TRANSPORTATION FUELS FROM LIGNOCELLULOSE IN A PROCESS COMBINATION

Report from an f3 project

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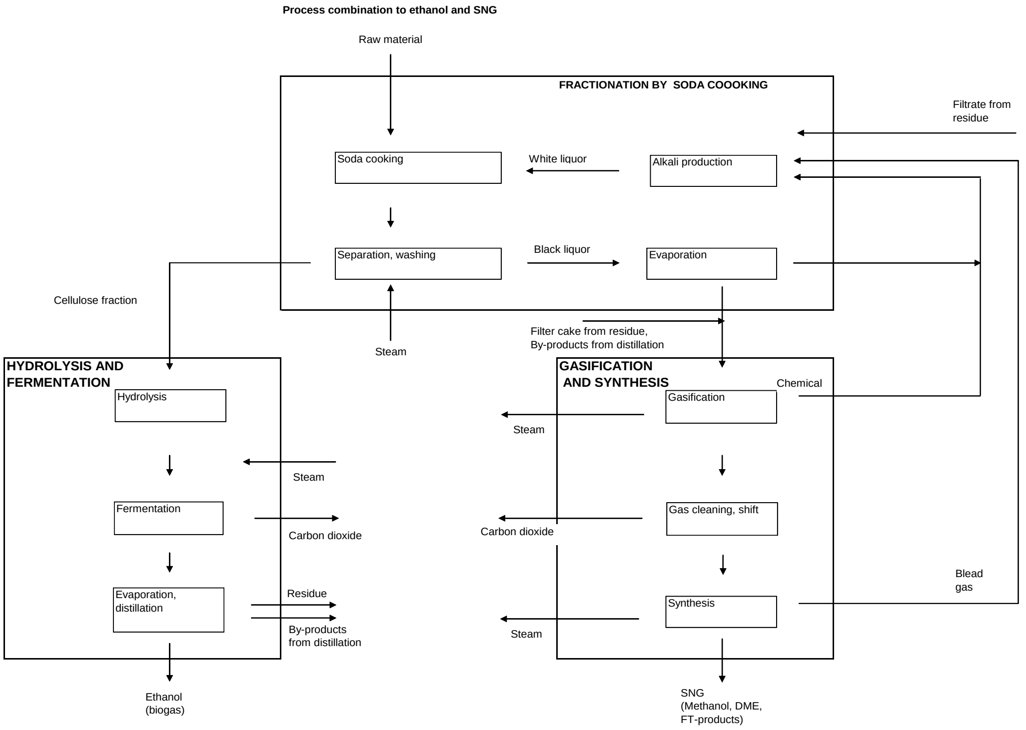

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 is a networking organization, which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities,
- Carries through system oriented research related to the entire renewable fuels value chain,
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. f3 also finances the collaborative research program Renewable transportation fuels and systems (Förnybara drivmedel och system) together with the Swedish Energy Agency. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

This project has been performed as a joint study between Lantmännen Agroetanol AB and Cellulose Fuels Sweden AB, patent holder of a process combination for the production of second generation transportation fuels. The report contains information referring to a number of discussions between Kemiinformation AB and representatives from several different companies over time. Kemiinformation AB takes full responsibility for all references to those discussions.

This report should be cited as:

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SUMMARY

The continuous evaluation of business opportunities for Agroetanol has identified a patented process combination for the production of second-generation transportation fuels. According to previous evaluations, this combination could produce such fuels from wood and straw at cost levels comparable to the present costs for first-generation fuels.

The overall process combines existing techniques and no basic R&D is required. Together with the dedicated production of transportation fuels without by-products and a minimum of waste product handling, this has prompted a joint study with the patent holder. The objective of the study is to evaluate the possibilities for the establishment of a demonstration unit at Agroetanol’s ethanol plant at Händelö. The capacity of the plant is 20 tonnes of DS wood and straw per hour, yielding some 4,100 litres of ethanol plus 4,900 m^3n of biogas (SNG, synthetic natural gas).

Detailed mass and energy balances give an energy efficiency of 71 % (74 % according to the external reviewer), calculated as energy in the transportation fuels produced divided by the energy in the raw material. The process combination is then balanced in steam consumption whereas power is bought.

The investments have been calculated mainly through comparable investment in existing sub-processes, to which is added the costs of establishment adjacent to the Agroetanol plant in Händelö. The total investment comes to EUR 172 million.

The process combination is very flexible with regard to raw material. A second grade of wood, not in demand by the pulp industry, is used together with straw and at prices of almost 19 EUR/MWh (lower heating value, LHV) the production cost for the transportation fuels is 0,09 EUR/kWh. For ethanol this is almost 0.55 EUR/litre and for biogas 0.9 EUR/m^3n.

A simplified comparison with alternative production of ethanol and SNG from wood/straw in Sweden shows the principal advantages of the process combination.

Considering the substantial investment and the fact that the sub-processes originate from, and involve, other industries, potential partners for establishing the process combination are sought. Letters of Interest have been signed by three companies.

The next stage of development will be laboratory investigation of the complete process combination, mainly covering the interconnections between the sub-processes.

SAMMANFATTNING

I den kontinuerliga utvärderingen av affärsmöjligheter för Agroetanol har en patenterad processkombination för produktion av andra generationens transportbränslen uppmärksammats. Enligt tidigare utvärderingar kan kombinationen producera sådana bränslen från trä och halm till kostnadsnivåer jämförbara med nuvarande kostnader för första generationens bränslen.

Den totala processen kombinerar redan befintliga tekniker och ingen grundläggande FoU krävs. Tillsammans med dedikerad produktion av transportbränslen utan sidoprodukter och med ett minimum av avfallshantering har detta initierat en gemensam studie med patentinnehavaren. Syftet med studien är att utvärdera möjligheterna att etablera en demonstrationsenhet vid Agroetanols etanolanläggning på Händelö. Anläggningens kapacitet är 20 ton TS-trä och halm per timme vilket ger cirka 4100 liter etanol plus 4900 m^3n biogas (SNG, syntetisk naturgas) per timme.

Genom en detaljerad mass- och energibalans beräknas en energieffektivitet på 71 % (74 % enligt extern granskare), beräknad som energi i de producerade transportbränslena dividerat med energin i råmaterialet. Processkombinationen är balanserad i ångförbrukning medan kraften köps.

Investeringarna har beräknats huvudsakligen genom jämförande investeringar i befintliga delprocesser, därtill läggs kostnaderna för etablering intill Agroetanols anläggning på Händelö. Den totala investeringen uppgår till 172 MEUR.

Processkombinationen är mycket flexibel när det gäller råmaterial. Då träkvaliteter, som inte efterfrågas av massaindustrin, används tillsammans med halm och till priser på nästan 19 EUR/MWh (lägre värmevärde, LHV) blir produktionskostnaden för transportbränslen 0,09 EUR/kWh. För etanol blir den knappt 0,55 EUR/liter och för biogas 0,9 EUR/m^3n.

En förenklad jämförelse med alternativ produktion av etanol och SNG från trä/halm i Sverige visar de huvudsakliga fördelarna med processkombinationen.

Med tanke på den betydande investeringen och det faktum att delprocesserna härrör från och involverar andra industrier, eftersträvas potentiella partners för att etablera processkombinationen. Letters of Interest har tecknats med tre företag.

Nästa steg i utvecklingen kommer att vara laboratorieundersökningar av den fullständiga processkombinationen som huvudsakligen omfattar sammankopplingarna mellan delprocesserna.

CONTENTS

1 INTRODUCTION

Swedish and European politics envisage a major reduction in fossil fuels used in transportation with regard to 2020, 2030 and 2050. Targets have been set to achieve double-digit percentage reductions in just ten years. Given the current vehicle fleets, today's liquid fuels will need to be replaced with renewable fuels. This will require immediate action from the industry in order to achieve the political ambitions. Even using existing technology, it takes years to establish regular large-scale production. Moreover, the suggested processes are in this case still under development or have, at any rate, not yet been commercially demonstrated.

As a major producer of ethanol as transportation fuel in Sweden, Lantmännen Agroetanol continuously monitors developments. Consequently, a number of processes and process developments have been observed and monitored from business perspectives as well as with regard to possible improvements. In this work, a patented process combination, potentially using a wide range of biomass as raw material, has been identified (SE 527 646 C2) [28]. One of the features of this process combination is that with the dedicated production of solely transportation fuels, no by-product markets have to be considered. This creates a freedom of establishment restricted only by the transportation fuel market.

Attracted by the fact that the process combination includes existing processes, Lantmännen Agroetanol decided to conduct further evaluation. Existing processes enable a more accurate assessment that is not complicated by R&D assumptions. By agreement with the patent holder, Cellulose Fuels Sweden AB, a desktop study has been carried for a demonstration plant located at Lantmännen Agroetanol's existing ethanol facility at Händelö, Norrköping.

Earlier studies and gathered information give a summary of process performance as per Table 1.

Table 1. Compilation of stated and calculated thermal efficiencies for processes for transportations fuels from biomass [21].

Process	Total thermal efficiency, %	Efficiency for transportation fuels, %	Thermal efficiency for by-product energy, %
Ethanol from biomass	45	30	15
Pyrolysis of wood	≈60	≈60	?
SNG via gasification of biomass	85	60	25
The focus process combination	70–75	70–75	-

1.1 AIM AND OBJECTIVES

The process combination shall be evaluated from a technical and economical view in order to provide a decision basis for further work towards a demonstration of the total process combination. Uncertainties in the starting data shall be identified and possible effects on the result shall be discussed. Any need for further experimental verification shall be identified.

1.2 CURRENT MARKET SITUATION FOR RENEWABLE TRANSPORTATION FUELS IN SWEDEN

Four alternative (renewable) transportation fuels are commercially established in Sweden:

1. Ethanol, which has been used for decades as a low blend in gasoline as well as a base fuel in E85 (Otto engines) and ED95 (Diesel engines).
2. RME (Rape seed oil Methyl Ester) which likewise has been used as a low blend in diesel. The raw material for this type of fuel has expanded to include other oils and fats giving the same fuel. The fuel is then designated FAME (Fatty Acid Methyl Ester).
3. Biogas, which has been supplied to Otto and Diesel engines for at least two decades.
4. HVO (Hydrogenated Vegetable Oil) and to some extent HEFA (Hydroprocessed Esters and Fatty Acids) which was introduced as a diesel fuel on the Swedish market less than five years ago but has experienced a dramatic boom.

Electric power is attracting a lot of attention in Sweden at present. The magnitude of use in electric-driven cars is very small, however, in comparison with the total amount of energy used in transportation fuels. It has not reached the levels of Norway, for instance.

The total consumption of ethanol has decreased to some 200,000 m^3 (2016) [1] mainly due to a significant decrease in E85. Most of the ethanol is used as a 5 % blend in gasoline which has also decreased in favour of diesel. The increased use of diesel has then resulted in a corresponding increase in RME/FAME consumption, which in 2016 was some 350,000 m^3 [1].

RME/FAME is facing competition from HVO, both on the market and for raw materials. The latter has an advantage in its product properties, which enable blending with conventional diesel at almost any ratios. This has resulted in an increase from about zero in 2012 to well above 1,000,000 m^3 in 2016/17 [1].

Biogas consumption has levelled out at the equivalent of about 150,000 m^3 of diesel or ca 178,000 m^3 of gasoline [1]. Most of the biogas is produced from sludge from waste water treatment and organic wastes, i.e. raw materials with zero or negative values. These raw materials are limited. Tellingly, very little biogas is produced from raw materials that have a significant cost, the gasification pilot plant in Gothenburg being a rare example.

RME and the bulk of the ethanol are produced from agricultural products. As these are potential food materials, there has been debate about the ethical question of transportation fuels versus food. Although the alleged competition between the production of food and fuel has been thoroughly refuted, this has resulted in a proposal from the European Commission that ethanol and RME from such raw materials should not get the same incentive in the future [29].

FAME, when produced from tall oil and used cooking oils, etc., suffers from the same restriction as biogas with regard to the limited supply.

HVO is mainly produced from palm oil (from tropical areas). The use of palm oil and the expansion of palm oil plantations – at the expense of tropical forests – have aroused a lot of concern from environmental organisations. In Finland, Neste [2] argues that they are not party to the deforestation since they use by-products from palm oil. The Swedish Society for Nature Conservation [3] claim otherwise. In Sweden, Preem claims that they do not use palm oil but solely tall oil and spent oils and fats [4]. According to the Swedish Energy Agency only a very small fraction of the HVO used in Sweden originates from tall oil [30].

Other environmental aspects of renewable fuels include the CO_2 effect and the impact of exhaust gases from engines. Concerning the latter, ethanol, biogas and HVO in general may be advantageous in relation to conventional fossil fuels. LCA's (Life Cycle Analysis) and similar evaluations of CO_2 emissions show little impact, or positive effects, when residues are used as raw materials. HVO results in small CO_2 emissions whereas the effect of ethanol is determined very much by the specific production method. In the case of Lantmännen Agroetanol, the production in Händelö is close to zero emissions of CO_2 [5, 6]. RME causes some CO_2 emissions, mainly originating from the fertilising of the crops and the fossil methanol component.

Being a large scale producer of renewable transportation fuels, Lantmännen Agroetanol focuses on the one hand on established fuels. Secondly, new fuels that can be introduced without major fundamental research and development are prioritised. From the above descriptions it is further concluded that the current production of alternative fuels from residues and waste products, as well as from agricultural products, in Sweden is limited with reference to limitations in the raw material availability, whether physical or regulatory.

2 METHODS

Mass balances for the complete process combination have been calculated from practical lab data and officially available data from established processes. The calculations have been carried out in quite extensive Excel sheets at the level of specific unit operations such as chemical reactions, evaporations and filtering.

For the calculations, a model was developed based on thermodynamics, equilibria and stoichiometry covering the gasification, cooling/quenching, shift reaction and synthesis. When used, the results corresponded well to the data published by Chemrec in, for instance, the aforementioned BLGMF II study [11]. The energy efficiency in the gasification is assumed at 85 %, calculated as energy in the raw gas divided by the energy in the feed to the gasifier. A substantial amount of steam is recovered.

2.1 ECONOMIC EVALUATION OF THE PROCESS COMBINATION – PRODUCTION COST ESTIMATE METHOD

The production cost estimate follows a conventional calculation: capital costs based on required investment, costs for process inputs (power, salaries, chemicals, etc.) and raw material costs. The last items are based on the above mass and energy balances.

The intended plant is located at Lantmännen Agroetanol’s site in Händelö (Norrköping), benefitting from the infrastructure and other process elements of the existing ethanol plant. The base capacity is 20 tonnes of DS lignocellulose per hour, composed of hardwood and straw. The run time is set to 7,920 hours (330 days at 24 hours/day).

2.2 EQUIPMENT INVESTMENT COST ESTIMATE METHOD

The investments are estimated for the capacity of 20 tonnes of DS raw material per hour fed to the fractionation process. For capacities of 10 and 30 tonnes of raw material, the investments are calculated using a cost-capacity factor of 0.65.

The same cost-capacity factor has been used when actual investments are quoted from existing industrial installations at capacities other than those the mass balances state. Almost all data comes from such actual installations. Atrax Energi och Miljö AB and Kemiinformation AB have been active as consultants and project leaders for a number of industrial establishments within ethanol manufacture, gasification and the chemical industry [23,8]. Consequently, a considerable amount of investment data is at their disposal and through contacts with specialists the validity of specific data may be verified.

Due to these experiences and contacts, the investment assessment is first made separately for the sub-processes and then as an overall sum for the total process combination, including required intermediate steps. The investment estimates are broken down into the boxes shown on the next page. The location is at Lantmännen Agroetanol’s site in Händelö and the additional costs for the infrastructure there are shown separately.

The stated investment costs refer to 2015 and later and euros are converted at a rate of 9.5 SEK/EUR. Since the figures are rounded, the actual rate corresponds to 9–10 SEK/EUR, which reflects the degree of uncertainty in the assessment.

No adjustment of older investment cost estimates for the gasification line to current cost level has been done. A brief sensitivity analysis shows that the conclusions would not be affected by including inflation.

2.3 PRODUCTION COST ESTIMATION

The calculation of production costs is made the traditional way as a sum of raw material cost, capital costs and production costs, where the latter comprise power, chemicals, salaries, etc. Prices are shown in Table 2. Not included are insurance costs and some other (minor) charges and fees that are dependent on local circumstances.

Table 2. Raw material, co-product and energy prices.

Material	**Price unit**	**Price**	**Source**
NaOH (cooking)	€/kg	0.6	In-house
Enzyme	€/kg	10	In-house
Yeast	€/kg	Internal production	In-house
Nutrients	€/kg	0.6	In-house
Gasification catalyst	€/kg SNG	0,5	In-house
CO2 product	€/kg	0	In-house
Salary cost – Labour	€/year	63,000	In-house
Salary cost – Engineers and administration	€/year	84,000	In-house
Maintenance cost, basis: Total investment	%/year	2	In-house
Calculation interest	%	8	
Depreciation time	Years	15	

3 PROCESS DESCRIPTION

3.1 RAW MATERIAL SITUATION IN SWEDEN

As mentioned above, most of the established production of renewable fuels is based on raw materials that are cultivated; in Sweden as well as internationally. Ethanol is manufactured from sugar cane (Brazil), from corn (USA), from grains and sugar beet (Europe) and, for instance, cassava (tropical areas). RME/FAME and HVO are produced from vegetable oils such as rape seed oil and palm oil.

Limited quantities are produced from waste, residues and by-products from other industrial activities: biogas from organic waste, ethanol from residues from the food and pulp industries and RME/FAME and HVO from residues and waste from the food industry. By-product fatty acids from the pulp industry (tall oil) are in demand to such an extent that previous buyers (chemical industry and energy production) are finding it hard to compete. Naturally all these sources are restricted by the activities in, for instance, the pulp industry. It is also evident that the amounts of fuel it is possible to obtain from them are limited to a small fraction of the total transportation fuel requirement.

Specifically in Sweden, the raw materials used have so far been produced on surplus farming land. However, also in Sweden it is argued that raw materials for transportation fuels should not compete with potential food production. As mentioned, it is proposed by the EU that incentives for the promotion of alternative fuels should be eliminated, or should be lowered, when they are based on potential food production.

In a broader sense, this includes the reclaiming of new land for sugar cane and palm oil plantations, for instance. A vast swathe of opinion has opposed the establishment of new cultivation areas where tropical wilderness has been subjected to deforestation.

As an alternative to these raw materials, lignocellulosic material from forests, grass, etc., has been suggested along with, for instance, algae and other maritime products and "oil" containing plants. Intensive R&D has been carried out for decades to establish processes for these materials. In Sweden, the focus has been on forestry materials and a couple of processes based on gasification hydrolysis/fermentation of cellulose have been demonstrated.

Lantmännen Agroetanol agrees with the general conclusion that if the envisaged substitution of fossil fuels is to take place in Sweden, forestry materials will be an important alternative raw material.

"Forestry materials" in this case covers any wood material that is not used by the timber industry or for pulping. By-products and waste from forestry activities and the processing industries are for example "wood" from thinning and clearing and sawdust. Special materials that have attracted attention lately have been stumps and branches and tree tops (GROT).

Political decisions in the 1980s and 90s meant that wood fuel was favoured in Swedish heat and power production. This has led to a situation where, according to Energiföretagen’s statistics [17], wood is the single largest fuel in district heating in Sweden (as in simultaneous power co-generation). Consequently, a wood fuel industry has been created with set market values for the products. "Products" include wood cuttings and chips and – further upgraded – wood pellets.

The market prices for chips have been some 0,18–0,2 SEK/kWh (0,02–0,022 EUR/kWh) (LHV) in recent years [7]. LHV, Lower Heating Value, corresponds to the effective heating value. The moisture content is then 20–25% (DS (Dry Substance) = 75–80%). In HHV (Higher Heating Value) terms this corresponds to some 0,16 SEK/kWh (0,018 EUR/kWh).

Market prices for wood logs are marginally lower than the prices for chips, whereas pelletising increases the price by at least 20 %. The energy consumption for pelletising is some 10–15 % of the energy content of the raw material [8].

A lot of attention has recently been paid to GROT. This material does not yet have a specified quality and samples of GROT show a wide variation. Not being specified, it could be called a felling residue with a quality depending on the particular situation. In general it could be said, however, that as a fuel it will probably have prices at the same level as chips in SEK/kWh (EUR/kWh). In a study from 2012, SLU evaluated the costs for GROT in a specific area [9]. In a forest with a radius of 100 km, some 25,000 tonnes of GROT were thought to be available and with a transport distance of 100 km to the consumer the cost was estimated at almost 0,2 SEK/kWh (0,022 EUR/kWh) (LHV). The transportation cost represented some 50 % of the total cost and was considerably influenced by what transportation system was used.

Beside forestry materials, Lantmännen Agroetanol also views straw as a potential raw material. Straw comes as a by-product from agriculture and it has been discussed to what extent it is available as a raw material for industrial use. Nowadays it is usually collected in the fields as bales and despite widespread use as bedding material in animal husbandry, a surplus exists. In Denmark, straw is conventionally used as fuel for heat and power production but this application is small in Sweden.

The compositions of hardwood (e.g. from thinnings) and straw are similar; some 40–50 % cellulose, 25–35 % hemicellulose and 20–30 % lignin.

The value of straw is mainly determined by the costs of collection and handling. The crop yield is some 3–4 tonnes per hectare – depending on the type of crop. Commonly, the cost of straw at the farm is 0,5–0,7 SEK/kg (0,055–0,075 EUR/kg), which corresponds to 0,1–0,14 SEK/kWh (HHV) (0,01–0,015 EUR/kWh (HHV))

In a slightly special case, Grontmij AB studied the pelletising of straw [10]. Due to the low bulk density of straw, the base transportation cost for straw in a truck loading 15 tonnes and carrying it 10 km is given as SEK 100/tonne (11 EUR/tonne). When pelletised, the transportation cost was lowered to some SEK 45/tonne (5 EUR/tonne).

In summary, the prime raw materials for the expanded production of renewable transportation fuels in Sweden would be secondary forestry materials and straw. In both cases the raw material costs are likely to be of the magnitude of 0,15–0,2 SEK/kWh (LHV) (0,018–0,022 EUR/kWh (LHV).

3.2 CELLULOSE FUELS’ PROCESS COMBINATION

Cellulose Fuels Sweden AB has the rights to a process combination for the production of renewable transportation fuels from lignocellulose. The combination covers fermentation products, as ethanol or biogas, produced simultaneously with gasification products such as methanol, DME (Dimethyl ether), SNG (Synthetic Natural Gas), hydrogen or FT products (Fischer-Tropsch Products).

The process combination enables these to be produced from virtually any lignocellulose, providing that the cellulose content is significant. Mixtures of different raw materials are also possible with minor changes in the process parameters.

The entire process combines existing technologies, which minimises development work and allows more immediate large-scale establishment. A key element in the combination is the initial fractionation of the raw material into

a) a cellulose fraction

b) a black liquor fraction which contains most of the hemicellulose and the lignin in the raw material. Inorganics, extractives and process chemicals are also contained in the black liquor

As may be recognised, the fractionation process is a common pulp process modified into sulphur-free free "soda cooking". Soda cooking preceded Kraft cooking and was abandoned mainly because the latter gave a better cellulose pulp. Some units still exist internationally and in the process combination tion an increased decomposition of the cellulose (pulp) is actually preferable. Technically the soda cooking is more or less identical to the Kraft cooking. The two fractions are then processed according ing to the process scheme in

Figure 1.

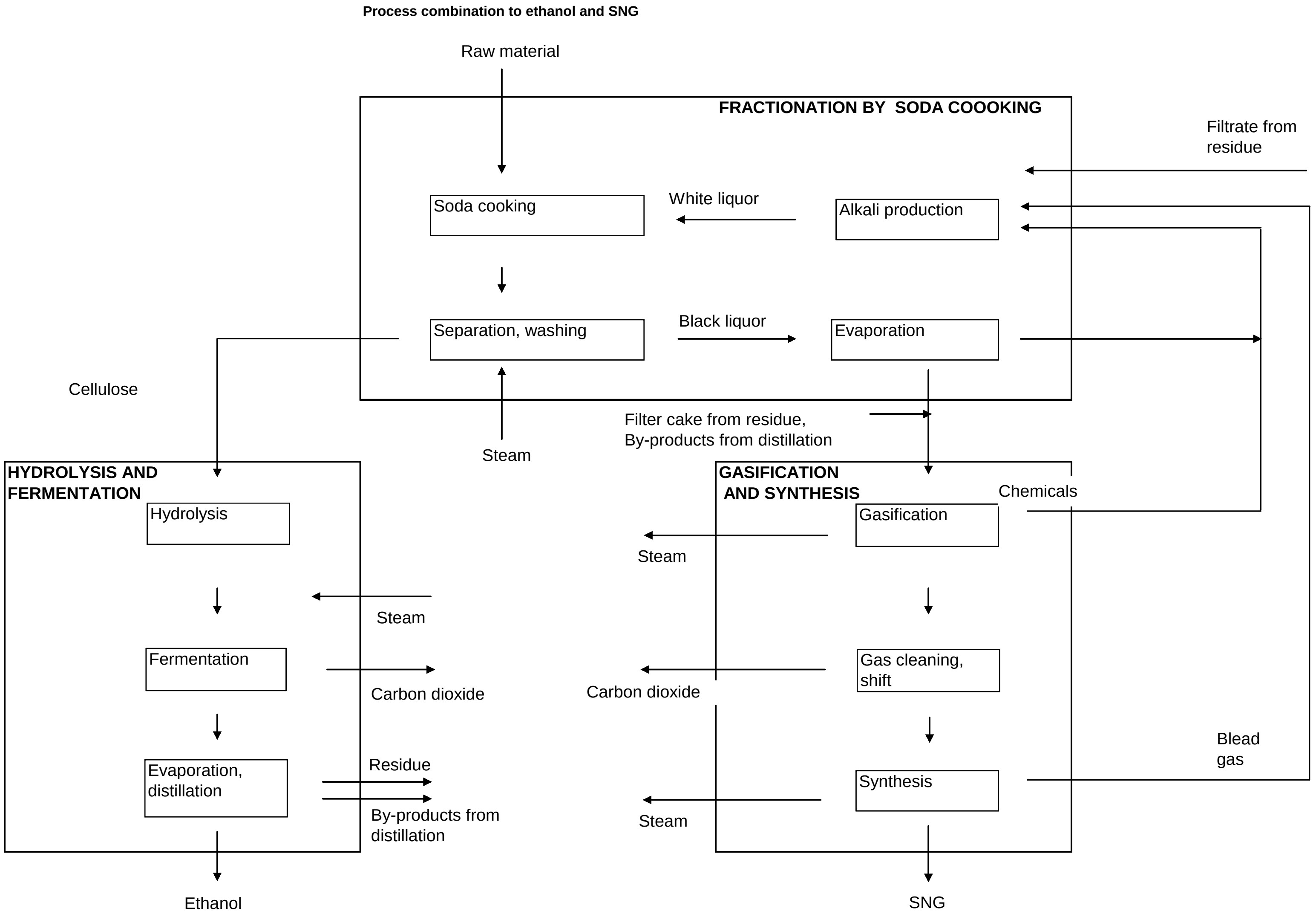

Figure 1 Principal structure of the process combination.

The cellulose fraction is washed and contains only smaller amounts of hemicellulose and lignin. It is enzymatically hydrolysed into mainly glucose. The limited amounts of lignin (and hemicellulose) result in greater efficiency with the enzymes and a simpler reactor system. The technique is analogous to that for the hydrolysis of starch at Lantmännen Agroetanol's unit in Händelö. Temperatures are lower but the reaction times are longer. The enzymes are different.

As in current production at Händelö, the entire wort (glucose solution from the hydrolysis) is fed to fermentation. Since the enzymes are not separated, unconverted cellulose will continue to be hydrolysed but at a slower rate as the temperature is lower. Conventional baker's yeast is used to ferment hexoses, almost exclusively glucose.

Also as in current production at Händelö, the entire mash is directed to a stripper. In the absence of larger amounts of solids, the stripping is rather simpler. Evaporated ethanol is upgraded in a rectification and dehydration identical to the existing distillation at Händelö.

The stillage from the evaporation is filtrated – not for upgrading into a by-product, but for recycling within the process combination.

To the black liquor fraction is added the filter cake from the stillage. Through evaporation, the DS content is raised to a level that allows efficient gasification by oxygen. A raw gas is produced containing carbon monoxide, hydrogen, carbon dioxide and steam (water) along with molten inorganics that are collected at the bottom of the gasifier. The inorganics are recycled to a white liquor plant feeding the soda cooking.

The raw gas is shifted and adjusted into a "synthesis gas" with different compositions for different end products. In hydrogen production all carbon monoxide is shifted into hydrogen. The upgrading into synthesis gas is conventional technology, applied internationally.

The adjusted synthesis gas is catalytically converted to methanol, DME or SNG in well-known, commercially available processes. FT processes are more complex. In these a number of product types may be manufactured, most of them hydrocarbons but sometimes also alcohols. Pressures, temperatures, residence times and, in particular, the catalyst determine the product distribution. At least a handful of processes are in commercial use today producing hydrocarbons like diesel from coal and natural gas.

The "diesel" in question is n-paraffins and as such corresponds to the HVO mentioned in the "Market" section. From this perspective the FT process is very interesting. However, it is difficult to get explicit data for the process. Theoretically, there is a lot of basic information to be collected from research reports, but in contrast to data for processes for methanol and SNG, etc., these are difficult to evaluate. This is according to information from Chemrec, which evaluated an FT process in the BLGMF II study [11].

Regardless of the end process in the black liquor/gasification line, gasification, upgrading and synthesis produce large amounts of steam and some bleed gas. The steam is used in the soda cooking and the ethanol line. The bleed gas is used as fuel in the lime kiln in the white liquor plant where sodium hydroxide is produced for the cooking.

Finally, the filtrate from the stillage is recycled to the soda cooking. In summary, no by-products are generated and a minimum of waste is produced. Organic build-up is prevented by the gasifier and inorganics are removed in the white liquor plant as precipitates. Current evaluations indicate that at least in some process combinations the steam production in the gasification line matches the consumption in the soda cooking and the ethanol line.

In the previous evaluations, an energy yield of some 75 % has been calculated as energy in the products divided by the energy in the raw material (LHV). The power consumption is then assumed to be bought, i.e. not included in the energy balance. Consequently, power is calculated as a cost.

3.3 THE PROCESS COMBINATION AT AGROETANOL'S PLANT IN HÄNDELÖ

Although the process combination utilises existing technologies and thus does not require basic R&D, it is judged that a demonstration plant will be necessary. One of the aims of this study is to evaluate the possibilities for such a unit built at Lantmännen Agroetanol's ethanol plant in Händelö. The overall objective is to establish performance data for the combination that is reliable enough to proceed to the next stage. This would presumably be to establish large-scale units jointly with other partners.

Händelö offers several advantages for a potential process combination. The synergy effects between the ethanol plant and the ethanol line in the process combination are obvious; ranging from the simple use of distillation to the almost complete use of the older ethanol line at the plant.

Potential use of Lantmännen Agroetanol's industrial resources, such as skilled staff, workshop and administration, etc., is equally beneficial. Furthermore, Lantmännen Agroetanol has an industrial infrastructure in place.

Lantmännen Agroetanol is co-operating with Eon on steam supply, which reduces the investment in a potential plant significantly. Co-operation has also been established with Linde, which is taking care of the carbon dioxide from the fermentation.

In the Norrköping-Östergötland area there are forests and farming land which may serve for raw material supply. One of Billerud's pulp mills is located in Skärblacka. The main E4 highway runs close to Händelö, which also has a shipping harbour.

Once the opportunities and advantages of a demonstration plant at the Lantmännen Agroetanol site in Händelö were realised, the evaluation was given the following basic design data:

- The raw material is a combination of wood (mainly hardwood from clearings), etc. and straw.
- Although FT products are attractive with regard to HVO, SNG has been chosen as a product in addition to ethanol in the evaluation. This decision is mainly based on the fact that the evaluation can be made more accurate with SNG than FT products.

The capacity should be high enough to be considered as at least a small production unit. The possible use of distillation at Lantmännen Agroetanol's plant should be considered. However, it is not a prime objective to substitute the current starch-based production in the older ethanol line. 20 tonnes of DS raw material per hour has been chosen as the capacity.

4 RESULTS

4.1 CALCULATIONS OF MASS AND ENERGY BALANCES

Starting with 20 tonnes of a raw material mix of hardwood and wheat straw with a content[1] of 40 % cellulose, 31.5 % hemicellulose, 21.5 % lignin, close to 5 % extractives and almost 2 % inorganics, the calculated yield of ethanol is 3,300 kg (4,130 litres) and the co-produced SNG 3,500 kg (4,900 m^3n).

Figure 2 shows the flows between the three main processes that form the process combination. Details are given below. The basis for the calculations has been a raw material intake of 20 tonnes of DS raw material. With a feed rate of 20 tonnes per hour, the flows can be read as kg/h and GJ/h. The energy content is consistently calculated using Boie's formula [18].

The figures in the flowsheet are rounded figures from Excel calculations and due to the recycling of material they are not 100 % exact. This would require iterations which have not been carried out further than to one exercise.

A summary of the calculated mass and energy balances for production of ethanol and SNG from a 50/50 mixture of hardwood and straw is shown in Figure 2.

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[1] The composition is a calculated average of several literature and experimental data for hardwood and straw.

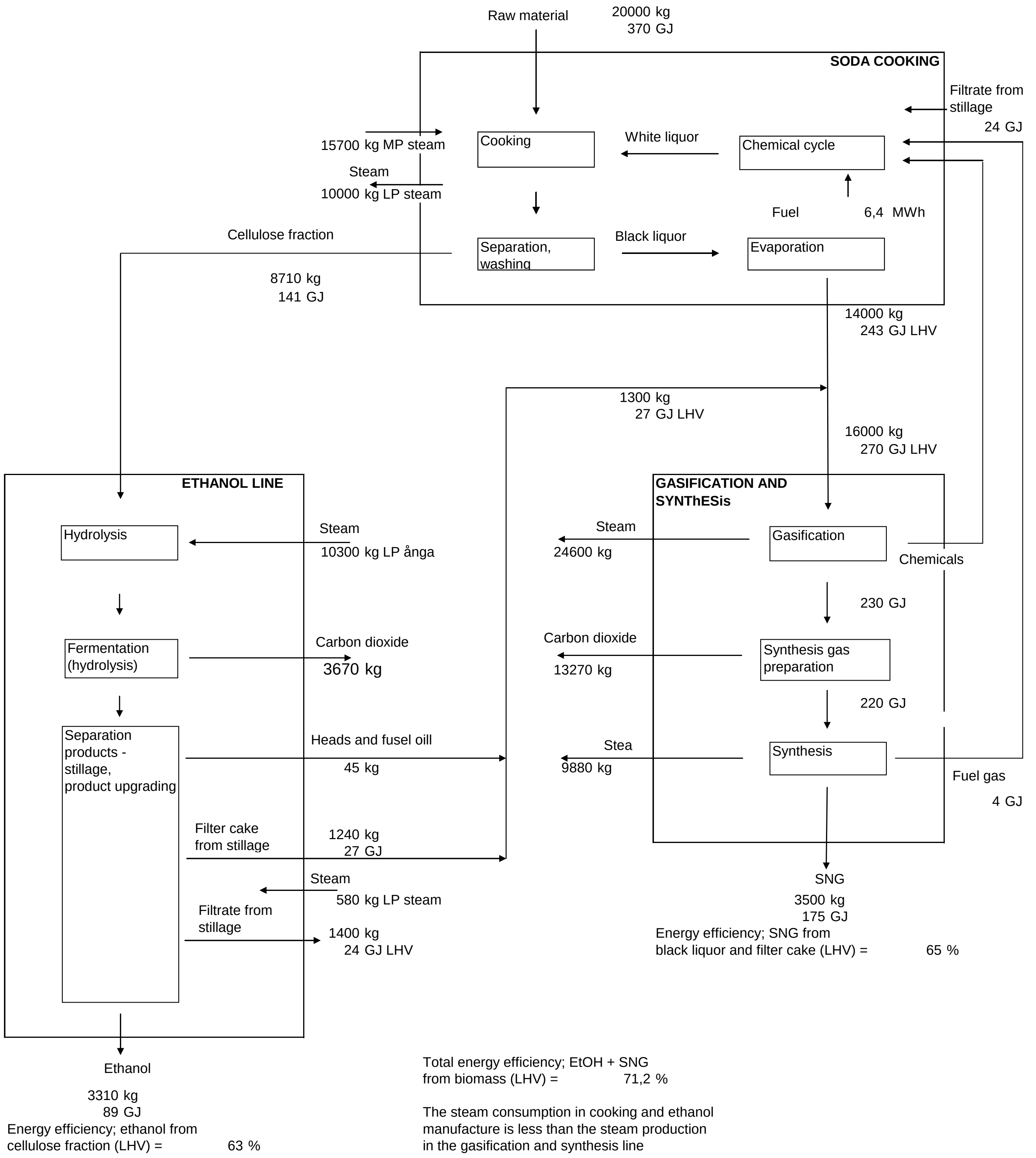

Figure 2 Mass and energy balance for the production of ethanol and SNG.

In the soda cooking, chipped material is digested for 4 hours at a temperature of 180 °C with a liquid:solids ratio of 4:1. Alkali in the form of NaOH is added at a concentration of 22 % of the DS material.

This reaction has been tested with a number of raw materials at lab scale [12, 13]. It was also tested on a large scale shortly before the closing of a pulp mill [8, not publically reported].

The results from these different tests were consistent and some 90–95 % of the cellulose was obtained in the cellulose fraction. In most cases virtually all hemicellulose was decomposed in the cooking. The lignin content in the cellulose fraction varied somewhat, but with a certain amount of washing a Kappa number of 30 (≈5 % of lignin) was easily achieved.

In the calculations, a yield of 95 % of the cellulose in the cellulose fraction is used. The lignin content has been set at 3 % and the hemicellulose content at 5 %.To achieve these results a countercurrent washing is applied in 4 stages. Tall oil and extractives are phase separated.

The white liquor plant, recovery of alkali, is completely conventional although working on material from the bottom of the gasifier. As this is a well-known process it has not been studied in this project. Apart from silica in the straw, the differences regarding black liquor gasification in a conventional pulp manufacture should be small.

The cellulose fraction is diluted to a 12 % DS slurry and enzymatically hydrolysed at some 55 °C for 72 hours. Enzymes are added at a rate of 5g/kg DS cellulose fraction. Like the cooking, the hydrolysis has been tested in the lab several times and a general “conversion versus time” curve shows that yields of more than 90 % may be obtained in 72 hours. In this evaluation almost 90 % conversion is used in the calculations. A small amount of glucose is assumed from the hemicellulose content.

The fermentation of the glucose produced is conventional. Baker’s yeast is used and the temperature is 35 °C. Pentose fermentation by special yeasts would raise the ethanol yield slightly – but not much – as the hemicellulose content in the cellulose fraction is low. (Pentoses originate solely from the hemicellulose.)

After 24 hours, 99 % of the glucose is assumed to be fermented. Recovery of the co-produced carbon dioxide is not considered in the evaluation. From the project results in e.g. “FibreEtOH” [14] and conventional ethanol fermentation, the ethanol/CO_2 efficiency in the fermentation is set at 88 %. The remaining 12 % is made up of metabolic by-products such as acetic acid, glycerol, “heads” and fusel oil, competing fermentation to lactic acid and yeast growth.

The entire mash is taken to evaporation where ethanol is extracted at about 40 % concentration. At this concentration hardly any ethanol remains in the stillage. The ethanol is further distilled to a concentration of 95 %. Small volumes of "contaminants", the so called "heads" and "fusel oil", are collected and recycled to the black liquor for gasification.

The fermentation of hydrolysed cellulose fraction has also been tested in the lab [12, 13].

Data used in the evaluation is based on these results as well as on practical data from established fermentation processes. A total energy efficiency for the conversion of the cellulose fraction to ethanol is 63 %.

The stillage contains unconverted sugars and cellulose, lignin, hemicellulose remnants (mostly organic acids), yeast, by-products from the fermentation and small amounts of inorganics (e.g. nutrients supplied to the fermenter). Most of these compounds are solid and not soluble in the liquid. They contain a significant amount of C (carbon) and energy. Through filtration they are separated from the liquid and the filter cake is recycled to the black liquor for gasification. This means that the energy (and C) is used for additional production of transportation fuel and – equally importantly – the requirement for waste water treatment is removed.

The energy added to the gasification line represents some 12 % of what is contained in the black liquor from the soda cooking.

The filtrate from the filtration of the stillage is recycled to the cooking liquor, either directly or via the white liquor plant.

To the black liquor from the soda cooking is added the filter cake from the filtration of the stillage. The liquid is concentrated to some 80 % DS and fed to an entrained gasifier. In this, the liquid material is gasified with oxygen in a downstream mode. The reactor principle is the same as the one long-used in Texaco gasifiers. In Chemrec’s version the gasifier is modified to stand sulphur in conventional pulp processes and supplied with extra energy recovery. [15]

Gasification is carried out at high temperature, >1,000°C, which minimises tar from the conversion. The raw gas is washed and then fed to a conventional line with shift, gas cleaning and compression into a synthesis gas.

In the preparation of the synthesis gas almost 5 % of the energy in the raw gas is lost, primarily in the shift reaction. Some of this, however, is also recovered as a low-pressure steam.

This leads to a total loss of about 20 % of the energy up to the synthesis reactor.

The synthesis reaction is calculated to have an energy efficiency of 82 %, which corresponds well to officially available information giving an energy efficiency of some 80 % to SNG [16]. Substantial amounts of steam are obtained from the synthesis reactor, along with a bleed gas that is used as fuel in the lime kiln.

The total energy efficiency from black liquor to SNG is therefore about 65 %.

The sodium in the black liquor is collected in the bottom of the gasifier. From this, it is fed to the white liquor plant serving the soda cooking. Through causticisation, NaOH is prepared in a conventional process. In this, slaked $Ca(OH)_2$ is produced from lime in a kiln fired by bleed gas from the SNG synthesis.

In energy terms, 71 % of the energy in the raw material is obtained in the products, ethanol and SNG (methane).

Excluding power, the process combination is regarded as self-sufficient in terms of energy. For the specific mass and energy balances that are calculated, there is actually a deficit in fuel to the lime kiln and a surplus of steam, but this is assumed to be balanced in an optimisation of the total process without significant change in the overall product yield. In the calculations, the fuel required for the lime kiln is set to 10 % of the energy content in the black liquor and the deficit therefore corresponds to about 1.25 tonnes of DS raw material. Nominally this would lower the energy efficiency of the process by some 4 %, giving 67 % instead of 71 %. The surplus of steam corresponds to more than double the deficit in fuel in energy terms; 14.6 MW versus 6.4 MW.

One alternative to supply the necessary fuel to the lime kiln is to use some of the phase-separated tall oil after the soda cooking. This would not alter the investment estimate. The tall oil is mixed into the black liquor in the base case and the effect of a withdrawal is a lowering of the energy efficiency to the same 67 % instead of 71 %.

With regard to the uncertainty in the fuel requirement for the lime kiln, the base calculation assumes the higher energy efficiency. In the economic evaluation, the case with 67 % energy efficiency is also considered.

For comparison with a combustion or gasification process, the energy efficiency should actually be stated some 4-5 % higher, reaching almost 75 %. The difference relates to the LHV value of the raw material containing some 15-20 % moisture.

4.2 PROCESS INVESTMENT

4.2.1 Fractionation of raw material by soda cooking, white liquor plant for recovery of cooking liquor

The soda cooking is analogous to conventional pulp cooking but without sulphur:

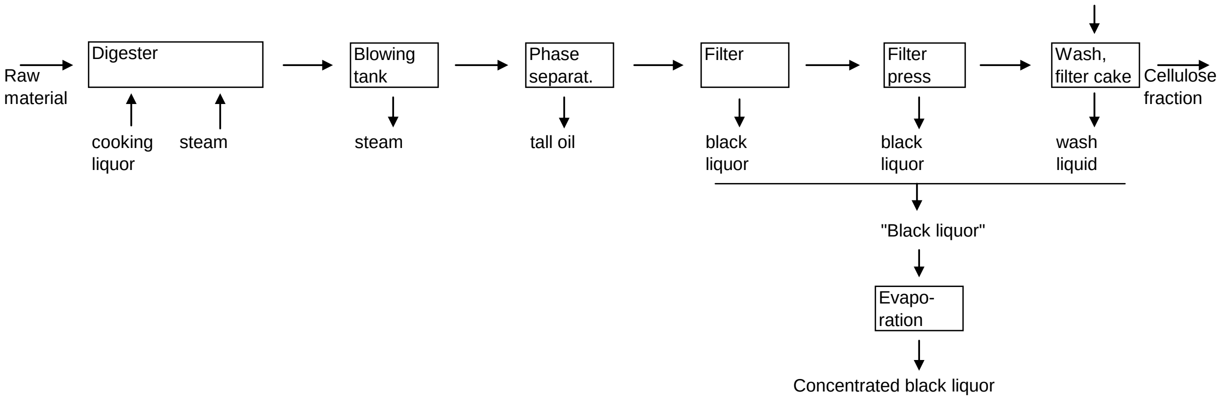

Figure 3. Soda cooking.

A major difference, however, lies in the recovery of sodium, which in a pulp mill is carried out in the recovery boiler. In the process combination this is substituted with a gasification of the black liquor (see section 4.2.3. below).

The rest of the recovery and upgrading of cooking liquor is also analogous to a conventional white liquor plant but simplified since sulphur is not involved in the cooking:

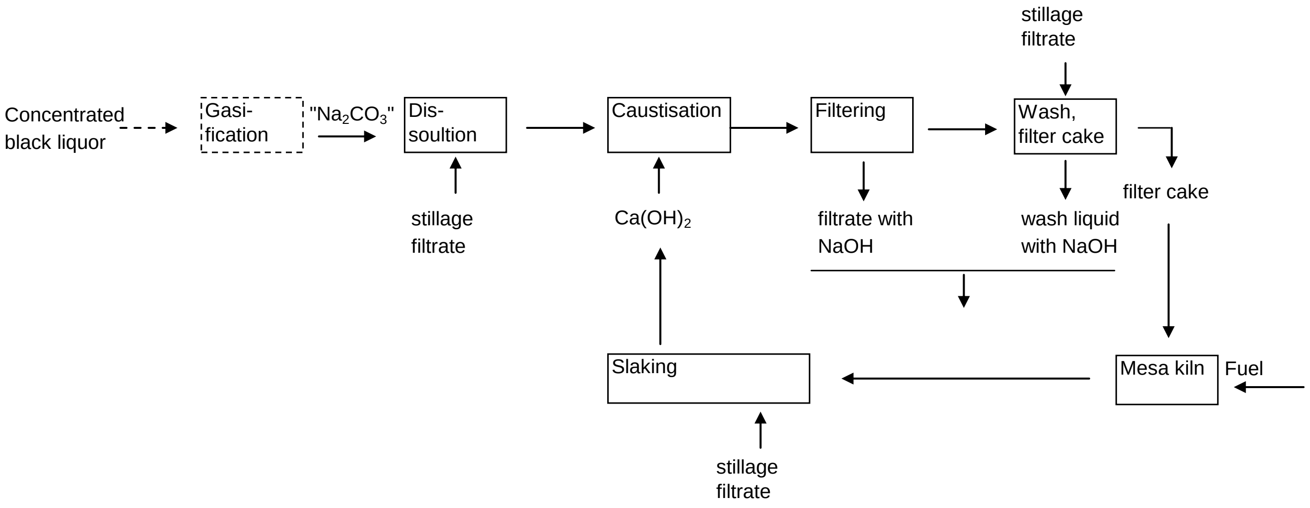

Figure 4. Cooking liquor recovery.

The investment for these units has been assessed from in-house information of Kemiinformation AB concerning complete pulp plants from which bleaching and pulp drying have been excluded, along with the recovery boiler, the power plant, the waste water treatment and the infrastructure costs [8]. The total investment for the original pulp plant is of the magnitude of 2,300 EUR/tonne of pulp with a raw material feed of about 1,700 tonnes of DS wood per day. Kemiinformation AB has confirmed the appropriateness of the assessment in private communication with ÅF, Innventia and Pöyry.

The original pulp plant was intended as green field. At the Händelö location, the infrastructure costs are excluded and treated separately. Co-operation with Eon dispenses with the need for a recovery boiler. Electric power is assumed to be bought and the need for waste water treatment is assumed to be negligible in the process combination.

The excluded items at the pulp plant represent in total some two thirds of the investment, i.e. the equipment used in the process combination is a third of what is installed at a complete pulp plant.

Table 3. Soda cooking: estimated investment in EUR million.

Item, cost (EUR million)	**Capacity**		
	10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Wood handling	10	15	20
Cooking, washing, screening	16	25	32
Evaporation	9	15	19
White liquor plant	10	15	20
Total equipment (installed)	***44***	***69***	***90***
Project indirects, 12%	5	8	10
Total cost (EUR million)	**49**	**77**	**101**

4.2.2 Hydrolysis and fermentation of the cellulose fraction

In principle, the hydrolysis and fermentation of the cellulose fraction are designed in the same way as for ethanol from starch:

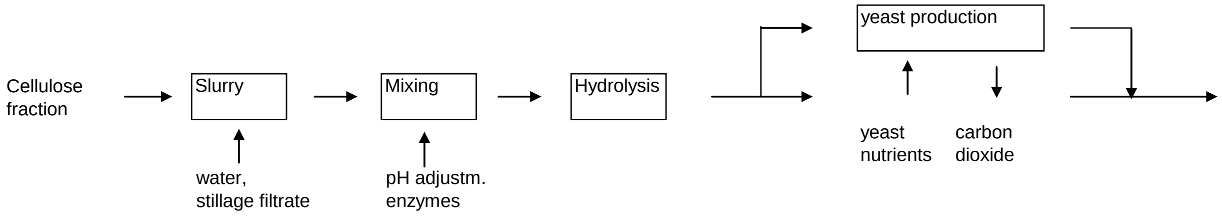

Figure 5. Ethanol production, hydrolysis stage.

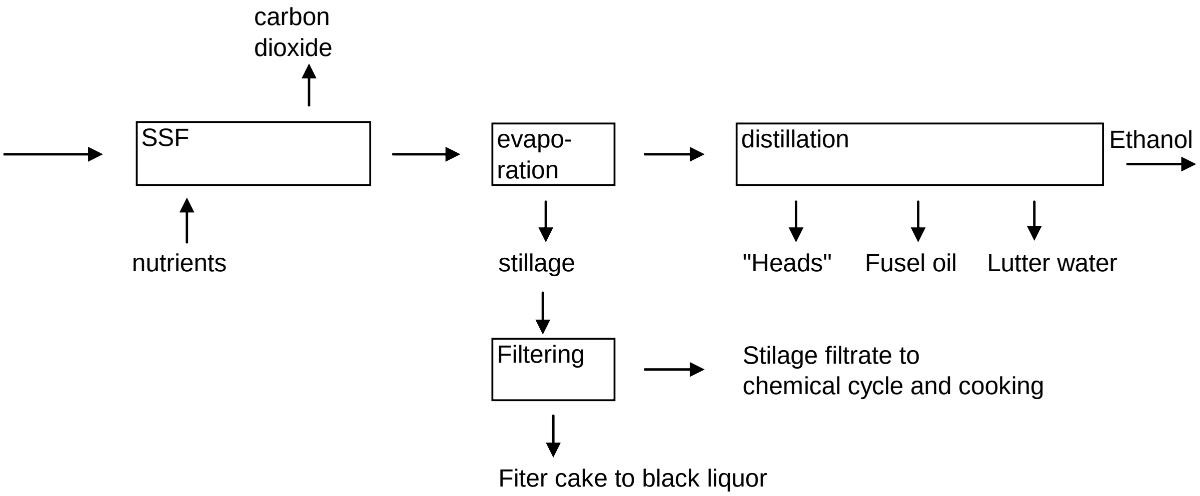

Figure 6. Ethanol production: fermentation and distillation.

Whereas hydrolysis of starch is carried out at higher temperatures and shorter residence times, hydrolysis of the cellulose fraction requires a longer residence time (about 48 hours) with enzymes that restricts temperature to less than 60 °C. This results in different reactor volumes but does not alter the basic configuration.

In comparison with ethanol from starch processes, the process combination does not require milling of the raw material and upgrading of the stillage in terms of dewatering and drying to obtain a marketable by-product. Furthermore, the recovery boiler is excluded for the same reasons as in the cooking process above.

From in-house data derived from the detailed engineering of ethanol processes [8, 23], investment estimates are made as shown in Table 4.

Table 4 Ethanol production: estimated investment in EUR million

Item, cost (EUR million)		**Capacity**		
		10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Production equipment				
	hydrolysis	1.6	2.5	3.3
	fermentation	0.8	1.3	1.6
	Evaporation/distillation	2.3	3.6	4.7
	Buffer tanks, storage tanks	0.8	1.2	1.5
	Heat exchangers	0.1	0.2	0.2
Total purchased equipment		*5.6*	*8.8*	*11.4*
	Freight and installation	2.0	3.2	4.2
Total installed equipment		*7.6*	*12.0*	*15.6*
Steam and cooling systems		1.1	1.1	1.1
Piping		0.3	0.5	0.6
Insulation		0.5	0.5	0.5
Foundations and scaffolding		0.9	1.4	1.8
Electrical		1.7	2.7	3.6
Control and regulation		3.2	3.2	3.2
Engineering total process		1.1	1.1	1.1
Total "functions"		***8.7***	***10.4***	***11.7***
Total cost (EUR million)		**16.3**	**22.3**	**27.3**

The investment of EUR 22.3 million in the 20 tonnes of DS raw material capacity corresponds to a production of almost 33,000 m^3 of ethanol annually according to the mass balance. A common indicator in the ethanol business is the investment per annual litre, which in this case is 0.68 EUR/litre of ethanol per year.

Modern, large-scale "ethanol from grains" processes have figures of the magnitude of 0.8 (or a little less) EUR/litre per year, including milling, upgrading of the by-product and a boiler for steam production. These units produce about 150,000 m^3 and scaled down to the capacity above using a scale factor of 0.65, this indicates a specific investment of some 1.4 EUR/litre per year for a complete ethanol plant. According to previous data from Atrax Energi och Miljö AB [23], the excluded items in a complete process account for more than 50% of the investment. Consequently, the above estimated investment of EUR 22.3 million for the items in the table is judged reasonable.

4.2.3 Gasification and synthesis to SNG

The gasification is carried out in a downstream entrained gasifier according to Chemrec's "Black Liquor Gasification" (home-page) [24]. Here, unconverted material, and in particular the sodium, is collected as a molten "slag" in the bottom of the gasifier. The molten material is cooled and dissolved in water and the "Na_2CO_3"-rich solution is fed to the white liquor preparation as shown in the soda cooking and white liquor plant section above.

The raw gas from the gasifier is cleaned according to the Chemrec process and introduced to a conventional synthesis gas preparation and final synthesis:

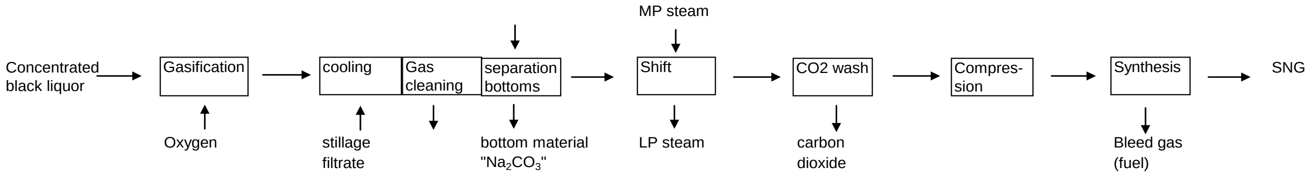

Figure 7. Gasification and SNG synthesis.

The entire process has been demonstrated in a small DME production in Piteå, where synthesis to DME is carried out instead of SNG synthesis [24]. The exchange of final product involves a different reactor technology and catalyst in the last stage but the techniques are equally commercial.

The investment estimates are based on information from the BLGMF II project [11] and in-house competence from Cellulose Fuels and Kemiinformation concerning oxygen production, gasification, shift reaction and gas cleaning [8, 26].

Table 5 Gasification and SNG synthesis: estimated investment in EUR million.

Item, cost (EUR million)	**Capacity**		
	10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Air separation unit	5.0	7.9	10.3
Gasifier	11.5	18.1	23.5
Shift and gas cleaning	4.8	7.5	9.8
Synthesis	6.1	9.6	12.5
Total installed equipment	***27.5***	***43.1***	***56.1***
Piping, electrical, control, engineering, etc.	11.0	17.3	22.5
Total cost (EUR million)	**38.5**	**60.4**	**78.6**

The estimated investments for gasification and synthesis are difficult to put in perspective as very few plants of this type have been established. The GoBiGas demonstration unit in Gothenburg is built with a different gasification principle. The non-pressurised gasifier with indirect heating there induces a separate combustion and a significant compressor before the synthesis. These two units cost some EUR 29 million according to Thunman [22]. Furthermore, the investment in the synthesis gas preparation and synthesis to SNG was stated as some EUR 36 million. This investment corresponds to about EUR 25 million in the estimated investment above (including piping, etc., for the gas upgrading and synthesis units). The difference is significant as the SNG capacity in the table is more than double the effect in the GoBiGas case (49 MW vs 20 MW).

The GoBiGas figure for the investment is stated at the actual cost for a built unit, whereas the table shows estimated costs based mainly on previous evaluations, primarily from BLGMF II within the ALTENER programme [11]. A third cost is given by a much smaller DME unit in Piteå which is stated some EUR 20 million [25]. Besides the time difference of some ten years between the BLGMF II estimate and the actual construction, it may be commented that gasification in GoBiGas is carried out at atmospheric pressure, whereas ALTENER and the above estimate refer to pressurised gasification. At atmospheric pressure the gas volumes are considerably larger, requiring large equipment in the gas cleaning and compression in several steps. Furthermore, the lower gasification temperature in GoBiGas results in a more contaminated raw gas containing tars, etc., which, in turn, requires more extensive gas cleaning. The smaller unit in Piteå has a different technique than was proposed in BLGMF II.

The discrepancy remains largely unexplained, but for the time being, the estimated investment is maintained in this evaluation for consistency.

It should be commented that the investment in the air separation unit may be replaced by an operating cost if an agreement is reached with a gas company. Such an agreement would give the gas company the rights to argon and nitrogen from the air separation and to charge for the oxygen supplied, providing they set up the unit. This arrangement is quite common in other industries.

4.2.4 Tanks for process chemicals, buffering and storage

A requirement has been identified for more than 15 tanks for process chemicals, buffering between reactors and storage. These have been cost-evaluated according to set volumes and a cost of some 850 EUR/m^3:

Table 6 Storage vessels: estimated investment in EUR million at a specific cost of 850 EUR/m^3.

Tanks outside the sub-processes	**Capacity**		
	10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Total tank volume (m^3)	400	699	1000
Total cost (EUR million)	**0.32**	**0.53**	**0.8**

4.2.5 Total for the combination process

The estimated investments above are summarised as (EUR million) in table 6.

Table 7 Combination process: estimated investment in EUR million

Sub-process, cost (EUR million)	**Capacity**		
	10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Fractionation via soda cooking. Evaporation of black liquor. White liquor plant	49	77	101
Hydrolysis and fermentation	16.3	22.3	27.3
Gasification and synthesis to SNG	38.5	60.4	78.6
Additional tanks	0.3	0.5	0.8
Total installed process combination, cost	**104**	**161**	**207**

4.2.6 Infrastructure at Händelö, project costs, etc.

By locating the process combination at Lantmännen Agroetanol's site in Händelö, the investments in infrastructure are minimised. Händelö is increasingly industrialised and Agroetanol has developed co-operation with adjacent industries, most notably with Eon, which supplies steam and receives condensates. This relieves Lantmännen Agroetanol of the burden of investments in steam production.

In an evaluation by Cellulose Fuels and Lantmännen Agroetanol, it has been concluded that the site needs construction work in terms of extended roads and foundations, pipe routes and similar [26]. As more or less a guess, the assumed investment in land development is of the magnitude of EUR 1.1 million (SEK 10 million). The same cost is attributed to the pipe routes. The extension of the steam supply system to cover all sub-processes and the cooling tower is set at EUR 4.4 million. For the corresponding extension of power, EUR 2 million is assumed. EUR 2 million is set aside in advance for complementary constructions in the environmental protection processes that exist at Lantmännen Agroetanol.

The project costs for establishing the process combination are estimated at EUR 2.5 million. All these costs are more or less independent of the capacity of the process combination. Assumed investment in infrastructure at Händelö and project costs are shown in Table 8.

Table 8. Infrastructure: estimated investment in EUR million.

Item, cost (EUR million)	**Capacity**		
	10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Land development	1.1	1.1	1.1
Pipe routes	1.1	1.1	1.1
Expansion of environmental protection processes	1.6	1.6	1.6
Extension of steam system	1.1	1.1	1.1
Cooling tower	2.2	4.4	6.6
Project cost	2.7	2.7	2.7
Total infrastructure costs and project costs	**9.8**	**11.8**	**14.2**

As mentioned above, the assumed investments in the table are the results of discussions between Cellolose Fuels and Lantmännen Agroetanol and are thus based on former experiences at Händelö. The infrastructure costs are, however, not within the competence of Cellulose Fuels and they are therefore denoted "assumptions" rather than "estimates".

4.2.7 Total investment for the combination process at Händelö

The estimated costs for establishing the process combination at Händelö are summarised in table 8.

Table 9. Total investment at Händelö, EUR million.

Item, cost (EUR million)	**Capacity**		
	10 tonnes DS/h	20 tonnes DS/h	30 tonnes DS/h
Total installed process combination	104	161	207
Infrastructure Händelö	7.1	9.2	11.5
Project cost	2.7	2.7	2.7
Total process combination established at Händelö, total cost	**114**	**172**	**221**

This type of investment estimate is often considered to have an accuracy of ±25 or even 50 %. Experience suggests it should instead be -10 % to +25–50 %. As it is composed of existing sub-processes, however, there is an argument for the narrower range. Most of the figures originate from data actually experienced in units built during 2010–2016. The sources are Atrax Energi och Miljö and Kemiinformation, companies that have been involved in the construction and suppliers of the technologies [8,23]. The figures have been further discussed in personal communication with people in the businesses , respectively. More technical details are given in a previous evaluation by Cellolose Fuels [26].

From these aspects, the uncertainty is related more to the effects of combining the sub-processes and the specific sites for building. At Händelö, the Lantmännen Agroetanol ethanol production comes from two ethanol plants: the original 50,000 m^3/year unit and a later 150,000 m^3/year unit. The capacity of the former is of roughly the same magnitude as the ethanol manufacture in the present process combination; 50,000 in comparison with 33,000 m^3. A number of options exist with regard to the cellulose fraction - ethanol line in the process combination:

- the existing ethanol plant can be modified in the hydrolysis section and replace the unit in the "*Hydrolysis and fermentation of the cellulose fraction*" section
- the existing fermentation and distillation units may replace the corresponding units

- the existing evaporation and drying of the present stillage may be used for the recycling of stillage in the process combination
- the over-capacity of the distillation in the present unit may be used for upgrading of ethanol in the process combination

The impact of alternatives like these would be that the decrease in investment in the process combination goes from EUR 1 million to about EUR 10 million. The scope of this study does not allow an evaluation of the alternatives but indicate the possibilities. (It may also be mentioned that locating at a pulp mill threatened by closure would have even more significant effects on the investments, as this unit accounts for almost half of them.)

4.3 CONSTRUCTION TIME AND INTEREST COST DURING CONSTRUCTION

Considering that the process combination is made up of three commercially established "sub-processes", it is estimated that it could be constructed on an industrial site within two years.

During the first year, site preparations and orders to suppliers are assumed possible, with payments comprising some 40% of the total investment. At 6% interest, this leads to interest costs as follows (Table 10):

Table 10. Interest during construction, EUR million.

Capacity		**10 tonnes DS/h**		**20 tonnes DS/h**		**30 tonnes DS/h**	
Interest = 6%	Payments as a % of the total investment	Payments, EUR million	Interest, EUR million	Payments, EUR million	Interest, EUR million	Payments, EUR million	Interest, EUR million
Year 1	40	46	5.5	69	8.3	89	10.6
Year 2	60	68	4.1	103	6.2	133	8.0
Total interest during construction		**9.6**		**14.5**		**18.6**	

The fact that the process combination is built on three commercially existing processes has a major impact on the construction time and the start-up operations. Two of the processes have several optional suppliers, which enables cost negotiations as well as pressure on the construction time. Even considering the modifications of the processes, the start-up operations should be minimised and subjected to contract stipulations (see further discussion in Chapter 5). A comparison can be made with the start-up in the GoBiGas project where the start-up operation is reported to have cost around EUR 35 million [23].

4.4 EVALUATION OF PRODUCTION COSTS FOR ETHANOL AND SNG FROM LIGNOCELLULOSE

The product yield and the consumption figures for process chemicals, etc., are given by the mass and energy balances, presented in Figure 2. For consistency reasons, the energy contents in respective streams are calculated using Boie’s equation for LHV (Lower Heating Value) [18].

The results for a raw material intake of 20 tonnes of DS material per hour are presented in Table 11 below. All consumption figures are collected from the aforementioned mass balance (section 4.1). In short, the background to the data is summarised as follows:

- For the base case, an energy efficiency of 71 % is used, i.e. 71 % of the energy in the raw material is obtained in the transportation fuels ethanol and SNG (methane). In 20 tonnes of DS raw material, there is 370 GJ of energy, producing 264 GJ/h of ethanol and SNG.
- The raw material price is set at 18.95 EUR/MWh LHV (=SEK 180/MWh at 9.5 SEK/EUR). The purchased raw material has a DS content of 80 % on average and at this moisture content 20 tonnes of DS means 25 tonnes of raw material. The LHV energy content in the raw material with 20 % moisture is 4.1 MWh/tonne.
- The power consumption has been estimated from officially published data for respective pieces of equipment and total processes. The ethanol manufacture from the cellulose fraction is assumed to consume ≈ 0.5 kWh/litre ethanol (= 1.66 MWh per 20 tonnes of DS raw material). The gasification line with air separation unit and synthesis reactor is the largest consumer of power, requiring 5.3 MWh per 20 tonnes of DS raw material or 30 kWh per GJ of SNG. The power consumption for the raw material handling and the soda cooking has not been obtained but is set at 1 MWh per 20 tonnes of DS raw material.

The consumption of process chemicals is calculated in the mass balances:

- The soda cooking requires 158 kg NaOH per 20 tonnes of DS raw material.
- For the hydrolysis of the cellulose fraction, 40 kg of protein enzymes are used per 20 tonnes of DS raw material.
- Yeast for the fermentation is produced in the process.
- About 100 kg of nutrients (N, P, K) are fed to the fermentation per 20 tonnes of DS raw material.
- Small amounts of NaOH and phosphoric acid are used for pH adjustment in cellulose fraction - ethanol line but are not included in the costs.

The consumption of catalysts in the gasification line is quoted from literature data results in some 18 EUR per 20 tonnes of DS raw material.

Labour costs are set at EUR 6.3 million per year for six shift teams of 10 people (two per sub-process and four for process functions (steam, electrical, mechanics, etc.), and 15 engineers and administrators.

Maintenance cost comes to EUR 153 million for 20 tonnes of DS raw material, as above.

Capital costs are calculated on total capital requirement, including interest during construction and arrives at EUR 187 million. Run time is 7,920 h/year (330 days, 24 h/day).

No income is calculated for the carbon dioxide produced.

A summary of calculated production cost for ethanol and SNG in the process combination is shown in Table 11.

Table 11 Hourly production cost at 20 tonnes/h DS raw material

Cost item	Consumption basis	Price	Cost, EUR/h	% of total cost
Raw material	20 tonnes DS at 5 MWh/tonne	19 EUR/MWh	1,947	29
Power	8 MWh	52.6 EUR/MWh	421	6
Auxiliaries				
NaOH	158 kg	0.63 EUR/kg	100	1
Enzymes	40 kg	10.5 EUR/kg	421	6
Nutrition	100 kg	0.63 EUR/kg	63	1
Catalysts			18	<1
pH-adjustm., etc.				<1
Salaries				
labour	60 persons	4,260 EUR/month	387	6
Adm., engineers	15 persons	5,680 EUR/month	129	2
Maintenance	2% per year of ”installed equipment”; EUR 161 million		406	6
Capital cost	12% annuity on total capital; EUR 187 million		2,833	42
Total			6725	100

With the product yield at 71 % energy efficiency for the transportation fuels, the cost per GJ of product is 25 EUR, or 0,09 EUR/kWh. This means a production cost for ethanol, at 6 kWh/litre (LHV), of 0.55 EUR/litre and a corresponding cost for SNG of 0.91 EUR/m^3 (at 9.9 kWh/m^3 (LHV)).

If the energy efficiency is lowered to 67 % and the rest of the cost items remain the same, the production costs are 0.58 EUR/litre of ethanol and 0.97 EUR/m^3 respectively. Considering the high impact of capital costs, almost 50 % for the annuity, the maintenance and labour costs, the calculations have been repeated for the capacities of 10 and 30 tonnes of DS raw material per hour. The results for 10, 20 and 30 tonnes of DS/h are shown in Table 12 below. Energy efficiency for the products = 71 %.

Table 12 Calculated production costs for ethanol and SNG

Raw material intake, tonnes of DS per hour	10	20	30
thousand tonnes/year	79	158	238
Production cost per GJ, EUR	31.4	25.5	23.1
Production cost per kWh, EUR	0.11	0.09	0.08
Production cost for ethanol at 6 kWh/litre	0.67	0.55	0.50
Production cost for SNG at 9.9 kWh/m^3	1.12	0.91	0.82
Volume of ethanol, m^3 per year	16,385	32,769	49,154
Volume of SNG, million m^3 per year	19.4	38.8	58.2

4.4.1 Production cost comparisons

The production cost calculated in the previous section should be compared to competing biofuel production methods. In the following the costs for grain ethanol, biogas and wood based SNG are discussed.

Grain ethanol

Depending on the cost of grains in Europe, the corresponding cost of ethanol from starch may be roughly calculated as 0.44–0.59 EUR/litre, where

- Capital costs = 0.1 EUR/litre using the stated investment of 0.8 EUR per litre of ethanol per year (section 4.2.2) and an annuity of 12%.
- Raw material cost = 0.4 EUR/litre of ethanol – 0.55 EUR/litre at prices of 0.13–0.18 EUR/kg of grains and a consumption of 3 kg of grains per litre of ethanol.
- Salaries and chemicals (including enzymes) are set at 0.11 EUR/litre of ethanol.
- Maintenance and other costs are set at 0.01 EUR/litre of ethanol.
- Total costs = 0.62–0.77 EUR/litre of ethanol.
- By-product (1 kg of stillage cattle feed) credit = 0.18 EUR per litre of ethanol, giving 0.44–0.59 EUR per litre of ethanol.

Biogas

In Sweden, the average cost of biogas in 2014 was stated as 1.14 EUR/m^3 in a report from the government to the EU (concerning the Swedish tax exemption) [27]. Considering that some 50 % of the Swedish production consisted of biogas from sludge from waste water treatment, it is concluded that the production from other sources was more costly than the average.

Wood based SNG

The production cost for SNG in GoBiGas is stated as 0,75 EUR/m^3 [22]. This cost then presumably requires sales of by-products to district heating. An equally rough calculation as for ethanol from starch above, indicates a price for the by-products of more than 0,025 EUR/kWh of steam/hot water to district heating, at an investment of some EUR 50 million for the process, where:

- Capital costs = 0,04 EUR/kWh at an investment of EUR 50 million and an annuity of 12 % for 20 MW of SNG.
- Raw material cost = 0,032 EUR/kWh at an energy efficiency of 60 % to SNG and a price for the raw material of 0,02 EUR/kWh.
- Salaries, catalysts, chemicals are set at 0,013 EUR/kWh of SNG.
- Maintenance and other costs are set at 0,003 EUR/kWh of SNG.
- Total costs = 0,088 EUR/kWh of SNG.

Stated cost for SNG = 0.74 EUR/m^3. SNG requires a credit from by-product district heating, which covers 30 % of the energy in the raw material (total energy efficiency = 90 %) that is 0,014 EUR. The 30 % of energy in the by-product corresponds to 0.5 kWh, resulting in a required price for the by-product of 0,027 EUR/kWh.

It should be commented that the stated investment in GoBiGas is significantly higher than EUR 50 million.

GoBiGas evidently encountered commercial problems due to cheaper biogas delivered from Denmark to the Gothenburg region. Denmark is a major producer of biogas with a total capacity of some 200–300 million m^3/year, mostly using manure as a raw material. Jacobsen et al (2014) [19] states production costs at the Danish units as 0.47–0.78 EUR/m^3. These low costs are achieved at biogas units with raw material intakes of 100,000–200,000 tonnes/year and outputs of more than half a million m^3 of methane. A prerequisite is that the transport distance for the raw material (manure, etc.) is just a few hundred metres.

Such conditions hardly exist in Sweden and consequently the assumed production costs for biogas are more like the figures stated by the Swedish government in 2014; 1.14 EUR/m^3 of biogas [27].

In conclusion, the calculated production costs for ethanol and SNG from lignocellulose in the process combination indicate that second generation transportation fuels may be produced at the same cost levels as first generation. Furthermore, the process combination is not tied to specific locations required by by-product markets. This may be particularly important in a possible installation at, for instance, a pulp mill threatened with closure or, as in the case studied, an existing ethanol plant. In both cases the investment may be lowered significantly.

5 UNCERTAINTIES AND REQUIRED TESTS FOR THE PROCESS COMBINATION

As mentioned, the process combination is composed of established and commercially available sub-processes:

- Soda cooking is still practised internationally at a number of pulp production units. In the case at hand it has been tested at lab scale, with several wood and straw materials showing good results.
- Ethanol production from hydrolysed starch is conventional. In this case the corresponding enzymatic hydrolysis of cellulose has been proven at lab scale and in a pilot test. The subsequent fermentation and upgrading of ethanol are identical.
- Black liquor gasification has been demonstrated at pilot scale for sulphate and sulphite cooking. Evaluations based on the analysis of black liquor from soda cooking have not shown any potential problems with gasification.
- The upgrading of the gas and the synthesis to SNG is not affected by the original raw material.
- Upgrading of white liquor to the soda cooking is conventional.

What has not been practically tested are some of the interconnections between the sub-processes:

- The black liquor gasification requires specific surface tensions and viscosities in the feed and soda-cooked black liquor may have different properties in these respects.
- Black liquor from soda cooking lacks sulphur and all tests on black liquor gasification have so far been made on sulphur-containing material. In principle, the absence of sulphur simplifies the process but sulphur also has an effect on the slagging in the gasifier. The overall effect needs further evaluation.
- The slightly different black liquor from soda cooking may affect its evaporation.
- The recycling of stillage filtrate to the cooking has not been tested.
- Recycling of the filter cake to the black liquor stream has not been tested either.
- With the almost completely closed process, most impurities (inorganics) are assumed to come out in the filter cake from the white liquor upgrading (“chemical cycle”) or “combusted” (organics) in the gasifier and lime kiln. This needs to be proven in a thorough chemical evaluation.

None of these uncertainties is regarded as a fundamental obstacle to the process combination, but practical data is required for further evaluations. A practical validation of the process combination on a large lab-scale, with soda cooking, hydrolysis and fermentation of the cellulose fraction, evaporation of the black liquor and gasification of the material, is planned to be carried out in 2017 [31]. The raw material is hard-wood clearings and straw and the products are passed between the laboratories testing the different process stages.

6 OVERALL CONCLUSIONS AND POSSIBLE FUTURE DEVELOPMENTS

The techno-economic evaluation of a demonstration plant for the process combination built at Händelö is showing a lower energy efficiency than in previous evaluations; 71 % compared with around 75 %. (The reason is that the moisture content in the raw material is not included in the LHV calculation which gives a higher energy in the raw material.

At capacities of 10, 20 and 30 tonnes of DS raw material, the production costs are calculated as 0.11, 0.09 and 0.08 EUR/kWh. In the last two cases, the costs may be regarded as potentially competitive, even with today's production of first-generation ethanol and the current biogas is Sweden.

Evidently the capacity is a significant factor for the costs. In combination with Lantmännen Agroetanol's ethanol units at Händelö, synergy effects could be achieved with the smaller unit, which has a capacity of some 50,000 m^3 per year. This could be utilised to a lesser extent by using the distillation, which is stated as having an additional capacity to handle ethanol from a process combination at a capacity of 20 tonnes of feed per hour. The production cost effect would be quite marginal in this case, however.

A more substantial effect would be achieved if the entire smaller ethanol unit at Händelö could be utilised in the process combination. This would require some 10 % lower investment which, in turn, results in a 5 % reduction in the production cost. Presumably, this would also have an effect on salaries and maintenance. At the same time it would have a drawback in terms of lost production during construction time. In a process combination with a capacity of 30 tonnes of DS raw material per hour, the ethanol capacity would thereafter be of about the same magnitude. At 20 tonnes of DS, the subsequent capacity would be some two-thirds of the current level.

Händelö offers advantages for a demonstration unit with capacities of some 20–30 tonnes of DS feed. Considering the high capital costs for the process combination, a more favourable capacity is instead 100 tonnes/h of feed, which might be the scale of a commercial plant. This can be compared to pulp mills in terms of raw material and investment. With reference to the official plans for the substitution of fossil fuels in the transportation sector, it would also be a realistic size.

For a full-scale process combination, the location is probably determined mainly by raw material and product transport. Händelö should not be ruled out, but significant advantages will be obtained if a pulp mill threatened with closure could be used. This would clearly lead to substantial reductions in the investments.

Another aspect of locating at Lantmännen Agroetanol – Händelö is the fact that not only ethanol is produced but also SNG, which is a transportation fuel not as yet marketed by Lantmännen Agroetanol. Furthermore, purchasing wood raw material is not currently part of Lantmännen Agroetanol's business. Given the large financial commitments associated even with a demonstration unit, partners must be sought for the project. A first step has been taken with potential partners within the forestry industry and oil companies, which have responded positively. The ultimate objective is then to establish one or several commercial plants in Sweden or abroad.

In summary, the results of the current techno-economic evaluation have not contradicted the initial perceptions of the process combination. As the next step in the continued evaluation, Lantmännen

Agroetanol – with the support of Energimyndigheten – is carrying out laboratory validation of the process steps referred to above.

If the results of this are positive, the detailed engineering of a demonstration plant at Händelö may be examined together with other potential stakeholders.

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