxides and the possibility of sulphate deposits should be taken into account when considering combustion applications of the solid residue.

2. Experimental study

The main objective of the experiments was to confirm that stable combustion of the hydrolysis residue powder could be achieved with a standard wood powder burner. The tests were carried out at the unit for Biomass Technology and Chemistry, Swedish University of Agricultural Sciences, Umeå, Sweden (BTC). A VTS powder burner (VTS, Nyköping, Sweden) with a capacity of approximately 150 kW was used for the tests.

Experiments with this burner using wood powder as feedstock had previously been done by BTC.

2.1. Description of the material studied

The material used for this study was produced at the Rundvik reactor in Örnsköldsvik, Sweden by two-stage hydrolysis of spruce sawdust using dilute sulphuric acid. Process parameters are listed in Table 2. The two-stage hydrolysis procedure has been described by Eklund and Pettersson [4]. The solid material was separated from the liquid by a centrifuge. It was air-dried in a clean environment and packed in plastic bags.

After drying, the material consisted of solid lumps with typical diameters between a couple of millimetres

Table 2
Process parameters for the hydrolysis of spruce sawdust

	Step 1	Step
Raw material	Spruce sawdust	–
Dry content of raw material (%)	53.1	42.0
Concentration of H_2SO_4 (g/l)	5	3
Reaction time (min)	10	7
Temperature ($^{\circ}\text{C}$)	188	212
Pressure (bar)	12	20

and a couple of centimetres. It was ground manually in a cleaned 1100 W Retsch SK1 electric mill so it could be used in a powder burner.

For determination of the size distribution of the powder, samples of 20 g were sieved for 10 min using a Frisch Analysett sieving machine with DIN sieves: 1.6, 1, 0.8, 0.5, 0.315 and 0.25 mm. The particle size distribution of the hydrolysis residue is plotted in Fig. 1, and comparison is made with the commercial wood powder used in the earlier tests with the VTS burner. It was found that 65% of the particles passed through the 250 μm sieve. Since it cannot be assumed that the particles are spherical, their average diameter is difficult to estimate.

Table 3 shows the chemical composition and some physical properties of the hydrolysis residue used for combustion tests as well as for the wood powder used in previous tests with the same burner.

The ash content of the solid hydrolysis residues is below 0.1% of the dry substance. This can be compared to the wood powder previously tested, with an ash content of 0.4%. Although no detailed mass balance has been done, it is clear that a large fraction of the ash-forming elements are removed by the sulphuric acid during the hydrolysis and concentrated in the liquid residue.

The melting temperature of the ashes from the hydrolysis residue has been measured by Öhman et al. [5] to 1120 $^{\circ}\text{C}$ (initial deformation temperature according to ISO 540 [14]).

2.2. Combustion equipment and experimental procedure

The experimental set up and the burner are shown in Figs. 2–4. The feeding bin used has a size of approximately 1.7 m^3 and a scraper in the bottom of the bin pushes the powder down on four feeding screws. From the feeding screws the powder falls through a downcomer, where it is accelerated horizontally by an ejector into a plastic hose with a diameter of 17 mm (Fig. 2). The fuel-feeding rate can be adjusted between 0 and 30 kg/h. The combustion air is divided into four flows: powder transport air, primary air (swirled and high pressure), secondary air and tertiary air (Fig. 3).

The air flows were measured using four rotameters (Yokogawa, the Netherlands). The relative air flow distribution had previously been optimised for wood powder. For that fuel it was found that equal flow rates of primary, secondary and tertiary air lead to reasonably low CO emissions. The same air flow distribution was initially used for the hydrolysis residue to facilitate comparisons between the results for the two fuels.

The burner is of the free-burning type. The burner was connected to a 150 kW boiler type Teem (Eryl, Falun, Sweden) designed for biomass fuels (Fig. 4). To avoid low temperatures locally in the combustion chamber, the inside surfaces of the combustion chamber were covered with insulating plates made of Kaowool. A ceramic cone was placed at the front of the burner (Fig. 4).

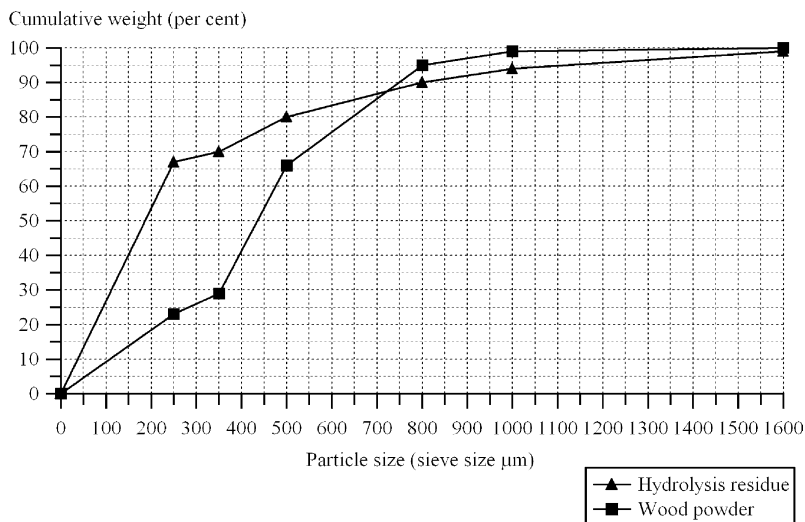


Fig. 1. Particle size distribution for hydrolysis residue powder and wood powder.

During the experiment the fuel mass flow was set to 19 kg/h, corresponding to a heat release rate of 108 kW. The flow of feeding air was set to 13.8 N m³/h. The other air flows were adjusted to reach an O₂ concentration of 4.5–5% in the exhaust. This would give an air-to-fuel equivalence ratio of 1.27–1.31. The primary, secondary and tertiary air flows were equal. The flow rate of each set were to approximately 33.6 N m³/h as measured by the flow meters. The temperature of the air and the fuel was approximately 20 °C.

The measuring period was 2 h. The burner was fired for 2 h before the start of the measurement period, to ensure that a thermal steady state had been reached.

2.3. Chemical analysis of flue gases and technical parameters

On-line measurements of the gaseous products O₂, CO₂, CO, NO, SO₂ and THC were performed during the entire test period. The concentrations of O₂, CO₂, CO and SO₂

Table 3
Chemical and physical properties of the hydrolysis residues

	Method	Reference	Hydrolysis residue	Wood powder
Moisture (total weight, %)	SS18 71 70	[6]	4.4	7.5
Carbon (dried weight, %)	LECO	[7]	55.7	49.8
Oxygen (dried weight, %)	By difference		38.5	43.7
Nitrogen (dried weight, %)	LECO	[7]	<0.1	<0.1
Hydrogen (dried weight, %)	LECO	[7]	5.8	6.2
Sulphur (dried weight, %)	SS 18 71 77	[8]	0.03	0.01
Ash content (dried weight, %)	SS 18 71 71:1	[9]	<0.1	0.4
Volatiles (dried weight, %)	ISO 562	[10]	78.4	84.5
Chlorine in ashes (dried weight, %)	ISO 587-1981 C	[11]	0.35	n.a.
K (dried weight, %)	ICP-AES	[12]	0.002	0.2 ^a
Na (dried weight, %)	ICP-AES	[12]	0.004	0.01 ^b
Heating value, calorific (dried weight, MJ/kg)	ISO 1928:1	[13]	22.8	19.3
Heating value, effective (sample weight, MJ/kg)	ISO 1928:1	[13]	20.5	17.7
Ash melting point, start of deformation (°C)	ISO 540	[14]	1120	n.a.
Ash melting point, spherical (°C)	ISO 540	[14]	1150	n.a.
Ash melting point, hemi-spherical (°C)	ISO 540	[14]	1200	n.a.
Ash melting point, float temperature (°C)	ISO 540	[14]	1270	n.a.

^a The potassium content of the wood powder was measured for a different batch, but for the same type of material.

^b The sodium content of the wood powder was measured for a different batch, but for the same type of material.

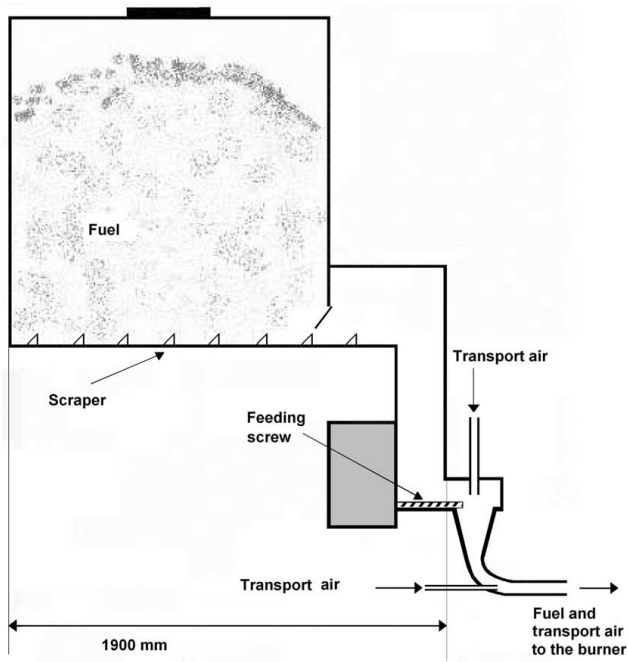


Fig. 2. Fuel feeding system.

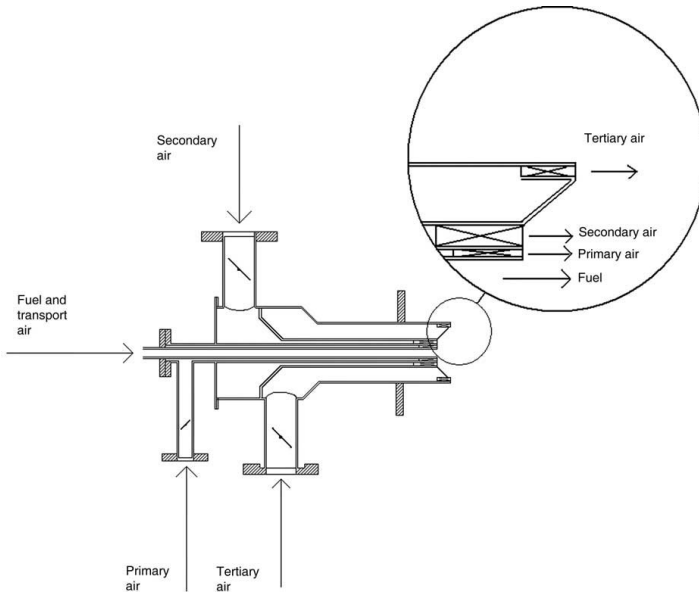


Fig. 3. The 150 kW burner.

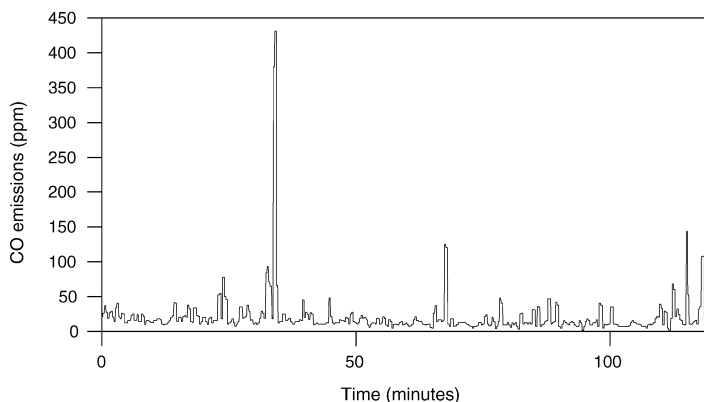


Fig. 5. Emissions of carbon monoxide from the 150 kW powder burner, at an average oxygen concentration of 4.6%.

The low fuel feeding rate of a 150 kW burner means that the combustion is rather sensitive to fluctuations in the fuel feeding rate, and the peaks in the CO emission graph were probably caused by such fluctuations.

Energy and mass balances are shown in Tables 5 and 6. The balances are based on the measured fuel and air flows. The discrepancy in the carbon balance of just below 10% indicates an error in either the fuel flow or the air flow measurements. This error is not important for the conclusion from the test results. The measured concentrations of oxygen and CO₂ in the flue gases show that the actual fuel-to-air ratio deviated by 5.4% from the set value (Table 6).

The ashes collected from the flue gas contained 27% unburned material (measured on dry substance). Since the ash content of the feedstock was below 0.1%, this also suggests that the combustion was reasonably complete.

The peak temperature measured in the furnace was 1332 °C which is 480 °C below the adiabatic combustion temperature.

4. Comparison with results obtained for combustion of wood powder

Table 4 includes results obtained from previous tests with combustion of wood powder. The results are similar to those obtained for combustion of hydrolysis residues.

Table 5
Energy balance

	kW	Percent of energy supplied
Supplied with fuel	108.2	100
Supplied with air	0	0
Delivered as heat in the flue gas	76.8	71
Heat transferred from the flame to the surroundings (by difference)	31.4	29

The main differences are a higher content of CO, a higher particle load and a much lower SO₂ content for wood powder combustion. The latter difference can be explained by the difference in sulphur content in the two fuels. The other differences indicate more complete combustion for hydrolysis residue, probably a consequence of the smaller fuel particles.

5. Assessment of hydrolysis residue as gas turbine fuel

The usefulness of hydrolysis residue as a gas turbine fuel depends on the possibilities to meet the gas quality criteria presented in Table 1.

The low contents of potassium and sodium in the hydrolysis residue mean that the potassium and sodium content in the gas entering a gas turbine can be kept just below the required 10 mg/kg gas at stoichiometric conditions and a gas temperature above 1300 °C in a gas turbine with pressure ratio of 12.5 bar. The required inlet temperature of the GT35P turbine designed by ABB Stal is 850 °C. With this temperature at the turbine inlet, a dilution corresponding to an oxygen concentration of 17.0% (assuming perfect combustion) would be necessary. This would give a potassium and sodium concentration of 2.2 mg/kg, which is well below the 10 mg/kg limit. The ash melting temperature was found to be well above 850 °C. However,

Table 6
Carbon balance

	kg/h	%
Supplied with fuel	10.11	100.0
Converted into CO ₂	9.12	90.2
Converted into CO	1.06×10^{-5}	0.0001
Unburned carbon in flue gas particles	0.02	0.2
Difference	0.97	9.6

as the composition of the ashes may vary, some particles could have melting temperatures considerably below 1120 °C, and the possibility that some could melt below 850 °C cannot be excluded.

The low particle content observed in the combustion tests presented here indicates that also the dust load requirements can be met. It must be realised however that the operating conditions of a gas turbine burner are different from those that could be achieved in the tests made so far. The design of a gas turbine combustor for hydrolysis residue powder must ensure sufficient residence time for particle burn-out before adding dilution air and sufficient residence time of ash particles in the dilution zone to ensure that particle temperatures are below the level where the particles become sticky.

6. Conclusions

- Feeding of the hydrolysis residues by a screw feeder and by pressurised air works at least as well as for wood powder. Improvements of the feeding system to reduce fluctuations in the fuel flow may however be necessary.
- The temperature and emission measurements show that the combustion of the hydrolysis residue in this particular powder burner is reasonably stable, at least as stable as when wood powder is used.
- It appears as justified to make further studies of direct-firing of the materials tested as an option for gas turbine operation. Design and testing of a pressurised powder combustor followed by extended tests with an integrated gas turbine system will be needed.

Acknowledgements

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University, Sweden for providing the hydrolysis residues. The financial support from the Swedish Energy Agency is gratefully acknowledged.

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Paper B

Thermogravimetric and differential thermal analysis (TGA/DTA) measurements of hydrolysis and fermentation residues from softwood ethanol production

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Abstract

The solid residue from wood-based ethanol production has a low ash content and high heating value, making it interesting for combustion applications, e.g. small-scale appliances and gas turbines. Combustion and gasification properties have been studied using thermogravimetric analysis (TGA) and differential thermal analysis (DTA). Char combustion rate data obtained could be used in combustion simulations. TGA and DTA data are useful for comparison with other fuels where data are available for similar heating rates.

1. Introduction

To be competitive in the motor fuel market, the production cost of ethanol must be low. The use of lignocellulosic materials like wood for production of ethanol results in large amounts of residues. It is crucial for the process economy that this material can be profitably used. Low ash and alkali content makes this residue an attractive fuel for gas turbines, making studies of its properties during combustion, pyrolysis and gasification worthwhile.

Combustion and gasification properties of residue from lab-scale dilute-acid hydrolysis of spruce wood is being investigated as part of a research project. Ignition was previously identified as a potential problem, either caused by slower release of volatiles during pyrolysis, or by higher ignition temperatures or lower heating value of the volatiles initially released. Clearly, when designing combustion and gasification systems for this material, the kinetics of devolatilisation is an important parameter for ignition and flame stability.¹

To develop equipment for combustion and gasification, computerised fluid dynamics (CFD) simulations is an important tool, and the rates of devolatilisation are needed as input parameters. Particle devolatilisation/gasification and combustion of volatiles in the gas phase are simulated separately. To quantify the devolatilisation properties,

¹ Use of hydrolysis residues as a gas turbine fuel. A pilot study, Luleå University of Technology, Final report for the Swedish Energy Agency, project P11454-1, 29 April 2002 (In Swedish)

thermo-gravimetric analysis (TGA) and differential thermal analysis (DTA) of the sample material has been done. These measurements give information about the weight loss rate of the material measured, and about the heat of reaction for devolatilisation/gasification. They do not give any direct information about the composition of the volatiles.

2. Properties of the material studied

The material studied is a solid residue from ethanol production based on softwood. Two processes are currently considered for future industrial production in Sweden. The first process uses dilute-acid hydrolysis to release the saccharides before fermentation. In the second process, enzymes are used for the hydrolysis, and the hydrolysis and fermentation takes place in a common reactor.

Two materials from different ethanol production processes were studied. In addition, a wood powder sample was studied.

The first material (1) was solid residue from the Rundvik reactor in Örnsköldsvik, Sweden, where spruce sawdust was hydrolysed in two stages using dilute sulphuric acid. The two-stage hydrolysis procedure has been described by Eklund and Pettersson.² For brevity the material is referred to as dilute-acid material in the following.

The second material (2) was from an enzymatic process. It was produced at the Process Development Unit, Lund University of Technology, Sweden from spruce stem wood. The process is called SSF (Simultaneous Saccharinification and Fermentation). The material is referred to as SSF material.

The third material (3) was a wood powder.

The yield of ethanol from the enzymatic process is 23 per cent, although this figure remains to be verified in industrial scale. The ethanol yield from the dilute-acid process is 15 per cent. On the other hand, the latter process has been used for decades. Both processes will be tested at the pilot plant at Örnsköldsvik, Sweden, which was inaugurated May 2004.

Of the three main components in wood, hemicellulose is most readily converted to saccharides. As mentioned, cellulose can be converted into ethanol with a considerably higher efficiency in the SSF process, which means that a large part of the material remaining in the solid will be lignin, the third main component which is not converted.

Results of proximate and ultimate analyses of the dilute-acid and enzymatic materials are listed in Table 1. Data for a comparable wood powder are included for comparison.

² Eklund R and Pettersson, P.O. (2000): Dilute-acid hydrolysis of softwood forest residues. International Symposium on Alcohol Fuels XIII, Stockholm, Sweden, 3-6 July 2000. Proceedings I:4

The chemical composition of the dilute-acid hydrolysis residue has been measured by NREL, the result is listed in Table 2. Analyses for the other materials are not available.

Table 1. Elemental composition for the material

	Method	Residue, dilute acid hydrolysis (1) ³	Residue, hydrolysis and fermentation, SSF process (before washing) (2)	Wood powder (3) ⁴
C (per cent of dry substance)	LECO	55.7	59.4	49.8
O (per cent of dry substance)	By difference	38.5	31.2	43.7
N (per cent of dry substance)	LECO	<0.1	2.9	<0.1
H (per cent of dry substance)	LECO	5.8	5.0	6.2
S (per cent of dry substance)	SS18 71 77	0.03	0.28	0.01
Ash (per cent of dry substance)	SS18 71 71:1	<0.1	1.2	0.4
Volatile matter (per cent of dry substance)	ISO 562:1	78.4	63.8	84.5
Lower heating value (MJ/kg TS)	ISO 1928:1	21.57	25.86	19.0

Tabell 2. Chemical analysis of dilute-acid material. Glucan is a component of cellulose.

	I	II	Average
Extractives	0,00	0,00	0,00
Ash	0,00	0,15	0,08
Lignin	53,40	53,62	53,51
Glucan	43,65	43,86	43,75
Xylan	1,29	0,86	1,07
Galactan	0,69	0,61	0,65
Arabinan	0,00	0,00	0,00
Mannan	0,91	0,46	0,69
Total	99,95	99,55	99,75

2 Experimental studies of combustion and gasification kinetics

Thermo-Gravimetric Analysis (TGA), where a sample is weighted during pyrolysis/combustion in a furnace is a commonly used method to obtain kinetic data for fuels. Weight changes are related to devolatilisation and oxidising reactions and

³ Fuel

⁴ samma

describe the overall kinetics of the event. However, experimental conditions and equipment specific factors strongly affects the results. It is often very difficult to completely exclude these factors in the evaluation process. Thus, obtained kinetic parameters are always to some extent method specific, and should preferably be used in comparison to other data obtained by the same technique rather than as generally valid entities.

Usually a TGA experiment is performed as in a dynamic mode. i.e. sample weight is recorded during linear heating in a horizontal or vertical tube furnace with a gas flow of 10 - 200 ml/min (NTP). The inner diameter of the furnace is typically 15-25 mm. Typical values for the heating rate is 5-40 °C/min. The heating rate is limited by furnace capacity and mechanical disturbances due to the gas flow. Slow reaction kinetics can be determined in an isothermal mode. The sample weight is recorded at a constant temperature and gas flow and the rate of weight change gives the isothermal kinetics of the reaction.

Another commonly used procedure is Differential Thermal Analysis (DTA), in which a sample is heated, and its temperature is compared to the temperature of a thermally inert reference material. This temperature difference, which is recorded as a function of the furnace temperature, provides a quantitative measure of changes in internal enthalpy due to chemical reactions and phase transformations e.g. drying, devolatilisation, condensation or depolymerisation. Whether the reactions are endothermic or exothermic is shown by the sign of the temperature difference between the sample and the inert reference, where an upward peak corresponds to an exothermic reaction. Baseline stability is important in DTA measurements in order to get quantitatively reliable results. Geometrical asymmetry between sample and reference and physical changes of the sample during the experiment are the most common reasons for baseline instability.

2.1 Experimental procedure

Experiments were made using two different equipments owned and operated by the Combustion and Materials Chemistry group at Åbo Akademi University in Finland. The first was a pressurized thermogravimetric reactor (PTG). The sample was suspended in vertical tube furnace with a gas flow coming from below. The sample holder was a platinum cup. In this device, both atmospheric and pressurized samples were studied. The second device was a TA Instruments SDT2960 simultaneous TGA-DTA analyser, where both thermogravimetry and differential thermal analysis are made at the same time. It has a horizontal tube furnace with the sample and reference placed symmetrically in the middle of the furnace. Platinum sample holders were used. This device operates only at atmospheric pressure.

Experiments were done at 1 bar and 12 bar total pressure. Three materials were studied:

- 1) Hydrolysis residue from dilute acid process
- 2) Hydrolysis/fermentation residue from the SSF process (an enzymatic process)
- 3) Commercial wood powder

Three sets of experiments were made using three different atmospheres: 1) Air; 2) N₂ and 3) CO₂. The experiments are listed in Table 3.

A particle undergoing devolatilisation in a combustor is surrounded by a layer of outward-moving gas, which prevents contact with oxygen from the air. During this phase, it is probable that a more inert atmosphere is a better approximation of the conditions in a combustor. Therefore, the results in N₂ are relevant.

At gasification conditions, where there is a deficit of oxygen in at least parts of the combustor/gasifier, the reaction of CO₂ with fixed carbon in the particle may have an important influence over the particle mass loss rate. That is the main reason to include the test runs using CO₂ as the purge gas.

Table 3. Survey of tests done.

Purge gas	Total pressure, bar	Dilute-acid hydrolysis residue	Enzymatic material	Wood powder
N ₂	1	Run 1	Run 2	Run 3
CO ₂	1	Run 4	Run 5	Run 6
Air	1	Run 7	Run 8	Run 9
N ₂	12	Run 10	Run 11	Run 12
CO ₂	12	Run 13	Run 14	Run 15
Air	12	Run 16	Run 17	Run 18

Runs 1, 3, 4, 6, 7 and 9 were made in the SDT 2960 with a gas flow of 100 ml/min (NTP). Runs 2, 5, 8, 10 to 18 were made in the pressurised thermogravimetric reactor. For runs 2, 5 and 8 the gas flow was 1 500 ml/min (NTP) and for runs 10-18 it was 3000 ml/min (NTP).

5 to 6 mg of the sample material was placed in a platinum holder in a furnace. The temperature difference to an inert reference material under the same conditions was measured.

From an initial temperature of 20 °C (runs 1-3, 7-9) or 200 °C (runs 4-6, 10-12, 16-18), the furnace was heated at a constant rate of 20 °C per minute up to 900 °C. After that the furnace temperature was kept constant at 900°C for 30 minutes. The weight of the sample and the temperature difference between the sample and the inert reference were measured continuously.

2.2 Experimental observations

The weight as a function of time for the SSF material is shown in Figure 1 for 1 bar, and in Figure 2 for 12 bar.

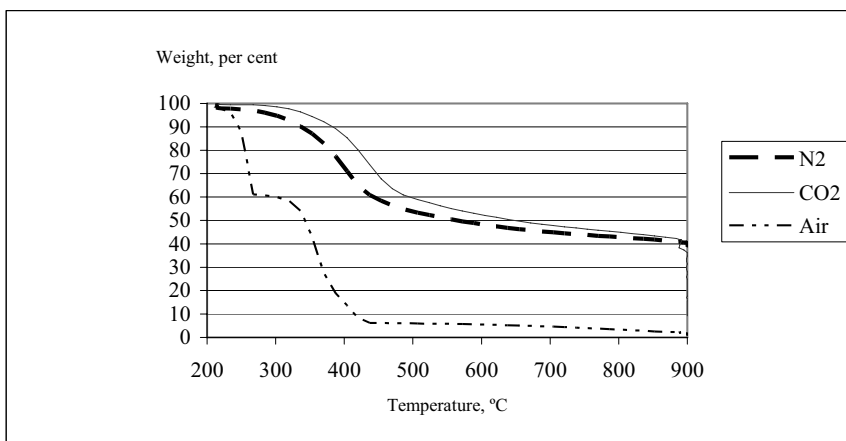


Figure 1. TGA graphs for SSF hydrolysis/fermentation residue for three different atmospheres, 1 bar total pressure. 1) Air, 2) Nitrogen and 3) Carbon dioxide. Heating rate: 20 °C per minute.

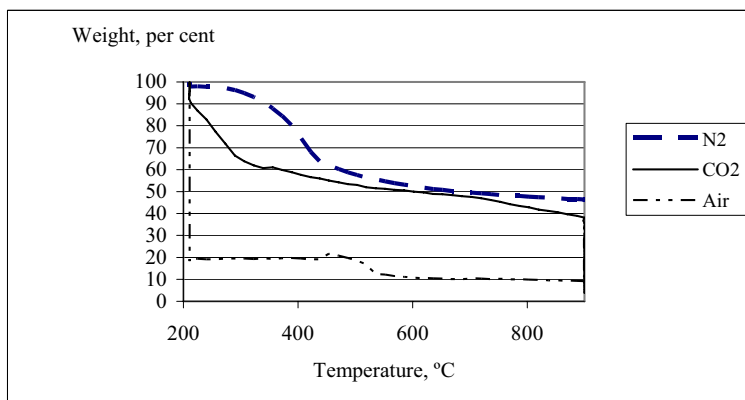


Figure 2. TGA graphs for SSF hydrolysis/fermentation residue for three different atmospheres, 12 bar total pressure. 1) Air, 2) Nitrogen and 3) Carbon dioxide. Heating rate: 20 °C per minute.

Temperatures for maximum mass loss rate

The respective temperatures where the mass loss rate is greatest are shown for each test run in Table 4.

Table 4. Temperatures for maximum weight loss rate

Purge gas	Total pressure, bar	Dilute-acid hydrolysis residue	Enzymatic material	Wood powder
N ₂	1	377 °C	420 °C	397 °C
CO ₂	1	349 °C	441 °C	391 °C

Air	1	330 °C	208 °C	330 °C
N ₂	12	384 °C	422 °C	419 °C
CO ₂	12	393 °C	420 °C	399 °C
Air	12	287 °C	208 °C	300 °C

Char yield and char kinetics

Since char burnout is typically completed in time scales which are much longer than the devolatilisation, char burnout time determines the necessary particle residence time. Char properties are therefore important for the design of combustion equipment.

Table 5. Comparison between char yield in N₂ and CO₂ atmosphere

Purge gas	Total pressure, bar	Dilute-acid hydrolysis residue	Enzymatic material	Wood powder
N ₂	1	18.3 per cent	41.1 per cent	10.9 per cent
CO ₂	1	14.0 per cent	40.9 per cent	6.7 per cent
N ₂	12	29.1 per cent	46.4 per cent	24.6 per cent
CO ₂	12	32.6 per cent	44.2 per cent	17.5 per cent

Char yields for N₂ and CO₂ atmosphere are listed in Table 5. They are consistent with earlier results that larger char particles are produced under higher pressure, reported for instance by Cetin et al (Cetin 2004).

Reactions between CO₂ and fixed carbon are likely to be important in gasifiers.

Latent heat of devolatilisation/gasification

The DT analyses show that the devolatilisation is slightly endothermic in the N₂ environment (Figure 3).

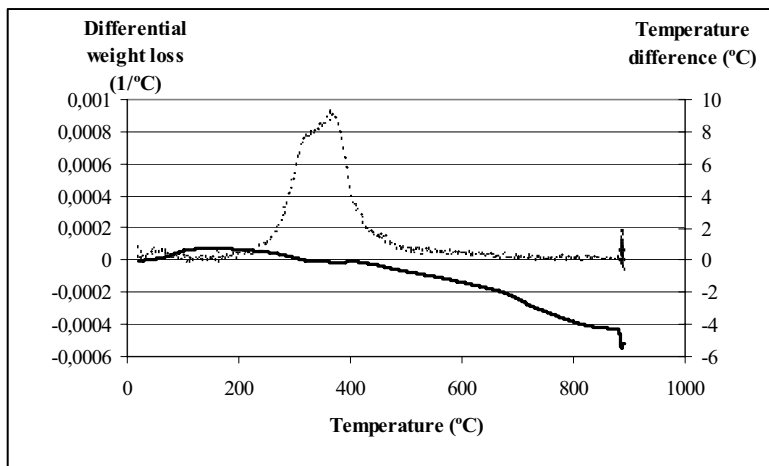


Figure 3. DT-analysis for hydrolysis residue in nitrogen atmosphere (with TG graph for comparison, thin curve). A positive temperature difference indicates that the

reaction is exothermic.

In air a reaction takes place between 200 and 500 °C which unsurprisingly is strongly exothermic.

In the CO₂ environment, the reaction is exothermic in the interval 275 to 525 °C, above that temperature it gradually becomes endothermic (Figure 4).

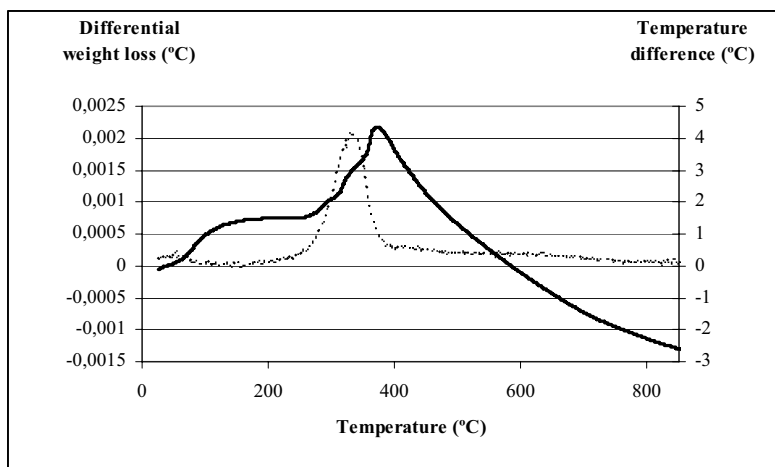


Figure 4. DT-analysis for hydrolysis residue in carbon dioxide atmosphere (with TG graph for comparison, thin curve). A positive temperature difference indicates that the reaction is exothermic.

Determination of kinetic data for devolatilisation of hydrolysis residue

The kinetics of devolatilisation has been determined for the three purge gases used. First order kinetics has been assumed, with the rate of conversion following the expression:

$$k=A*\exp(-E_a/RT)$$

where T is the temperature, R is the gas constant, the preexponential factor A has the dimension s⁻¹ and E_a is the activation energy.

A model with three parallel and independent reactions has been used. It has been suggested that the three main components of wood, hemicellulose, cellulose and lignin are devolatilised independently, meaning that the total rate is simply a weighted sum of the rate for each material (Hanaoka 2005, Heikkinen 2004, Várhegyi 1997).

The time derivative of the measured weight curve was computed for each data point using the difference between the adjacent points. Only the part of the data with a constant heating rate of 20 °C per minute were used. To eliminate random high frequency fluctuations from the measured function to facilitate the numerical determination of the kinetic parameters a Butterworth filter was used.

For the dilute-acid material and the enzymatic material, analyses have shown that very little hemicellulose remains after the chemical treatment, and therefore only two parallel reactions were considered. The weight loss rate of wood was considered to be the sum of three parallel reactions.

The preexponential factors and the activation energies for the parallel reactions together with the weight fraction of each material were determined numerically using the non-linear optimisation algorithm in Matlab. The sum of squares of the difference between the measured and the assumed weight loss rate for all data points were minimized. The resulting kinetic parameters are listed in Tables 6 and 7.

Table 6. Kinetic constants computed from the TGA measurements at 1 bar total pressure. A is the pre-exponential factor for each reaction, E is the activation energy and x is the relative weight for each reaction.

Purge gas	Dilute-acid material					
N ₂	A ₁ (s ⁻¹)	1.9 *10 ⁴	E ₁ (kJ/mol)	82.31	x ₁ (%)	70.79
	A ₂ (s ⁻¹)	3.4 *10 ⁻²	E ₂ (kJ/mol)	22.00	x ₂ (%)	29.21
CO ₂	A ₁ (s ⁻¹)	1.5*10 ⁵	E ₁ (kJ/mol)	89.07	x ₁ (%)	66.28
	A ₂ (s ⁻¹)	2.1*10 ⁻¹	E ₂ (kJ/mol)	36.84	x ₂ (%)	33.72
Air	A ₁ (s ⁻¹)	3.7 *10 ³	E ₁ (kJ/mol)	90.69	x ₁ (%)	59.56
	A ₂ (s ⁻¹)	4.3*10 ³	E ₂ (kJ/mol)	89.74	x ₂ (%)	40.44
Purge gas	Enzymatic material					
N ₂	A ₁ (s ⁻¹)	4.1*10 ⁴	E ₁ (kJ/mol)	91.85	x ₁ (%)	47.29
	A ₂ (s ⁻¹)	1.3*10 ⁻²	E ₂ (kJ/mol)	19.37	x ₂ (%)	52..71
CO ₂	A ₁ (s ⁻¹)	4.3*10 ⁴	E ₁ (kJ/mol)	95.41	x ₁ (%)	50.59
	A ₂ (s ⁻¹)	1.4*10 ⁻²	E ₂ (kJ/mol)	22.72	x ₂ (%)	49.41
Air	A ₁ (s ⁻¹)	1.8*10 ⁴	E ₁ (kJ/mol)	59.70	x ₁ (%)	1
	A ₂ (s ⁻¹)	-	E ₂ (kJ/mol)	-	x ₂ (%)	0

Purge gas	Wood powder					
N ₂	A ₁ (s ⁻¹)	5.3*10 ⁶	E ₁ (kJ/mol)	105.2	x ₁ (%)	25.72
	A ₂ (s ⁻¹)	8.0*10 ¹³	E ₂ (kJ/mol)	203.8	x ₂ (%)	53.20
	A ₃ (s ⁻¹)	3.2*10 ⁻²	E ₃ (kJ/mol)	21.79	x ₃ (%)	21.08
CO ₂	A ₁ (s ⁻¹)	5.4*10 ⁶	E ₁ (kJ/mol)	104.3	x ₁ (%)	20.09
	A ₂ (s ⁻¹)	1.5*10 ¹⁴	E ₂ (kJ/mol)	205.1	x ₂ (%)	49.34
	A ₃ (s ⁻¹)	1.0*10 ⁻²	E ₃ (kJ/mol)	19.21	x ₃ (%)	30.57
Air	A ₁ (s ⁻¹)	3.2*10 ²	E ₁ (kJ/mol)	60.02	x ₁ (%)	14.12
	A ₂ (s ⁻¹)	3.0*10 ³	E ₂ (kJ/mol)	73.39	x ₂ (%)	71.43
	A ₃ (s ⁻¹)	4.4*10 ²	E ₃ (kJ/mol)	79.25	x ₃ (%)	14.45

Table 7. Kinetic constants computed from the TGA measurements at 12 bar total pressure. A is the pre-exponential factor for each reaction, E is the activation energy and x is the relative weight for each reaction.

Purge gas	Dilute-acid material					
N ₂	A ₁ (s ⁻¹)	1.7*10 ⁵	E ₁ (kJ/mol)	95.03	x ₁ (%)	49.29
	A ₂ (s ⁻¹)	4.5*10 ⁻²	E ₂ (kJ/mol)	24.04	x ₂ (%)	50.71
CO ₂	A ₁ (s ⁻¹)	1.1*10 ⁷	E ₁ (kJ/mol)	119.0	x ₁ (%)	43.80
	A ₂ (s ⁻¹)	2.3*10 ⁻²	E ₂ (kJ/mol)	22.11	x ₂ (%)	56.20
Air	A ₁ (s ⁻¹)	5.0*10 ¹²	E ₁ (kJ/mol)	156.7	x ₁ (%)	61.31
	A ₂ (s ⁻¹)	1.4*10 ⁵	E ₂ (kJ/mol)	103.5	x ₂ (%)	38.69
Purge gas	Enzymatic material					
N ₂	A ₁ (s ⁻¹)	2.3*10 ⁵	E ₁ (kJ/mol)	101.9	x ₁ (%)	47.83
	A ₂ (s ⁻¹)	1.3*10 ⁻²	E ₂ (kJ/mol)	18.90	x ₂ (%)	52.17
CO ₂	A ₁ (s ⁻¹)	1.4*10 ⁵	E ₁ (kJ/mol)	100.1	x ₁ (%)	49.75
	A ₂ (s ⁻¹)	4.5*10 ⁻³	E ₂ (kJ/mol)	16.00	x ₂ (%)	50.25
Air	A ₁ (s ⁻¹)	9.8*10 ⁹	E ₁ (kJ/mol)	112.5	x ₁ (%)	100.00
	A ₂ (s ⁻¹)	-	E ₂ (kJ/mol)	-	x ₂ (%)	0.00

Purge gas	Wood powder					
N ₂	A ₁ (s ⁻¹)	2.7*10 ⁵	E ₁ (kJ/mol)	97.40	x ₁ (%)	34.46
	A ₂ (s ⁻¹)	1.0*10 ¹³	E ₂ (kJ/mol)	202.4	x ₂ (%)	31.44
	A ₃ (s ⁻¹)	1.0*10 ⁻²	E ₃ (kJ/mol)	20.16	x ₃ (%)	34.10
CO ₂	A ₁ (s ⁻¹)	3.8*10 ⁶	E ₁ (kJ/mol)	106.3	x ₁ (%)	22.01
	A ₂ (s ⁻¹)	1.0*10 ¹³	E ₂ (kJ/mol)	195.7	x ₂ (%)	38.92
	A ₃ (s ⁻¹)	5.0*10 ⁻³	E ₃ (kJ/mol)	19.45	x ₃ (%)	39.07
Air	A ₁ (s ⁻¹)	3.1*10 ²	E ₁ (kJ/mol)	11.54	x ₁ (%)	100.00
	A ₂ (s ⁻¹)	-	E ₂ (kJ/mol)	-	x ₂ (%)	0.00
	A ₃ (s ⁻¹)	-	E ₃ (kJ/mol)	-	x ₃ (%)	0.00

In Figures 5 to 7 the curves for all three materials at 1 bar total pressure are shown.

Flat, wide peaks are usually associated with lignin (Várhegyi 1997), which suggests that the extremely low pre-exponential factors seen here could be caused by lignin. The highest activation energies, 90 to 202 kJ could, according to the same kind of reasoning, be identified with cellulose. This leaves hemicellulose for the peaks with activation energies in between seen in wood.

As the enzymatic material is known to contain less cellulose than the dilute-acid material, it should in this case be expected that the sharp peak is less prominent, and indeed this seems to be the case, at least at atmospheric pressure. For 12 bar, the effect is very small for N₂ and apparently reversed for CO₂, on the other hand this may have something to do with the increased char formation at high pressure.

It is clear however that the small but rather sharp peak present for wood is missing for the two other materials, so it is probably reasonable to identify it with hemicellulose.

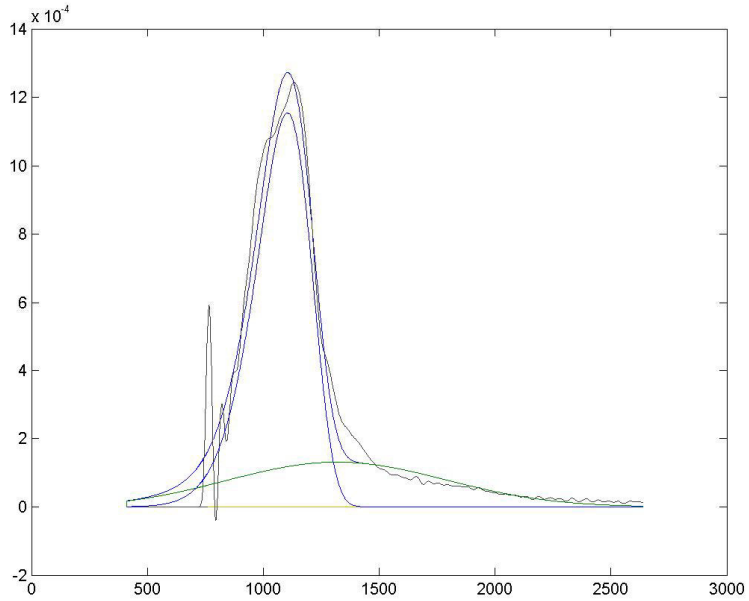


Figure 5. Normalised weight loss rate for dilute-acid material in N_2 atmosphere at 1 bar (the black curve is the measured mass loss ratio).

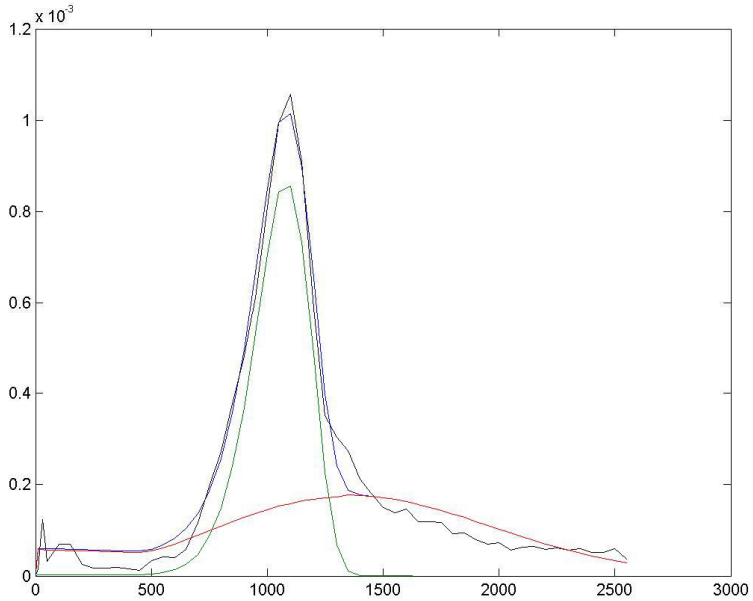


Figure 6. Normalised weight loss rate for SSF material in N_2 atmosphere at 1 bar (the black curve is the measured mass loss ratio).

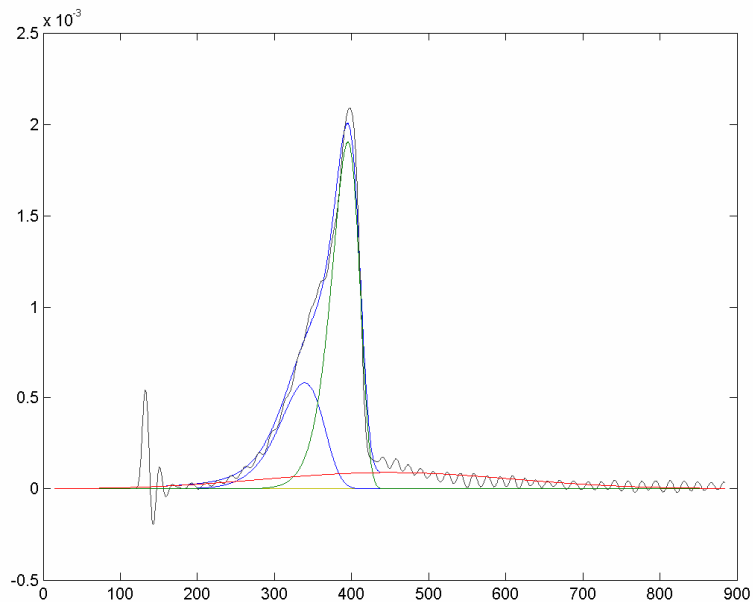


Figure 7. Normalised weight loss rate for wood powder in N_2 atmosphere at 1 bar (the black curve is the measured mass loss ratio).

4. Conclusions and discussion

The heating rates in any combustor used in practice are several orders of magnitude higher than in the TGA/DTA runs, and the results must therefore be used with care. It is well known that the kinetic parameters are different for different heating rates. The data may of course be used for combustion simulations for want of anything better.

Still, the results may possibly be useful if data on combustion with other materials are available. The TGA data could be used for comparison, to see how similar the hydrolysis residue and the hydrolysis/fermentation residue are to the other materials, where the combustion behaviour is better known. This could give a hint which input parameters to use for the combustion simulations. The ultimate test of any simulation model is of course whether it produces results which can be verified through measurements.

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Paper C

Economic assessment of Combined Heat and Power (CHP) production integrated with ethanol production from softwood

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Abstract

When ethanol for for substitution of gasoline as transportation fuel is produced from wood, about 30 per cent of the dry raw material mass remains in the solid residue. The hydrolysis/fermentation residue has very low ash and alkali content. This a possible use is direct-firing of gas turbines for Combined Heat and Power (CHP) at the site of the ethanol plant. Another possible use of the material is for the production of fuel pellets. Process parameters, investments, costs and revenues for these two production options have been estimated. The conclusion is that CHP is the most profitable use, although the uncertainties in estimated costs are considerable. Reductions of greenhouse gas emissions are decidedly larger for the CHP option. It has been concluded that CHP production is an option worth pursuing further. The technical feasibility of using the material for direct-firing of a gas turbine remains to be established however.

1. Introduction

When ethanol is produced from wood, most of the hemicellulose and some of the cellulose is converted into fermentable hexoses. About 30 percent of the dry weight remains as a solid residue, consisting mainly of lignin with some cellulose. In addition, approximately 15 per cent of the dry mass ends up in the slop (liquid residue) from the distillation. For simplicity this residue will be referred to a 'lignin', although it contains some cellulose as well. The energy content in the lignin per tonne of raw material is 2.6 times the fuel value of the ethanol. The energy content in the slop is roughly equal to the fuel value of the ethanol. It is clear that the use of these materials is important to the total process economy.

An obvious use of the lignin to combust it to generate process steam and electricity needed for the ethanol production process. High-pressure steam is needed for pre-treatment of the wood chips. There is more than enough solid residue to make the ethanol plant self-sufficient on steam and electricity. The surplus lignin can either be sold as a fuel or used to produce additional heat and power for sale.

Some non-energy uses of the lignin have been considered, for instance additives for motor fuels. While it may be worthwhile to explore such high-value uses further, the quantities produced will be huge in case ethanol becomes widely used as a motor fuel, and so it seems likely that much of it will be available as a fuel whatever the other uses.

A pilot plant with a production capacity of 400 litres of ethanol per day has been commissioned in April 2005 at Örnsköldsvik in northern Sweden. Experiments with both dilute acid production processes and enzymatic production are scheduled. The designer of this plant has suggested ethanol production plants co-located with existing heat and power production in 'bioenergy refineries' (Lindstedt 2003).

Another option would be to produce fuel pellets at the plant. They could either be used at existing heat and power plants, or they could be used for small-scale residential heating where

the high heating value and low ash content would be useful. On the latter market the price is higher. A study of the combustion characteristics of fuel-pellets has been done at ETC, Piteå, Sweden (Öhman 2002). The conclusion was that soot-formation could be a problem for small-scale applications, although there is still a possibility that this could be overcome through appropriate design of the combustion equipment. Only large-scale applications are considered here.

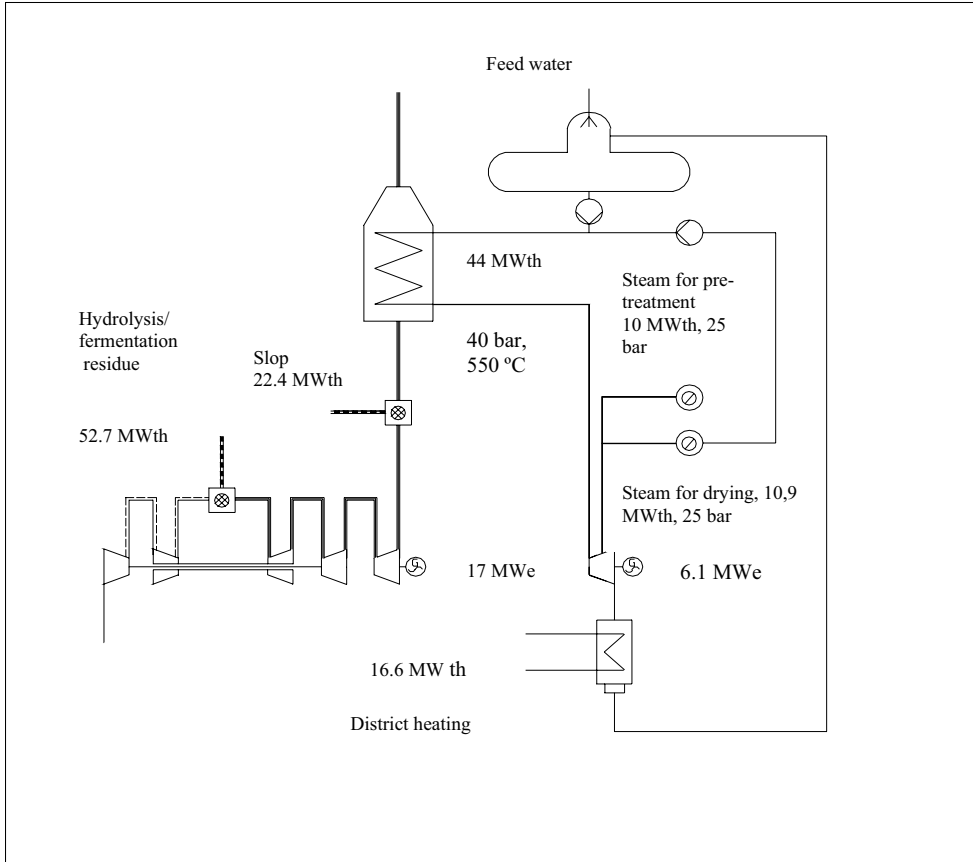


Figure 1. Process chart for process steam and CHP generation with gas turbine and steam turbine.

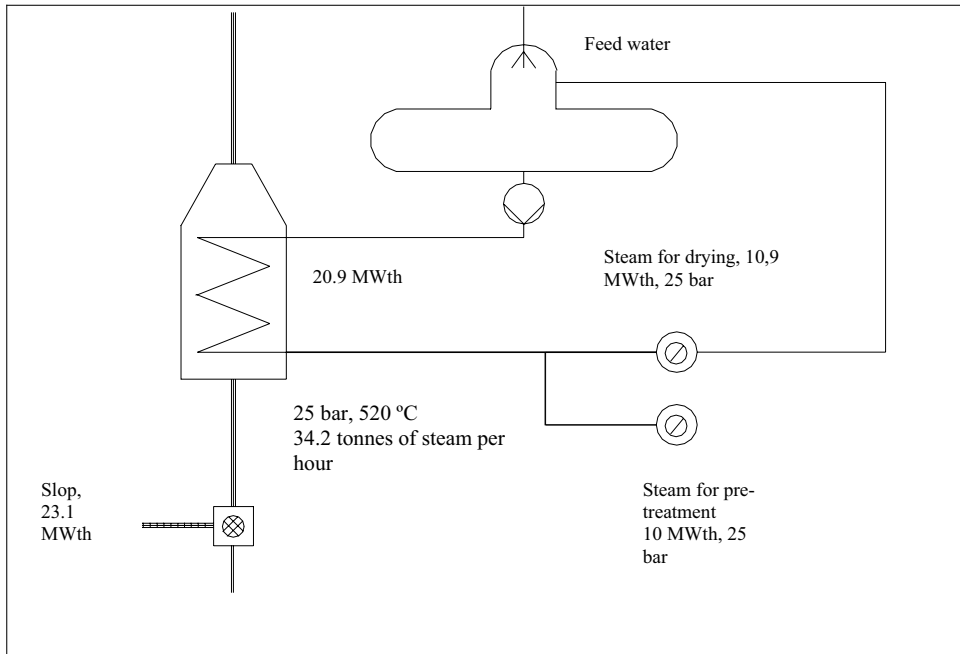


Figure 2. Process chart for process steam generation for the pellets production case.

In this study, two options are being considered: 1) All lignin is used for combined heat and power production at the site of the ethanol plant, 2) The lignin is used for fuel pellet manufacturing and the slop is used for process steam generation.

The two cases considered are described in Table 1.

Table 1. Summary of the two production alternatives considered

	Ethanol production and CHP (Combined Heat and Power) production	Ethanol production and pellet production
Raw material used, tonnes of dry substance per year	200 000	200 000
Ethanol production, m ³ per year	58 800	58 800
Lignin, MWh per year	450 000	450 000
Slop, MWh per year	166 000	166 000
Process steam used, MWh per year	167 000	167 000
Electricity used, MWh per year	60 000	60 000
Electricity produced, MWh per year	184 000	0
Heat produced, surplus, MWh per year	133 000	0
Pellets produced, tonnes of dry substance per year	0	60 000
Pellets produced, MWh per year	0	450 000

Several other production alternatives are of course conceivable. For instance, electricity could be produced using only a gas turbine, or only a steam turbine.

1.1 Properties of the materials studied

The ethanol production plant considered here uses an enzymatic process with simultaneous saccharinification and fermentation (SSF). The solid hydrolysis/fermentation residue consists mainly of lignin, and some cellulose. The slop contains most of the extractives and ashes. The main component is pentoses (which are non-fermentable using the process considered here) and non-fermented hexoses. There may also be some organic matter from yeast.

The elementary compositions of the lignin and the slop are shown in Table 2. Wood powder is included for comparison. The composition of the lignin is from simulations performed by Lund University at Technology, Sweden, using Aspen + (Wingren 2005). The slop is considered to consist entirely of saccharides. The heating values have also been estimated during the simulations.

Table 2. Approximate chemical composition of hydrolysis/fermentation residue('lignin') and slop. The slop is assumed to consist of pentoses and hexoses. Wood powder is included for comparison

	Hydrolysis/fermentation residue	Slop residue) (distillation	Wood powder
C (per cent of dry ash free substance)	62.1	40.0	49.8
H (per cent of dry ashfree substance)	5.2	6.7	6.2
O (per cent of dry ash free substance)	32.6	53.3	43.7

2. Assumptions used in the study

To make a precise calculation of the cost using detailed data from manufacturers for all items is outside the scope of this study. The investment and the costs for operation and maintenance are estimated from available data, and there are considerable uncertainties.

The process parameters for the CHP option and the pellet production option have been estimated. Information about the yield of ethanol, lignin and slop have been supplied by Lund University of Technology. They have also supplied data for steam and electricity demand (Wingren 2004).

Costs for purchase of land, interest during construction, pre-project preparatory work are not included in the investment

2.1 Size and performance of the ethanol production plant

The ethanol production plant considered here uses an enzymatic process with simultaneous saccharinification and fermentation (SSH). Although not proven outside the laboratory, this process is considered to have a higher ethanol yield than a traditional dilute-acid process (22.3 and 14.9 per cent of the dry raw material mass flow respectively) (NUTEK 1995, Wingren 2005)

It is assumed that the annual raw material use is 200 000 tonnes (dry substance) of logging residues.

The size of the plant has not been optimised, taking the possibilities of CHP production and pellet production into account. Such an optimisation would be a trade-off between economics of scale and transportation costs. For the CHP case, a larger plant also means that the plant location has to be chosen with more care to find use for the heat produced. The size used here was chosen to fit the process data provided by Lund University of Technology, who have worked mainly with the ethanol production process.

It is assumed in all cases that flue gas condensation is not used. The reason for this is the low hydrogen content in the solid fuel, and the high dilution of the flue gas in the gas turbine combustor (necessary to satisfy the gas quality requirements of the gas turbine), which makes the moisture content too low for flue gas condensation to be practical. The moisture content is higher in the other cases, and may be higher depending on how the drying process is devised. Here it is assumed for simplicity that the fuel is completely dry after the drying process. To let more moisture remain in the material would reduce the steam demand. A complete optimization of this is outside the scope of this work.

2.2 CHP production

It is assumed that the gas turbine GT35C is used to combust most of the lignin. Information was available from the manufacturer, Siemens Industrial Turbines, Finspång, Sweden. The electric efficiency for the turbine GT 35P which is similar is 33 per cent when coal is used. The efficiency should be roughly the same for the lignin powder, provided that excessive pressure losses in the combustion chamber can be avoided. The temperature at the turbine inlet is limited to 850 °C, which requires an air factor above 5.7, and the outlet temperature is 400 °C (Strand 2005).

The oxygen content in the flue gas from the gas turbine is 17 per cent due to the high air factor. Supplementary firing of the remaining lignin and the slop is therefore possible. Here it is assumed that a steam boiler with a powder burner is used. The steam is produced at 40 bar and 550 °C.

The steam is expanded through a steam turbine, where process steam is extracted at 25 bar.

The steam extracted is superheated. The process steam needed for the ethanol production process is saturated. 10 MW are to be used for pre-treatment of the logging residues, and 10.9 MW for evaporation and drying of the material from the ethanol production process. It is assumed that the steam used for pre-treatment of the logging residue becomes fouled and has to be replaced completely with feed water at 0 °C. The steam used for drying is recirculated as condensate, still at 25 bar.

After the turbine the steam is condensed. The condensation heat can be used for district heating. This means that the plant will have to be located where there is sufficient heat demand.

2.3 Fuel pellet production

While the lignin could have a considerable economic value as a fuel due to its high heating value and low ash content and could be worth transporting some distance, it is probable that the best use for the slop is to burn it on site. The slop would be sufficient to most of the process steam demand. Very little of the lignin would have to be used for this purpose and the rest could be sold.

For the purpose of this study it is assumed that the pellets must be sold to bulk users (as mentioned it could be possible to use it for small-scale heating using certain suitable burners, but this requires further study).

2.4 Investments for CHP production

The following main components of the combined heat and power process have been identified:

- 1) gas turbine with gear and generator;
- 2) fuel feeding and pressurisation system;
- 3) steam boiler;
- 4) steam turbine.

The cost for the gas turbine GT 35C including gear and generator is 74 million SEK, according to the manufacturer.

It is assumed that the solid fuel is pressurised and fed into the gas turbine combustor (through an intermediate store) using a lock-hopper system. Costs have been supplied by a manufacturer (Koch 2005).

For the steam boiler, a cost of 343 million SEK has been used for the CHP option and 264 for the pellets production option (Kjellström 2005) The figures suggested vary widely.

2.5 Investments for pellet production

For the investment for pellet production equipment, historical data have been used. (Hirsmark 2002). Investment costs reported vary widely, and the value chosen was 1 million SEK per 1000 tonnes of annual production capacity. To get a better estimate, it is necessary to look at the process in more detail.

2.6 Costs

It is assumed that the price for the raw material is 550 SEK per ton. This has been calculated from contacts with the forest industry (Söderström 2005, Olsson 2005), and is consistent with published figures (Swedish Energy Agency 2005)

According to official statistics, the price for electricity for larger industries is SEK 293 per MWh (Statistics Sweden 2004).

For the CHP and process steam production, it is assumed that the costs for operation and maintenance are 2 percent of the total investment.

Operation and maintenance costs for the ethanol production process have been estimated in study from 1995 (NUTEK 1995).

2.7 Revenues

For electricity sold, the price used is equal to the spot market price of Nordel, SEK 250 per MWh. In addition, electricity production using renewables will give the producer electricity certificates which can be sold at market price. It is assumed here that the price is SEK 200 per MWh (the average price between 24 November 2003 and 24 November 2004 was SEK 222.98).

The price for heat produced has been assumed to be 317 SEK per MWh which was the average for heat traded between producers and distributors in 2003 according to official statistics (Statistics Sweden 2005) For this, the facility must be located where there is a sufficient heat demand. Several such locations exist in Sweden.

It is assumed that any pellets produced are sold for SEK 184 per MWh, which is the price offered for bulk distribution (mainly to heat plants and other large-scale users) (Bioenergi Luleå 2004)

2.8 Financial assumptions

A five per cent rate of interest and a depreciation time of 25 years has been assumed for all investments, which gives an annuity factor of 7.1 per cent.

2.9 Greenhouse gas emissions

Only emissions of CO₂ are taken into account, contribution from other greenhouse gases is considered to be negligible in this context.

When ethanol produced from biomass replaces gasoline, net CO₂ emissions to the atmosphere are reduced, assuming that CO₂ fixed as the biomass is replaced compensates for the CO₂ emissions from the ethanol combustion.

Each MWh of ethanol produced is assumed to replace one MWh of gasoline. Differences in vehicle engine efficiency when different fuels are used are not taken into account. For each MWh of gasoline combusted it is assumed that 242.0 kg of CO₂ are released, this is simply a function of the lower heating value and the carbon to hydrogen ratio (figures published vary slightly but that is not important for the conclusion).

Marginal increases in the production of biomass fuelled CHP can be assumed to replace Danish coal-fired condensing power plants, given the current production in the Nordic countries. The figure 860.4 kg of CO₂ per MWh has been used by Wahlund et al (Wahlund 2004). For larger increases, this assumption will have to be reconsidered.

1 MWh pellets which replace coal will reduce CO₂ emissions by 327,6 kg per MWh according to Wahlund. For district heat, the figure used is 302.4 kg CO₂ per MWh.

3. Results and discussion

Production costs per litre of ethanol have been estimated. The production costs for the two options are shown in Figures 3 and 4.

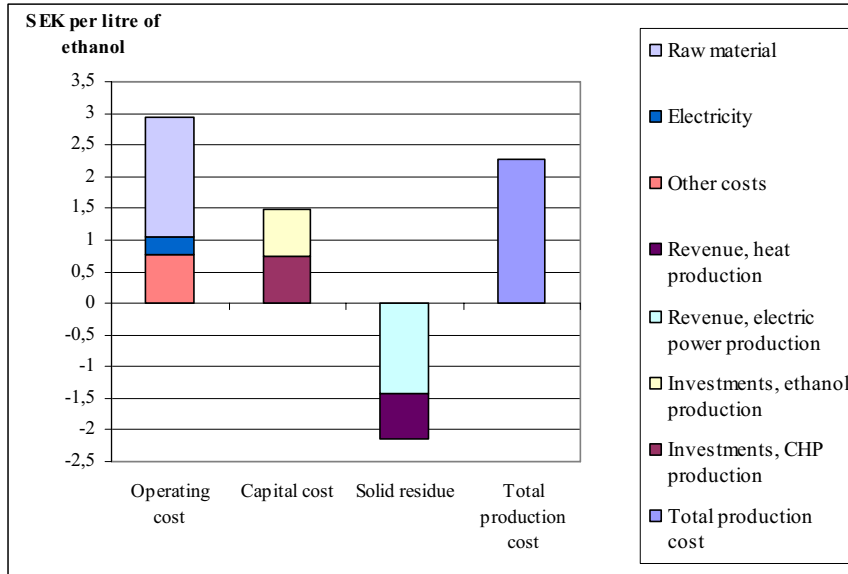


Figure 3. Production cost per litre of ethanol when the residue is used for CHP production.

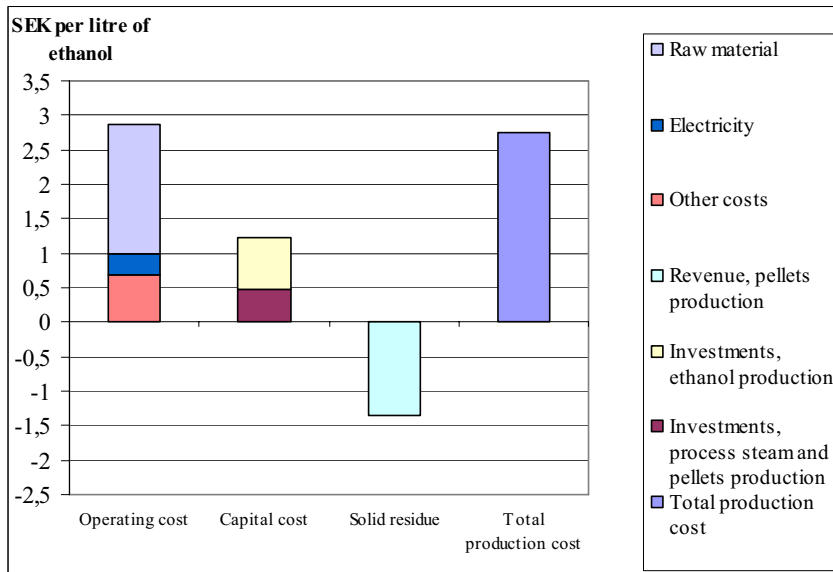


Figure 4. Production cost per litre of ethanol when the lignin is used for pellets production.

3.1 Impact on greenhouse gas emissions

The reductions in net CO₂ emissions when gasoline is replaced by ethanol, and fossil fuel generated heat and electric power production is replaced by renewable CHP production have been calculated, using the assumptions above. The result for the two production options is presented in Figure 5.

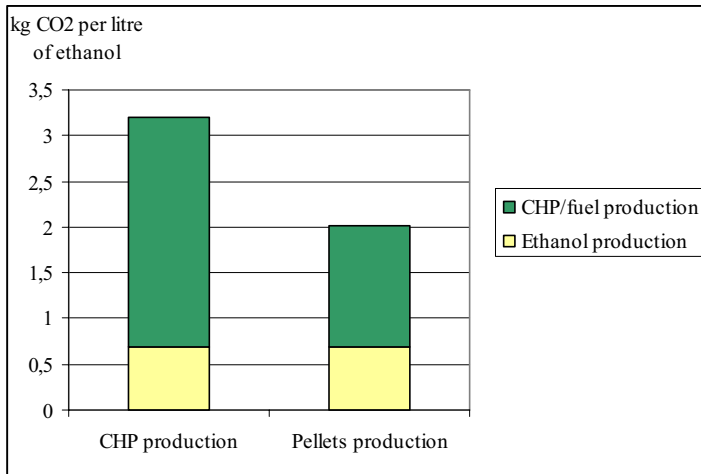


Figure 5. Reductions in anthropogenic CO₂ emissions for each litre of ethanol with the two production alternatives.

For public policy considerations, the respective costs for CO₂ reductions for the two production options have been calculated. The result is shown in Figure 6.

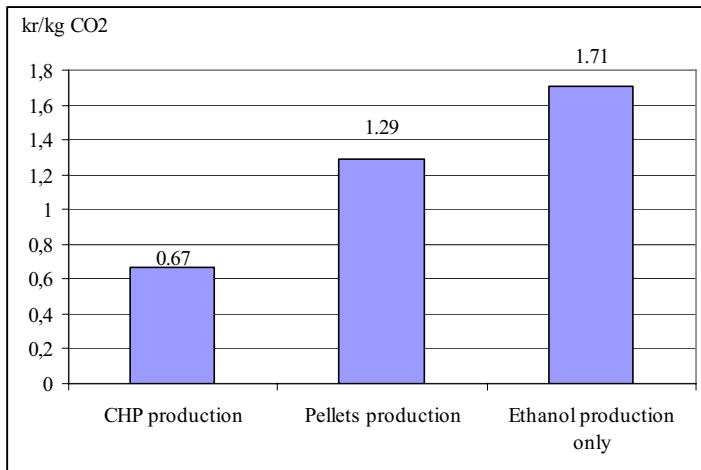


Figure 6. Net cost for substituting gasoline with ethanol, divided by the avoided quantity of CO₂ emissions from fossil fuels for the two production options. Ethanol production without fuel use of the lignin and slop as fuel was included for comparison.

3.2 Sensitivity analysis

A sensitivity analysis is presented in Figures 7 and 8 for the CHP case and pellet production case, respectively. The following parameters have been varied:

1) Investment, 2) Depreciation time, 3) Interest rate, 4) Price of electricity and heat and 5) Raw material cost.

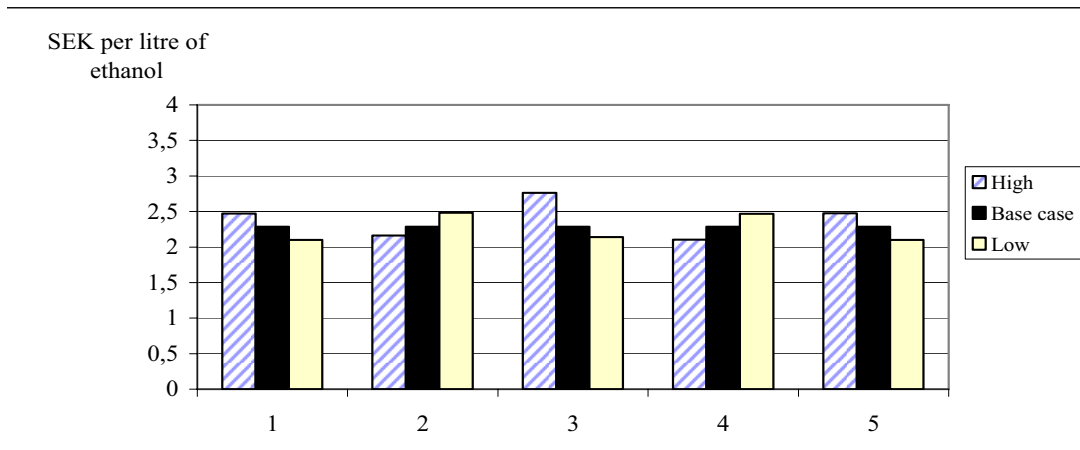


Figure 7. Sensitivity analysis for the CHP production alternative.

1. Investment, CHP production and steam generation, plus-minus 30 per cent,
2. Depreciation time, 30 years, 25 years and 20 years,
3. Interest rate: 8 per cent, 5 per cent, 4 per cent,
4. Energy prices (electricity, heat and pellets): plus-minus 10 per cent.
5. Cost of raw material: plus-minus 10 per cent.

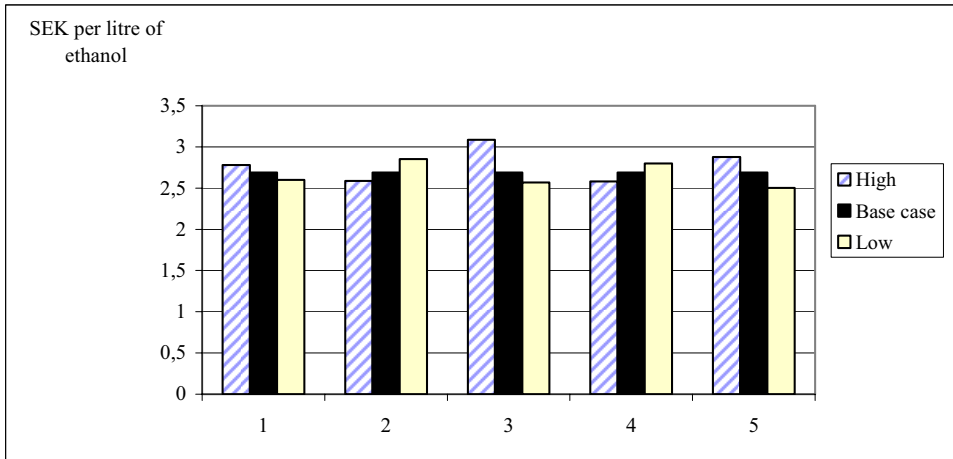


Figure 8. Sensitivity analysis for the pellet production alternative.

1. Investment, pellets production and steam generation, plus-minus 30 per cent,
2. Depreciation time, 30 years, 25 years and 20 years,
3. Interest rate: 8 per cent, 5 per cent, 4 per cent,
4. Energy prices (electricity, heat and pellets): plus-minus 10 per cent.
5. Cost of raw material: plus-minus 10 per cent.

The result that CHP production is more profitable is than pellets production seems to be reasonably robust.

4. Conclusions

CHP production and pellet production are both profitable uses of the by-products from wood-based ethanol production.

Given the assumptions described above, the economic result for the CHP option is better. However, the range of uncertainty for the investments are considerable, and the result must therefore be treated with caution.

The economic result is very sensitive to the investment. The investment has to be estimated more precisely, in particular the steam boiler and steam turbine with auxiliary equipment.

From a climate policy point of view CHP production is a vastly better option. Since climate policy considerations are one of the main reasons for developing ethanol production from wood in the first place, this is very important.

It is also obvious that if there are no major unforeseen discoveries of oil, energy prices in general will increase sooner or later. In the medium to long run it is therefore plausible that the economic result of CHP production will be considerably better.

It must be emphasised that the results above are only valid on the condition that gas cleaning equipment before the gas turbine inlet is not necessary. Further work must be devoted to verify that direct-firing of the lignin in a gas turbine is technically feasible.

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Appendix 1. Investments including installation

	Combined cycle. co-located	Reference case.
		pellet manufacturing
	MSEK	MSEK
Gas turbine with gear	74	0
Oil fired starter	0.05	0
Wood powder handling system	2	2
Pressurising feeder for wood powder (lock hoppers)	15.3	0
Powder storage	2	0
Powder burner, GT-combustor	3.3	0
		0
Steam boiler	342.6	263.8
Steam turbine, incl.generator (6,1 MW)	31.6	0
Filter (ESP) incl. ash discharge and fly ash silo	20	9.5
Power transmission	14	6.8
Control system	12	5.8
Buildings	5	5
Connection to existing system	4	4
Pellet manufacturing equipment	0	50
Sum before project adm costs	525.8	346.8
Project administration (+10 %)	52.6	34.7
Contingency (+5 per cent)	26.3	17.3
Sum Total project costs	604.7	398.9

Appendix 2. Process parameters, CHP production case

	kg/s	kg/h	Nm ³ /s	Nm ³ /h	kJ/kg (bränslen, ånga)	MW	Tryck, bar	Temp. °C
Fuel flow, lignin, gas turbine	2.11	7 600			25	52.8	15	0
Air fed, gas turbine	90.8	327 000	70.6	254 000			1	0
Power, combustion, gas turbine combustor						52.8	15	
Flue gas flow, gas turbine			71.6	258 000		35.0	1	400
Turbine power						17 (MWe)		
Fuel flow, lignin, steam boiler	0.0669	240.8			25	1.67	1	
Fuel flow, slop, steam boiler	1.17	4 200			17.7	20.7	1	
Enthalpy in, flue gas from gas turbine						35.0		
Power, combustion, steam boiler						22.3		
Enthalpy, flue gas before heat transfer to water/steam						57.3		
Enthalpy transferred from flue gas for steam generation						57.3		
Enthalpy, flue gases released through chimney, 140 °C	94.3	339 500	73.2			13.7	1	140
Steam generated	14.6	52717.74				43.6	40	550
Process steam, pre-treatment	2.92	10 526			3420	10.0	25	
Water injected for saturation of steam for pre-treatment	0.66	2 383			2.5	0.002	25	0
Process steam, drying	4.81	17 343			3420	16.48	25	
Water injected for saturation of steam for drying	1.091	3 926			2.5	0.003	25	0
Condensed water recirculated from drying	5.91	21269			943.75	5.58	25	
Feeding water	3.59	12 909			4	0.014	40	
Power, steam turbine						6.11		
Power transferred after condensor (district heat)						16.61		

Appendix 3. Process parameters, pellets production case

	kg/s	kg/h	Nm3/s	Nm3/h	MJ/kg (bränslen, ånga)	MW	Pressure, bar	Temp. °C	ton TS/år
Fuel flow, lignin, steam boiler	0	0			25	0	1		0
Fuel flow, slop, steam boiler	1.17	4212			17.7	20.7	1		33 700
Air flow, steam boiler	12.979	46724.42	10.1	36 300			1	0	
Power, combustion						20.7	1		
Enthalpy released through smoke stack	55.7	201 000	43.18218			2.2	1	140	
Enthalpy used for steam generation						23.0			
Process steam, pre-treatment	3.59	12 909			2.8	10.0	25	255	
Process steam, drying	5.91	21269			2.8	16.5	25	255	
Recirculated water from drying	5.91	21 300			0.9	5.58	25	220	
Feeding water	3.59	12 900			0	0	1	0	
							ton TS/år		
Lignin for pellet manufacturing	2.11	7596				52.8			61 000

