Technical and Commercial Feasibility
Study of Black Liquor Gasification with
Methanol/DME Production as Motor Fuels
for Automotive Uses - BLGMF

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COLOPHON

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Black Liquor Gasification with Motor Fuels production - BLGMF

Wood → Methanol

Carbon dioxide

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PREFACE

The BLGMF (Black Liquor Gasification to Motor Fuels) project shows a route to convert low-grade renewable energy to high-quality energy products such as carbon dioxide neutral methanol or DME for automotive uses. The new technology is based on gasification of spent cooking liquids (black liquor) in the pulp and paper industry, which is integrated with commercial synthesis technology, today used in the petrochemical industry.

This new innovative concept thus provides a highly cost-effective route for increasing the Community’s use of renewable energy with large-scale replacement of fossil motor fuels. The results show that alternative fuels produced in conjunction with the production of pulp and paper may with small fiscal and other incentives may be competitive even with fossil automotive fuels as traded on a free open market.

This gives real opportunity for a co-production scheme for the world’s pulp mills. The production of “green” transport fuels in addition to the traditional pulp mill output of pulp and paper, as part of the pulp mill energy and chemicals recovery cycle. The new concept has sometimes been referred to as a transition from the traditional pulp mill configuration to a “bio-refinery” configuration.

In a previous ALTENER project, BioMeeT II, (Contract No. XVII/4.1030/C/00-014/2000), the formation of a stakeholder group was made and barriers of a market introduction identified. The BioMeeT II project focused on efficient ways to produce transport fuels based on biomass gasification with co-production of electricity and heat. The results will be valuable when discussing introduction strategies and stakeholder analysis, also for the BLGMF route to production of “green” transport fuels.

The European Commission has adopted a White Paper for a Community Strategy and Action Plan for the Future: Renewable Sources of Energy with an indicative objective of 12% for the contribution of renewable sources of energy (RES) to the European Union’s gross inland energy consumption by 2010. Among the important sectors, promoted in the Campaign for Take-Off 1999–2003, is 5 million tonnes of liquid biofuels.

The BLGMF project contributes in several ways to the development of European Union Agriculture and Forestry Policies, in particular to international commitments on sustainable forestry as expressed in AGENDA 21. This initiative demands the development and improvement of by-products upgrading (and concomitantly waste minimisation) technologies to maximise the efficiency of the utilisation of forestry products.

Ultimately, this project shows an example on how to use biomass most energy-efficiently and cost-effectively. A continuation has been established with €10 million funding secured in the RENEW project within the 6th Framework programme, which includes a feasibility study project with the goal to construct a BLGMF plant at a Swedish pulp mill.

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APPENDICES

APPENDIX 1: CHEMREC® — black liquor gasification

APPENDIX 2: Paper I — Efficient Production of Methanol from Biomass via Black Liquor Gasification (Prepared for TAPPI Engineering Conference, San Diego, USA, 8–12 September, 2002)


APPENDIX 5: Paper IV — Preliminary Economics of Black Liquor Gasification with Motor Fuels Production (Prepared for the Colloquium on Black Liquor Combustion and Gasification, Park City, Utah, USA, 13–16 May, 2003)
SUMMARY

Background

There is a growing interest in finding cheap and efficient ways to produce CO$_2$-neutral automotive fuels, by using biomass as the raw material, as CO$_2$ is the main gas responsible for climate change. However, the consumption of fossil fuels for road transport increases and in the long run there is a need to cut down on CO$_2$ emissions. There is therefore urgent need to develop not only alternative but also additional fuels.

Emissions from the transport sector are growing at an alarming rate. Road transport in particular generates 85% of the European Union transport sector’s emissions. Furthermore, 98% of the European transport market is dependent upon oil. The external energy dependence has passed 50% and will increase to more than 70% and 90% for oil in particular, in 20–30 years if nothing is done. This is viewed as economically and strategically unacceptable.

China has in parallel come to the same conclusions for same reasons but with different means as the task is much greater. China has today 16 million vehicles with an increase of two to three million annually. It has been estimated that from 2000 to 2020 there will be a 24-factor increase of cars in China while a three to four factor increase of cars in India. Already 13 of the 15 dirtiest cities are located in Asia. In 2000 China imported 70 million tonnes of crude oil and more than 30 million tonnes of oil products at the cost of $25 billion. This is a heavy burden on the national economy and seriously endangers national energy security.

The Chinese Academy of Sciences has concluded that it is a definite must to develop additional fuels to meet the expected increase of fuel consumption. However, China has abundance of coal and the proven recoverable coal reserve is estimated as 765 billion tonnes that could be used for 400 years. The fuel of choice is therefore coal-derived fuel methanol (or DME). For some time they have made research in coal gasification to produce methanol and recently DME, however, the petroleum companies have been reluctant to methanol because of health reasons (toxicity) which was much debated in the 80s in USA. Therefore, they made a three-year methanol test and toxicity study that concluded that methanol is safer than petrol.

Consequently, the Chinese government is currently executing a diversified energy strategy: Five-Year Plan for the Development of Fuel Methanol and Vehicle in Shanxi Province of China. Shanxi Province will be the production base for 3.7 million tonnes of methanol produced and used for demonstration of 5000 vehicles from 2002–2006. The five-year programme is envisioned for extension to 10 million tonnes of methanol per year (current world production is 28 million tonnes) by 2007–2011.

In the European Union, since 1970, the number of passenger-kilometre (pkm) for cars and lorries has increased by a staggering 140% to 3800 billion pkm and goods transport tonne-kilometre (tkm) has increased by 215% to 1300 billion tkm. During same time, the number of cars in the European Community trebled from 62.5 million to nearly 175 million. This trend seems to be slowing down now, but the number of private cars in the European
Community is still rising by more than 3 million every year. With current increase of 3% per year, it is projected that by 2020 transportation will account for a third of EU final energy carrier consumption.

As a step to change current trends, the European Parliament and the Council of the European Union has issued a Council Directive (2003/30/EC) on the promotion of the use of biofuels for transport. The Directive sets a minimum percentage of biofuels to replace diesel or petrol for transport purposes in each Member State. By end of 2005 a 2% minimum proportion of biofuels of all petrol and diesel fuels sold on their market must be ensured with a 0.75 percentage point yearly increase to 5.75% by 2010 with a target of 20% by 2020. In addition, a Council Directive has recently been issued modifying Directive 92/81 on excise duties on mineral oils with main products eligible to differentiated excises duties until 2010.

The BLGMF project

The present project to investigate Black Liquor Gasification with Motor Fuels (BLGMF) production was initiated within the EU ALTENER II programme in 2001 and started up in February of 2002. The work was carried out by a consortium including Nykomb Synergetics (process engineering consultant), STFI, Skogsindustrins Tekniska Forskningsinstitut (pulp and paper research company), Chemrec (process technology supplier), Ecotraffic ERD³ (automotive and environmental consultant), Volvo Group (automotive producer), OK-Q8 (national fuel distributor) and Methanex (world-wide methanol producer and distributor).

In the short term, the goal was to establish the preliminary engineering and a cost estimate for calculating the economic performance of a BLGMF system. In addition, the proposed actions lead to a checklist of necessary conditions for a market introduction of renewable fuels. The long-term goal was to initiate a broad interest group in the European pulp and paper industry to support the development of such a system. The main objectives were:

- To study the process integration of the Black Liquor Gasification with Motor Fuels production (BLGMF) system with an existing, and a future modern ecocyclic, pulp mill for the production of renewable energy sources in the form of CO₂ neutral fuels for automotive uses. The emphasis of the study was to use existing conditions for creating added value for the pulp mill industry.
- To study the technical and economical feasibility of black liquor gasification integrated with methanol/DME production as motor fuels for automotive uses. A preliminary engineering study made for the plant with a ±30% cost estimate.
- To investigate a group of stakeholders willing to support preparations for investments for developing resources, for plant construction and for marketing of renewable energy products and
- To define the economic framework conditions and identify barriers of various kinds and market obstacles to implementation of said project under conditions for private enterprises.

In general, to calculate plant economics in a feasibility study the reference is usually a separate plant, which can be self-sustained in energy and services and at a "greenfield" site.
or at an industrial “brownfield” site. However, to justify a replacement investment at a plant and replacing an existing process where the economic life has ended, we have decided to calculate an incremental investment cost with incremental production costs. This is the normal procedure, as in this case the host (the pulp mill owner) can choose between investing in the same technology – a new recovery boiler – or in a new technology, the gasification plant (BLGMF). Thus, the investment decision would normally be based on a comparison between the two alternatives: a) reference mill with a recovery boiler and b) same type of mill with a BLGMF plant. It should therefore be noted that the results in this report are based on a comparison and that the incremental investment cost and production costs are calculated.

In the long term, conversion to hydrogen is an attractive route, but this requires far greater changes to distribution systems and vehicles. Furthermore, as long as fuel cells will be much more expensive than current engines per kilowatt it is unlikely that the gain in energy efficiency or lower emissions will be enough as argument for replacement. On the other hand, methanol can and is transported today easily at large volumes with little energy needed for the transportation work compared with the methanol energy transported. DME can be easily pressurised and handled as a liquid. Both methanol and DME show promising features as fuel candidates with the Otto and the diesel engine and comparing with other fuels from an LCA point of view, these fuels show highest energy efficiency from “well-to-wheel”.

Pulp & paper and benefits of black liquor

The European pulp and paper industry is a vital part of an economic cluster – the paper and forest cluster – that generates an annual turnover of more than EUR 400 billion. In 2002, more than 1260 pulp and paper mills produced some 91 million tonnes of paper and board. The industry provides direct employment for about 250 000 people, and indirect employment – through the paper and forest cluster – for 3.5 million people.

A pulp mill that produces bleached kraft pulp generates 1.7–1.8 tonnes of black liquor (measured as dry content) per tonne of pulp. Black liquor thus represents a potential energy source of 250–500 MW per mill. As modern kraft pulp mills have a surplus of energy, they could become key suppliers of renewable fuels in the future energy system. Today, black liquor is the most important source of energy from biomass in countries such as Sweden and Finland with a large pulp and paper industry. It is thus of great interest to convert the primary energy in the black liquor to an energy carrier of high value.

World-wide, the pulp and paper industry currently processes about 170 million tonnes of black liquor (measured as dry solids) per year, with a total energy content of about 2 EJ, making black liquor a very significant biomass fuel. In comparison with other potential biomass sources for chemicals production, black liquor has the great advantage that it is already partially processed and exists in a pumpable, liquid form. Using black liquor as a raw material for methanol/DME production would have the following advantages:

- Biomass logistics are extremely simplified as the raw material for fuel making is handled within the ordinary operations of the pulp & paper plant
- The process is easily pressurised, which enhances fuel production efficiency
- The produced syngas has a low methane content, which optimises fuel yield
• Pulp mill economics becomes less sensitive to pulp prices as the economics are diversified with another product
• Gasification capital cost is shared between recovery of inorganic chemicals, steam production and syngas production.

Energy efficiency and economy

Based on the ecocyclic pulp mill reference (KAM2 model mill), where all energy and by-products are recovered with today’s most efficient technology, a BLGMF concept was designed and calculated. The results are thus based on a comparison with a Reference mill with a capacity of 2000 ADt/day of pulp and with a modern recovery boiler producing electricity for export. Two configurations were calculated, methanol and DME, equally based and calculated on the same black liquor capacity.

The resulting biomass to methanol energy efficiency when only biomass is used as an external energy source was very high, 66% for methanol and 67% when DME was produced. The BLGMF plant generated additional electricity, solely consumed by internal plant units in that there was no need for additional energy. The energy streams passing the boundary of the various plant configurations are given below in Table 1. At the bottom of the table, the efficiencies for the respective fuel are given divided on the two feedstocks, i.e. biomass and black liquor.

<table>
<thead>
<tr>
<th>Table 1. Summary of consumed and produced energy products.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel options</strong></td>
</tr>
<tr>
<td>Biomass consumption</td>
</tr>
<tr>
<td>Black liquor consumption</td>
</tr>
<tr>
<td>Fuel production</td>
</tr>
<tr>
<td><strong>Energy efficiency (LHV)</strong></td>
</tr>
<tr>
<td>Black liquor to fuel</td>
</tr>
<tr>
<td>Biomass to fuel</td>
</tr>
</tbody>
</table>

It should be noted that the biomass to fuel efficiency could be significantly larger if a biomass IGCC should be used instead of the calculated power boiler with a condensing steam turbine. Nevertheless, the BLGMF plant shows, as it is a very efficient use of biomass energy to produce motor fuels.

To assess the performance economics of the BLGMF technology at the mill level an investment cost assessment was done both for a modern recovery boiler and a BLGMF plant based on the KAM2 mill at 2000 ADt/day of pulp. The net incremental capital investment cost to the Reference Mill was estimated as EUR 150 million for the BLGMF Methanol case and EUR 164 million for the BLGMF DME case, based on a pulp mill capacity of 2000 ADt/day.
The resulted production costs were EUR 29¢ per petrol equivalent litre for Methanol (SEK 2.6 per p.e.litre) and EUR 32¢ per diesel equivalent litre for DME (SEK 2.9 per d.e.litre). Table 2 below summarises the incremental operating benefit and production costs.

**Table 2. Summary of incremental operating benefit and production costs.**

<table>
<thead>
<tr>
<th>Production costs</th>
<th>BLGMF Methanol</th>
<th>BLGMF DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental BLGMF operating benefit</td>
<td>M EUR/year</td>
<td>36.7</td>
</tr>
<tr>
<td>Production cost</td>
<td>EUR ¢/kWh</td>
<td>3.3</td>
</tr>
<tr>
<td>Production cost</td>
<td>EUR/tonne</td>
<td>182</td>
</tr>
<tr>
<td>Production cost, petrol/diesel eq. litre(^a)</td>
<td>EUR ¢/equivalent litre</td>
<td>28.7</td>
</tr>
<tr>
<td>Production cost, petrol/diesel eq. litre(^a)</td>
<td>SEK/ equivalent litre</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Notes:
\(^a\) The methanol production cost was recalculated for the cost of one equivalent litre of petrol, using fuel properties for the specified methanol/DME fuel and petrol properties of 11.626 MWh/tonne, 750 kg/m\(^3\) at 20 °C. Similarly, the DME production cost was recalculated for diesel with properties of 11.750 MWh/tonne, 815 kg/m\(^3\) at 20 °C.

The sensitivity analysis yielded a modest sensitivity on the production cost for all parameter changes (purchased biomass cost, purchased electricity cost and incremental investment cost) except availability.

To estimate the potential revenue of methanol and DME a selling price of methanol and DME at the mill gate was calculated by assuming that the cost for the consumer should be the same as for petrol (methanol) and diesel (DME). The estimated price is about SEK 2095 (€231) per tonne of methanol, when considering the current Swedish CO\(_2\) tax on petrol and similarly about SEK 3100 (€341) per tonne of DME.

A cash flow Internal Rate of Return (IRR) analysis was carried out for both cases, considering the incremental investment and operating costs for the BLGMF system relative to a new recovery boiler investment. The capital costs in this study have an accuracy of ±30% due to the level of detail included in the cost estimates and to inherent uncertainties in projecting “N\(^{th}\) plant” costs given the pre-commercial status of the BLGMF technology today. Future energy price levels are also uncertain and prices can vary considerably from one region of the country to another.

The incremental investment gave an IRR of 26% with a pay-back of 4.0 years for both the Methanol and the DME case (see Table 3).
Table 3. Results on return on investment.

<table>
<thead>
<tr>
<th>Results</th>
<th>Methanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback</td>
<td>4.0 years</td>
<td>4.0 years</td>
</tr>
<tr>
<td>Real Return on Total Capital</td>
<td>24%</td>
<td>23%</td>
</tr>
<tr>
<td>IRR</td>
<td>26%</td>
<td>26%</td>
</tr>
</tbody>
</table>

The recovered sulphur may be used in a beneficial way in a newly developed poly-sulphide cooking process to further enhance the yield of fibre from the wood. Assuming an increased pulp yield of 5% and with a capacity of 2000 ADt/day, this would give an additional revenue of EUR 16.5 million per year, calculating with an average pulp price of USD 550/ADt. The resulting additional revenue gives a significantly lower production cost, EUR 22.3¢/petrol equivalent litre (SEK 2.0 per p.e.litre) and higher returns on investment, 37% and a pay-back of 3.2 years.

Fuel market and possible distribution strategy

The demand for transportation fuels in Europe will increase more than the increase in energy efficiency of the vehicles. In particular, the demand for diesel fuel and middle distillate will be increasing in the future. As there will be limitations for the share of these products from crude oil, a shortage of supply of these products could be foreseen in the future. Therefore, a substitute of diesel fuel with alternative fuels would be a desirable solution. International trade with markets having a surplus of diesel fuel could be a temporary solution. To some extent, this is already being done (e.g. USA and Europe).

It should also be noted that substituting diesel fuel with alternative fuels seems to be more difficult than substituting petrol. The reason is that most of the fuel candidates are better suited for spark ignition (SI, or otto) engines. This imposes limitations on the number of fuels suitable for substitution of diesel fuel. It is also obvious that energy converters (engines) and fuels must be developed as a complete system.

DME, hydrogen (GH₂ and LH₂) and methanol had the highest efficiency, when analysed from “Well-to-Wheel”. Hydrogen could be of great interest in the long-term future but it is obvious that DME and methanol could be of great interest on a shorter timeframe. It could be noted that an otto engine optimised for the use of neat methanol could have a higher WTW efficiency than the FTD and diesel engine combination. Furthermore, otto engines are cheaper to manufacture than diesel engines and have a potential for lower exhaust emissions. DME could provide an even higher efficiency but in this case, a new fuel infrastructure has to be considered.

It can be concluded that the “best” use of methanol on a short-term horizon is as a low blending component or the use in fuel-flexible vehicles. As no new methanol compatible FFV vehicles are available at the moment, the use of methanol for low blending is most likely in the near future. In view of the limited prospects for methanol-fuelled diesel engines and fuel cells on a short-term horizon, new methanol plants should initially focus on the use of methanol as a low blending component. In addition, DME should initially be used in dedicated fleets with their own fuel infrastructure.
Market opportunity
There are 236 recovery boilers in the world that have not been rebuilt during the last 20 years and thus can be suitable for replacement with gasification technology. However, the majority of these boilers have quite low capacities, less than 500–600 tDS/day. Many of the smaller recovery boilers have been due to significant modifications during the years such as increasing the dry solids content of the black liquor, rebuilding of the boiler and other debottlenecking actions. Nevertheless, Chemrec BLGMF system would not be a realistic replacement alternative for small boilers.

One can assume that a mill, which is replacing an outdated recovery boiler, would desire somewhat more capacity (perhaps 25%) than the old boiler provided. A Chemrec BLGMF system is a competitive alternative for capacities of roughly 1000 tDS/day and higher. Hence, the actual market is for replacement of boilers with a capacity of 800 tDS/day or more, and which have not been built or extensively renovated in the last 20 years. There are 57 such boilers in the world today, about half of which are in the United States. The majority of the remainder is located either in Canada or in Japan.

The market for the Chemrec BLGMF system will expand in the future due to the obsolescence of more and larger recovery boilers. In short, each of the world’s 327 recovery boilers with a capacity of more than 800 tDS/day can be considered a candidate for eventual replacement by a Chemrec BLGMF system. It is becoming common for mills with multiple recovery boilers to replace several or all with one unit having a capacity of 2000 tDS/day or more. A Chemrec BLGMF system is clearly an alternative for these mills, so the market is actually larger than earlier suggested.

Potential fuel production and carbon dioxide reduction

From the material and energy balances, various pulp mill cases have been calculated for the energy efficiency of biomass to methanol. In the KAM2 pulp mill (2000 ADt/day) the methanol yield from black liquor is 1183 t/d (or 824 t/d DME), which is equivalent to 56.1%. The theoretical maximum production of methanol (or similarly for DME) can thus be calculated for countries in the European Union with black liquor production.

For the whole European Union as much as 61 TWh or some 11 million tonnes of methanol could be produced each year. This may be compared with current total consumption of motor fuels for the road transport sector and a calculated maximum replacement percentage (on energy basis) for each country. Finland could replace more than 50% of all transport fuels consumed, Sweden and Portugal nearly 30% and 10% respectively.

In absolute terms, Sweden and Finland could produce about 4 million tonnes each, a substantial amount. Thus, the production potential in the European Union is concentrated to a few countries, which have a large potential and for Sweden and Finland extremely high replacement potential.

For each tonne of methanol produced about 1.5 tonnes of carbon dioxide could be saved, with an average value of 85% carbon in 1 tonne petrol and with energy content of 11.626 MWh. Thus, the potential carbon dioxide reduction in EU if fully implemented is 16.4 million tonne per year. Finland and Sweden already fulfils the Kyoto target but have potential of reducing current emissions with 5.9 and 5.7 million tonnes of carbon dioxide or 11% and 12% of year 2000 emissions, respectively.
Outside Europe, Canada has a potential of more than 7 million tonnes of methanol to be produced. With the reported consumption of petrol and diesel fuel oil for road transport the calculated potential replacement is 7.2%, which is of course substantial and, not before noticed, offers great help in the commitment to the Kyoto protocol cut down on use of fossil fuels.

USA has the world’s largest methanol potential by amount, but not with replacement percentage. Potentially, a staggering 28 million tonnes of methanol could be produced. Astonishingly, this already equals today’s world methanol production from mainly natural gas based plants, which are all commercial and can be of 5000 t/d or more. However, just the US national petrol consumption totals the equivalent of 1000 million tonnes of methanol or 21 500 PJ. The resulting possible potential replacement is about 2.2% if also the diesel fuel oil consumption would be accounted for.
**SAMMANFATTNING**

**Bakgrund**


Utsläpp från transportsektorn ökar med en alarmerande hastighet. Bara vägtransporter producerar 85% av utsläppen från Europeiska Unionens transportsektor. Dessutom är EUs transportmarknad till 98% beroende av olja. Det externa energibehovet har passerat 50% och kommer öka till över 70% och för olja 90% om 20–30 år om inget görs. Det är ansett som ekonomiskt och strategiskt oacceptabelt.


Kinesiska vetenskapsakademien har konkluderat att det är ett definitivt måste att utveckla ytterligare drivmedel för att möta den väntade konsumtionsökningen av drivmedel. Kina har ett stort överflöd av kol och den säkra åtkomliga kolreserven är uppskattad till 765 miljarder ton som skulle kunna räcka i 400 år. Valet av drivmedel är därför kolbaserad metanol (eller DME). Sedan en tid har de forskat i kolförgasning för produktion av metanol och nyligen DME, men oljebolagen har varit motvilliga till metanol p g a dess hälsoriser (giftighet), vilket debatterades flitigt under 80-talet i USA. De gjorde därför en treårs metanolstudie där slutsatsen blev att metanol är ofarligare än bensin.


Sedan 1970 har antalet passagerarkilometer (pkm) för bilar och lastbilar ökat i EU med hela 140% till 3800 miljarder pkm och godstransportkilometer (tkm) har ökat med 215% till 1300 miljarder tkm. Under samma tid har antalet bilar i EU tredubblats från 62,5 miljoner till närmare 175 miljoner. Den här trenden ser ut att minska nu, men antalet privata bilar i EU ökar fortfarande med mer än 3 miljoner bilar varje år. Med dagens
ökning om 3% per år har det framhävts att till 2020 kommer transportsektorn att stå för en tredjedel av EUs hela konsumtion av energibärare.


BLGMF-projektet


I det korta perspektivet var målet att etablera den preliminära tekniken och kostnadsuppskattningen för att beräkna ekonomiska prestanda för ett BLGMF-system. Dessutom leda de föreslagna aktiviteterna till en checklista av nödvändiga villkor för en marknadsintroduktion av förnyelsebara bränslen. I det långa perspektivet var målet att initiera en bred intressegrupp i den europeiska pappersmassaindustrin för att stödja utvecklandet av ett sådant system. De huvudsakliga målen var:

- Att studera processintegrationen av BLGMF-systemet med ett existerande, och ett framtida modernt kretsloppsanpassat massabruk (KAM) för produktion av förnyelsebara energiprodukter i form av CO₂-neutrala drivmedel. Tyngdpunkten på studien var att använda befintliga förutsättningar för att skapa mervärde för massaindustrin.
- Att studera tekniska och ekonomiska möjligheten av svartlutsförgasning integrerad med metanol/DME-produktion som drivmedel. En preliminär teknikstudie gjord för en anläggning med en ±30% osäkerhets kostnadsuppskattning.
- Att undersöka en grupp av investerare villiga att stödja förberedelser för investeringar av utvecklingsresurser, för anläggningskonstruktion och för att marknadsföra förnyelsebara energiprodukter och
- Att definiera de ekonomiska ramvillkoren och identifiera barriärer av skilda slag och marknadshinder för att kunna implementera sagda projekt under villkor för privata företag.

Normalt är referensen vid beräkning av en anläggning i en *feasibility*-studie en separat anläggning som är självförsörjande på energi och tjänster och vid en ny egen plats eller vid en industriell delad plats. För att berätta om ersättningsinvestering vid en anläggning och

På lång sikt är konvertering till vätska en attraktiv väg, men det förutsätter långt större förändringar till distributionssystem och fordon. Så lange bränsleceller kommer att vara mycket dyrare än dagens motorer per kilowatt år det dessutom inte troligt att vinsten i energiverkningsgrad eller lägre utsläpp är tillräckliga skäl för en ersättning. Å andra sidan kan metanol transporteras enkelt till stora volymer och görs så idag med liten energiåtgång för transportarbetet jämfört med metanolenergin som transporteras. DME kan lätt trycksättas och hanteras som en vätska. Både metanol och DME visar lovande egenskaper som drivmedelskandidater med otto- och dieselmotor och jämfört med andra drivmedel har dessa högst energiverkningsgrad från “well-to-wheel” i ett LCA-perspektiv.

Papper- och pappersmassa och fördelar med svartlut


Ett massabruk som producerar blekt massa genererar 1,7–1,8 ton svartlut (som torksubstans) per ton massa. Svartlut representerar därmed en potentiell energikälla av 250–500 MW per massabruk. Ett modernt massabruk har ett överskott av energi, de kan därfor bli viktiga leverantörer av förnyelsebara bränslen i ett framtida system. Svartlut är idag den mest betydelsefulla källan till bioenergi i länder som Sverige och Finland med en stor pappers- och massaindustri. Det är därför av stort intresse att konvertera primärenergins i svartluten till en energibärare med högt värde.

Pappersmassaindustrin bearbetar ca 170 miljoner ton svartlut (som torksubstans) i hela världen per år med ett totalt energinnehåll om ca 2 EJ, vilket gör svartlut till ett signifikant biobränsle. I jämförelse med andra potentiella biomassakällor för kemikalieproduktion har svartlut den stora fördelen att den är delvis förädlad och är i en pumpbar vätskeform. Användandet av svartlut för metanol/DME-produktion skulle ha följande fördelar:

- Biomassalogistik är extremt förenklad eftersom råmaterialet för drivmedelsproduktion hanteras inom den ordinarie driften av massabrukets
- Processen trycksätts lätt, vilket ökar verkningsgraden för drivmedelsproduktion
- Den producerade syntesgasen har ett lågt metaninnehåll, vilket optimerar drivmedelsutbytet
- Ekonomin för massabruck bli mindre känslig för massapriser eftersom intäkterna blir diversifierade med en till produkt
Kapitalkostnaden för förgasning delas mellan återvinning av oorganiska kemikalier, ångproduktion och syntesgasproduktion.

**Energiverkningsgrad och ekonomi**


Den resulterande verkningsgraden biomassatill-metanol när bara biomassan används som en extern energikälla blev mycket hög, 66% för metanol och 67% när DME istället producerades. BLGMF-anläggningen genererar ytterligare elektricitet, uteslutande konsumerad av interna anläggningseffekter och förligger. Energiströmmar som passerar systemgränserna av de olika konfigurationerna ges nedan i Tabell 1. I den nedre delen av tabellen ges för varje drivmedel verkningsgraden delat på de två tillförselbränslen, d v s biomassan och svartlut.

**Tabell 1.** Summering av konsumerade och producerade energiprodukter.

<table>
<thead>
<tr>
<th>Bränslen</th>
<th>Metanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biobränsle, konsumtion</td>
<td>414 MW</td>
<td>408 MW</td>
</tr>
<tr>
<td>Svartlut, konsumtion</td>
<td>487 MW</td>
<td>487 MW</td>
</tr>
<tr>
<td>Drivmedel, produktion</td>
<td>273 MW</td>
<td>275 MW</td>
</tr>
</tbody>
</table>

Det bör noteras att verkningsgraden biomassatill-drivmedel skulle kunna bli signifikant högre om en biomassa-IGCC skulle användas istället för den beräknade biobränslepannan med en kondenserande ångturbin. BLGMF-anläggningen visar hur som helst som den är en mycket effektiv användning av biomassaenergi för att producera drivmedel.


Den resulterande produktionskostnaden blev EUR 29€ per bensinekvivalentliter för metanol (SEK 2,6 per b.e.liter) och EUR 32€ per dieselkevivalentliter för DME (SEK 2,9 per d.e.liter). Tabell 2 nedan summerar den inkrementella driftsintäkten och produktionskostnaden.
Tabell 2. Summering av inkrementella driftsintäkter och produktionskostnader.

<table>
<thead>
<tr>
<th>Produktionskostnader</th>
<th>BLGMF Metanol</th>
<th>BLGMF DME</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inkrementell BLGMF driftsintäkt</strong></td>
<td>M EUR/år</td>
<td>36.7</td>
</tr>
<tr>
<td>Produktionskostnad</td>
<td>EUR ¢/kWh</td>
<td>3.3</td>
</tr>
<tr>
<td>Produktionskostnad</td>
<td>EUR/ton</td>
<td>182</td>
</tr>
<tr>
<td><strong>Produktionskostnad, bensin/diesel-ek.liter</strong></td>
<td>EUR ¢/ekvivalentliter</td>
<td>28.7</td>
</tr>
<tr>
<td><strong>Produktionskostnad, bensin/diesel-ek.liter</strong></td>
<td>SEK/ekvivalentliter</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Not:

a Metanolproduktionskostnaden räknades om till kostnaden av en ekvivalentliter bensin, med bränslevärdena för den specifikerade metanol/DME bränslet och bensinvärden 11,626 MWh/ton, 750 kg/m³ vid 20 °C. På samma sätt räknades produktionskostnaden om för DME till diesel med värdena 11,750 MWh/ton, 815 kg/m³ vid 20 °C.

Känslighetsanalysen gav en mycket modest känslighet på produktionskostnaden för alla parametrarändringar (köpt biobränslekostnad, köpt elproduktionskostnad och den inkrementella investeringskostnaden) förutom tillgängligheten.

För att uppskatta den potentiella intäkten av metanol och DME beräknades ett försäljningspris av metanol och DME vid fabrik med antagandet att kostnaden för konsumenten skulle bli densamma för bensin (metanol) och för diesel (DME). Det uppskattade priset är ca SEK 2095 (€231) per ton metanol, när man beaktar dagens svenska CO₂-skatt på bensin och på samma sätt ca SEK 3100 (€341) per ton DME.

En kostnadsintäktsanalyse (IRR) gjordes för båda fallen beaktande en inkrementell investering och produktionskostnad för BLGMF-systemet relativt till en investering för en ny sodapanna. Kapitalkostnaden i den här studien har en osäkerhet av ±30% beroende av grunden noggrannhet inkluderad i kostnadsuppskattningen och den inneboende osäkerheten att projekttera en "N:e anläggnings" kostnader givet den förkommersiella statusen av BLGMF-tekniken idag. Framtida energiprisnivåer är också osäkra och priser kan variera stort från en region av landet till en annan.

Den inkrementella investeringen gav en IRR om 26% med en pay-back av 4.0 år för både Metanol- och DME-fallet (se Tabell 3).
Den återvunna svavlet kan med fördel användas i en nyutvecklad polysulfid-kokprocess vilket förbättrar ytterligare utbytet av fiber från träflisen. Med antagandet om en inkrementell massaökning av 5% och med en kapacitet om 2000 ADt/dag skulle detta ge en extra intäkt på EUR 16,5 miljoner per år räknat på ett pris av USD 550/ADt. Den resulterande extra intäkten ger en signifikant lägre produktionskostnad, EUR 22.3¢/ekvivalentliter bensin (SEK 2.0 per b.e.liter) och en högre avkastning, IRR 37% med en pay-back om 3.2 år.

**Drivmedelsmarknad och möjlig distributionsstrategi**


Det kan sammanfattnas med att **bästa användning av metanol på kort sikt är som en låginblandnings-komponent eller använd i bränsleflexibla fordon.** Eftersom inga metanolkompatibla FFV-fordon är tillgängliga på marknaden för tillfälle är användning av metanol som låginblandning mest troligt i den nära framtiden. I ljuset av begränsade utsikter för metanol drivna dieselmotorer och bränsleceller på kort sikt bör nya metanolanläggningar fokusera initialt på användning av metanol som en låginblandningskomponent. Dessutom bör DME initialt användas i avsedda flottor med dess egen infrastruktur.
Marknadspotential
Det finns totalt 236 sodapannor i världen som under de senaste 20 åren inte genomgått ombyggnationer, vilket därmed gör dem lämpliga att ersätta med förgasningsteknik. Dock har de flesta av dessa pannor relativt liten kapacitet, mindre än 500–600 tDS/dag. Många av de mindre sodapannorna har genomgått större modifieringar genom åren, t.ex. avseende ökning av torrandelen i svartluten, ombyggnad av pannan i syfte att bygga bort flaskhalsar i processen. Chemrecs BLGMF-begrepp är dock inget realistiskt alternativ för små sodapannor.

Man kan anta att en massafabrik som ersätter en föråldrad sodapanna, samtidigt eftersträvar en viss kapacitetsökning (kanske 25%) i förhållande till den gamla pannan. Ett BLGMF-system från Chemrec är ett konkurrenskraftigt alternativ för kapaciteter av ca 1000 tDS/dag och större. Detta innebär att den verkliga marknaden omfattar sodapannor med en kapacitet om 800 tDS/dag eller mer, som är äldre än 20 år och inte heller genomgått större renoveringar under denna period. Det finns 57 sådana sodapannor i världen idag, varav halften hittas i USA. Resterande pannor återfinns till största del i Kanada eller i Japan.

I takt med att fler och större sodapannor äldras kommer marknaden för Chemrecs BLGMF-system att successivt öka. I kort sikt kan samtliga 327 sodapannor i världen, med en kapacitet större än 800 tDS/dag, anses som kandidater för en framtida ersättning med ett BLGMF-system. Massafabriker med flera sodapannor byter idag allt oftare ut samtliga eller flera av sina pannor mot en större sodapanna med kapacitet om 2000 tDS/dag eller mer. Chemrecs BLGMF-system är helt uppenbart ett alternativ för lösningar av detta slag och marknaden är därmed större än vad som tidigare har föreslagits.

Potentiell bränsleproduktion och koldioxidreducering

För hela EU skulle så mycket som 61 TWh, eller 11 miljoner ton metanol kunna produceras varje år. Detta kan ställas i jämförelse med den totala förbrukningen av motorbränslen i transportsektorn och en beräknad ersättningssandel (på energibas) för varje land. Finland skulle kunna ersätta mer än 50% av sin drivmedelskonsumtion, Sverige och Portugal nära 30% respektive 10% av sin konsumtion.

In absolute terms, Sweden and Finland could produce about 4 million tonnes each, a substantial amount. Thus, the production potential in the European Union is concentrated to a few countries, which have a large potential and for Sweden and Finland extremely high replacement potential.

I absoluta mått skulle Sverige och Finland vardera kunna producera 4 miljoner ton metanol, vilket är ansenliga mängder. Således är produktionspotentialen inom EU koncentrerad till ett fåtal länder, vilka har stor potential och för Sverige och Finland mycket stor ersättningspotential.
För varje ton producerad metanol kan ca 1,5 ton koldioxid minskas med ett medelvärde om 85% kol i 1 ton bensin och med ett energivärde om 11,626 MWh. Den potentiella koldioxidreduktionen i EU om fullt implementerad är därmed 16,4 miljoner ton per år. Finland och Sverige uppfyller redan målet för Kyoto-protokollet men har en potential att reducera dagens utsläpp med 5,9 respektive 5,7 miljoner ton koldioxid, eller 11% respektive 12% för utsläppen år 2000.

Utanför Europa har Kanada en produktionspotential av mer än 7 miljoner ton metanol. Med en rapporterad konsumtion av bensin och diesel för vägtransporter är den beräknade potentiella ersättningsandelen 7,2%, vilket är förstås substantiellt, och inte tidigare uppmärksammat ger stor hjälp i åtagandet till Kyotoprotokollet att reducera den fossila bränsleanvändningen.

USA har världens största metanolpotential till storlek, men inte till ersättningsandel. Potentiellt kan enorma 28 miljoner ton metanol produceras. Detta är förvånansvärt nog redan lika mycket som hela dagens världspröduktion av metanol från huvudsakligen naturgasbaserade anläggningar, som är alla kommersiella och kan vara på 5000 t/d eller mer. Bara USAs nationella bensinkonsumtion är dock lika mycket som 1000 miljoner ton metanol eller 21 500 PJ. Den resulterande möjliga ersättningspotentialen är omkring 2,2% om också dieselkonsumtionen räknas in.
1 INTRODUCTION

There is a growing interest in finding ways to produce CO$_2$-neutral automotive fuels, by using biomass as the raw material as CO$_2$ is the main gas responsible for climate change. One reason is that the European Union committed at the UN’s climate conference in Kyoto in December 1997 to lower its CO$_2$ emissions with 8% from the level in 1990 measured as the average value of emissions during the years 2008–2012.

However, emissions from the transport sector are still growing. Road transport in particular generates 85% of the transport sector’s emissions. Furthermore, 98% of the European transport market is dependent upon oil. The external energy dependence has passed 50% and will increase to more than 70% and 90% for oil in particular, in 20–30 years if nothing is done [1]. This is viewed as economically and strategically unacceptable.

Since 1970, the number of passenger-kilometre (pkm) for cars and lorries has increased by a staggering 140% to 3800 billion pkm and goods transport tonne-kilometre (tkm) has increased by 215% to 1300 billion tkm. During same time the number of cars in the European Community trebled from 62.5 million to nearly 175 million. This trend seems to be slowing down now, but the number of private cars in the European Community is still rising by more than 3 million every year [2]. With current increase of 3% per year, it is projected that by 2020 transportation will account for a third of EU final energy carrier consumption [3].

Therefore, the European Parliament and the Council of the European Union has issued a Council Directive (2003/30/EC) on the promotion of the use of biofuels for transport. The Directive sets a minimum percentage of biofuels to replace diesel or petrol for transport purposes in each Member State. By end of 2005 a 2% minimum proportion of biofuels of all petrol and diesel fuels sold on their market must be ensured with a 0.75 percentage point yearly increase to 5.75% by 2010 with a target of 20% by 2020 [4]. In addition, a Council Directive has recently been issued modifying Directive 92/81 on excise duties on mineral oils with main products eligible to differentiated excises duties until 2010.

1.1 Alternative transport fuels

The primary route to produce CO$_2$-neutral motor fuels is through conversion of agricultural and forestry residues and organic wastes to gas (biogas), hydrocarbons (biodiesel, Fischer-Tropsch diesel), alcohols (methanol and ethanol), or dimethyl ether (DME). The hydrocarbons and the alcohols can be blended into petrol or diesel to facilitate market introduction and distribution. For example, 18% of the petrol in Sweden is today blended by 5% with ethanol (E5) without adjustments needed for the vehicles [5]. The infrastructure could likewise accommodate methanol without much change.

In the long term, conversion to hydrogen is an attractive route, but this requires far greater changes to distribution systems and vehicles. Furthermore, as long as fuel cells will be much more expensive than current engines per kilowatt it is unlikely that the gain in energy efficiency or lower emissions will be enough as argument for replacement. The cost of a modern automobile engine is roughly $50/kW and for a suitable PEM fuel cell about 5000/kW. Thus, just the engine cost for a premium 160 hp automobile would be $590 000 instead of today’s $5900. Hydrogen has physical properties that make it most unsuitable
for distribution with current materials and technology. Distributed in a liquid form the hydrogen needs conversion energy for the liquefaction, transportation and the following evaporation corresponding to 40% of the transported hydrogen energy, even at large scale. Distribution in gas form including compression to conventional gas tanks on trucks needs no less than 25% of the hydrogen energy transported. Pipelines is a better option, however, extremely hazardous and needs five times more energy for the transport work compared with natural gas [6].

On the other hand, methanol can and is transported today easily at large volumes with little energy needed for the transportation work compared with the methanol energy transported. Di-Methyl-Ether (DME) can be easily pressurised and handled as a liquid. Both methanol and DME show promising features as fuel candidates with the Otto and the diesel engine. Thus, in the present study, methods to convert black liquor to methanol or DME are evaluated. The conversion of other biomass feedstocks to renewable fuels has been investigated in a large number of studies, some of which discuss methanol production [7, 8, 9, 10, 11, 12].

Meanwhile, the pulp and paper industry is turning its attention to black liquor gasification as a possible means of improving the economic and environmental performance of the chemical pulp mill. Pressurized gasification of the black liquor has a potential to improve the mill energy efficiency, while generating conventional or modified cooking liquors and a synthesis gas (syngas). Previous concepts have mainly aimed to use the syngas in a gas turbine as part of an integrated black liquor gasification combined cycle, BLGCC, for electricity generation [13, 14, 15].

A few studies have investigated the manufacture of renewable fuels from black liquor syngas [16, 17]. Considerable efforts have been made to find ways to more efficiently utilise the energy in the black liquor but this project is a first attempt to estimate the technical and economical performance of motor fuel plant integrated with a pulp mill.

1.2 Swedish national activities

Swedish national goals aim to limit the energy and transport sectors effect on the climate. In accordance with the UN’s Framework Convention on Climate Change (UNFCCC), the greenhouse gases should be stabilised so that the humans’ effect on the climate will not be dangerous. In Sweden a national environment quality goal has been set for 2050 with a stabilisation of CO\textsubscript{2} in the atmosphere lower than 550 ppm and that the percentage of other greenhouse gases does not increase.

To achieve this goal the Swedish national energy policy calls for replacement of fossil sources to mitigate and combat the effects of increased greenhouse gases in the atmosphere. Replacement in all sectors (power, heat, and transport) is planned. The project proposed falls well within the objectives of both Swedish and European Union energy policies and, since the Kyoto-meeting, in most other regions.

Sweden studied the use of motor methanol during the 1980’s and added R&D on ethanol in the 1990’s. Currently ethanol production is located at 4 plants, with the Norrköping facility being the largest with 50,000 m\textsuperscript{3} pear year produced via conventional wheat fermentation. Currently, a subsidised SEK 137 million (€15.2 million) ethanol pilot-plant is being built in Örnsköldsvik based on weak acid hydrolysis of cellulose for production of 0.5 m\textsuperscript{3} pear
day, almost identical to a plant in Denver, Colorado financed by National Renewable Energy Laboratory (NREL).

The government authorities are now interested in finding the most economical and health & environment beneficial bio-alcohol/ether for motor fuels. In doing so, the Swedish Energy Agency (Energimyndigheten) and the Swedish National Energy and Road Administration (Vägverket) have identified alcohol as interesting/preferred in the transport sector and has indicated a policy to take a more active part in the production of bio-methanol. Gasification has been proposed as the most effective route for producing transport fuels by the above authorities and the Swedish Agency for Innovation Systems (VINNOVA) and the Swedish National Environment Protection Agency (Naturvårdsverket).

As one measure, a 4-year programme totalling SEK 56 million (€6.2 million) has been started by the Swedish Energy Agency and a complementing project, BLGMF II, to current project has been accepted for funding for estimation on same basis the production of Fischer-Tropsch diesel. Sweden and the Nordic neighbours have large black liquor biomass resources but also the resources within other parts of the European Union are substantial. The outcome will therefore be beneficial for other countries within the Union on a greater scale and to other similar projects.

The Council Directive of fossil fuel replacement will be an important driver for further development. For example, actions are currently underway by OK-Q8 and Statoil to include all petrol in Sweden to be blended by 5% with ethanol (E5) without adjustments needed for the vehicles. Tax exemption has already been declared by the government (however only for one year), which if fully used totals SEK 900 million (€100 million). On a European level, Sweden has possibly the highest replacement percentage of renewable fuels with about 2%.

1.3 Swedish authorities

Due to recent European Parliament Directive on promotion of the use of biofuels for transport four Swedish authorities have together formed a declaration of preferred Swedish future research to secure the long-term replacement of today’s fossil-based fuels. The declaration has been signed by the Director-generals from the Swedish Agency for Innovation Systems, the Swedish Energy Agency, the Swedish Environmental Protection Agency and the Swedish Road Administration.

In the highlight of recent promising Swedish research studies on methanol/DME alternative fuels they state that gasification of biomass to produce synthesis gas is a key technology and that cost-effective production and market introduction of biofuels must be developed. In addition the introduction of biofuels should occur in the form of low blending for most of the volume.

The declaration further describe that the production of synthesis gas, or syngas, (CO + H₂) by gasifying biomass or CO₂-neutral raw materials, and from natural gas, is advantageous since several different fuels can be produced from the gas. Implementing relatively small adjustments to the final stages of the process can produce either methanol or DME. Synthesis diesel and other hydrocarbons can also be produced from synthesis gas if the process is customised at an earlier stage. Hydrogen gas can also be produced from syngas.
Producing syngas from natural gas is a commercial process. This is also true concerning the production of synthetic diesel, methanol and DME from syngas. There are currently no commercial plants for the production of syngas from biomass. Neither are there any plants which manufacture ethanol from biomass (cellulose). Methanol gives a greater yield than ethanol when produced from forest raw materials. The total energy yields from the processes provide similar results, however.

The methanol process produces a lot of heat and the ethanol process gives a solid fuel residue (lignin). Some studies indicate that biofuels based on syngas provide better yields at a lower cost than cellulose-based ethanol. The advantage of syngas produced by gasification is that the end-product is almost completely independent of the raw material, which offers greater flexibility.

Lastly, they summarise with that current research into alternative fuels needs to be supplemented with the following measures to promote a long-term perspective for fuel in a sustainable transport system.

1. A synthesis gas programme should be initiated as soon as possible. This should include technological development, demonstration and full-scale biomass gasification plants. The programme should begin with the production of small volumes and scaled-up at a rate that allows us to make use of our experiences. The following fuels can be produced from synthesis gas:
   - Synthetic diesel (Fischer-Tropsch)
   - DME
   - Methanol

2. Ethanol production from cellulose should be demonstrated in a plant and evaluated.

3. A niche programme should be developed for specific vehicle fleets. The aim is better air quality in urban areas combined with CO₂ neutrality for fuel, which can already provide good cost/benefit conditions. Several fuels are still being developed and cannot be expected to provide immediate environmental benefits that are proportionate to the costs. The costs of these projects should be considered as development costs.
   - Biogas/natural gas
   - Biomass-based F-T diesel
   - Biomass-based DME
   - Electric vehicles
   - Hydrogen gas.

4. Possible short-term measures to achieve the objective of the EU directive. The objective in the directive, 2% biofuels in 2005 and 5.75% in 2010 are considered very difficult and costly to achieve. What can be done in the short-term is:
   - Maintain volumes of FAME, Fatty Acid Methyl Esters
   - Develop ethanol production and make it more efficient
   - Double the current production of biogas for fuel.
1.4 International Symposium on Alcohol Fuels

ISAF, International Symposium on Alcohol Fuels, is an international organisation working globally in the area of intersection between energy, environment and transport and holds a symposium about every second year to provide a forum for the presentation of research being conducted and practical steps towards sustainable alcohol fuel markets. ISAF has an International Organising Committee (IOC) but no secretariat, neither employees nor budget. In 2002, the main theme for the ISAF XIV was “The Role of Alcohol Fuels in Meeting the Energy, Environmental and Economic Needs of the 21st Century”.

240 delegates from 20 countries visited the conference with about 90 presentations out of a total of 111 submitted papers, which was almost twice that of last conference held in Stockholm 2000. Next conference will be held in San Diego, USA in 2004. Preliminary results from this project were presented at the conference (see Enclosures for paper). The conference with its most interesting results, views and international activities are here reported as followed.

1.4.1 Plenary panel discussion

Prof., Dr. Shuichi Kajitani, Department of Mechanical Engineering, Ibaraki University, Hitachi, Japan concluded that with current population increase the world’s population would total 8 billion in 2040. Even with keeping current levels of world oil production there is such a future demand that there is need not for alternative fuels but for additional fuels to stabilize the market. Just to keep up with the sheer volume of future petrol consumption there is a strong incentive apart from ecological, environmental and health reasons to develop additional fuels.

Prof., Dr. Kuiran Pan, Chinese Academy of Sciences, China concluded that China has a population of about 1240 million people and there is a vehicle growth of 15% per year. With coal as major primary energy supply in the country, it is a definite must to develop additional fuels to meet the expected increase of fuel consumption. For some time they have made research in coal gasification to produce methanol and recently DME, however, the petroleum companies have been reluctant to methanol because of health reasons (toxicity) which was much debated in the 80s in USA. Therefore they made a three-year methanol test and toxicity study that concluded that methanol is safer than petrol. Dr. Roberta Nichols, Alternative Fuels Consultant, Ford Motor Company, USA (Retired) who was in charge of the alternative fuel and vehicle programme in USA in the 70s and 80s focusing at that time on methanol concurred of their findings.

Dr. Paritud Bhandhubanyong, Director, National Metal and Materials Technology Center, Bangkok, Thailand concluded that if Thailand will introduce alternative fuels in the fuel market on a large scale they have to adopt tax exemption on alternative fuels, further contribute R&D funding, guarantee a price market level for distributors and introduce gasohol and diesohol as established fuel products.

Prof., Dr. Joseph M. Norbeck, Director, Center for Environmental Research and Technology – CE-CERT, University of California Riverside, USA concluded that there are an estimated 800 million vehicles around the world and in 2020 half of that market will be in Asia, which today have about only 160 million vehicles. The number of vehicles per 1000 people is about 900 for Los Angeles and less than 200 for Asian cities, but with coming years the today’s trend is that by 2020 the major Asian cities will reach this level.
There is therefore an urgent need to develop alternative (clean petrol and clean diesel) fuels maybe mainly because of the poor air quality situation and not to further add on the pollution. Reformulated petrol will be an important part of this mix and ethanol blends are in developing stages with promises of lower vehicle emissions.

Dr. Alfred Szwarc, União da Agroindústria Canavieira de São Paulo – UNICA, Brazil informed that at recent world summit meeting of greenhouse gases in September 2002 in Johannesburg, South Africa it was announced that Germany would buy carbon credits under the Clean Development Mechanism (CDM) from Brazil to a total value of $45 million for about 100,000 cars ($430 per vehicle). These credits will be sold to fleet owners and make a big step in establishing CDM projects as tool for greenhouse gas mitigations in line with signed Kyoto protocol.

### 1.4.2 Environmental and economic impact

Dr. Guido Reinhardt, Scientific Director, Institute for Energy and Environmental Research Heidelberg, Germany reported on Bioethanol and ETBE Versus Other Biofuels for Transportation in Europe: An Ecological Comparison [18]. Dr. Reinhardt has made >100 paper contributions and presented in this conference also Liquid Biofuels for Europe: “Which Ones Fit Best?” [19] in co-operation with 26 other co-author scientists from 9 organizations from 8 European countries. Their findings on an LCA environment study for which an LCA method was adapted according to ISO 14043:43 for some alternative fuels showed that methanol and DME were best choices of all agriculture products. However all products have advantages and disadvantages and therefore no objective decision were possible of one or another fuel.

Dr. J. Michael Davis, U.S. Environmental Protection Agency, USA presented Methanol: The Current Status of Environmental Health Issues [20]. Dr. Davis informed that their renewed interest on methanol was based on the development of fuel cells and the possible increased use of methanol with population exposures, which could increase well beyond that which occurs with currently limited use of methanol as an alternative fuel. In March 1996 the American Forest and Paper Association (AFPA) submitted a petition to the U.S. Environmental Protection Agency (EPA) to remove methanol from the Clean Air Act (CAA) that the U.S. Congress identified for special consideration in the 1990 CAA Amendments. However it took to February 1999 until a modified and acceptable final complete petition was submitted to EPA for review.

The APFA health assessment proposed that 83 mg/m³ was “safe exposure level”, however, EPA reviewed their assessment and found it unacceptable although AFPA had followed generally accepted procedures for derivation of inhalation reference concentrations at that time. Instead they included a more recent study in 1999 by Burbacher et al. where 12 monkeys were exposed to doses of methanol. Some evidence of developmental toxicity was found. The National Toxicology Program administered within the National Institute of Environmental Health Sciences within the U.S. Department of Health and Human Services convened a panel of 12 independent scientists from federal and state government agencies, academia and the private sector on developmental toxicity of methanol and a report was submitted in April 2002.

The panel had minimal concern or negligible concern for methanol exposure with except for developmental toxicity in pregnant women and that insufficient data exists. Two members of the panel including Dr. Davis did not concur with Section 5 of the report. EPA
Black Liquor Gasification with Motor Fuels production - BLGMF

has thus concluded that further scientific investigation is crucial and that current uncertainty is a hindrance to the development and use of methanol as a fuel.

1.4.3 Government roles and strategies

Senior Engineering Professor Peng Zhigui, Vice Chairman of Standing Committee for Shanxi Province’s People Congress Taiyuan, China presented *Five-Year Plan for the Development of Fuel Methanol and Vehicle in Shanxi Province of China* [21]. Prof. Peng concluded that the Chinese government is executing a diversified energy strategy. In 2000, China imported 70 million tonnes of crude oil and more than 30 million tonnes of oil products at the cost of $25 billion. This is a heavy burden on the national economy and seriously endangers national energy security.

However, China has abundance of coal and the proven recoverable coal reserve is estimated as 765 billion tonnes that could be used for 400 years. Consequently, the fuel of choice is coal-derived fuel methanol (or DME). China has today 16 million vehicles with an increase of two to three million annually. It has been estimated that from 2000 to 2020 there will be a 24 factor increase of cars in China while a three to four factor increase of cars in India. Already 13 of the 15 dirtiest cities are located in Asia.

Shanxi Province will be the production base for *3.7 million tonnes of methanol produced and used for demonstration of 5000 vehicles from 2002–2006*. The five-year programme is envisioned for extension to 10 million tonnes of methanol per year (current world production is 28 million tonnes) by 2007–2011.

1.4.4 Fuel technologies

Mr. Gunnar Fransson, Vice-President, Etek Etanolteknik AB, Ornskoldsvik, Sweden presented *A Pilot Plant for Ethanol from Wood Waste* [22]. Mr. Fransson informed of the current $16 million ethanol from wood project in Ornskoldsvik where the three universities of Umea, Lulea and mid-Sweden will commit themselves to build a 400–500 litre per day pilot plant at an existing sulphite pulp plant.

The ethanol plant will be based on a diluted acid hydrolysis process in two steps with a possible third step for enzymatic hydrolysis and for softwood residues as cellulose material. The second step in the reactor is a 12 bar countercurrent reactor, which has in principle the same design as the reactor at NREL, Golden, Colorado, USA.

The plant is scheduled for completion in the end of 2003 and then starts two years of verification tests, which will cost about $1–2 million in running cost. Diluted acid will be tested the first year. Basically, they have only possibility to use cellulose and sugar as raw material as enzymatic pentose fermentation has not yet been developed.

A feasibility study has been made for the studied process in a 60 million litre bioenergy combine and the results for ethanol from wood may be compared with previous studies BAL-Fuel and BioMeet II made by Nykomb Synergetics and Ecotraffic ERD_AB on wood biomass gasification plants (see Table 1.1) [7, 23].
Table 1.1. Comparison of three feasibility studies of methanol/ethanol production plants.

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<tr>
<td></td>
<td>Methanol</td>
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<td>Ethanol</td>
</tr>
<tr>
<td>Capital cost</td>
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<td>€248 million</td>
<td>€130 million</td>
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<tr>
<td>Efficiencya</td>
<td>49%</td>
<td>47%</td>
<td>37%</td>
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<tr>
<td>Efficiencyb</td>
<td>49%</td>
<td>47%</td>
<td>25%</td>
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<tr>
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<tr>
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<td>EUR 50¢/litre³</td>
<td>EUR 55¢/litre³</td>
<td>EUR 52¢/litre³</td>
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</tbody>
</table>

Notes:

a Calculated as exergy of products divided with LHV energy of reactants.
b Calculated as LHV energy of the fuel product divided with LHV energy of reactants.
c Litre petrol equivalent (adjusted for difference in volume and energy density).

In the BAL-Fuel study, ethanol from lignocellulose was investigated for several studies/processes and the reported production cost ranged EUR 60 to 68¢ per petrol litre with LHV efficiencies ranging 25 to 39% (see Figure 1.1). The production cost of ethanol in the ETEK study is remarkably lower than others reported, even on the same level as for methanol. However, it assumes sales of substantial amounts of by-product because of additional very low ethanol yield as well as high contents of convertibles (cellulose and hemicellulose) in the wood.

Figure 1.1. Comparison of reported energy efficiencies for ethanol and methanol from lignocellulosic feedstock and production costs in petrol equivalent litre.
1.5 Previous work

Nykomb Synergetics and Ecotraffic ERD³ AB participated in the “BAL-Fuels” project (Contract No.: XVII/4.1030/Z/95-124). The report titled “Feasibility phase project for biomass based alcohols for automotive fuel and industrial uses” was issued in 1998. The study defined a methanol plant, self-sufficient in energy, using biomass as feedstock for production of methanol through oxygen/steam driven gasification to be located in south Sweden producing 1000 t/d at an estimated cost of SEK 2.3/litre (€0.25/litre) or SEK 3000/tonne (€317/tonne) [7].

Nykomb Synergetics, Ecotraffic ERD³ AB, Air Products, and Trollhättan Municipality (with a consortium of Trollhättan Energy, Volvo Aero, Saab Automobile, the University of Trollhättan-Uddevalla and Vattenfall AB) participated in the “BioMeeT” project (Contract No.: XVII/4.1030/Z/98-368. The report titled “Planning of Biomass based Methanol/DME energy combine – Trollhättan region (Motor fuels, fuel gas, power, and heat by biomass gasification)” was issued in 2000 [24].

The study addressed a balanced production of various energy carriers to serve the regional energy market of the south-west Swedish cities Trollhättan, Uddevalla and Vänersborg and showed an energy conversion complex plant, based on biomass gasification, to supply motor fuels (methanol/DME), electricity & heat, and optional fuel gas for heat production.

Nykomb Synergetics, Ecotraffic ERD³ AB, Air Products, and Trollhättan Municipality (with a consortium of Trollhättan Energy, Volvo Aero, Saab Automobile, the University of Trollhättan-Uddevalla and Vattenfall AB) participated in the “BioMeeT II” project (Contract No.: XVII/4.1030/C/00-014. The report titled “Stakeholders for Biomass based Methanol/DME/Power/Heat energy combine” was issued in 2003 [23].

In order to create a principals and investors group and in order to establish the economic preconditions and obstacles the project was launched. The objective of the project was to establish a stakeholder group to prepare for the establishment of the first commercial plant of this particular kind and the product off-take basis for such a facility. Those tangible objectives are intended to provide a platform for the market introduction of methanol/DME.

1.6 Methodology

1.6.1 Project management

The present project to investigate Black Liquor Gasification with Motor Fuels (BLGMF) production was initiated within the EU ALTENER II programme in 2001 and started up in February of 2002. The work was carried out by a consortium including Nykomb Synergetics (process engineering consultant), STFI, Skogsindustrins Tekniska Forskningsinstitut (pulp and paper research company), Chemrec (process technology supplier), Ecotraffic ERD³ (automotive and environmental consultant), Volvo Group (automotive producer), OK-Q8 (national fuel distributor) and Methanex (world-wide methanol producer and distributor). The project spanned over 18 months.

Identifying and clearing the hinders for a market introduction of CO₂ neutral renewable transport fuels demands a consortium that involves the whole chain of actors, from production of renewable energy sources, process engineering with integration, fuel
distribution, to automotive use. Consequently, the consortium formed was a well-balanced group of participants, including industrial actors from several European countries, a major pulp producer, fuel distributors, automotive producer, SME consultants, and a research institute.

The result was a co-ordinated effort involving two European countries: Sweden and Belgium (Denmark and Germany with subcontractors) integrating partners’ experience and complementary skills as indicated below and in Figure 1.2, a schematic organogram with respective area responsibility:

- **Nykomb Synergetics**, a process architect engineering consultant, with experience in integration technologies for the pulp and paper industry
- **STFI**, researches centre with great experience in working and developing new technologies for pulp and papermaking. STFI handled the contacts with Södra Cell, a major pulp and paper producer (and end user) involved in the whole value chain from forest to final products.
- **Chemrec**, a process technology company, supplier of engineering and process solutions to the pulp and paper industry.
- **OK-Q8** and **Methanex**, two distributions companies, one with world-scale coverage of methanol, and other with national perspective.
- **Volvo**, a world-known automotive and engine developer.

![Figure 1.2. Project organogram with participants and related companies.](image-url)
Nykomb was the general co-ordinator of the project and responsible for the execution of the contract, for the co-ordination of the various tasks and for maintaining contact with the Commission.

STFI was responsible for the pulp mill area with support of the pulp mill (Södra Cell) and headed the activity with the project definition in Phase 1. Chemrec was responsible for the engineering and the cost estimation with support of subcontractors.

Ecotraffic was responsible for product market issues with support of Methanex and OK-Q8 and in identifying technical, legal, environmental, and economical hinders for a successful development to market introduction. They were also responsible for the automotive use and its perspectives of performance, with support from Volvo.

### 1.6.2 Project approach

In general, to calculate plant economics in a feasibility study the reference is usually a separate plant, which can be self-sustained in energy and services and at a “greenfield” site or at an industrial “brownfield” site. However, to justify a replacement investment at a plant and replacing an existing process where the economic life has ended, we have decided to calculate an incremental investment cost with incremental production costs. This is the normal procedure, as in this case the host (the pulp mill owner) can choose between investing in the same technology — a new recovery boiler — or in a new technology, the gasification plant (BLGMF). Thus, the investment decision would normally be based on a comparison between the two alternatives: a) reference mill with a recovery boiler and b) same type of mill with a BLGMF plant. It should therefore be noted that the results in this report are based on a comparison and that the incremental investment cost and production costs are calculated.

In the short term, the goal was to establish the preliminary engineering and a cost estimate for calculating the economic performance of a BLGMF system. In addition, the proposed actions lead to a checklist of necessary conditions for a market introduction of renewable fuels. The long-term goal was to initiate a broad interest group in the European pulp and paper industry to support the development of such a system. The project comprised six main phases:

- **Phase 1.** Technology selection (gas cleaning and methanol/DME synthesis) and engineering design information. Here the process plant units were specified and battery limits identified. The acquired engineering design information formed the basis for Phase 3 of engineering and cost estimation.

- **Phase 2.** Overview of product market situation, competitive economic strategy to implementation. Here the market was analysed and barriers identified for a market introduction of renewable transport fuels. Specifically, discussions were held with biomass resource owners (such as pulp and paper companies) and their interest organisations, trade and development industries and engineering companies related to motor fuels production, oil companies (distributors), and motor industry companies.

- **Phase 3.** Engineering design work on process units with conceptual and basic plant design establishing battery limit specifications and cost data. Here the obtained engineering design information from Phase 1 was used as base for performing preliminary engineering of the process plant with attention to process integration with the mill’s energy and chemicals system.
**Phase 4.** Necessary conditions for implementation of a system using motor alcohols/ethers were identified. A potential stakeholder group was identified with local community representatives and entrepreneurs, national and regional energy authorities/companies, auto and oil companies. Strategic economic solutions were sought to any technical, environmental, organisational, legal and economic barriers.

**Phase 5.** Investment estimation with capital investment cost and operating costs for the plant financial modelling. Here the technical and economical performances were measured against certain parameters for sensitivity. A number of plant configurations were used as input data.

**Phase 6.** Dissemination of project results. Along the project duration time, information and project results were presented at various conferences, seminars and to authorities and interest groups.

### 1.7 Objectives

The project aimed to combine

a) Finding new efficient use of the energy in black liquor from pulp mills by high pressure, oxygen blown black liquor gasification and methanol/dimethyl-ether (DME) synthesis production as renewable CO\(_2\) neutral fuels for automotive uses, and

b) Identifying and clearing of market hinders (e.g. technical, environmental, legal and economical) for a successful market introduction of methanol/DME as renewable transport fuels.

The main objectives were:

- To study the process integration of the Black Liquor Gasification with Motor Fuels production (BLGMF) system with an existing, and a future modern ecocyclic, pulp mill for the production of renewable energy sources in the form of CO\(_2\) neutral fuels for automotive uses. The emphasis of the study was to use existing conditions for creating added value for the pulp mill industry.

- To study the technical and economical feasibility of black liquor gasification integrated with methanol/DME production as motor fuels for automotive uses. A preliminary engineering study made for the plant with a ±30% cost estimate.

- To investigate a group of stakeholders willing to support preparations for investments for developing resources, for plant construction and for marketing of renewable energy products.

- To define the economic framework conditions and identify barriers of various kinds and market obstacles to implementation of said project under conditions for private enterprises.

The proposed actions would be first concrete steps to biomass-derived methanol/DME production based on black liquor gasification as alternative CO\(_2\) neutral motor fuels in the transition into a long-term sustainable energy system.
2 BACKGROUND

2.1 Pulp and papermaking

2.1.1 General introduction

The European pulp and paper industry is a vital part of an economic cluster – the paper and forest cluster – that generates an annual turnover of more than EUR 400 billion. In 2002, more than 1260 pulp and paper mills produced a total of some 91 million tonnes of paper and board. The industry provides direct employment for about 250 000 people, and indirect employment – through the paper and forest cluster – for a total of 3.5 million people (according to CEPI 2003).

Most of the pulp and paper produced today (90%) originates from wood. The major components of softwoods (e.g. pine, spruce) as well as hardwoods (e.g., birch, aspen, eucalyptus) are cellulose (40–50%), hemicellulose (25–30%) and lignin (25–30%). Extractives constitute a minor part.

Pulp for paper production is obtained via two classes of processes that differ greatly in principle:

- Mechanical pulping, in which the fibres are separated mainly through mechanical treatment in refiners. Most of the wood thus becomes pulp, including the lignin.
- Chemical pulping, in which the fibres are separated mainly through chemical treatment in either acidic or caustic solutions. These processes aim to separate the lignin from the cellulose fibres.

Due to their high lignin content, mechanical pulps quickly become yellow in colour. They are therefore used mostly for products with a short life span, such as newsprint and magazine paper. Another reason that mechanical pulps are used in these products is that they contain large fractions of relatively short fibres and fibre fragments; therefore they make dense and opaque sheets that are suitable for printing paper. Approximately one third of the pulp produced in the European Union is mechanical pulp.

Chemical pulps constitute the other two thirds of the pulp production. These pulps are characterised by high strength and, if bleached, by high brightness and long-term brightness stability. Typical products made from bleached chemical pulp include fine paper, tissue, and a number of board grades. Unbleached chemical pulp is mostly used to produce corrugated board and sack paper.

Out of the total fibre furnish used for papermaking in Europe, about half the pulp is supplied directly from the processes above as "virgin fibre". Recovered paper makes up the remaining fraction, which has increased from 40% in 1990 to 54% in 2002 (FAOSTAT 2003, Table 2.1).
Table 2.1. Fibre furnish used in the production of paper in the current 15 member states of the European Union.

<table>
<thead>
<tr>
<th>European union (15)</th>
<th>Year</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical pulp</td>
<td>18 264 000</td>
<td>19 411 000</td>
<td>21 180 100</td>
<td>22 904 400</td>
</tr>
<tr>
<td>Mechanical pulp</td>
<td>11 992 000</td>
<td>11 624 000</td>
<td>11 908 600</td>
<td>11 574 000</td>
</tr>
<tr>
<td>Recovered paper</td>
<td>20 489 000</td>
<td>28 291 000</td>
<td>29 943 271</td>
<td>40 031 740</td>
</tr>
<tr>
<td>Total</td>
<td>50 746 990</td>
<td>59 327 994</td>
<td>63 033 969</td>
<td>74 512 142</td>
</tr>
</tbody>
</table>

In addition to pulp, paper contains up to one third of additives and coatings that are used to give the product certain desired properties or simply to reduce the cost of the finished product. Additives include alum, starches, clays and sizing agents, all of which are intended to increase the density of the paper, and provide a good printing surface. Coatings are often applied to make the paper suitable for modern, high speed printing processes. While several processes are used, all involve the application of a thin coat of clay or calcium carbonate pigments, and binders such as starch or polyvinyl alcohol. The coat is dried to give a very uniform and smooth surface.

From energy point-of-view the two classes of processes differ greatly. Mechanical pulping consumes electrical energy, which to some extent is recovered as steam and usable low-grade heat. Only a small fraction of the wood is dissolved in the process. In contrast, about 50% of the wood are dissolved in chemical pulping. The processing of this dissolved organic substance can make a mill self-sufficient in energy and, depending on the type of product, even generate a surplus of steam or electricity. It is this dissolution of the energy-rich lignin fraction from the pulp fibres that makes chemical pulping an interesting candidate for the production of liquid fuels from biomass.

The dominant process for chemical pulping (at about 90%) is the kraft process, sometimes called the sulphate process. It will therefore be described in greater detail below.

2.1.2 Kraft pulping process

Nearly all of today’s paper is manufactured by a century-old sulphur-based chemical process known as the “kraft pulping” process. In Figure 2.1 a schematic is shown of a modern kraft mill that produces bleached market pulp. Many mills have integrated pulp and paper production where only a part of the pulp production, or none at all, is sold on the market. In principle, in an integrated mill, the pulp dryer in Figure 2.2 is replaced by a paper machine.

The process starts in the wood yard where logs are debarked and cut into wood chips a few centimetres in length. It is also common for mills to use a fraction of purchased sawmill chips. The wood chips are impregnated with cooking liquor and then fed to the digester, commonly of the continuous type, although there are many mills that use batch digesters as well. The residence time in the digester is several hours, during which the chips are cooked at a temperature of 150–170 °C under strongly alkaline conditions and in the presence of sulphide. The main objective is to dissolve as much of the lignin as possible while minimising the simultaneous dissolution of the carbohydrates.
Sulphide has two positive effects; it both reduces the reaction rate for carbohydrate dissolution and increases the delignification rate. The drawback is that small amounts of sulphide react to produce organic sulphur compounds such as methyl mercaptan and dimethyl sulphide. The odour threshold for these compounds is very low, and despite the efficiency of modern collection systems for odorous gases there is always a characteristic smell from a kraft pulp mill, which may be almost negligible under continuous trouble-free operation, but becomes evident during up-sets or accidental spills.

The pulp produced in the digester is washed to recover the cooking liquor and reduce the carryover of dissolved organic material to the oxygen delignification stage. This stage is more selective than cooking, i.e. the yield loss is smaller per unit of lignin removed. After further washing, the pulp goes to the bleach plant. Final bleaching is still more selective than oxygen delignification and is usually done in a sequence of acidic and alkaline stages with washing in between the stages. The most common bleaching chemicals used today are chlorine dioxide and hydrogen peroxide. After final bleaching the lignin content is very low, giving the pulp high brightness stability.

In a market pulp mill, the bleached pulp is dried with hot air in a pulp dryer before it is baled and shipped to the customers (paper mills). In an integrated mill the pulp is not dried but pumped to the paper machine, where it can be mixed with other pulps and additives to give the paper its desired properties. Even integrated mills sometimes produce market pulp, since the optimal size of a pulp mill is larger than that of a paper machine.

**Figure 2.1.** Schematic of a modern kraft pulp mill with its process units. In a BLGMF system only the recovery boiler (marked with red dotted box) has to be replaced.

### 2.1.3 Recovery cycle

An extremely important part of the pulp mill is the recovery cycle, which is shown as the circle in the centre of Figure 2.1. In this cycle, energy is recovered from the dissolved
organic material and the cooking chemicals are regenerated. Without the recovery cycle, the process would be both economically and environmentally impossible. A more detailed drawing is shown in Figure 2.2.

The raw material for the recovery cycle is the cooking liquor that has been displaced during washing of the pulp. Due to its colour, it is called black liquor. It contains approximately half of the organic material that was originally in the wood and almost all of the inorganic chemicals that were used for delignification. The solids content of the black liquor is relatively low when it is withdrawn from the digester, and to produce a combustible material the black liquor is evaporated to high dryness in a multi-stage evaporation plant.

After evaporation, the black liquor is burned in the recovery boiler, often referred to as a Tomlinson boiler after its inventor. By employing a staged combustion process, the conditions in the furnace can be reducing at the bottom and oxidising at the top. In this way, the sodium and sulphur can be recovered as molten sodium sulphide and sodium carbonate – called smelt – that is tapped from the bottom of the boiler. Meanwhile, the organic material is completely oxidised in the upper parts of the furnace to provide heat for high pressure steam generation.

After the smelt has been dissolved in weak wash it is known as green liquor. Before it can be reused in the cooking process, the carbonate ions in the liquor need to be replaced by hydroxide ions. This is done through a process called causticising where the green liquor reacts with quick lime to produce calcium carbonate and sodium hydroxide. The result is called white liquor, which is the cooking liquor needed to start the delignification process again.

The calcium carbonate formed in the causticising vessels is washed (giving weak wash) and then burned in the lime kiln to regenerate the quick lime. The kraft process is thus nearly self-sufficient in the production of the major chemicals used for cooking. Small amounts of sodium and sulphur must sometimes be added to compensate for losses. The most common make-up chemical is sodium sulphate, which has given the process its alternative name. Due to steadily increasing closure of the process the natural losses are diminishing, and it is therefore necessary in some mills to purge sodium and sulphur rather than supplying them as make-up.

2.1.4 Modern mills

A modern kraft pulp mill is energy self-sufficient; it can produce all the steam and power that is needed for the process as well as a surplus (see later chapter for a detailed energy balance). The major part of the energy comes from the combustion of black liquor in the recovery boiler. The second boiler on site (power boiler in Figure 2.1) is used to burn the bark and sometimes biosludge from the effluent treatment. In older, less energy-efficient, pulp mills and in most integrated mills, purchased fuels are also burned in the power boiler. These are mostly wood fuels, but some oil is also used. The lime kiln is then usually fired with oil or natural gas, but in modern market pulp mills the surplus of biofuels is used to provide heat also for the lime kiln. Available methods include bark gasification and direct firing of pulverised bark.
High-pressure steam is generated in both boilers, and electric power is generated in one or two back-pressure steam turbines. The heat demand of the mill is usually split between two steam levels, medium pressure at 10–12 bar(a) and low pressure at 4–5 bar(a).

The logistics of handling biomass feedstock are well developed around a pulp mill. Large mills that produce on the order of 2000 tonnes of pulp per day handle 3–4 million cubic metres of wood per year. In energy terms, the wood that is processed corresponds to 800–900 MW.

![Simplified flow diagram of the chemical recovery cycle in the kraft pulping process.](image)

**Figure 2.2.** Simplified flow diagram of the chemical recovery cycle in the kraft pulping process.

### 2.1.5 Black liquor

As it exits the digester, the black liquor contains 15–17% solids, consisting of dissolved organics from the wood and spent pulping chemicals. A typical pulp mill uses several hundred tonnes of inorganic chemicals per day. For both environmental and economic reasons, it is desirable to recover and recycle these chemicals. Black liquor has a high organic content from the dissolved lignin and carbohydrates, and in concentrated form (>60% solids) it burns in a manner similar to heavy oil. In a modern pulp mill, the black liquor is usually concentrated to 70–80% dry solids.

A typical black liquor composition is shown in Table 2.2. The inorganic content is high – about 45% of the black liquor exits the recovery boiler as smelt. The heating value per tonnes of black liquor solids is thus relatively low, despite the fact that black liquor is rich in lignin, which has a higher heating value than the other major components of the wood.
Note that it is common practice to correct the heating value for both hydrogen content (as for all fuels) and sulphur content, since the desired product from the recovery boiler is sodium sulphide rather than sodium sulphate (the latter is formed in the bomb calorimeter).

A mill that produces bleached kraft pulp generates 1.7–1.8 tonnes of black liquor (measured as dry content) per tonne of pulp. Black liquor thus represents a potential energy source of 250–500 MW per mill. As modern kraft pulp mills have a surplus of energy, they could become key suppliers of renewable fuels in the future energy system. Today, black liquor is the most important source of energy from biomass in countries such as Sweden and Finland with a large pulp and paper industry. It is thus of great interest to convert the primary energy in the black liquor to an energy carrier of high value. The amount of black liquor available in different regions is discussed in later chapter.

### Table 2.2. Elemental analysis and heating value of black liquor solids (corresponds to the composition used for the balances in later chapter).

<table>
<thead>
<tr>
<th>Black Liquor Composition</th>
<th>% Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>35.7</td>
</tr>
<tr>
<td>H</td>
<td>3.7</td>
</tr>
<tr>
<td>S</td>
<td>4.4</td>
</tr>
<tr>
<td>O</td>
<td>35.8</td>
</tr>
<tr>
<td>Na</td>
<td>19.0</td>
</tr>
<tr>
<td>K</td>
<td>1.1</td>
</tr>
<tr>
<td>Cl</td>
<td>0.3</td>
</tr>
<tr>
<td>N</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total (%)</td>
<td>100.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combustible Characteristics</th>
<th>% Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL, Dry Solids</td>
<td>80%</td>
</tr>
<tr>
<td>HHV</td>
<td>14.50</td>
</tr>
<tr>
<td>NHV</td>
<td>12.29</td>
</tr>
</tbody>
</table>
Recovery boiler

As indicated above, pulp mills of today process the black liquor in large recovery boilers (shown in Figure 2.4), which are similar in principle to other large-scale boilers, e.g. those burning pulverised coal. The inorganic cooking chemicals are not burned, but rather fall to the bottom of the boiler to form a smelt bed of molten salts. The smelt flows out of the boiler and is dissolved with weak wash in a tank to form green liquor, which is then processed further as described previously.

The distribution of recovery boilers in Europe can be seen in Figure 2.3, where some are gathered in large mill clusters with a large recovery boiler capacity and some others are isolated, however equally important. In general, about one third of the capacity (and consequently black liquor production) are located in Sweden, one third in Finland and the remainder on the European continent.

![Figure 2.3. Distribution of recovery boilers and their capacities in Europe and consequently production of black liquor, the basis for alternative fuels production.](image)

In the recovery boiler, the energy released from black liquor is recovered and used to generate steam to provide heat and power for the mill. Due to the extremely high alkali content of the fuel, the steam parameters must be chosen very conservatively. An amount corresponding to as much as 6–7% of the black liquor solids is recovered in the form of dust in the flue gas path. The dust tends to stick to heating surfaces; if these deposits melt completely they are very corrosive, and it is therefore vital to keep superheater surface temperatures relatively low. The most advanced recovery boilers operate at steam...
temperatures close to 500 °C, which is well below that of other advanced boilers even those designed for biomass combustion.

To avoid plugging due to deposits, the heating surfaces in the flue gas path are more widely spaced than in conventional boilers, and a large number of sootblowers are installed in all sections. The steam requirements for sootblowing are considerable, 4–5% of the total steam production in a new boiler, but sometimes much higher in boilers that are operated far above their design capacity.

![Diagram of recovery boiler system]

**Figure 2.4.** Example of a recovery boiler system (data correspond to the balances in Chapter 5). Non-condensable gases (NCGs) are odorous gases collected in various parts of the pulp mill.

Dust that is not captured in the heater sections is removed in an electrostatic precipitator before the stack. Most of the dust is recycled to the black liquor. A small part may be purged to control the concentrations of sodium, sulphur, chlorine and potassium in the liquor cycle.

Sulphur is captured very efficiently in a recovery boiler, especially when the solids content of the black liquor is high, which gives a higher smelt bed temperature. The thermodynamic equilibria are then favourable for sodium sulphide formation. NO\textsubscript{X} formation is relatively low due to low local combustion temperatures. Emissions are therefore almost exclusively related to the nitrogen content of the black liquor.

The recovery boiler represents proven and relatively mature technology – a well-designed compromise between a chemical reactor and a steam boiler – but it is not without weaknesses. From an operating point-of-view the greatest complication is the risk for smelt-water explosions. If water reaches the smelt bed (e.g. due to a leak in a floor or wall
tube) the result is a violent reaction that often leads to rupture of the entire boiler construction. Despite advanced emergency shutdown procedures and leak detection systems, accidents occur with an average frequency of one to two per year. Some accidents lead to fatalities, but even under better circumstances the economic consequences are considerable since the mill cannot operate for months when the boiler is shut down.

2.2 **Black liquor gasification (BLG)**

2.2.1 **Introduction**

Gasification of black liquor is an alternative recovery technology that has gone through a step-wise development since its early predecessor was developed in the 1960s (Bergholm, 1963). The currently most commercially advanced BLG technology is the CHEMREC® technology, which is based on entrained-flow gasification of the black liquor at temperatures above the melting point of the inorganic chemicals. The history and current status of BLG and the CHEMREC® technology is described in Appendix 1.

In a BLG system, the recovery boiler is replaced with a gasification plant. The evaporated black liquor is gasified in a pressurised reactor under reducing conditions. The generated gas is separated from the inorganic smelt and ash. The gas and smelt are cooled and separated in the quench zone below the gasifier. The smelt falls into the quench bath where it dissolves to form green liquor in a manner similar to the dissolving tank of a recovery boiler.

The raw fuel gas exits the quench and is further cooled in a counter-current condenser. Water vapour in the fuel gas is condensed, and this heat release is used to generate steam. Hydrogen sulphide is removed from the cool, dry fuel gas in a pressurised absorption stage. The resulting gas is a nearly sulphur-free synthesis gas (syngas) consisting of mostly carbon monoxide, hydrogen and carbon dioxide.

2.2.2 **BLGCC**

Most of the development of large-scale systems for BLG has been aimed at using the syngas to fire a gas turbine in which power is generated. The hot flue gas from the gas turbine is then used to generate steam in a waste heat boiler, and the generated high-pressure steam is used in a steam turbine for additional power generation. The concept is known as BLGCC (Black Liquor Gasification Combined Cycle). It is described here to provide background information. The alternate route for the use of the syngas, i.e. synthesis of motor fuels, is what has been investigated in the present project. The new concept, Black Liquor Gasification with Motor Fuels Production, (BLGMF) is described in next chapter.

The use of BLGCC, as compared to a recovery boiler system, increases the potential to generate power and reduces the heat surplus of the mill. Because a large amount of the sulphur can be separated from the smelt the possibility to generate liquors with different sulphidity increases. This is of interest to be able to further optimise the kraft cook. For example, it is easier to divide the sulphur between different white liquor streams for modified cooking. It is also straightforward to produce elemental sulphur from the H₂S gas if the plant is integrated with a Claus reactor. Sulphur can be mixed with cooking liquors to produce polysulphide and then returned for use in impregnation.
The gasification process is described in Figure 2.5. At the heart of the process is an oxygen-blown, entrained-flow gasifier. The gasifier can be either ceramic-lined or have water-cooled walls.

Figure 2.5. Black liquor gasification combined cycle (BLGCC) with air separation unit (ASU), gasifier and syngas cooler, acid gas removal (AGR), sulphur recovery unit (SRU), gas turbine (GT), heat recovery steam generator (HRSG) and steam turbine (ST). The flowsheet shows sulphur recovery in a Claus plant. Another alternative is reabsorption of H₂S in white liquor.

The alkali smelt, with a relatively low content of sulphide, from the gasification plant is dissolved and forms green liquor. The green liquor is causticised in the conventional manner before the separately recovered H₂S sulphur is returned to the white liquor. Hydrogen sulphide removal from the gas is preferably done by physical absorption in a conventional acid gas treatment plant. Some CO₂ is absorbed both when the gas and smelt are quenched with weak wash and when the H₂S is reabsorbed in the white liquor. The causticising plant is of a conventional type, but it requires a larger amount of lime from the lime kiln due to the higher fraction of alkali present as carbonate in the green liquor. A more detailed description is given in Berglin et al. (1999).

2.2.3 Process integration

The cleaned pressurised gas is fired in a gas turbine of industrial, heavy-duty type. The gas turbine model chosen is representative of large machines currently being used for cogeneration as well as in stand-alone combined-cycle power plants. There is also considerable experience from operating these on gasified coal and oil. Black liquor syngas is similar in composition to the one obtained from coal or oil gasification.
The expanded flue gas is cooled in a boiler producing HP, MP, LP, and LLP steam. The high-pressure steam is passed through a back-pressure steam turbine before it is used by mill consumers. The steam turbine is smaller than in a recovery boiler system because the steam production is lower and a large fraction of the MP and LP steam is generated directly in the gasification plant.

The incineration of malodorous weak gases calls for another solution than in the conventional mill where they are destroyed in the recovery boiler. The strong gases can be burned in a dedicated incinerator or in the lime kiln. Between 2 and 3 percent of the sulphur captured in the gas cleaning unit will also leave with tail gases from the sulphur recovery unit, adding to the amount of strong gases.

Since precipitator ash is not generated, purging of potassium and chloride would call for another process, e.g., evaporation and crystallization of a part of a green or white liquor stream. On the other hand, control of the sodium and sulphur balances would be facilitated by the fact that Na and S are enriched in separate streams.

If the H₂S is reabsorbed to make conventional green liquor there is no effect on the pulp properties. However, there is a potential to use modified cooking liquors with different sulphide contents, in particular a polysulphide liquor. Polysulphide impregnation improves yield by retaining more hemicellulose. Because wood represents the dominant operating cost in a pulp mill, a higher yield can provide a substantial economic benefit. On the other hand, pulps rich in hemicellulose sometimes exhibit lower tear strength than conventional kraft pulps, which may reduce their value in some applications.

Combustion in the gas turbine takes place at a high pressure and temperature, which are conditions that promote the formation of thermal-NOₓ. Conventional low-NOₓ burners cannot be used for synthesis gas, because the flame propagation speed is too high. The main methods to prevent NOₓ formation are therefore steam or nitrogen injection. In addition to this, the nitrogen in the black liquor will form ammonia that may increase NOₓ emissions if it is incinerated with the sulphur-containing gases.

The physical absorption system used to remove H₂S is designed so that SO₂ emissions are on par with those from the recovery boiler. Higher removal efficiencies can be achieved but at a higher cost. To minimise CO₂ absorption, some H₂S will be allowed to slip through the reabsorption system. These gases are burned with the weak gases.

### 2.2.4 Performance

The power generation in the gas turbine corresponds to about 138 MW for a model mill producing 2000 ADt/day, and the total power generated is 2070 kWh/ADt. The auxiliary power consumption is also much higher, however, than in the Reference Mill, mainly because of the compression requirements for air separation. Nevertheless, the amount of excess power that can be sold to the grid nearly doubles compared to the same mill with a recovery boiler system.

A general disadvantage of a black liquor gasification combined cycle process is the limited flexibility of the gas turbine. It is only possible to purchase units with fixed capacities i.e. they cannot be tailor-made as is possible with steam turbines, and they are not very flexible, from an operational point of view. Their efficiency decreases significantly when they are operated at part load. It is normal that a pulp mill capacity increases considerably during its first five to ten years after start-up. At different times there will therefore be a
mismatch between the amount of gas produced and the amount of gas that can be fired in the gas turbine. If the gas turbine is undersized relative to the amount of gas, some of the gas will be burned in the heat recovery steam generator; this leads to a decrease in power generation efficiency, but the overall efficiency increases. If there is another gas turbine fuel available, the gas turbine can be oversized relative to the fuel gas flow only.

### 2.2.5 BLGMF

A novel concept here developed from the BLGCC is the Black Liquor Gasification with Motor Fuels production (BLGMF) system is an alternative for processing black liquor and is intended to replace the conventional recovery boiler. A schematic drawing of the BLGMF system is shown in Figure 2.6. The gasifier/quench system is analogous to the recovery boiler system in the respect that it converts black liquor into green liquor. But rather than burning the black liquor to form steam, the BLGMF system partially converts (gasifies) the liquor with oxygen to produce a synthesis gas and a molten salt smelt. The gas and smelt are cooled and separated in the quench zone below the gasifier. The smelt falls into the quench bath where it dissolves to form green liquor in a manner similar to the dissolving tank of a recovery boiler (Figure 2.4).

![Figure 2.6. Black liquor motor fuel system (here with optional auto-thermal reformer).](image)

The raw fuel gas exits the quench and is cooled in a counter-current condenser. Water vapour in the fuel gas is condensed, and this heat release is used to generate steam. Hydrogen sulphide is removed from the cool, dry fuel gas in a gas cleaning stage and the synthesis gas is compressed and converted into methanol or alternatively DME in a synthesis reactor.

The raw methanol/DME is further distilled and a clean product is obtained. Additional steam and power are needed for the compression, synthesis and distillation units. This is foreseen at being produced in an adjacent power boiler, which is fed with extra biomass. With this process scheme, almost 70% of the extra biomass energy is transformed to
methanol/DME, giving an exergy efficiency about twice that of a recovery boiler system. The extraordinary methanol/DME output of a black liquor motor fuel system offers the potential to significantly reduce fossil fuels used for transport. In short, “green” methanol/DME from biomass and black liquor replaces fossil fuel-based energy.

Aside from energy-related advantages, a black liquor motor fuel system offers improved environmental performance and safety compared to a recovery boiler. Efficient sulphur removal from the fuel gas before the synthesis results in significantly lower levels of reduced sulphur compounds exiting the system, thus eliminating the disturbing pulp mill smell. The lack of a smelt bed in the gasification reactor also means that there is no risk for a deadly smelt-water explosion inherent with recovery boilers.

2.2.6 CHEMREC® high temperature gasification

The pressurised, oxygen-blown Chemrec system provides a totally new approach for the recovery of chemicals and energy for chemical pulping processes. A demonstration programme was initiated in Sweden 1997 with a comprehensive FABEL grant of €26.4 million provided by the Swedish Energy Agency. Awaiting the development, an atmospheric version, Boostern is currently in demonstration. The world’s only commercial black liquor gasifier, developed by Chemrec, has been operating for more than two years. The atmospheric Booster is a 300 tonnes dry solids/day unit located at Weyerhaeuser’s New Bern mill in North Carolina, USA (see Figure 2.7 and Figure 2.8).

Figure 2.7. New Bern Booster plant under construction. Work has been started on the building to house the Booster © Chemrec 1998.
Figure 2.8. New Bern Booster plant in December 1998. The large building to the right houses the recovery boiler and the Booster is placed in the smaller left building. © Chemrec 1998.
3 PROCESS PLANT DESCRIPTION

3.1 Introduction

3.1.1 Scope of engineering work

To make a preliminary engineering model of the BLGMF (black-liquor-gasification-to-motor fuels) production plant with all process units including a biomass power boiler to provide the required heat and power to the mill. The model should be dimensioned as a commercial industrial full-scale plant and be located at a large pulp and paper mill producing 2000 tonnes (ADt) per day of paper pulp.

The preliminary engineering work will be based on the following assumptions:

- No further R&D is needed and no technology gaps remain to be solved before the realisation of such large-scale unit can be accomplished.
- The plant concept shall be an “Nth plant” assuming that all units as well as the integrated plant concept are technically proven and reliable and illustrates the features of a typical commercial unit and not a first of a kind plant.
- Identification of investment/Capital costs. The preliminary engineering model and the calculated technical performance of the plant which will serve as basis for financial modelling. Investment costs will be based on quoted budgetary information from vendors and on in-house data from previous projects for process units in the same size or that differ no more than 35% in size.
- Identification of operating costs. The applied running costs used in the financial modelling should reflect expected cost levels for a future plant in present values (3Q-2003). The perspective for the price level is what can be prognosed or predicted from the horizon of today e.g. regarding electric power price, biofuels, salaries, taxes and the produced renewable motor fuels. The financial model should also include sensitivity illustrations for a variety of important cost items.
- Definition of accuracy. The accuracy estimated is ±30% for the engineering effort applied in this study. The cost estimate for most process units is based on costs of major equipment while other plant costs are factored. The work does not include detailed dimensioning of various parts and pieces. On the other hand it is important to notice that each plant unit is well-known by the sub-supplier and therefore the sub-unit can be regarded as a package with well defined battery limits and performance.

Base case

The base case described in this report focuses on a new process concept using the black liquor for producing motor fuels without introducing any other process improvements that could enhance the performance of a pulp mill. The base case described will handle the recycling of sulphur via absorption of H$_2$S into white liquor from the pulp mill. This concept will produce white liquor with the same performance as from a recovery boiler based system.
Alternate integration concepts

A gasification based concept will offer new potential advantages for the chemical recovery in a pulp mill. Switching from combustion to gasification means new opportunities to produce new cooking liquors that are difficult to produce with the conventional technology. The alternate integration concept described will lead to a new way of producing polysulphide cooking liquor which is known to increase the overall pulp yield with up to 5 percentage points which means a significant improvement of the plant earnings. Producing more pulp product from the incoming wood also means that there will be less black liquor and thus less motor fuels produced from the same plant scale.

3.2 Project definition

The principle idea behind the project is to convert a conventional pulp mill of today into a pulp mill that also produces methanol or DME via gasification of black liquor. To give a background, this section will here begin with a brief description of a conventional kraft (sulphate process) pulp mill of today as shown in Figure 3.1.

The incoming wood is normally transported from the forest by trucks in the shape of fairly thin timber without roots and branches. The timber is stored outdoors in the wood yard and soaked with water to prevent drying.

Before the wood can be treated, it has to be prepared in order to minimize cooking time and the required amount of expensive cooking chemicals. Since the bark does not become paper pulp it would just consume cooking chemicals in the digester. Therefore all bark is peeled off and the bare timber is chopped into equally sized chips that are usually in a one-inch size. The removed bark is sent to the bark boiler for combustion and adds a portion of the heat and power needed in the pulp mill.

The wood chips are then pumped into the digester where the delignification takes place in white liquor (Na$_2$S + NaOH) at elevated temperature and the pure cellulose fibres (pulp) are released. The pulp is separated from the thin black liquor, which is the mixture of spent cooking chemicals and wood residue (lignin). The raw pulp is then ready but is often further treated in bleaching units and can be exported either as wet or dry pulp.

3.2.1 Chemicals recovery

In order to enable efficient combustion, the thin black liquor is concentrated in the evaporators to a dry solids content of >70%. The evaporator plant normally consists of 5–6 evaporator units in series heated by steam. In the recovery boiler, the black liquor is combusted whereby the inorganic sulphate salts are regenerated (reduced to Na$_2$S). Only a part of the black liquor energy is needed for the (sulphate) reduction and the remaining part is used for production of HP-steam. The steam is fed to back pressure turbines generating electric power and the pass out steam is used for heating purposes in the pulp mill (evaporation, digester, bleaching, drying, etc).

The recycled chemicals from bottom of the recovery boiler are in a melted state and are dissolved into water and then forms green liquor that besides from Na$_2$S also has a large content of soda (Na$_2$CO$_3$). In order to become active the soda has to be reduced to NaOH, which is accomplished in the causticizing by adding burnt lime (CaO). The reduction of soda to NaOH is made by adding lime, which is then oxidized to limestone, CaCO$_3$. The
limestone is reduced back to lime by calcination in a bark (or biomass) fired lime kiln where CO$_2$ is driven off at near 900 °C and recycled. Na$_2$S and NaOH together form white liquor and are recycled back to the digester to again be used as cooking chemical.

**Figure 3.1.** A flow scheme illustrating the more vital units and liquor streams in a conventional kraft pulp mill (sulphate based) with recovery boiler.

### 3.2.2 Scope of plant

The changes in the pulp mill are illustrated by comparing Figure 3.2 and Figure 3.3 below, where Figure 3.2 shows a conventional pulp mill and Figure 3.3 shows a pulp mill with BLGMF. The BLGMF plant is further described in Section 2.1.2.

The BLGMF plant scope comprises all units in the plant from black liquor to motor fuel process and a new biomass power boiler, which is significantly larger than the existing bark boiler, which is replaced by the new boiler. Necessary changes within the existing pulp mill are also part of the scope.

A CHEMREC® type of pressurised entrained flow gasification process is the chosen basis for the preliminary design and represents a developed process with high conversion efficiency.

### 3.2.3 Definition of battery limits

The block diagram in illustrates the main blocks in a conventional pulp mill. Figure 3.3 shows the same process where the recovery boiler has been replaced with a BLGMF-plant and a modern power boiler.
The BLGMF plant will be a part of an industrial entity for production of paper pulp. The BLGMF plant imports spent pulping chemicals (black liquor) from the pulping process and generates motor fuels from the combustible part of the black liquor and also handles the recycling of the inorganic chemicals in the black liquor which are exported as green liquor back to the pulping process.

The battery limits of the BLGMF plant are further defined in Section 3.2.4. All off-sites and utilities that are required for the operation of the BLGMF plant are part of the scope of services.

The host pulp mill plant is a modern eco-cyclic pulp mill, which uses best available and ecologically sustainable technology. It is based on the well-referenced KAM2 MISTRA model. (KAM = Kretsloppsanpassad massafabrik, MISTRA = Stiftelsen för miljösstrategisk forskning).

**Conventional pulp mill of today**

![Diagram](image)

*Figure 3.2. Simplified block flow diagram showing the chemical and energy recovery in a conventional pulp mill of today.*

Figure 3.2 and Figure 3.3 illustrate the change of main blocks. The pulping operation in the BLGMF case is identical to that in a conventional pulp mill while the old power boiler is replaced by a new biofuelled power boiler with new steam turbines for production of power and heat.
Figure 3.3. A simplified block flow diagram of the entire plant complex of a pulp mill combined with a BLGMF process, where the recovery boiler and the bark boiler in Figure 3.2 have been replaced with a BLGMF plant and a new power boiler and also a new steam turbine.

3.2.4 BLGMF plant

The BLGMF plant will be neighbouring a modern pulp mill with no internal chemical recovery boiler. The unit operations of the BLGMF plant and the battery limits are illustrated by the block flow diagram in Figure 3.4.

The BLGMF plant is briefly described as follows: Air is compressed into the Air Separation Unit and then separated into nitrogen and oxygen. The oxygen is sent to the gasifier and probably also exported to the pulp mill. Most of the nitrogen is vented to the atmosphere except for a small part, which is used in the gas cleaning unit.

Concentrated black liquor is taken from the final concentration in the evaporator unit in the pulp mill and pumped to the intermediate storage tank and further on via the black liquor feeding system into the black liquor gasification unit where the black liquor is converted to reduced cooking chemicals (green liquor) and raw syngas. Low sulphidity green liquor is sent back to the pulp mill via the green liquor storage tank. The tie-in point for green liquor from the BLGMF plant is the causticization unit as shown in Figure 3.1.

The raw syngas, which is saturated with moisture at 220 °C, is cooled and scrubbed in the raw gas cooling and washing unit. The raw gas cooling unit generates MP- and LP-steam that are exported to the pulp mill. LLP-steam is also produced and used for heating in the final distillation of methanol/DME.
The cooled raw gas is cleaned from tars, other condensables, sulphur components and CO₂ in the gas cleaning unit. The composition of the cleaned and sulphur-free gas is modified by a CO-shift located within the gas cleaning unit and then more CO₂ is separated from the syngas before it is finally pumped/compressed to the methanol/DME unit as a clean methanol synthesis gas.

The sulphur that is removed from the syngas can be recycled in two different ways. One alternative is just to directly absorb the concentrated H₂S rich gas from the gas cleaning unit into white or green liquor which then forms a high–sulphidity liquor which can be valuable for use in the mill. The other alternative is to recycle the sulphur as elemental sulphur which is dissolved in white liquor then forming a polysulphide white liquor, which is an efficient pulp yield enhancer. See further Section 3.3.5.

A concentrated stream of CO₂ which is removed from the syngas can be made available from the gas cleaning unit and be a valuable commodity for use in the pulp mill.

The cleaned and shifted syngas from the gas cleaning unit is compressed from approx. 30 bar to 60 bar and added into the methanol/DME synthesis loop. The DME/methanol reactor is a catalytic reactor through which a mixture of recycle gas and fresh feed gas is pumped. The process is exothermic and heat is removed as IP-steam, which is used in the BLGMF plant internally in the CO-shift unit. A portion of the recycled gas mixture is withdrawn as a purge gas stream in order to remove inert material that is accumulated in the recycle loop. The purge gas is used as an added fuel in the power boiler.

The raw DME/methanol is then purified in a final distillation unit in order to remove water and impurities down to a specified commercial grade level after which it is pumped to the product storage and being ready for export. Waste fusel oil from the distillation is also sent to the power boiler as an additive fuel and for destruction.

The scope of this study also includes a new, larger power boiler. This burns the increased quantity of biomass which is needed to replace the energy withdrawn when the black liquor is converted to motor fuels. The power boiler will supply heat and power to the pulp mill as well as electric power the BLGMF plant. The boiler is dimensioned to primarily supply the required amount of steam. The Boiler is fuelled by imported biofuel as well as falling bark and waste streams from the methanol/DME unit. High-pressure steam is produced and fed to a new backpressure steam turbine generating the electric power. The backpressure steam is exported to the pulp mill.

There is a further need of electric power to equal the power need for the mill with a BLGMF plant (Figure 3.3) with a mill having a recovery boiler (Figure 3.2). This need is quantified in the overall energy balance and in the efficiency calculations where the net biomass to fuel (methanol or DME) efficiency is estimated. Depending on the site-specific situation this power may be generated at site or at another location.
Figure 3.4. Block flow diagram showing the battery limits of the BLGMF plant, the power boiler and the pulp mill.
3.2.5 Power boiler

The supply of steam and electricity in a conventional mill is accomplished by combustion of black liquor in the recovery boiler and by combustion of a second fuel (oil and/or biomass) in a power boiler. In a pulp mill with BLGMF this supply is instead met in a modern high-performance biofuel fired boiler. The new boiler will be fuelled with forestal waste biomass. The biofuels are imported to the plant and a minor portion of biofuels is falling bark from the incoming wood that used to be fed to the bark boiler.

The biofuel boiler is part of the scope and the power and the steam production is adjusted to meet with the needs of the pulp mill as well as the BLGMF plant.

The boiler will be of advanced type with high performance steam data. The thermal efficiency of the boiler to be specified the vendor. Approx. 75% of the fuel will be hog fuel, bark or waste wood. In addition, the boiler will use purge gas from the methanol/DME loop for approx. 25% of its thermal throughput. The purge gas is a clean fuel with a composition of: >60% H\textsubscript{2}, 5% CH\textsubscript{4}, 8% CO and the balance is CO\textsubscript{2} + N\textsubscript{2}/Argon. The boiler will also burn smaller amounts of waste organic liquids (1–3 MW of alcohols, oxygenates and some benzene). All fuels contain only small amounts of sulphur.

3.2.6 Impact on the pulping operation

Causticizing need

In a conventional mill with a recovery boiler, all sulphur in the black liquor is recycled as Na\textsubscript{2}S. The Na\textsubscript{2}S is dissolved in water in the smelter which will be hydrolysed to NaHS and NaOH an in the green liquor. If the process route of pressurised gasification is chosen a significant part of the sulphur in the black liquor will leave the gasifier reactor as H\textsubscript{2}S and not as Na\textsubscript{2}S. Only approx. 45% of the incoming sulphur is converted to Na\textsubscript{2}S.

The concentration of NaOH in the green liquor will thus be lower than in green liquor from a recovery boiler, which has to be compensated for by adding more NaOH to the green liquor whereby it is converted to white liquor. This is done internally in the pulp mill in the causticizing unit where burnt lime, (CaO) is added to the green liquor whereby Na\textsubscript{2}CO\textsubscript{3} is reduced to NaOH as CaO is oxidised to limestone (CaCO\textsubscript{3}). The limestone is reburned to CaO in the lime kiln which is fired with biomass (bark). The assumed increase in causticizing need is calculated to 25%.

3.3 Process design basis

3.3.1 Plant capacity

The plant capacity is calculated based on a pre-selected pulp mill/recovery boiler capacity. The host mill is defined for 2000 t/d of air dried pulp (ADt) which corresponds to a recovery cycle for the pulping chemicals of 3420 t/d of black liquor solids (BLS, as dry).

Operating conditions: Swedish/Nordic country conditions.

Operating hours/year: 355 operating days per year with 98% availability.

Project lifetime: 25 years.
**Raw syngas from gas cooling outlet**

<table>
<thead>
<tr>
<th>Gas component</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>mole%</td>
<td>39.17</td>
</tr>
<tr>
<td>CO</td>
<td>mole%</td>
<td>38.08</td>
</tr>
<tr>
<td>CO₂</td>
<td>mole%</td>
<td>19.05</td>
</tr>
<tr>
<td>CH₄</td>
<td>mole%</td>
<td>1.34</td>
</tr>
<tr>
<td>N₂</td>
<td>mole%</td>
<td>0.24</td>
</tr>
<tr>
<td>H₂O</td>
<td>mole%</td>
<td>0.18</td>
</tr>
<tr>
<td>H₂S</td>
<td>mole%</td>
<td>1.88</td>
</tr>
<tr>
<td>COS</td>
<td>mole%</td>
<td>0.06</td>
</tr>
<tr>
<td>Total gas flow</td>
<td>Nm³/h</td>
<td>141 938</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>31.5</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>31</td>
</tr>
</tbody>
</table>

**Cleaned, shifted syngas to methanol/DME loop**

<table>
<thead>
<tr>
<th>Gas component</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>mole%</td>
<td>66.89</td>
</tr>
<tr>
<td>CO</td>
<td>mole%</td>
<td>28.17</td>
</tr>
<tr>
<td>CO₂</td>
<td>mole%</td>
<td>3.00</td>
</tr>
<tr>
<td>CH₄</td>
<td>mole%</td>
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</tr>
<tr>
<td>N₂</td>
<td>mole%</td>
<td>0.30</td>
</tr>
<tr>
<td>H₂O</td>
<td>mole%</td>
<td>0.00</td>
</tr>
<tr>
<td>H₂S</td>
<td>ppm (vol)</td>
<td>0.1</td>
</tr>
<tr>
<td>COS</td>
<td>ppb (vol)</td>
<td>0.5</td>
</tr>
<tr>
<td>Total gas flow</td>
<td>Nm³/h</td>
<td>115 335</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>30</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>27</td>
</tr>
</tbody>
</table>

### 3.3.2 Feedstock and utilities

**Black liquor**

The composition of black liquor is taken on the reference model pulp mill is given in the below. The NHV (Net Heating Value) is the lower heating value after deduction of the energy required for reducing the sulphate in the black liquor to sulphide in the green liquor. Data source: KAM2 MISTRA Project.
<table>
<thead>
<tr>
<th>Element</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>mass%</td>
<td>35.69</td>
</tr>
<tr>
<td>H</td>
<td>mass%</td>
<td>3.68</td>
</tr>
<tr>
<td>S</td>
<td>mass%</td>
<td>4.41</td>
</tr>
<tr>
<td>O</td>
<td>mass%</td>
<td>35.82</td>
</tr>
<tr>
<td>Na</td>
<td>mass%</td>
<td>19.04</td>
</tr>
<tr>
<td>K</td>
<td>mass%</td>
<td>1.08</td>
</tr>
<tr>
<td>Cl</td>
<td>mass%</td>
<td>0.28</td>
</tr>
<tr>
<td>N</td>
<td>mass%</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>Total (%)</strong></td>
<td>mass%</td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

*Combustible characteristics*

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL, dry solids</td>
<td>mass%</td>
</tr>
<tr>
<td>HHV</td>
<td>MJ/kgDS</td>
</tr>
<tr>
<td>NHV</td>
<td>MJ/kgDS</td>
</tr>
</tbody>
</table>

**Oxygen**

Oxygen to the gasifier shall be of high purity in order to minimize inerts in the syngas.

<table>
<thead>
<tr>
<th>Oxygen quality</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>vol%</td>
<td>&gt;99.0</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>vol%</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Argon</td>
<td>vol%</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>120</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>45</td>
</tr>
</tbody>
</table>

**Mechanical design conditions**

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
</tr>
</tbody>
</table>

**Nitrogen**

Nitrogen is needed for purging in various units and for solvent stripping in the gas clean up system.
### Nitrogen quality

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>&gt;99.5</td>
</tr>
<tr>
<td>Oxygen</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

### Mechanical design conditions

<table>
<thead>
<tr>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>70</td>
</tr>
<tr>
<td>Pressure</td>
<td>14</td>
</tr>
</tbody>
</table>

### Burner fuel (stand-by), gasol propane 95

<table>
<thead>
<tr>
<th>Compound</th>
<th>Vol%</th>
<th>Vol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(<em>{2})H(</em>{6})</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>C(<em>{3})H(</em>{8})</td>
<td>96.0</td>
<td>&gt;95.0</td>
</tr>
<tr>
<td>C(<em>{4})H(</em>{10})</td>
<td>2.0</td>
<td>&lt;5.0</td>
</tr>
<tr>
<td>C(<em>{5})H(</em>{12})</td>
<td>0</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Olefins</td>
<td>1.0</td>
<td>&lt;2.0</td>
</tr>
</tbody>
</table>

Calorific value, lower heating value:
- MJ/kg: 46.38
- MJ/Nm\(^3\): 94.45

Calorific value, higher heating value:
- MJ/kg: 50.45
- MJ/Nm\(^3\): 101.90

Maximum sulphur content: 10 mg/kg
Normal sulphur content: 5 mg/kg
Residue from evaporation, max: <25 mg/kg

### BFW

Required for steam generation in biomass boiler and heat recovery units of the plant. Quality, colourless, clear, free from non-dissolved matter.
### BFW quality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td></td>
<td>9–10</td>
</tr>
<tr>
<td>Conductivity at 25 °C (polished water)</td>
<td>µS/cm</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Oxygen</td>
<td>ppm wt</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total iron as Fe</td>
<td>ppm wt</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Total copper as Cu</td>
<td>ppm wt</td>
<td>&lt;0.003</td>
</tr>
<tr>
<td>Total silica as SiO₂</td>
<td>ppm wt</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>Total alkali as Na</td>
<td>ppm wt</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total chlorides as Cl₂</td>
<td>ppm wt</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Total sulphur as SO₄²⁻</td>
<td>ppm wt</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>TOC</td>
<td>ppm wt</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>120</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>2</td>
</tr>
</tbody>
</table>

### Mechanical design conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>150</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>4.5</td>
</tr>
</tbody>
</table>

### Electric power

#### Motors
- 0–350 kW motors: 690 V 3 Phase switchboard supply
- >350 kW motors: 6.3 kV 3 Phase switchboard supply
- MCC: 230/400V 3 Phase switchboard supply

#### Lighting
- Various consumers: 230/400V 3 Phase switchboard supply

#### Uninterrupted power supply
Supplied by host pulp mill to DCS system and emergency lighting

### 3.3.3 Products and byproducts

#### Methanol

<table>
<thead>
<tr>
<th>Purity requirements</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>%w/w</td>
<td>99.19</td>
</tr>
<tr>
<td>Water</td>
<td>%w/w</td>
<td>0.09</td>
</tr>
<tr>
<td>CO₂</td>
<td>%w/w</td>
<td>0.59</td>
</tr>
<tr>
<td>Higher boiling components</td>
<td>%w/w</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Temperature | °C | 30
Pressure | bar(a) | 6

**Mechanical design conditions**

| Temperature | °C | 70
Pressure | bar(a) | 9

### Dimethyl ether (DME)

<table>
<thead>
<tr>
<th>Purity requirements</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>%w/w</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Water</td>
<td>%w/w</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Methyl ethyl ether</td>
<td>%w/w</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Higher alcohols</td>
<td>%w/w</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Higher ethers</td>
<td>%w/w</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>Ketones</td>
<td>%w/w</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>Odorant (e.g. ethylmercaptane)</td>
<td>ppm</td>
<td>20</td>
</tr>
<tr>
<td>Lubricant (e.g. Lubrizol or Hitech)</td>
<td>ppm</td>
<td>500 – 2000</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>30</td>
</tr>
</tbody>
</table>
| Pressure | bar(a) | 7

<table>
<thead>
<tr>
<th>Mechanical design conditions</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>70</td>
</tr>
</tbody>
</table>
| Pressure | bar(a) | 10

### Green liquor

The green liquor from the green liquor cooler.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>87</td>
</tr>
<tr>
<td>Mass flow</td>
<td>kg/s</td>
<td>117.7</td>
</tr>
<tr>
<td>Na₂CO₃</td>
<td>g/kg H₂O</td>
<td>163</td>
</tr>
<tr>
<td>Na₂S</td>
<td>g/kg H₂O</td>
<td>20</td>
</tr>
<tr>
<td>NaOH</td>
<td>g/kg H₂O</td>
<td>21</td>
</tr>
<tr>
<td>H₂O</td>
<td>g/kg H₂O</td>
<td>1000</td>
</tr>
<tr>
<td>Green liquor</td>
<td>g/kg H₂O</td>
<td>1204</td>
</tr>
</tbody>
</table>

### Sulphur (option)

**H₂S rich gas (option)**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conc. H₂S + COS</td>
<td>vol%</td>
<td>50</td>
</tr>
<tr>
<td>Conc. CO₂</td>
<td>vol%</td>
<td>50</td>
</tr>
<tr>
<td>Gas flow</td>
<td>Nm³/h</td>
<td>5400</td>
</tr>
</tbody>
</table>

**Steam (HP, IP, MP, LP, LLP)**

<table>
<thead>
<tr>
<th>Pressure steam</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP pressure steam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>140</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>545</td>
</tr>
<tr>
<td>IP pressure steam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>30</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>234</td>
</tr>
<tr>
<td>MP pressure steam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>12</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>195</td>
</tr>
<tr>
<td>LP pressure steam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>4</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>150</td>
</tr>
<tr>
<td>LLP pressure steam</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>1.43</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>110</td>
</tr>
</tbody>
</table>

**CO₂**
Gas flow: 24 000 Nm³/h.

An impure stream of CO₂ (contaminated with N₂ and traces of H₂S) can be exported from the gas purification unit. CO₂ may be of interest for the pulping process as well as product for export. Purification technology is well-known all the way to food use.

**Used chemicals**
Used chemicals (scraped refractory lining, catalysts, waste lubrication oils, scrap materials, methanol from pre-wash). No fixed quantities at this project phase.

**Waste water from the methanol synthesis unit**
The methanol plant will produce approx 3.2 t/h of waste distillation water that contains 0.01% of methanol and the remaining 99.99% is water.
Waste water from the DME synthesis unit

The DME plant option will produce a 15.1 t/h stream of wastewater that also contains 1 kg/h of methanol and 3 kg/h of higher alcohols.

3.3.4 Site conditions

The plant has a Nordic location. It is assumed that the plant will be located in a so-called brown field area with normal soil conditions at an existing kraft pulp mill that has decided to replace the Tomlinson recovery boiler with a BLGMF plant and a new biofuel boiler.

It has been assumed that the plant is accessible by roads capable of bearing transport of heavy equipment. Furthermore, it has been assumed that all the utilities except inert gas will be available at battery limits and that all products, by-products and effluents can be disposed off to the pulp mill at the battery limits.

3.3.5 Alternate integration concepts

Using pressurized gasification for recovery of the pulp cooking chemicals will open the door towards new attractive pulp cooking processes by utilising the sulphur splitting between green liquor and gas. Sulphur is present as \( \text{H}_2\text{S} \) in the synthesis gas and will be separated from the syngas and recycled to the pulp mill. Besides from direct absorption of \( \text{H}_2\text{S} \) in white liquor, \( \text{H}_2\text{S} \) can be converted to elemental sulphur which is an excellent feedstock for production of polysulphide white liquor.

Polysulphide white liquor is known to increase the pulp yield up to 5 percentage points. Polysulphide pulp processing was developed in the 1970’s but without the sulphur split made by a pressurized gasifier it is difficult to accomplish high concentrated, pure PS-cooking chemicals which are optimal in order to reach full potential of this cooking route.

3.4 Process plant configuration

The following section describes important aspects for establishing the concept of the BLGMF-plant. Initially, the overall concept will be described followed by a description of the individual process steps and explaining the ideas behind the process concept.

3.4.1 Overall BLGMF plant concept

The BLGMF plant concerned will be an integrated part of a pulp mill complex and must therefore meet the specific requirements of such a facility. Consequently its main characteristics should be:

- Reliable and simple configuration
- High efficiency
- Low emissions
- Adequate partial load behaviour.

As a matter of principle, it was decided that only such process steps and plant components should be used that have proved to work satisfactorily under comparable conditions or which can reasonably be deemed to function reliably.
The development of Chemrec® pressurised black liquor gasification was originally focusing on electric power production via combustion of syngas in a gas turbine in a BLGCC scheme as shown in Figure 3.5. The BLGMF concept was invented during 2000 and developed as an analogue to the power generation scheme, see Figure 3.6. It was realised that the syngas could also be an excellent feedstock for production of methanol, DME or other syngas derived transport fuels and the production chain was unusually energy efficient. On a conceptual level, the BLGCC and the BLGMF schemes only differ on the desired end product which is the power generation island (gas turbine and HRSG) in the BLGCC scheme and the fuel synthesis unit (gas compression and methanol/DME synthesis and purification) in the BLGMF scheme, respectively.

In the BLGMF plant the gasifier raw gas needs to be further treated and purified compared with the BLGCC plant. In a BLGCC plant, the gas turbine needs a fuel gas with sufficient heating value for the purpose of clean combustion with low NOX formation in the gas turbine combustor.

When the desired end-production is automotive motor fuels, the raw gas must be upgraded in the downstream facilities to meet the requirements of the intended application. For instance, the \((\text{H}_2\text{CO})/(\text{CO}+\text{CO}_2)\) ratio must be adjusted to approx. 2 in order to produce methanol or DME. The syngas must also be free of sulphur components that would poison the catalyst material. As the liquid fuels production unit is a synthesis loop where the reactant syngas is recirculated, the feed syngas must be very low in inerts as they otherwise would accumulate in the loop and lower the production efficiency per pass thereby require larger and more expensive equipment.

A typical Chemrec® pressurised black liquor gasification scheme for automotive fuels production comprises the following process steps:

- Air Separation Unit (ASU) of cryogenic type
- Black liquor storage and preheating
- Gasification with quench cooling and green liquor handling
- Raw gas cooling with steam generation and particulate removal
- Gas cleaning for complete removal of sulphur components and CO\(_2\) including a guard bed for sulphur components
- CO-shift conversion in order to adjust CO/H2
- Gas compression
- Methanol or DME synthesis and purification.
In general, the arrangement of the gas compression unit and the CO-shift unit (upstream or downstream of the COS/H\textsubscript{2}S removal unit) depends on several factors (such as type of feedstock and product, plant capacity, gasification pressure, pressure of the synthesis loop, type of scrubbing unit) and should be subject to optimisation for any individual case of application.

**Figure 3.5.** Pressurised black liquor gasification based power plant.

**Figure 3.6.** Pressurised black liquor gasification based automotive fuels plant.
The following comments are reflected in the flow scheme lay-out for a BLGCC plant, Figure 3.5:

- For a syngas derived from kraft black liquor the arrangement of the gas compression unit is determined by the gas quality. Compression of raw gas upstream the gas cleaning is unfavourable since the raw gas contains large quantities of CO$_2$, which would lead to a higher consumption of electric power. In addition, the high content of corrosive COS and H$_2$S would require more advanced construction materials in the compressor machinery. It is therefore obvious to compress the cleaned gas after CO-shift and CO$_2$ removal.

- In the CO-shift reactor, CO reacts with H$_2$O to H$_2$ and CO$_2$. For this unit, the location is less evident as there is a choice between a so-called “clean” or “dirty” shift catalyst. A dirty CO-shift can handle syngas contaminated with H$_2$S and COS and will convert COS to H$_2$S via hydrolysis reaction. A clean type of CO-shift is more compact and more efficient but requires a syngas with no sulphur components. As steam is required in a quantity with a ratio to dry gas: ≥0.9:1 it would be a great advantage to shift the raw gas directly after the gasifier quench unit as the raw gas at that location is saturated with steam.

- Since the CO-shift however is a fixed bed catalytic unit and the raw gas must be free from particulates and tars that could carbonise on the catalyst surfaces this location is not possible. The raw gas from the quench is uncleared and it contains alkali particulates and also tars that will have to be removed before CO-shifting. If a high efficiency venturi scrubber is added upstream the CO-shift unit at least the particulates could be removed but the tars would remain a technical obstacle. Because of these limitations, the CO-shift is put downstream the prewash and the sulphur removal. Therefore, the type is a so-called “clean” catalyst. The CO$_2$ removal is also located upstream to minimise the steam requirement for the shift reaction.

- The DME/methanol production efficiency is very dependent of the presence of process inerts. Methane is such an inert component and is mostly undesired syngas component since it has a high calorific content and thus represents a large part of the energy of the syngas. As mentioned above, the methane and other inerts will have to be purged from the methanol/ DME synthesis loop and valuable reactants (H$_2$, CO, CO$_2$ are purged along with the undesired inerts. If the amount of methane is large it can be favourable to produce additional syngas from the purge gas applying proven catalytic reforming technologies such as ATR (autothermal reforming). This is not the case for black liquor derived gas.

- The synthesis gas produced from gasification of black liquor has low methane content and the purge gas from the methanol/ DME synthesis process is of less significance than for e.g. gasification of solid biomass. The purge gas can therefore be used as a fuel gas in a boiler or perhaps a gas engine.

- Certain quantities of pressurised inert gas are needed for purging detectors, burners and for dilution of fuel gas to the pilot burner. In general, nitrogen or carbon dioxide could be used as an inert gas. The use of CO$_2$ obtained in the regeneration section of the CO$_2$/H$_2$S removal unit offers certain advantages, since an elevated CO$_2$ content in the raw gas does not increase the inert gas level in the methanol/DME synthesis loop, as in the case for N$_2$. The excess CO$_2$ is removed in the gas cleaning section.
3.4.2 Selection of gasification pressure

Operating experience with Chemrec’s entrained flow black liquor gasifier is available for pressure up to 15 bar at present. The new development plant in Piteå is designed for operating at max. 32 bar in order to supply syngas to a gas turbine at 29 bar level. Similar gasifiers using oil or coal from Shell and Texaco are operated at 65 bar. For black liquor gasification, the opportunity to select a higher pressure is limited for material reasons. There are only few construction materials that withstand high temperature alkaline solutions (200–225 °C) and raising the gasifier pressure means higher saturation temperature in the water cooled quench and thus higher green liquor temperatures.

Based on operating data from the pilot plant and on chemical equilibrium calculations, the raw gas composition at the gasifier outlet before quenching is expected as follows:

<table>
<thead>
<tr>
<th>Gas component</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>mole%</td>
<td>30.55</td>
</tr>
<tr>
<td>CO</td>
<td>mole%</td>
<td>29.70</td>
</tr>
<tr>
<td>CO₂</td>
<td>mole%</td>
<td>14.93</td>
</tr>
<tr>
<td>CH₄</td>
<td>mole%</td>
<td>1.05</td>
</tr>
<tr>
<td>N₂</td>
<td>mole%</td>
<td>0.19</td>
</tr>
<tr>
<td>H₂O</td>
<td>mole%</td>
<td>22.09</td>
</tr>
<tr>
<td>H₂S</td>
<td>mole%</td>
<td>1.44</td>
</tr>
<tr>
<td>COS</td>
<td>mole%</td>
<td>0.047</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>975</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar(a)</td>
<td>32</td>
</tr>
</tbody>
</table>

Selecting a gasification pressure above 25 bar has many advantages. One is the temperature level on the cooling curve in the raw gas cooling as shown in Figure 3.7. If the gasifier and gas cooler were operated at atmospheric pressure the average cooling curve temperature would be around 60 °C because of the steam saturation temperature. On the other hand cooling pressurised raw gas from the saturation temperature of 220 °C, which is the case if the gasifier pressure is 32 bar means that most of the available heat of condensation can be utilised for production of both MP- and LP-steam as well as BFW preheat. Only a small amount of cooling water for final cooling is necessary. It should be remembered that a kraft pulp mill is a process, which needs large quantities of heat as MP- and LP-steam.

There is also an advantage with high pressure regarding the compression of syngas: Compression to the methanol/DME synthesis pressure (usually in the order of 60–100 bar) can be accomplished by a one or two stage compressor with moderate power consumption instead of a three stage compressor.

In addition, the refractory lined gasifier will be more compact and have a smaller diameter at higher pressure and therefore become cheaper. On the other hand, higher process pressure means generally more stringent requirements on the construction materials as well as their thickness. Also engineering and safety aspects will cost more at higher process pressure.
Figure 3.7. The quality of the recoverable heat from raw gas cooling in a (2400 t/d of BLS) CHEMREC® pressurised BLG process.

Due to equilibrium conditions, the methane content of the raw gas should increase at higher gasification pressure, but the effect is not significant when gasifying black liquor in entrained flow gasifier. Due to high temperature the amount of methane in the raw gas is low but still higher than what can be expected at chemical equilibrium conditions. In this aspect, gasification at high pressure has no disadvantage as compared to lower gasification pressure.

### 3.4.3 Availability requirement

**Plant capacity, parallel trains**

The BLGMF plant is an integrated production process, which is analogue to processes generating synthesis products (e.g. methanol, ammonia) from heavy fuel oil or coal and to the well-known IGCC concept. An IGCC produces electric power via a combined cycle and a BLGMF plant has a similar scheme but the combined cycle is replaced with a methanol or DME synthesis unit and produces green motor fuels instead of electric power. Instead of oil or coal that are typical feedstocks to an IGCC or a chemicals production plant, a BLGMF plant is fed with black liquor. A BLGMF plant is connected to a pulp mill which at its turn, also is a large integrated industrial unit. Even if the degree of integration between the processes are kept at a minimum there will be strong requirement of high availability since a unexpected down time of a single unit within the plant complex could cause a severe profit loss not only for the BLGMF plant but also for the pulp mill.
The overall plant philosophy of the BLGMF is to design for robustness and a reliable concept by minimising the number of process integrations and avoiding complexity therefore establishing a degree of non-dependence between the plant units.

**Stand-by philosophy/configuration**

The BLGMF plant is configured as a single train process except in the gasification and cooling, as shown in Figure 3.8. The down-stream units and the utility facilities are in single trains since there are no restrictions for the plant capacity.

The installation of three parallel gasification trains would give rise to the question whether such a configuration could be regarded as a reliable design since the replacement of reactor ceramic lining will take approximately 15 days. It would lead to a reduced capacity for 5 operating days even if the annual shutdown of ten days for service and maintenance is included. Therefore the proposed configuration for the gasification unit contains four parallel gasifier and gas cooling units, with 33% capacity each. This means redundant capacity and the ability to operate three gasifiers (3 x 33%) and to have one standby unit which rapidly can be put into operation if needed.

The standby train can thus change its ceramic lining when it is worn out and not at the annual shutdown. In this way the length of life of a ceramic lining does not need to be an even number of years. Another advantage is that the refractory change out work is spread out over the year.

The structure of the black liquor based methanol or DME synthesis plant linked to a 2000 t/d pulp mill unit can be summarised as shown in Table 3.1.

### Table 3.1. Process layout in a 2000 t/d pulp mill with a BLGMF plant.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Number of trains in parallel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Separation</td>
<td>1</td>
</tr>
<tr>
<td>Oxygen supply and nitrogen system</td>
<td>1</td>
</tr>
<tr>
<td>BL Feeding system</td>
<td>4</td>
</tr>
<tr>
<td>Gasification and quench with green liquor handling</td>
<td>4</td>
</tr>
<tr>
<td>Raw gas cooling</td>
<td>4</td>
</tr>
<tr>
<td>CO$_2$/H$_2$S Removal incl CO-shift</td>
<td>1</td>
</tr>
<tr>
<td>Sulphur recovery</td>
<td>1</td>
</tr>
<tr>
<td>Gas compression</td>
<td>1</td>
</tr>
<tr>
<td>Methanol/DME synthesis loop</td>
<td>1</td>
</tr>
</tbody>
</table>

As a matter of interest when the Japanese company Ube Ammonia built its coal to ammonia plant in the early 80’s the plant was equipped very much in line with this philosophy. Four coal gasifiers at 4 x 33% and the other units as 1 x 100%. This back-up philosophy is selected since the gasifiers must secure a 100% capacity and continuous supply of good quality green liquor to the pulp mill and also generate syngas to the methanol or DME synthesis unit. If two gasifier units are out of operation, e.g. one as planned and a second unplanned, the BLGMF plant can still operate with a reasonable part-load factor of 66%. The min. turn-down ratio for the fuel synthesis unit is 60%.

A gasifier which is to handle 1140 t/d of black liquor solids is a significant scale-up from the planned Swedish demonstration plant (DP-2) plant of 300 t/d. The thermal load of
170 MW corresponds to about 16 t/h of heavy fuel oil. This is not a very large gasifier compared to major gasification installations around the world.

**Gasifier and gas cooling**

The required downtime of a gasifier quench reactor is governed by the need of replacement of worn out refractory lining in the reactor compartment. The down-time is based on experience from atmospheric air-blown black liquor gasifier in a 300 t/d scale at the Weyerhaeuser mill in New Bern US which has approximately the same size as a 1000 t/d oxygen-blown pressurised gasifier.

The turn-around from shut down until being back on-stream, including scrapping of worn out lining, allowable time for maintenance and service of reactor vessel, installation of new refractory as well as time for controlled heat up for curing is excepted to be approx 15–17 days. In an “Nth plant” the gasifier reactor is estimated to need new refractory lining after 36 months operation.

The intermediate storage capacity of green liquor and black liquor will buffer the capacity alterations of the BLGMF plant and make the pulp mill independent of minor disturbances occurring e.g. when a burner nozzle is changed in one of the gasifiers.

Sufficiently large intermediate storage tanks for black liquor and green liquor shall be included as buffer tanks between the pulp mill and the BLGMF plant. Processing 2 tonnes of black liquor (as dry solids) will produce 5.5 m$^3$ of fresh green liquor. The daily production of green liquor is thus about 9600 m$^3$ per day from 3400 tonnes of black liquor. An 8 h intermediate storage for green liquor has been included in the scope of the plant. The storage capacity requirements for green liquor and black liquor are comparable to recovery boiler based systems of today.

**Parallel trains**

The plant is not planned to be equipped with standby equipment for major process equipment such as reactors, heat exchangers or compressors. This philosophy is common practice in large-scale industrial plants, for instance natural gas based ammonia plants or modern air separation units. Continuously operated pumps, certain in-line filters etc as well as critical key instruments are duplicated which means that 2 x 100% capacity is installed.
3.4.4 Air Separation Unit

Oxygen is required as oxidising agent for gasification of black liquor and for oxidation of sulphide components to elemental sulphur in an oxygen-blown Claus plant (option). To supply the oxygen, the well-known cryogenic air separation process will be applied. In order to minimise the inert gas content of the synthesis gas, (in view of the negative effect of an elevated inert gas level would have on the methanol synthesis loop), oxygen of high purity is required. An oxygen concentration of >99% is a common figure in synthesis gas production.

The air separation unit also supplies the required quantities of nitrogen, which is utilised as inertisation gas for various purposes within the BLGMF plant.

With an air separation plant of this more advanced concept, argon could be produced as a by-product provided that certain additional facilities are installed. This option has not been considered in the present stage of the project for the synthesis gas plant in question.

The air separation unit within the 3400 t/d of black liquor complex has a moderate capacity only. It could therefore be taken into consideration to install an air separation unit of a larger capacity and to sell the surplus air gases (in liquefied state) to external consumers.
The ASU is of cryogenic type and supplies the oxygen needed for the black liquor gasification. There is also minor supply of oxygen to an oxygen-blown Claus plant (option) as well as an opportunity of export of oxygen to the pulp mill for use in the bleach plant as well as in the wastewater treatment.

**Inert gas supply**

Nitrogen is obtained as a by-product in the air separation unit supplying the oxygen for gasification. It has a high purity and can easily be stored in liquid state in standard storage tanks. Within the BLGMF plant nitrogen is used as inert gas and will only be used for solvent stripping of CO$_2$ within the Gas cleaning unit. If desired, nitrogen can also be exported to external consumers.

Since N$_2$ would dilute the methanol syngas compressed CO$_2$ from the solvent stripping will instead be used for purging and blanketing at various places in the BLGMF process, mostly in the entrained flow reactor and quench. Since the injected CO$_2$ is again separated from the syngas in the gas cleaning unit it will not dilute the methanol/DME syngas. An additional compressor is required for pressurisation of the CO$_2$ from 2–3 bar to 45–50 bar pressure.

### 3.4.5 Black liquor preparation & feeding

Black liquor must be transferred from the pulp mill to the BLGMF plant via a pipeline. Black liquor is the aqueous, concentrated mixture of organic wood residue and spent cooking chemicals from the pulping process in the digester. The content of the solids is 50% organic combustible and 50% inorganic salts. Normally black liquor is concentrated to a dry solids content of 70–80% and must be kept at elevated temperature by steam tracing to remain pumpable. It is well known in the pulp industry that black liquor must not be allowed to stay still in pipe-work as it will quickly cause severe plugging. Therefore the black liquor must either be pumped continuously in all black liquor bearing equipment or must be immediately washed with warm water in order to avoid plugging. For pipelines this generally means that a dual pipe arrangement is chosen in order to ensure constant circulation of the black liquor as it would be not enough reliable to always wash pipe systems.

The black liquor also contains particulates and it can polymerise and form lumps that could clog important kinds of equipment carrying black liquor such as the black liquor burner nozzle, therefore the black liquor should be filtered. A filter/strainer can remove most of the particulate material which is then split off as a reject stream which has to be treated before being sent back to the main black liquor stream and the gasifier reactor.

From the pressurising pump to the black liquor nozzle in the gasifier the feeding system is regarded as part of the gasifier. This means that it is dedicated for just one of the gasifiers. Upstream of the pressurising pump piping, vessels, instruments etc may serve more than one gasifier and still meet the availability criteria laid out in Section 3.4.3.

### 3.4.6 Gasification with quench cooling and green liquor handling

This study is based on the use of ceramically lined gasifiers. Chemrec has two types of pressure vessel protection systems under development, ceramic lining and a cooling screen cooled with pressurised hot water. Experiences from the New Bern atmospheric show that the ceramic lined gasifier is promising and this version is therefore chosen as base for this
study. For the Chemrec development plant under construction in Piteå the plan is to test both systems.

The quench cooling design is a two stage design developed from the Skoghall initial trials and further developed and tested in the Piteå development plant.

The green liquor handling system is as the pressurised black liquor feeding system dedicated to just one gasifier and quench. After depressurisation the green liquor streams from the different gasifier trains is fed into the same green liquor system. Piping handling green liquor will be duplicated in the same way, as today is the case for recovery boiler systems. Degree of redundancy will depend on experience from the first pressurised BLG plants.

3.4.7 Raw gas cooling system and particulates removal

The fuel gas from the gasifier quench is saturated with water vapour that represents a significant amount of valuable recoverable heat. As the raw gas is saturated with water vapour at elevated pressure (31.5 bar(a)) with a saturation point of approx 220 °C, the steam partial pressure is around 23 bar(a). (The steam content of the quench outlet gas is 23/31.5 bar(a) ⊨ 73 vol%). The moist raw gas from the gasifier quench also contains fines of alkali salts and tars which have to be completely removed. As a result of testing in Chemrec’s previous pilot plant in Skoghall, Sweden it has been found that a combined gas cooling and particle removal can be accomplished very reliably in a counter current condenser type of gas cooler. For further description of the raw gas cooling see Section 3.5, plant description.

3.4.8 Traces/CO₂/H₂S – removal and CO shift reactor

Desulphurization and CO₂ removal

The catalytic synthesis unit for production of methanol (or DME) requires a high-purity syngas with a specific gas composition but the raw gas from the entrained flow black liquor gasifier process contains large quantities of CO₂ and H₂S, some COS plus condensable tars, mostly benzene and also some small amounts of naphthalene.

The syngas to the methanol/DME synthesis unit needs to be free of both sulphur components and condensable tars. The syngas composition also needs to be adjusted by increasing hydrogen/carbon monoxide ratio via a CO-shift unit (see below). Furthermore, the content of carbon dioxide needs to be reduced to near 3%.

For a good overall performance of the BLGMF plant, it is essential to obtain an efficient gas cleaning unit. As the amount of removed gas components is large it leads to that the preferred type of purification technology is a so called physical absorption process and not a chemical absorption based system that would be a cheaper investment but would require a larger quantity of steam for solvent stripping.

Also the selection of absorber solvent is an important factor since the solvent can be contaminated with tars that can be difficult to remove unless a bleed out of solvent is accepted. Selecting a solvent that easily can be purified and which is cheap to replace when needed is the most preferred solution. The requirement on the purified syngas, in particular regarding sulphur components is very high (0.1 ppm) which also leads to the selection of a high performance gas cleaning unit.
The selected technology needs to purify the syngas down to less than 1 ppm of total sulphur in the syngas. The remaining sulphur (if any) can be removed by a guard bed of zinc oxide which reacts irreversibly with any remaining sulphur in the gas forming ZnS thereby removing sulphur down to below 0.1 ppm. Finally, the selected process needs to be selective with respect to removal of sulphur components and carbon dioxide respectively. This is important as the technology selected for recycle of the sulphur can be made more efficient if the H$_2$S and COS containing stream has a high concentration of these gases. A commercial process which fulfils these different demands is the Rectisol process which uses cold methanol as absorber liquid.

The removed sulphur is concentrated to an H$_2$S/COS rich off gas, which is treated via direct absorption into white liquor. The Rectisol can produce a separate CO$_2$ stream removed and produce a CO$_2$ stream, which can be sold or used in the pulp mill. The utility consumption in a Rectisol (steam, power, water, etc) is low and the absorber solvent (methanol) is a standard commodity low in price.

A Rectisol system is perhaps known to be more expensive than many of the competitors but more efficient and uses a non-license solvent (methanol) which is produced in the both methanol and the DME plant.

One other important feature is the pre-wash unit for the complete removal of tars and other condensable. A pre-wash unit is a part of the Rectisol unit and located upstream the absorber uses cold methanol as solvent. The pre-wash removes all kinds of condensable tar components like benzene, naphthalene and water.

The contaminated methanol from the pre-wash unit can either be burnt in the power boiler but if the amount is large, burning methanol would be a cost burden. The bulk removal of tar components from methanol is therefore preferably done by liquid/liquid extraction after dilution with water and the final removal by distillation.

As both the methanol and DME plant produces, handles and purifies methanol as product or intermediate by-product it can be foreseen to easily integrate the handling of the tar contaminated methanol stream from the pre-wash unit containing mostly benzene and some naphthalene in the distillation section following the respective synthesis plant. If the product methanol contains small amounts of benzene (<0.1%wt) should likely not be a problem since it will be used as a low additive to petrol that itself contains up to 5–6 % of benzene.

**CO-shift reactor**

The raw syngas contains excess CO and too little H$_2$ for the methanol/DME synthesis. In the catalytic CO-shift conversion process, the water-gas shift reaction, CO is reacted with steam and is converted to H$_2$ via the following reaction:

\[
\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2 + \text{Heat.}
\]

This is an equilibrium reaction and is influenced by the following parameters:

- Variable stoichiometry of the dry gas due to the gasification of black liquor of different dry solids content and slightly different conditions.
- In particular, alternating steam quantities in the feed syngas to the shift unit.
- Varying reactivity of the catalyst (between start-of-run and end-of-run.)
Varying residence time of the gas because of fluctuations in flow rate and pressure.

As the methanol syngas is required to contain about 30 vol% CO only partial conversion of the syngas is necessary. For this reason and in order to maintain the CO/H₂ ratio constant at these changing parameters, it is necessary that the process gas quality is controlled by means of a bypass. For this purpose, the raw syngas is split up and approx 50% of the part is fed to the CO-shift catalyst unit where it undergoes conversion until almost complete equilibrium. Downstream the CO-shift reactor, the converted and non-converted by-pass streams are mixed to form a product gas at a CO/H₂ ratio that is required for the methanol/DME synthesis processes.

Selection of the CO-shift catalyst

There are in general two types of catalyst materials to be considered here for CO-shift conversion:

- The conventional catalyst for desulphurised gases based on the oxides of iron and chromium; inlet temperature 300–340 °C.
- The sulphur resistant type for gases typically found after coal or oil gasification based on cobalt and molybdenum oxides; inlet temperature approx. 280–300 °C.

Haldor Topsoe offers a special sulphur-tolerant catalyst suitable for extraordinary low inlet temperatures e.g. 225 °C.

The conventional catalyst tolerates a certain amount of sulphur in the raw gas but with increasing sulphur content also, the required catalyst inventory will increase. For 100 ppm sulphur (by volume wet gas) in the raw syngas, an increase of the catalyst volume by 25% is required. This is economically and technically the limit for the iron catalyst.

For the sulphur resistant type, the sulphur concentration should not be less than 100 ppm sulphur (by volume wet gas) for optimum conversion conditions.

With the sulphur content in the selected feedstock both catalyst types can be applied but at different locations (see Section 3.4.1). For process reasons described in Section 3.4.1, the conventional catalyst has been selected. This arrangement results in lower capital investment. The first assumption for the steam to dry gas ratio at the shift reactor inlet is 0.9/1 on molar basis. However, a lower steam to dry gas ratio is probably possible resulting in a reduction of the IP-steam consumption.

3.4.9 Sour gas treatment

The sulphur in the sulphur-rich off-gas from the gas treatment plant (Chapter 3.4.8) must be recycled to the pulp mill to virtually 100%. The base case is designed to create a system for the recovered chemicals, which is similar to the chemicals coming from the recovery boiler. Therefore, the sulphur containing off-gas is brought in contact with white liquor in a number of contact devises put in series. The H₂S is absorbed together with small amounts of CO₂ and the high sulphidity white liquor is brought back to the pulp mill. This liquor can be mixed with the re-causticized low sulphidity green liquor from the quench downstream the gasifier and become the white liquor for re-use in the digester.

An alternative sour gas treatment for sulphur recycle is presented in Section 3.4.16.
3.4.10 Methanol synthesis and purification

The methanol unit is designed to generate methanol in accordance with the fuel grade specification supplied to the process supplier Haldor Topsøe by the project co-ordinator, shown in Table 3.2. For background to this specification see Chapter 6.

Table 3.2. Fuel grade specification, methanol.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Limit [% w/w]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>99.19</td>
</tr>
<tr>
<td>Water</td>
<td>0.09</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.59</td>
</tr>
<tr>
<td>High boiling components</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Methanol technology can be supplied from a number of suppliers. For selection of Haldor Topsøe see Chapter 3.4.11.

3.4.11 DME synthesis and purification

The DME unit is designed to generate DME in accordance with the fuel grade specification supplied to the process supplier Haldor Topsøe by the project co-ordinator, shown in Table 3.3. For background to this specification see the main report.

Table 3.3. Fuel grade specification, DME.

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Recommended value [% w/w]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Methanol</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Methyl Ethyl Ether, MEE</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Higher alcohols</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Higher ethers</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Ketones</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Odorant (e.g. ethylmercaptane)</td>
<td>20 [ppm]</td>
</tr>
<tr>
<td>Lubricant (e.g. Lubrizol or Hitech)</td>
<td>500–2000 [ppm]</td>
</tr>
</tbody>
</table>

3.4.12 Central control room & laboratory

The BLGMF plant with its biomass-fed heat and power boiler will be operated from a separate control room. For laboratory work co-operation will be established with the exiting pulp mill laboratory.

3.4.13 Emissions & residues

The plant is constructed to recycle gaseous and liquid streams to a maximum extent. Gaseous and liquid purge streams with too little value to be upgraded and recycled are used as supplementary fuels in the power boiler.
Waste water from the production of methanol and DME that contains highly limited quantities of organic compounds (methanol and higher alcohols only) is fed to the waste water treatment plant of the pulp mill.

3.4.14 Power boiler

A kraft pulp mill has a significant need of heat (steam) and electric power. The new biomass-fuelled boiler is dimensioned to supply the steam earlier produced from the recovery boiler and the old bark boiler and to balance the net steam production from the BLGMF plant. This is done in the back pressure mode and corresponding power is generated in a back pressure turbine. The back pressure boiler will be equipped with a modern steam turbine cycle and will be located at the pulp mill.

The role of the back pressure boiler is to cover the steam needs of the pulping operation and generate maximum amount of back pressure power. For the purpose of being fully renewable the pulp mill will still need to import renewable power from elsewhere to balance the power consumption of the mill and the BLGMF plant. This power can be imported from the national grid which means that the location of this second boiler generating power from renewable feedstock can be operated independently and at a location far away from the pulp mill with the BLGMF plant.

The entire plant complex must be operated continuously almost all the year except for an annual shutdown of 10 days. Unplanned shutdowns must be carefully avoided.

3.4.15 Impact on the pulp mill

The two new plants have been laid out in such a way that operational disturbances in the new plants will have as low impact as possible on the operation of the mill. The following will contribute to this design philosophy:

- Intermediate storage of black liquor, low sulphidity and high sulphidity green liquor or, for the alternative case, low sulphidity green liquor and liquid sulphur.
- No other process connection of importance from the BLGMF plant back into the pulp process.
- Independent production of process steam and power from the power boiler and supply of electric power from the grid.

The increased causticizing demand on the re-causticization plant in the mill due to the quality of the BLGMF green liquor leads to a need to upsize this part of the mill. There are commercially proven ways to accomplish this increased capacity. For some mills it may be necessary to change out some equipment that is if the just mentioned ways to increase the capacity already has taken place. If the pulp mill is new then this part of the unit will be design to cope with the extra demand.

Developments are under way which may lead to decreased demand for re-causticization for the pressurised black liquor gasification process. The level of decrease may be so big that the causticizing demand will even be less than for the recovery boiler case.
3.4.16 Alternate integration concepts

Instead of the sour gas treatment scheme presented in Chapter 3.4.9 the sulphur-rich gas can be converted to elemental, liquid sulphur. This sulphur is then reacted with white liquor in the pulp mill forming polysulphide liquor.

It was chosen to maintain the pulp mill plant size which means that the base case 2000 ADt/d pulp mill of 3420 t/d black liquor solids (BLS) will produce 2100 ADt/d and 3320 t/d BLS. This reflects the increased yield.

3.5 BLGMF plant description

The process scheme and the interaction between the individual plant sections within the BLGMF unit is presented in the overall process flow diagram in Figure 3.9 below. This chapter is a technical description of all process units. Section 3.5 will give brief overall description of the interaction of the different process units which is then followed by more detailed descriptions of the different process parts.

Figure 3.9. Flow scheme lay-out of the pressurized BLGMF (black liquor gasification automotive fuels) plant.

This section is a brief introduction of the overall process and the relationship between all plant units as shown in Figure 3.10 where also the pulp mill and the power boiler are included.

Black liquor is pumped from the pulp mill via the black liquor intermediate storage tank and further on to the preparation and feeding system (Section 3.5.1) and is the fed together with oxygen from the ASU (Section 3.5.7) to the gasifier quench reactor (Section 3.5.2) where it is converted to raw syngas and melted inorganic salts. The products leave the
reactor via the outlet in the bottom and are then rapidly cooled by water injection in the quench. The melted inorganic salts are dissolved in aqueous solution in the bottom section of the quench forming fresh green liquor.

**Figure 3.10.** Block flow diagram of the pressurised black liquor gasification to automotive fuels plant.
Before being depressurised the hot green liquor is cooled against cold incoming weak wash in a tube heat exchanger. The raw gas leaving the quench is saturated with moisture at near 220 °C and is cooled by raising steam in the counter current gas cooler (Section 3.5.3). The cooled raw gas is subjected to a sequence of cleaning and syngas upgrading operations (Section 3.5.4). The first cleaning operation will remove all tars and other condensables including water. The gas is then introduced to the Rectisol unit for complete removal of sulphur components such as H₂S and COS and most of the CO₂ (Section 3.5.4). The cleaned syngas is then adjusted in composition by a CO-shift unit and finally CO₂ formed in the shift unit is removed in a second absorber unit. The cleaned and shifted gas is then sent to the methanol/DME unit (Section 3.5.6A-B).

The methanol/DME feed gas is first compressed from 30 bar to around 90–100 bar needed for the methanol/DME synthesis loop. The synthesis loop differs depending on whether the selected process is for methanol or DME production. The methanol loop has a single methanol reactor and raw methanol from the isothermal catalytic reactor is condensed from the synthesis loop and brought to the distillation section for purification. The DME loop contains two reactors of which the first is a methanol reactor converting a part of the syngas to methanol which is then mixed to the feed gas to the second reactor which contains catalytic reactors for both methanol and DME production. DME is separated from the synthesis loop by condensation as crude DME. In addition, a mixture of DME and methanol is condensed by refrigeration and sent to a third reactor for conversion of methanol to DME. The crude DME is purified by distillation before being finally ready for export to the fuel distributor.

Waste gases and small amount of waste liquids from the methanol/DME synthesis are used as supplementary fuel in the new power boiler that produces electric power and steam to fulfil the heat demand of the pulp mill. Additional renewable electric power import is needed in order to cover the needs of the pulp mill and the BLGMF plant.

### 3.5.1 Black liquor preparation/feeding system

A flow scheme of the preparation and feeding system is shown in Figure 3.11.

**Filtration**

Black liquor from the evaporation plant within the pulp mill is pumped to the black liquor storage tank at the battery limit of the BLGMF plant at sufficient pressure. The black liquor feed from the pulp mill is filtered for removal of solid impurities, if any.

**Pre-heating**

The purpose of the heaters is to control the black liquor viscosity for achievement of good atomisation in the gasifier burner. After filtering and transfer to the Chemrec® unit, black liquor is pressurised by a high pressure pump and pumped to a black liquor pre-heater in which the temperature is raised to 120 °C.

**Black liquor burner**

Black liquor is introduced in the main burner together with oxygen. A gas fuelled pilot burner (natural gas or propane) is placed nearby the main burner has the purpose of preventing flame outage of the main burner and will immediately re-ignite the black liquor oxygen mixture in case of a flame out. In the burner nozzle, black liquor is atomised in order secure a good atomisation at different capacity loads. The black liquor flow is atomised into a fine spray with a suitable droplet diameter and size distribution in to
achieve high carbon conversion of the black liquor organic content and at the same time a high reduction rate of the inorganic salts in the black liquor.

\[ \text{Figure 3.11. Flow scheme of the feeding and preparation system for black liquor before it is fed to the gasifier.} \]

### 3.5.2 Black liquor gasification/quench system

**Entrained flow reactor**

Black liquor is introduced into the gasification reactor via the black liquor main burner nozzle and is gasified at 32 bar and 950–1000 °C, using oxygen as gasifying agent. The CHEMREC® type of gasifier is shown in Figure 3.12. The gasification reactor vessel is a vertical entrained flow reactor with refractory lining on the inside the pressure vessel shell. The reactor burner assembly is designed to establish plug flow. After a residence time of within 5–10 seconds, the product gas and melted inorganic salts flow downwards to the reactor outlet.

**Quench design**

In the quench vessel the products from the gasification reactor, i.e. fuel gas with entrained smelt droplets, are cooled by injection of condensate from the Gas cooling unit. The smelt droplets are solidified, separated from the gas and dissolved in the condensate (or weak wash) to form green liquor in the lower section of the quench vessel. The smelt free gas is further cooled to saturation by additional contact with recirculated process condensate from the gas cooling step. The smelt dissolution rate is enhanced by recirculating the quench liquor content via a circulation pump.

**Green liquor system**

The green liquor is cooled from the quench temperature of 220 °C to about 90 °C in two parallel heat exchangers. In the first heat exchanger, weak wash (dilute sodium hydroxide) from the mill is preheated to about 205 °C before entering the bottom section of the quench vessel and in the second heat exchanger evaporator condensate from the mill is heated to about the same 205 °C before entering the bottom section of the counter current condenser. The weak wash is added through weak wash feed pump and the condensate through a condensate pump.

After cooling to about 90 °C the green liquor is depressurized and passed on to green liquor degassing pot for release of dissolved gases (CO, H₂, CO₂ and H₂S), and routed to the dissolved gas scrubber for removal of H₂S and then the sulphur free gas is sent to the power boiler for destruction. The degassed green liquor product is pumped to the mill green liquor settling tank via a green liquor transfer pump.
3.5.3 Raw gas cooling and particle/solid removal

The counter current condenser is designed as a single cylindrical pressure vessel with three or four cooling sections as shown in Figure 3.13. The raw gas from the quench enters at the bottom of the CCC and flows upwards and is counter currently washed by the formed condensate falling downwards. The temperature in the bottom of the counter current condenser is the same as in the quench, 220 °C. Due to the counter current cooling and washing the precipitated condensate is not subcooled as it would have been in co-current gas cooling.

The lowest and warmest section of the counter-current gas cooler is used for generation of saturated MP steam. In the following section saturated LP steam is generated. At this stage the temperature on the process gas side has decreased to about 150 °C. In the upper sections LLP steam is produced and the remaining heat in the process gas down to about 90 °C is used for boiler feed water preheat. The final cooling is achieved by cooling water coils in the top section. The condensate collected in the bottom of the counter current
condenser is pumped via a condensate pump to the gas cooling section of the gasifier quench vessel.

![Diagram of gas cooler](attachment:image)

**Figure 3.13.** The counter current gas cooler in a CHEMREC® type of pressurised black liquor gasification plant.

### 3.5.4 Tar pre-wash and H₂S and CO₂ removal incl CO-shift

The raw gas from the black liquor gasification contains certain amounts of tar components that must be removed from the syngas (see Figure 3.9). A pre-wash unit is therefore a part of the Rectisol system. The solvent for the pre-wash should be a small split stream of the methanol from the bottom of the main absorber. Required methanol flow rate (as 100% methanol) is approx. 6 t/h. The methanol from the pre-wash will contain the water from the feed gas and all the tar components like benzene and naphthalene.

The tar loaded methanol from the pre-wash will be treated in the distillation section of the methanol/DME plant where the tars are concentrated and removed from the methanol and the same amount of fresh methanol will be fed back to the pre-wash unit as a make-up. See Figure 3.14.
According to the methanol/DME synthesis supplier, the light tars (xylene and toluene) and the naphthalene follows the water product of the column. Benzene is predicted to have a profile similar to the higher alcohols. Thus, the benzene can properly be withdrawn with the higher alcohols purge stream which is to be combusted in the boiler but will also be present in both the methanol and water products. Contamination of the methanol or DME with trace amounts of benzene should be highlighted but means no risk to the environment.

Otherwise the methanol from the pre-wash solvent has to be recovered within the scope of the Rectisol unit. This means a not negligible increase of the operating and investment cost. The bulk removal of the tar components from the methanol is then done by liquid/liquid separation after dilution with water, the final removal by distillation. Afterwards the methanol/water mixture is separated; internal enrichment of tar components in this separation column has to be considered.

A Rectisol unit with such a pre-wash/methanol recovery system was successfully operating for many years downstream a Winkler gasifier that was operated on lignite coal.

After cleaning in the pre-wash unit, the raw syngas is first cooled down in a refrigeration unit and then sent to absorber unit 1 where H2S, COS and CO2 are removed (see Figure 3.9). In absorber unit 1, the gas is contacted with cold methanol at -60 °C, which absorbs these components. In the bottom section of the absorber the gas is washed with methanol pre-loaded with CO2 from the top section of absorber 1 in order to remove the bulk of the H2S and COS. In the top section of absorber 1 the tail end of the undesired gas components are removed. The syngas leaving absorber 1 is thereby almost free from H2S, COS and CO2.

Figure 3.14. Illustration of the handling of contaminated methanol from the pre-wash unit. The methanol is purified in the distillation unit of the methanol/DME plant.
The raw gas from the black liquor gasification contains too much CO and too little H\textsubscript{2} for the methanol/DME syntheses processes. As the methanol synthesis gas must still contain a high portion of CO only partial conversion of the syngas is required. Downstream of the CO-shift reactor, the converted and non-converted gas streams are mixed to form a product gas at a CO/H\textsubscript{2} ratio required for the methanol/DME syntheses (see Figure 3.9). The requirement of CO shifting is the same for methanol and DME synthesis alternatives.

Approx. 53\% of the syngas needs to be shifted. The cleaned gas from absorber one is divided into a CO-shift feed stream (53\%) and a by-pass stream (47\%). The shift feed stream is heated from -60 °C first by heat exchanging in the refrigeration and then with warm water then finally IP-steam is added in order to reach the correct steam to dry gas ratio before being fed to the CO-shift loop, where the incoming gas is warmed up by cooling the shift outlet gas by a heat exchanger and the feed stream is thereby heated up to the reaction temperature of approx 300 °C before being fed to the catalytic CO-shift reactor.

The shifted gas stream is then cooled down by raising MP-, LP- and LLP steam and finally by refrigeration as the gas is sent to a second absorber in the Rectisol system for removal of CO\textsubscript{2} formed in the CO-shift unit after which the cleaned shifted gas stream is the mixed to the by-pass stream. The cleaned syngas is now adjusted to a methanol/DME syngas and is sent to the methanol/DME unit for further synthesis.

The loaded methanol stream is first expanded to intermediate pressure level in order to recover an impure CO\textsubscript{2} gas stream. The flashed CO\textsubscript{2} is warmed up and sent to recompression in a small compressor. The still loaded methanol is then expanded to close to ambient pressure for further CO\textsubscript{2} flashing forming a so-called tail gas with approx. 85\% vol CO\textsubscript{2}, 15 vol\% of N\textsubscript{2} and approx. 2 ppm (vol) of H\textsubscript{2}S. The methanol stream is then splitted. One part is pumped back to the main absorber as semi-lean solvent and the other part is stripped with low-pressure nitrogen in order to recover the heat of solution and thereby decrease the consumption of external refrigeration. The overhead gas is (mainly CO\textsubscript{2} and N\textsubscript{2}) then warmed up in the feed gas cooler.

The cold-stripped methanol is warmed up and fed into the regeneration column, where all yet dissolved acid gases are stripped off by the means of methanol vapour generated in a reboiler heated by steam. The H\textsubscript{2}S rich gas from the regeneration column contains approx. 50\% H\textsubscript{2}S and COS, 47\% CO\textsubscript{2} and 3\% of N\textsubscript{2} and is sent to the sulphur recovery unit (Section 4.1.5) for further treatment. The lean solvent from the bottom is cooled and pumped back to the top of the both absorber columns. Methanol vapour is condensed from the acid gas fraction before leaving the regeneration column overhead.

### 3.5.5 Sulphur recovery

*Base case: direct absorption in short time contactors*

The H\textsubscript{2}S rich gas from the regeneration column in the Rectisol unit is routed to a short time contactor unit which consists of three short time contactors in series where the gas stream is contacted with a fine spray of aqueous NaOH (white liquor from the pulp mill) which thereby selectively absorbs all sulphur components. The outlet (tail) gas from the last short time contactor will contain 0.1\% of the incoming H\textsubscript{2}S content which corresponds to less than 500 ppm, vol. The tail gas is recompressed and sent back to the Rectisol absorber, i.e. unit 1.
The short time contactors have previously been successfully tested in lab-scale but need to be further tested in the development plant (DP-1) which is currently under construction in Piteå, Sweden.

**Option: Claus unit sulphur recovery – polysulphide liquor**

Instead of the direct absorption of H\textsubscript{2}S into white liquor as described above, polysulphide liquor can be produced via the production of elemental sulphur from the H\textsubscript{2}S rich gas in a Claus unit. A Claus sulphur recovery unit can be installed to convert H\textsubscript{2}S and COS gases contained in the H\textsubscript{2}S rich gas from the Rectisol unit. The H\textsubscript{2}S rich gas is fed to the Claus burner where a fuel gas (propane or fossil gas) is burnt with air for heating purpose. Around the burner nozzle, a number of H\textsubscript{2}S burners are located. All burners eject the gas into a combustion chamber where the feed gas is converted to elemental sulphur by partial oxidation and approx 50% of the sulphur components are converted to elemental sulphur. The outlet gas from the combustion chamber is first cooled (by generation of MP-steam) which cools down the gas and precipitates a great percentage of the sulphur vapours. The cooled gas is then led through three catalytic Claus reactors that further convert the sulphur components in the gas to elemental sulphur. After each reactor the outlet gas is cooled (by generation of LP-steam) in order to condense formed elemental sulphur. Prior to entering the second and third Claus reactor the feed gas is heated up in re-heaters warmed by HP-steam.

In case an increased sulphur recovery is desired, the steps of heating, catalytic reacting and cooling are repeated. Downstream of the last sulphur condenser the process gas passes a special sulphur separator and is then routed as Claus tail gas to the battery limits of the Claus plant. The Claus tail gas is then recompressed and sent back to the Rectisol absorber unit 1.

The converted liquid sulphur drains via double shell traced pipes into a Sulphur collecting tank which is equipped with degassing pumps before the sulphur is pumped over to the intermediate sulphur storage and then further on to the polysulphide liquor preparation facilities.

The elemental sulphur is divided into droplets by a perforated distributor pipe and the sulphur droplets are mixed into a stirred tank with white liquor with a residence time of approx 20–30 minutes which is enough to allow the sulphur to be completely dissolved. The polysulphide liquor is then ready for use and is then pumped over to the pulp mill.

**3.5.6 Methanol (A) or DME (B) synthesis**

* A. Methanol synthesis

The methanol synthesis plant is sized to produce approximately 1180 t/d methanol according to or better than the specification listed in the design basis. This process description refers to the following process units representing EOR (end-of-run) conditions:

- The methanol synthesis section (Methanol synthesis, Desulphurisation, Compression, Methanol synthesis loop).
- Methanol distillation section (Methanol distillation, Stabiliser column, Methanol columns).
The process gas is received at battery limit at a pressure of 26 bar(g) and a temperature of 30 °C. The stoichiometric module of the gas is 2.05 as needed for the methanol synthesis. The process gas feed has to be desulphurised, as the methanol synthesis catalyst is highly sensitive to poisoning by sulphur-containing compounds. The process gas is heated in the Feed/Effluent Exchanger by heat exchanging with the effluent from the Sulphur Absorber. The process is heated further by condensation of IP steam in the Process Gas Preheater, before entering the Sulphur Absorber, where virtually all sulphur compounds are absorbed.

The desulphurised synthesis gas is cooled by the aforementioned feed/effluent exchanger, and further by the Synthesis Gas Cooler, before entering the Synthesis Gas Compressor, where it is compressed to the loop pressure. The compressed synthesis gas forms the make-up gas to the methanol synthesis loop. The make-up gas is mixed with recycle gas from the methanol loop. The recycle gas stream has been compressed in the Recirculator, to match the pressure of the make-up gas. The mixed synthesis gas is preheated in the Feed/Effluent Exchanger, before entering the methanol reactor, where hydrogen, carbon monoxide, and carbon dioxide are converted into methanol according to the following reaction schemes:

\[
\begin{align*}
\text{CO}_2 + 3\text{H}_2 & \rightleftharpoons \text{CH}_3\text{OH} + \text{H}_2\text{O} \\
\text{CO} + \text{H}_2\text{O} & \rightleftharpoons \text{CO}_2 + \text{H}_2.
\end{align*}
\]

In addition, some side reactions take place to a very limited extent whereby traces of oxygenates is formed, boiling at temperatures both lower than and higher than methanol. The reactors are boiling water reactors, i.e. the methanol synthesis catalyst, MK-121, is loaded into several tubes, all surrounded on the shell side by boiling water, which efficiently removes the heat of reaction from the methanol synthesis. Adjusting the pressure of the boiler water/steam mixture easily controls the cooling temperature of the shell side.

The steam from the reactors is used as:
- Heat source for process gas preheater, E 3001
- Export to IP steam header

The condensate from the preheater is recycled via the Condensate Circulation Pump, to the Steam Drum. Make-up boiler feed water to the Steam Drum is imported from battery limits via the BFW Pump. A small blow down from the Steam Drum is routed to battery limits.

The synthesis gas exit the reactors is cooled in the Feed/Effluent Exchanger, and further cooled and condensed in the Air Cooler, and the Final Condenser. The crude methanol is separated in the High Pressure Separator and sent to the Low Pressure Separator. The make-up gas contains a small quantity of inert gases, i.e. N$_2$ and CH$_4$. In order to prevent these gases from accumulating in the synthesis loop, a certain amount of gas is purged from the loop. The purge is withdrawn downstream the High Pressure Separator, where the inert gas concentration is at its highest.

After withdrawal of the purge gas, the synthesis gas from the High Pressure Separator is returned to the Feed/Effluent Exchanger by the Recirculator. The crude methanol is partly de-gasified in the Low Pressure Separator and sent to the Raw Methanol Buffer Tank. The purge gas is routed to an Ejector, where it is mixed with low pressure OH gas from the distillation section. The mixed gases from the Ejector are also mixed with the gas separated
in the Low Pressure Separator. The resulting mixture of purge gases is sent to battery limits where it may be used as fuel in other parts of the plant.

The crude methanol contains about 5 wt% of water and traces of reaction by-products, i.e. ethanol, higher alcohols, di-methylether, acetone and methylformate. The upgrading of the crude methanol occurs in a 3-column distillation system. The crude methanol produced in the methanol synthesis loop enters the distillation section via the Raw Methanol Buffer Tank. The tank is provided with a small Vent Wash Column, fed with demineralised water to minimise methanol escape through the vent. The facility to treat off-spec methanol from outside battery limits or reprocessing off-spec product is provided by an inlet to.

The Raw Methanol is sent to the Stabiliser Column by the Raw Methanol Pump. Before entering the Stabiliser Column, the methanol is preheated by condensation of LLP steam in the 1st Column Feed Preheater. The stabilisation of the crude methanol is done in order to remove dissolved gases. The off-gas runs through the Stabiliser Column OH Condenser, and the gas/liquid mixture produced is separated in the Stabiliser Column OH Accumulator. The gaseous fraction is cooled further in the OH Gas Condenser before being routed to the Ejector.

The liquid fraction is recirculated via the Stabiliser Column Reflux Pump as reflux to the top of the Stabiliser Column. The heat required for the distillation process in the Stabiliser Column is supplied by condensation of LLP steam in the Stabiliser Column Reboiler. The Stabiliser Methanol Pump pumps the stabilised methanol withdrawn from the bottom of the Stabiliser Column to the feed tray of the 2nd MeOH Column.

In the 2nd MeOH Column, the content of various volatile compounds is stripped off. The off-gas runs through the 2nd Column OH Condenser and the gas/liquid mixture produced is separated in the 2nd Column OH Accumulator. The gaseous fraction is routed to the Ejector. The liquid fraction is recycled via the 2nd Column Reflux Pump, to the top of. A small fraction of the liquid fraction is purged to the 1st Stabiliser Column OH Accumulator to reduce the byproduct concentration.

The methanol product is withdrawn a few trays below the top tray in order to minimise the content of dissolved gases and byproducts.

The heat required for the distillation process is supplied by condensing the OH vapour from the 3rd MeOH Column in the 2nd Column Reboiler. The bottom stream from the 2nd MeOH Column is pumped to the 3rd MeOH Column via the 3rd MeOH Column Feed Pump. In this column water and higher alcohols are separated from the product methanol.

The methanol product stream from the 3rd MeOH Column is withdrawn from the overhead system of the concentration column. The water stream is withdrawn from the bottom of the 3rd MeOH Column. The excess distillation water containing less than 0.1 wt% is sent to battery limits. A small purge stream containing higher alcohols is withdrawn. The stream is routed to battery limits where it may be used as fuel in other parts of the plant. The heat required for the distillation process in the 3rd MeOH Column is supplied by condensing MP steam in the HP Column Reboiler.

The two methanol product streams are cooled in the Product Coolers. The methanol product streams are mixed and sent to the Product Polisher Unit, where amines are removed by ion exchange. The methanol product is sent to battery limits.
**B. DME synthesis**

The Haldor Topsøe part of the BLGMF fuel grade DME plant comprises the following sections and subsections:

- DME synthesis section (Desulphurisation, Compression, DME synthesis loop)
- Distillation section (Stabiliser column, DME column, MeOH column)
- Ammonia refrigeration

**B. DME synthesis section**

The process gas is received at battery limit at a pressure of 26 bar(g) and a temperature of 30 °C. The stoichiometric module of the gas is 2.05 as needed for the DME synthesis, but sulphur compounds have to be removed in order not to poison the DME/methanol synthesis catalyst in the DME synthesis loop.

The process gas is heated in the Feed/Effluent Exchanger by heat exchanging with the effluent from the Sulphur Absorber and further heated in the Process Gas Preheater, before entering the Sulphur Absorber, where virtually all sulphur compounds are absorbed. The desulphurised synthesis gas is cooled by the aforementioned feed/effluent exchanger and further by the Synthesis Gas Cooler before entering the Synthesis Gas Compressor, where it is compressed to the loop pressure.

The compressed make-up gas is mixed with recycle gas from the Recirculator. The synthesis gas is preheated in the Feed/Effluent Exchanger by heat exchange with the effluent from the MeOH/DME Reactor before entering the first synthesis converter. The synthesis section consists of two separate converters, where hydrogen, carbon monoxide and carbon dioxide are converted over three beds of catalyst into methanol and/or DME according to the following reaction schemes:

\[
\begin{align*}
\text{CO}_2 + 3\text{H}_2 & \rightleftharpoons \text{CH}_3\text{OH} + \text{H}_2\text{O} + \text{Reaction heat} \quad (1) \\
\text{H}_2\text{O} + \text{CO} & \rightleftharpoons \text{CO}_2 + \text{H}_2 + \text{Reaction heat} \quad (2) \\
2\text{CH}_3\text{OH} & \rightleftharpoons \text{DME} + \text{H}_2\text{O} + \text{Reaction heat} \quad (3)
\end{align*}
\]

The first catalyst bed is placed in the first reactor and the second and third catalyst beds are placed in second reactor. The two reactions (1) and (2) take place along side in the first bed, whilst in the second bed all of the reactions (1), (2), and (3) are catalysed in combination. In the third reactor bed solely reaction (3) is carried out.

Part of the synthesis gas is bypasses the first reactor. The bypass serves as a control of the inlet temperature to second reactor. Thus after the passage of the first reactor, the synthesis gas is mixed with the synthesis gas by-passed (optionally heated in Trim Heater) and introduced into the second bed placed in second reactor (first bed of the second reactor). The effluent from the second bed being rich in both methanol and DME is sent directly to the third bed also placed inside the second reactor.

In addition, some side reactions take place to a very limited extent. Two of these are:

\[
\begin{align*}
2\text{CO} + 4\text{H}_2 & \rightleftharpoons \text{CH}_3\text{CH}_2\text{OH} + \text{H}_2\text{O} + \text{reaction heat} \\
\text{CH}_3\text{OH} + \text{CH}_3\text{CH}_2\text{OH} & \rightleftharpoons \text{CH}_3\text{OCH}_2\text{CH}_3 + \text{H}_2\text{O} + \text{reaction heat}
\end{align*}
\]
The methanol and DME synthesis reactions liberate a considerable amount of heat.

First reactor is a tubular reactor with catalyst on the tube side and boiling water on the shell side. Heat liberated during reaction in the catalyst bed of the reactor is absorbed on the boiling water side from which IP steam is generated.

Second reactor is an adiabatic reactor, and the effluent gas from this reactor is cooled through the Feed/Effluent Exchanger. Further cooling is done by means of the Air Cooler. The final cooling is done in the Final Condenser and the gas/liquid is sent to the HP Separator, where the vapour/liquid phase is separated.

The vapour phase is divided into two streams. The major stream is recycled to the DME/methanol synthesis via the Recirculator. The smaller stream is cooled, washed and purged. Cooling takes place in the Purge Gas Exchanger and further in the Purge Gas Chiller and the cooled gas is led to the Purge Gas Scrubber, wherein it is washed with cold methanol provided from the distillation section. The purge stream now freed of product is heated in Purge Gas Exchanger and sent to battery limit. The DME/methanol mixture outlet the scrubber is sent to the MTD Reactor in the distillation section.

The crude DME/methanol product is sent to the Flash Separator in the distillation section. The crude DME/methanol contains about 20–25 wt% water, 4–6% dissolved gases, and small amounts of byproducts, primarily higher ethers, alcohols and MEK. The crude DME/methanol is first led to the Flash Separator, where the pressure is reduced and part of the dissolved gases are released. From there, the crude product is sent to the Crude Product Tank, which has a capacity of 24 hours of production. The purpose of this storage is to insert a degree of operational freedom between the synthesis section and the distillation section allowing for upset situations and time to bring products on spec. In order to reduce product losses, the Flash Separator is equipped with an OH Scrubber, whereas the small amounts of gases released from the crude product tank are added to other distillation off gases and sent to the battery limit.

In order to protect the storage tank as well as downstream equipment, morpholine is added from the Morpholine Dosing Unit to the crude DME/methanol upstream tank continuously. The purpose of adding morpholine is to neutralise the very small quantities of organic acids in the crude DME/methanol.

The fractionation of the raw product is carried out in three columns. The stabilisation of the crude DME in the Stabiliser Column is done in order to remove dissolved gases from the crude product before further processing. Furthermore, an effluent stream from the downstream dehydration reactor is added to the OH in order to remove gases contained in the stream.

Considerable amounts of DME are released at the top of the stabiliser column, and in order to reduce the distillation losses, a Stabiliser Column OH Scrubber is installed in the OH gas stream from the stabiliser column.

The stabilised crude product from the bottom of the stabiliser column is led to the DME Column, where DME, higher ethers, and other light components are withdrawn from the DME Column Reflux Drum. This product stream is cooled in the DME Product Cooler and passed through the Ion Exchanger for removal of amines after which it is sent to battery limit. A small purge stream containing higher ethers is drawn and sent to battery limit via the HE Purge Pump.
The bottom product from the DME column containing methanol, water, and small amounts of primarily higher alcohols and ethers is sent to the MeOH Column. The MeOH Column services primarily the separation of methanol, higher alcohols and water. A methanol rich stream is taken out at the top section of the column. A part of this stream is cooled in the Solvent Cooler and further in the Solvent Chiller before being recycled as solvent to Purge Gas Scrubber located in the synthesis section and to the OH Scrubbers located in the distillation section.

The solvent returning from the Purge Gas Scrubber serves as coolant in the refrigeration loop Ammonia Cooler and is, together with the solvent returning from the OH Scrubbers sent to the Methanol-To-DME (MTD) Reactor. A stream of methanol is sent directly from the top section of the MeOH Column to the MTD Reactor. In the MTD Reactor, the methanol is partly converted into DME and water. The effluent from the reactor is returned to the Stabiliser Column. A small purge stream containing higher alcohols is drawn from the Methanol Column. The stream is, via the HA Purge Pump combined with the corresponding stream from second Methanol Column before being sent to battery limit where it may be used as fuel in other parts of the plant.

Excess water containing max. 0.1 mole% of methanol is withdrawn in the bottom of the column. The Excess Water Pump pumps the water to the battery limit.

3.5.7 Air Separation Unit (ASU)

To supply the required quantity of oxygen with a purity of >99 vol%, a simple cryogenic air fractionation process will be provided. Ambient air is compressed to approx. 6 bar with the aid of a four-stage turbo compressor. The compressed air is pre-cooled to approx. 8 °C by direct contact with cold water and the passed through molecular sieves where it is then freed from CO₂, hydrocarbons and the remaining water vapour.

The purified air then enters the separation unit (cold box) and passes through the main heat exchanger in counter current to the cold products, oxygen and nitrogen. The air is thereby cooled to liquefaction temperature and is then fed to the pressure column. In this column the air is separated by rectification into pure nitrogen and a crude oxygen fraction.

A minor stream of air is withdrawn from the central part of the main heat exchanger at a temperature of approx. -90 °C and expanded in an expansion turbine in order to cover the cold requirements of the process. The cold air, which is at almost atmospheric pressure, is fed to the low-pressure column.

In the low-pressure column, the crude oxygen from the pressure column is subjected to final separation into the pure components, nitrogen and oxygen. The purity of the oxygen is determined by the number of trays used. Both products are withdrawn in the gaseous state and heated by transforming their cold to the process air in the aforementioned main heat exchanger.

3.5.8 Boiler Feed Water (BFW) preparation

The quantity of steam needed in the pulp mill is the same as for a recovery boiler and the overall steam quantity is only marginally changed and is part of the Balance of plant system. The need of preparation of Boiler Feed Water for the BLGMF plant as well as the Power boiler means a slight capacity expansion of the existing BFW preparation unit that already exists in the pulp mill.
3.5.9 BFW and steam supply

Headers for BFW and all necessary steam qualities within the BLGMF plant as well as the Power Boiler and for transfer to the Pulp Mill are included in the Balance of plant system.

3.5.10 Cooling water system

The need of cooling water is increased significantly as there are large needs of final cooling in both the Gas Cooling, Gas Cleaning as well as in the Methanol/ DME synthesis and Final product distillation. Introduction of BLGMF plant on a 2000 t/d mill (ADt), will increase the required amount of approx 2700 m$^3$/h of cooling water based on a temperature increase of 10 °C. This means that the cooling water of the existing pulp mill has to be expanded by adding more capacity in pumping, sand filtering and supply pipe network. The cooling water system is part of the balance of plant system.

3.5.11 Power boiler

The selected boiler, as shown in Figure 3.15, represents the newest bubbling fluidized bed boiler (BFB) technology and is designed to generate steam, at 141 bar(a) and 545 °C. The steam is fed to a new back pressure steam turbine and IP-, MP-steam are withdrawn from the turbine at different stages. LP-steam from the steam turbine outlet is conditioned by water injection and finally exported to the pulp mill.

The boiler has been selected to balance the remaining steam need of the pulp mill where a part of the steam (mainly LP- and MP-steam) is a by-product from the BLGMF process.

The fuel for the boiler is bark, wood fuel, organic liquid and synthesis gas. The start-up fuel can be light or heavy fuel oil. This specification is based on assumption, that all fuels are considered as non-waste fuels.

Fluidised bed combustion

Fuel is fed into the furnace through fuel feed chutes. The combustion air is staged by utilising primary air and overfire air. The fluidising air is introduced into the furnace through the water-cooled distribution system while the staging air, which completes the combustion, is introduced through air openings located on the furnace walls. The fluidisation results in an expanded combustion zone with high turbulence, intimate solids-to-gas contact and a high heat transfer rate within the bed.

The bed temperature depends on the quality and amount of the fuel in the bed. Normally the bed temperature varies between 750 °C and 950 °C. The bed temperature is controlled by a flue gas recirculation system in which primary air and flue gas is mixed to lower the oxygen content in the bed.

Furnace

The bubbling fluidized bed boiler is a single drum unit, which consists of a furnace, second pass and third pass. The furnace and the second pass are of gas-tight, membrane construction. The lower furnace walls are protected with refractory, which promotes an elevated combustion temperature zone to efficiently burn the high moisture fuel and to protect the tubes from erosion. Due to water-cooled design, only a thin cement refractory is needed.
The water-cooled membrane construction of the air distributor with no moving parts yields an extremely high availability. The grate is part of the overall natural circulation, ensuring proper cooling of the grate also in upset conditions.

![Diagram](image)

**Figure 3.15. Cross sectional view of the power boiler excluding stack and steam turbine system.**

**Fuel feeding**

There are two fuel silos for the fuel mixture. The silos are equipped with a rotating discharger screw. The fuel is fed from the silo into the furnace chain conveyors and metering screws. There are two fuel feeding chutes and openings on each furnace sidewall.

The fuel chutes are furnished rotary valves in order to prevent any back flow from the furnace. The fuel feeding chutes are equipped with a feed/purge air system, which improves the fuel injection and distribution while also cooling the fuel chute. The cooling air is extracted from primary air duct after the fan.

**Steam generation**

The design basis for steam data is (case 100 % load)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>bar(g)</td>
<td>140</td>
</tr>
<tr>
<td>Steam flow</td>
<td>kg/s (235 t/h)</td>
<td>65.3</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>545</td>
</tr>
<tr>
<td>Feed water temperature</td>
<td>°C</td>
<td>180</td>
</tr>
</tbody>
</table>

**Fuels**

The main fuels are bark, wood fuel, organic liquid and synthesis gas. For support and start up fuel oil is to be used. The assumed fuel analyses are as follows.

<table>
<thead>
<tr>
<th>Bark</th>
<th>Unit</th>
<th>Design</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating value</td>
<td>dry MJ/kg</td>
<td>19.4</td>
<td>18–21</td>
</tr>
<tr>
<td>Moisture</td>
<td>%</td>
<td>59</td>
<td>50–62</td>
</tr>
<tr>
<td>Ash</td>
<td>(dry base) %</td>
<td>1.8</td>
<td>2.0–3.0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>(dry base) %</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>(dry base) %</td>
<td>40.25</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>(dry base) %</td>
<td>0.04</td>
<td>0.02–0.04</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>(dry base) %</td>
<td>0.4</td>
<td>0.3–0.5</td>
</tr>
<tr>
<td>Carbon</td>
<td>(dry base) %</td>
<td>51.7</td>
<td></td>
</tr>
<tr>
<td>Volume weight</td>
<td>kg/m³</td>
<td>300</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wood fuel</th>
<th>Design</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating value</td>
<td>dry MJ/kg</td>
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</tr>
<tr>
<td>Moisture</td>
<td>%</td>
<td>50</td>
</tr>
<tr>
<td>Ash</td>
<td>(dry base) %</td>
<td>1.8</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>(dry base) %</td>
<td>6.1</td>
</tr>
<tr>
<td>Oxygen</td>
<td>(dry base) %</td>
<td>40.54</td>
</tr>
<tr>
<td>Sulphur</td>
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</tr>
<tr>
<td>Nitrogen</td>
<td>(dry base) %</td>
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</tr>
<tr>
<td>Carbon</td>
<td>(dry base) %</td>
<td>51.1</td>
</tr>
<tr>
<td>Volume weight</td>
<td>kg/m³</td>
<td>300</td>
</tr>
</tbody>
</table>

**Particle size**

<table>
<thead>
<tr>
<th>Bark and wood fuel</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Max length</td>
<td>cm</td>
</tr>
<tr>
<td>Max cross section</td>
<td>cm²</td>
</tr>
<tr>
<td>Screening result</td>
<td>mm</td>
</tr>
<tr>
<td>Screening result</td>
<td>mm</td>
</tr>
</tbody>
</table>

Maximum 2% of the fuel are allowed to be wood slices up to 250 mm, when the other dimensions are below 30 mm.
### Organic liquids

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Design</th>
<th>Range</th>
</tr>
</thead>
<tbody>
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<td>dry MJ/kg</td>
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<td>28–32</td>
</tr>
<tr>
<td>Moisture</td>
<td>%</td>
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<td></td>
</tr>
<tr>
<td>Composition:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixture of alcohols, oxygenates,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>benzene</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Waste synthesis gas

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Design</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating value</td>
<td>dry MJ/kg</td>
<td>19.4</td>
<td>18–21</td>
</tr>
<tr>
<td>Moisture</td>
<td>%</td>
<td>59</td>
<td>50–62</td>
</tr>
<tr>
<td>Ash</td>
<td>(dry base) %</td>
<td>1.8</td>
<td>2.0–3.0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>(dry base) %</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td>(dry base) %</td>
<td>40.25</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>(dry base) %</td>
<td>0.04</td>
<td>0.02–0.04</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>(dry base) %</td>
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<td>0.3–0.5</td>
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<tr>
<td>Carbon</td>
<td>(dry base) %</td>
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<tr>
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<td></td>
</tr>
</tbody>
</table>

### Waste synthesis gas

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating value</td>
<td>dry, MJ/Nm³</td>
<td>35.9</td>
</tr>
<tr>
<td>Moisture</td>
<td>%</td>
<td>0</td>
</tr>
<tr>
<td>Composition:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂</td>
<td>vol%</td>
<td>60</td>
</tr>
<tr>
<td>CH₄</td>
<td>vol%</td>
<td>5</td>
</tr>
<tr>
<td>CO</td>
<td>vol%</td>
<td>8</td>
</tr>
<tr>
<td>CO₂, N₂</td>
<td>vol%</td>
<td>27</td>
</tr>
</tbody>
</table>

Heavy fuel oil for start-up and back-up.

### Fuel oil

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower heating value</td>
<td>dry, MJ/kg</td>
<td>40</td>
</tr>
<tr>
<td>Sulphur content</td>
<td>wt%</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- **Design fuel mixture**
  
  Boiler design fuel mixture complies 50% bark, 24% wood fuel, 1% organic liquids and 25% synthesis gas of fuel heat input.

- **Feed water and condensate quality**
  
  The feed water and condensate quality requirements according to DENÅ requirements.

- **Boiler feed water quality**
  
  The boiler water quality requirements according to DENÅ.

- **Sand**
Fluidized bed make-up sand shall be of natural, sieved sand with the amount of quartz as mineral less than 70%.

<table>
<thead>
<tr>
<th>Natural sand fraction size:</th>
<th>&lt;1.20 mm</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;0.70 mm</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>&lt;0.50 mm</td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td>&lt;0.10 mm</td>
<td>1%</td>
</tr>
</tbody>
</table>

| Softening/sintering temperature according to DTA-method | °C | >1100 |

3.5.12 Impact on pulp mill

The two new plants have been laid out in such a way that operational disturbances in the new plants will have as low impact as possible on the operation of the mill. See Section 3.4.15 Impact on the mill.

See also Section 3.5.8 Boiler feed water preparation, 3.5.9 BFW and steam supply, and 3.5.10 Cooling water system where the consequences are described for these systems in an existing pulp mill when the recovery boiler is replaced with a BLGMF plant and a new power boiler.
3.6 Space requirement – BLGMF plant plot plan

In Figure 3.16 the required space areas for the different process units in the BLGMF plant are shown. Distances are reported in meters.

Figure 3.16. BLGMF plot plan with areas stated in meters.
4 MATERIAL AND ENERGY BALANCE

4.1 Basis for calculations

4.1.1 Reference pulp mill
System performance was calculated for a mill used as a reference mill in the "Ecocyclic Pulp Mill" programme (also referred to by the Swedish acronym, KAM), a large research effort in the Swedish pulp and paper industry. The process equipment, the mode of operation, and material and energy balances have been well defined for the reference mill [25, 26, 27] which is assumed to employ late 1990s state-of-the-art technology in all process units. Although the actual reference mill has not been built, its characteristics well match those of mills that have been built or rebuilt in the last few years. Except for the black liquor gasification systems, all the equipment assumed to be used in the reference mill is in operation in existing mills.

The research programme has been carried out in two programme periods: KAM1, 1996–1999 and KAM2, 2000–2002. There has therefore been some development in the definition of the reference mill. Material and energy balances presented here are based on the 2000 ADt/day KAM1 TCF mill and the 2000 ADt/day KAM2 ECF mill. The preliminary cost estimate was carried out for the KAM2 mill only.

Out of the four cases defined by Jönsson et al [25], the "TCF, Summer" case was used for the KAM1 mill calculations, mainly because the steam consumption approximately corresponded to the average of the four cases. Note that process consumption has been separated from steam and power consumption inside the powerhouse, since the latter figures will vary depending on the studied configuration. The major difference between the KAM1 and KAM2 mills is the production capacity, resulting in a lower specific investment cost for the 2000 ADt/day KAM2 mill.
Figure 4.1. Process flow diagram for black liquor gasification system with motor fuels production (BLGMF). In addition to the gasification and methanol synthesis plant, the figure shows the air separation unit (ASU), acid gas removal system (AGR), Claus plant sulphur recovery unit (SRU), and steam turbine (ST). Note that the calculations in the present paper are based on reabsorption of H₂S in green liquor rather than conversion in a Claus plant.

From an energy perspective, the major difference between the TCF and ECF cases is the pulp yield and therefore the specific amount of black liquor solids recovered per tonne of pulp, 1.8 tDS/ADt in the TCF case, 1.71 tDS/ADt in the ECF case. Bleach plant steam consumption is slightly higher in the TCF case ("Totally Chlorine Free"), where more of the bleaching is carried out in pressurised hydrogen peroxide stages, than in the ECF case ("Elemental Chlorine Free"), where chlorine dioxide is used in one of the bleaching stages.

**Recovery boilers**

Background data for the reference mill include calculations for one recovery boiler, generating steam at 79 bar(a), 485°C (KAM1) or 81 bar(a), 490°C (KAM2). Recovery boiler performance was calculated with a model derived from the one used for the black liquor gasifier to ensure thermodynamic consistency between the models.

**Black liquor gasification systems**

The studied systems are centred around a high-temperature, oxygen-blown gasifier, and are implied to approximate the systems being developed by Chemrec [14, 28]. Gasifier performance was estimated with GIBBSGAS, a chemical equilibrium model based on Gibbs energy minimisation [29]. The remaining systems – air separation, gas and smelt cooling, acid gas removal and recovery, methanol plant, gas turbine, and steam cycle – were modelled either in the process simulator HYSYS or in spreadsheet models according to the flow sheet in Figure 4.1. Specifically, for the methanol plant, product yields, utility...
consumption, etc., were based on calculations from a supplier for a plant of similar size. Heat losses and pressure drops were estimated for each unit operation. Auxiliary calculations for the chemical recovery cycle and the bark boiler were carried out in a spreadsheet model.

**Recausticizing**

In the gasifier, a large fraction of the sulphur in the black liquor is converted to hydrogen sulphide. There are three principal routes to convert the concentrated H$_2$S stream from the acid gas removal system to sulphur in a useful form in the pulping liquor:

- Reabsorption in green or white liquor
- Recirculation to the gasifier
- Conversion to liquid sulphur, which is dissolved to give a polysulphide liquor.

The first two routes will yield a white liquor with essentially the same composition as a conventional liquor, while the third route can be utilised for pulping modifications. The first route does also make it possible to prepare white liquors with different sulphonidities, if desired. Although the sulphur split may be put to an advantage in the pulping process, it also leads to an increased load on the lime kiln. The effects on energy efficiency are described in greater detail by Larson *et al* [15] and Berglin *et al* [30].

### 4.2 Summary of process streams

Important process streams in the BLGMF plant are presented below. These streams represent the additional requirements and the generated products on the mill following an implementation of the BLGMF concept.

#### 4.2.1 Overall plant data

- **Black Liquor feed:** 3420 t/d
- **Oxygen consumption:** 1172 t/d (as 100% O$_2$)
- **Methanol Production:** 1183 t/d (as 100% methanol)
- **Option (DME production):** 824 t/d (as 100% DME)
- **Biofuel import:**
  - Case (Methanol): 129 MW$_{th}$ or 23.9 t/h as dry bark (19.4 MJ/kg bark)
  - Case (DME): 125 MW$_{th}$ or 23.2 t/h as dry bark (19.4 MJ/kg bark)

#### 4.3 Consumption figures, production rates and emissions

The summarising performance estimates for the two BLGMF cases, i.e. mass and energy flows, are given in Table 4.2. The figures presented concern the battery limits for the BLGMF plant introduced in Figure 3.10. From the summarising lines, it could be seen that
the requirement on external power purchase is 56.1 and 55.4 MW\textsubscript{e}, respectively for the methanol and DME case. The total power generated amounts to 41.0 and 43.1 MW\textsubscript{e}, respectively, electricity that is solely consumed by internal plant units.

The gasifier considered is the same regardless the fuel produced. The operating conditions for the gasifier, as well as the steam quality for the power boiler, are summarised in Table 4.1.

**Table 4.1. Operating conditions of the BL gasifier.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier Temperature</td>
<td>°C</td>
<td>950</td>
</tr>
<tr>
<td>Gasifier Pressure</td>
<td>bar(a)</td>
<td>32</td>
</tr>
<tr>
<td>H\textsubscript{2}S Processing</td>
<td>Reabs</td>
<td></td>
</tr>
<tr>
<td>Fraction of BLS to BLGMF plant</td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>Mill type</td>
<td>Market</td>
<td></td>
</tr>
<tr>
<td>HP Steam Pressure</td>
<td>bar(a)</td>
<td>140</td>
</tr>
<tr>
<td>HP Steam Temperature</td>
<td>°C</td>
<td>545</td>
</tr>
</tbody>
</table>
Table 4.2. Summarising mass and energy balances for BLGMF configurations in a market pulp mill.

<table>
<thead>
<tr>
<th>Description</th>
<th>Market Pulp Mill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BLGMF</td>
</tr>
<tr>
<td></td>
<td>MEOH</td>
</tr>
<tr>
<td><strong>Case No.</strong></td>
<td></td>
</tr>
<tr>
<td>ELECTRIC POWER</td>
<td></td>
</tr>
<tr>
<td>Producers</td>
<td></td>
</tr>
<tr>
<td>Gas Turbine*</td>
<td>MWe</td>
</tr>
<tr>
<td>Back-Pressure Steam Turbine</td>
<td>MWe</td>
</tr>
<tr>
<td>Condensing Steam Turbine</td>
<td>MWe</td>
</tr>
<tr>
<td>Consumers</td>
<td></td>
</tr>
<tr>
<td>Boilers</td>
<td>MWe</td>
</tr>
<tr>
<td>ASU</td>
<td>MWe</td>
</tr>
<tr>
<td>N2 Compressor</td>
<td>MWe</td>
</tr>
<tr>
<td>LLP Compressor</td>
<td>MWe</td>
</tr>
<tr>
<td>Gasification (BL &amp; WW feed + contgcy)</td>
<td>MWe</td>
</tr>
<tr>
<td>Gas Cooling (Circ + BFW feed)</td>
<td>MWe</td>
</tr>
<tr>
<td>Acid gas removal plant</td>
<td>MWe</td>
</tr>
<tr>
<td>Methanol/DME synthesis</td>
<td>MWe</td>
</tr>
<tr>
<td>Distillation</td>
<td>MWe</td>
</tr>
<tr>
<td>Miscellaneous: Pre-wash, CO-shift</td>
<td>MWe</td>
</tr>
<tr>
<td>BLGMF Plant consumption</td>
<td>MWe</td>
</tr>
<tr>
<td>Summary</td>
<td></td>
</tr>
<tr>
<td>Power Generated, Gross</td>
<td>MWe</td>
</tr>
<tr>
<td>Power Generated, Net</td>
<td>MWe</td>
</tr>
<tr>
<td>Power Consumed in Mill</td>
<td>MWe</td>
</tr>
<tr>
<td><strong>Excess Power</strong></td>
<td><strong>MWe</strong></td>
</tr>
<tr>
<td>Excess Power</td>
<td>kW/ADt</td>
</tr>
<tr>
<td>Excess Power</td>
<td>GJ/ADt</td>
</tr>
<tr>
<td>STEAM</td>
<td></td>
</tr>
<tr>
<td>Producers</td>
<td></td>
</tr>
<tr>
<td>HRSG</td>
<td>t/h</td>
</tr>
<tr>
<td>Recovery Boiler</td>
<td>t/h</td>
</tr>
<tr>
<td>Bark Boiler</td>
<td>t/h</td>
</tr>
<tr>
<td>Purge Gas in RB/BB</td>
<td>t/h</td>
</tr>
<tr>
<td>NCG Klin</td>
<td>t/h</td>
</tr>
<tr>
<td>Gasifier Island</td>
<td>t/h</td>
</tr>
<tr>
<td>CO Shift Loop</td>
<td>t/h</td>
</tr>
<tr>
<td>Methanol Synthesis</td>
<td>t/h</td>
</tr>
<tr>
<td>MP Condensate Flash</td>
<td>t/h</td>
</tr>
<tr>
<td>Desuperheaters</td>
<td>t/h</td>
</tr>
<tr>
<td>Subtotal producers</td>
<td>t/h</td>
</tr>
<tr>
<td>Internal Consumers</td>
<td></td>
</tr>
<tr>
<td>AGR</td>
<td>t/h</td>
</tr>
<tr>
<td>CO Shift Loop</td>
<td>t/h</td>
</tr>
<tr>
<td>Methanol /DME Distillation</td>
<td>t/h</td>
</tr>
<tr>
<td>Fuel Gas Heater</td>
<td>t/h</td>
</tr>
<tr>
<td>Boilers</td>
<td>t/h</td>
</tr>
<tr>
<td>Desaerator/Feedwater Heater</td>
<td>t/h</td>
</tr>
<tr>
<td>Subtotal consumers</td>
<td>t/h</td>
</tr>
<tr>
<td>Net Steam Produced</td>
<td>t/h</td>
</tr>
<tr>
<td>Mill Consumers</td>
<td></td>
</tr>
<tr>
<td>LP steam to Mill</td>
<td>t/h</td>
</tr>
<tr>
<td>MP steam to Mill</td>
<td>t/h</td>
</tr>
<tr>
<td>LP Steam to Cond Turbine</td>
<td>t/h</td>
</tr>
<tr>
<td>Total Steam Consumed</td>
<td>t/h</td>
</tr>
</tbody>
</table>
## Table 4.2. cont.

| FUEL** | 
|-----------------|-----------------|
| Black Liquor | 
| Produced/Consumed | GJ/ADt | 21.02 | 21.02 |
| Bark (or other wood residues) | 
| Consumed in Lime Kiln *** | GJ/ADt | -2.12 | -2.12 |
| Consumed in Biomass Boiler | GJ/ADt | -6.34 | -6.16 |
| Production | GJ/ADt | 2.90 | 2.90 |
| Purchased | GJ/ADt | 5.56 | 5.38 |
| Purchased | MW | 129 | 125 |
| Tall Oil | 
| Consumed in Biomass Boiler | GJ/ADt | 0.00 | 0.00 |
| Production | GJ/ADt | 1.37 | 1.37 |
| Sold | GJ/ADt | 1.37 | 1.37 |
| Tall Oil | 
| Consumed in Biomass Boiler | GJ/ADt | 0.00 | 0.00 |
| Production | GJ/ADt | 1.37 | 1.37 |
| Sold | GJ/ADt | 1.37 | 1.37 |
| Methanol /DME | 
| Production | t/d | 1183 | 824 |
| MEOH | 11.78 | 11.87 |
| DME | 272 | 275 |
| Incremental Power | MW | -101.3 | -100.5 |
| Imported Power Efficiency (Biomass) | % | 40% | 40% |
| Incremental Biomass Used in Mill | MW | 161.0 | 156.9 |
| Incremental Biomass Used for Power | MW | 253.1 | 251.2 |
| Total Incremental Biomass | MW | 414.1 | 408.1 |
| Biomass to MeOH, Efficiency | % | 66% | 67% |

* The calculations were done for a gas turbine of fixed size (General Electric 6FA); the results in the table have been scaled to the generic 2000 ADt/d mill.

** The lime kiln is fired with dried pulverised bark. A fraction of the bark is used to heat the bark dryer.

*** Based on the lower heating value of each fuel: Black liquor (reduced sulphur), 12.1 MJ/kg DS; Bark, 19.4 MJ/kg DS (59% moisture); Tall oil, 39 MJ/kg; Methanol, 19.8 MJ/kg

A schematic process flow diagram, with a more detailed layout, is shown in Figure 4.2. The complete BLGMF process is described, ranging from the incoming black liquor to the resulting methanol/DME product. The unique numbers given to the process streams are referring to the produced synthesis gas as well as the steam supplied for heating purposes and as reactant in the CO-shift unit (stream 7 and 6 respectively). The complete gas data sheet is reported in Table 4.3, using also the fact that 1 Nm³ is equal to 44.62 moles. In the bottom part of each stream, the lower heating value of the stream is given as well as the corresponding energy flow, i.e. the mass flow multiplied with the heating value.
Figure 4.2. Schematic process flow diagram for the complete BLGMF system with relevant mass flow streams given.
### Table 4.3
Gas composition divided on process streams, numbered in accordance to the nomenclature introduced in Figure 4.2.

<table>
<thead>
<tr>
<th>Product Gas</th>
<th>Heat of comb.</th>
<th>Molar weight</th>
<th>Gasifier outlet gas</th>
<th>Gasifier outlet, as dry</th>
<th>Gas Cooler Inlet</th>
<th>Cleaner syngas</th>
<th>To shift (% by vol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
<td>kJ/mol</td>
<td>g/mol</td>
<td>mol/s</td>
<td>% vol</td>
<td>mol/s</td>
<td>% vol</td>
<td>mol/s</td>
</tr>
<tr>
<td>H₂</td>
<td>241.94</td>
<td>2.016</td>
<td>869.77</td>
<td>39.19%</td>
<td>689.33</td>
<td>14.08%</td>
<td>688.92</td>
</tr>
<tr>
<td>CO</td>
<td>282.38</td>
<td>2.016</td>
<td>670.58</td>
<td>38.10%</td>
<td>670.23</td>
<td>13.69%</td>
<td>669.75</td>
</tr>
<tr>
<td>CH₄</td>
<td>802.35</td>
<td>16.04</td>
<td>23.71</td>
<td>1.35%</td>
<td>23.00</td>
<td>0.46%</td>
<td>23.57</td>
</tr>
<tr>
<td>H₂S</td>
<td>n.a.</td>
<td>34.08</td>
<td>33.64</td>
<td>1.91%</td>
<td>33.29</td>
<td>0.68%</td>
<td>34.12</td>
</tr>
<tr>
<td>N₂</td>
<td>28.01</td>
<td>0.23%</td>
<td>5.19</td>
<td>0.30%</td>
<td>4.41</td>
<td>0.24%</td>
<td>4.22</td>
</tr>
<tr>
<td>H₂O</td>
<td>18.016</td>
<td>22.05%</td>
<td>0.00</td>
<td>0.00%</td>
<td>3138.68</td>
<td>64.11%</td>
<td>3.17</td>
</tr>
<tr>
<td>CH₃OH (g)*</td>
<td>675.9</td>
<td>32.042</td>
<td>100.00%</td>
<td>100.00%</td>
<td>1428.59</td>
<td>100.00%</td>
<td>763.19</td>
</tr>
</tbody>
</table>

Pressure: bar(a) 30 30 30 29 28.5 28 25
Temperature: (°C) 233.9 233.9 15 450 15 15 25
Av. mol wt. (g/mol) 18.02 18.02 0.00 16.45 15.83 6.10 10.25
NormDensity: (kg/Nm³) 0.00 0.73 0.71 0.27 0.46
Flow (kg/sec) 11.53 1.65 0.00 23.14 16.00 4.58 14.36
Vol flow (Nm³/sec) 14.84 2.05 14.91 31.53 22.64 16.83 31.39
Molar flow (kmol/sec) 0.66 0.09 0.67 1.41 1.01 0.75 1.40
LHV (MJ/Nm³) - - 0.00 6.01 8.37 11.26 11.60
MWLHV(gas) - - 174.69 189.45 189.45 189.45 364.13

*) MeOH product at battery limits = liquid state.
4.3.1 Effluents (liquids)

*Waste water from methanol distillation plant:*

Distillation water from methanol plant: 3.2 t/h
- Water Purity 99.99%
- Methanol 0.01%.

The distillation water stream will be sent to a biological water-treatment plant for purification.

*DME option:*

Waste water from DME distillation plant/excess water to battery limits:
- Water 15.1 t/h
- Methanol 1.0 kg/h
- Higher alcohols 3.0 kg/h.

The excess water stream will be sent to a biological water-treatment plant for purification.

*Cooling water:*

Warm Cooling water: 2 700 m$^3$/h.

4.3.2 Emissions (gases from power boiler)

Emissions from power boiler:
- Dust after ESP (6.0% O$_2$ as dry) <0.4 kg/ADt of paper pulp
- NO$_X$ <0.55 kg/ADt of paper pulp
- SO$_2$ -
- CO 1.95 kg/ADt of paper pulp
- N$_2$O <0.12 kg/ADt of paper pulp.

4.4 Impact on the pulp mill

There are several ways to make the comparison with respect to a pulp mill of today. The BLGMF concept will produce a higher-value product, but this is associated with an increased consumption of biomass. The energy derived from biomass has to suffice not only the internal needs of the pulp mill but also the produced automotive fuel. This fact is visualised in Figure 4.3 and the discussion regarding comparison alternatives is further developed in Chapter 5. The choice between production of methanol or DME alters the energy balance somewhat, but in large the flow streams are the same. From Figure 4.3 it is also seen that the steam generated in the BLGMF unit alone does not suffice the internal needs of the mill. The quality of the steam is also lower compared to the recovery boiler in the conventional mill; i.e. it is not possible to expand this steam in the existing steam...
turbine. That is, the BLGMF plant requires additional biomass to an added power boiler for steam and power generation purposes.

Figure 4.3. Comparison between a conventional pulp mill of today and a pulp mill equipped with a BLGMF plant.

4.5 Summary of steam producers and consumers

The flow of steam in the BLGMF plant is reported below in Table 4.4. They are divided into process units and reported for the two BLGMF cases, i.e. methanol and DME production respectively. These figures are more extensive than the overview provided in Table 4.2. The process units are shown in Figure 4.2. For a more extensive depiction of the steam qualities and the absolute mass flows of the respective streams, the reader is directed to the report enclosures.

Table 4.4. Summary of net steam production (negative sign represent consumption) in the BLGMF plant, flow rates in t/h for the 3400 t/d BLS BLGMF plant.

<table>
<thead>
<tr>
<th></th>
<th>Gasifier/CCC</th>
<th>Rectisol</th>
<th>Claus</th>
<th>CO-shift</th>
<th>Methanol synthesis</th>
<th>DME synthesis</th>
<th>Power boiler</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>172.8</td>
<td>-20</td>
<td>7.1</td>
<td>-3.9</td>
<td>-1.9</td>
<td>-</td>
<td>223.2</td>
<td>377.3</td>
</tr>
<tr>
<td>DME</td>
<td>172.8</td>
<td>-20</td>
<td>7.1</td>
<td>-3.9</td>
<td>-</td>
<td>-12.9</td>
<td>234.2</td>
<td>377.3</td>
</tr>
</tbody>
</table>

4.6 Energy efficiency results

The energy streams passing the boundary of the various plant configurations are given below in Table 4.5. The specific amounts in energy terms of produced motor fuels using the configuration and the option described in this report are reported. At the bottom of the table, the efficiencies for the respective fuel are given divided on the two feedstocks, i.e. biomass and black liquor.
Table 4.5. Summary of consumed and produced energy products.

<table>
<thead>
<tr>
<th>Fuel options</th>
<th>Methanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass consumption</td>
<td>414 MW</td>
<td>408 MW</td>
</tr>
<tr>
<td>Black liquor consumption</td>
<td>487 MW</td>
<td>487 MW</td>
</tr>
<tr>
<td>Fuel production</td>
<td>273 MW</td>
<td>275 MW</td>
</tr>
</tbody>
</table>

Energy efficiency (LHV)

<table>
<thead>
<tr>
<th></th>
<th>Methanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass to fuel</td>
<td>66%</td>
<td>67%</td>
</tr>
<tr>
<td>Black liquor to fuel</td>
<td>56%</td>
<td>56%</td>
</tr>
</tbody>
</table>

The results are based on a comparison with a Reference mill with a modern recovery boiler producing electricity for export. The above configurations are thus equally based and calculated on the same black liquor capacity.

It should be noted that the biomass to fuel efficiency could be significantly larger if a biomass IGCC should be used instead of the calculated power boiler with a condensing steam turbine. Nevertheless, the BLGMF plant shows, as it is a very efficient use of biomass energy to produce motor fuels.
4.7 Power boiler

Predicted performance of the power boiler for BLGMF, synthesis of methanol, is reported in Table 4.6. (DME is not shown since data are almost same).

**Table 4.6. Performance of the power boiler included in the BLGMF plant.**

<table>
<thead>
<tr>
<th>Load</th>
<th>%</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel input:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bark (falling + imported)</td>
<td>MW&lt;sub&gt;lh&lt;/sub&gt;</td>
<td>146.8</td>
</tr>
<tr>
<td>Organic liquids</td>
<td>MW&lt;sub&gt;lh&lt;/sub&gt;</td>
<td>1.8</td>
</tr>
<tr>
<td>Synthesis gas</td>
<td>MW&lt;sub&gt;lh&lt;/sub&gt;</td>
<td>32.06</td>
</tr>
<tr>
<td>Fuel heat input</td>
<td>MW&lt;sub&gt;f&lt;/sub&gt;</td>
<td>180.62</td>
</tr>
<tr>
<td>Feedwater and steam:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam flow</td>
<td>kg/s</td>
<td>62.3</td>
</tr>
<tr>
<td>Steam temperature</td>
<td>°C</td>
<td>545</td>
</tr>
<tr>
<td>Steam pressure</td>
<td>bar(g)</td>
<td>140</td>
</tr>
<tr>
<td>Drum pressure</td>
<td>bar(g)</td>
<td>155</td>
</tr>
<tr>
<td>Feed water temperature</td>
<td>°C</td>
<td>180</td>
</tr>
<tr>
<td>Pressure before economizer</td>
<td>bar(g)</td>
<td>160</td>
</tr>
<tr>
<td>Flue gases:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue gas flow (wet)</td>
<td>Nm&lt;sup&gt;3&lt;/sup&gt;/s</td>
<td>134.5</td>
</tr>
<tr>
<td>Flue gas flow, (wet, ash free)</td>
<td>kg/s</td>
<td>104.5</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt; content (dry)</td>
<td>%</td>
<td>4.1</td>
</tr>
<tr>
<td>Flue gas outlet temp.</td>
<td>°C</td>
<td>150</td>
</tr>
<tr>
<td>Emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dust after ESP (6.0 % O&lt;sub&gt;2&lt;/sub&gt;, dry)</td>
<td>mg/Nm&lt;sup&gt;3&lt;/sup&gt;</td>
<td>&lt;50</td>
</tr>
<tr>
<td>NO&lt;sub&gt;x&lt;/sub&gt;</td>
<td>mg/MJ</td>
<td>&lt;70</td>
</tr>
<tr>
<td>SO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>mg/MJ</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>mg/MJ</td>
<td>&lt;250</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>mg/MJ</td>
<td>&lt;15</td>
</tr>
<tr>
<td>Heat balance (DIN 1942):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal capacity (steam)</td>
<td>MW&lt;sub&gt;lh&lt;/sub&gt;</td>
<td>165.45</td>
</tr>
<tr>
<td>Boiler efficiency</td>
<td>%</td>
<td>90.0</td>
</tr>
<tr>
<td>Estimated consumption figures:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric power</td>
<td>kW</td>
<td>6.4</td>
</tr>
<tr>
<td>Soot blower steam</td>
<td>t/d</td>
<td>26.7</td>
</tr>
<tr>
<td>Pressurised air at 7 bar(g)</td>
<td>m&lt;sup&gt;3&lt;/sup&gt;/min</td>
<td>43</td>
</tr>
</tbody>
</table>
5 COST-BENEFIT ASSESSMENT

5.1 Economy approach and assumptions

5.1.1 Introduction
In general, to calculate plant economics in a feasibility study the reference is usually a separate plant, which can be self-sustained in energy and services and at a “greenfield” site or at an industrial “brownfield” site. However, to justify a replacement investment at a plant and replacing an existing process where the economic life has ended, we have decided to calculate an incremental investment cost with incremental production costs. This is the normal procedure, as in this case the host (the pulp mill owner) can choose between investing in the same technology – a new recovery boiler – or in a new technology, the gasification plant (BLGMF). Thus, the investment decision would normally be based on a comparison between the two alternatives: a) reference mill with a recovery boiler and b) same type of mill with a BLGMF plant. It should therefore be noted that the results in this report are based on a comparison and that the incremental investment cost and production costs are calculated.

5.1.2 Study approach
To assess the performance economics of the BLGMF technology at the mill level firstly an investment cost assessment was done both for a modern recovery boiler and a BLGMF plant based on the KAM2 mill at 2000 ADt/day of pulp. Secondly, material and energy balances were finalised for the reference case (Reference Mill) and for both cases Methanol and DME. Thirdly, an operating cost/benefit analysis was made and the production costs for methanol and DME were calculated for an incremental capital investment required for a BLGMF over the Reference Mill and incremental operating costs. Lastly, return on investment values, such as the Internal Rate of Return (IRR) was calculated with a given sales price of methanol and DME.

5.1.3 Input variables, parameters and assumptions
Key inputs to the financial analysis include the detailed mass and energy balances and engineering cost estimates for each process unit as described in earlier chapters. The investment cost estimate was based on both budget quotations with scaling and some in-house estimates as well as direct price offers. Estimated costs from scaled sources had an initial accuracy of ±30% and scaling adds an additional uncertainty of ±10%. However, as some costs were based on direct price offers with a better accuracy it is the belief that altogether the investment cost estimate has an accuracy of not much more than ±30%.

Table 5.1 summarises the key input financial variables and parameters and Table 5.2 gives the basic energy input and output balance with respective product’s prices.
Table 5.1. Financial variables and parameters used in the financial analysis.

<table>
<thead>
<tr>
<th>Financial Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Money year</td>
<td></td>
<td>3Q 2003</td>
</tr>
<tr>
<td>Escalation rate&lt;sup&gt;a&lt;/sup&gt;</td>
<td>%/year</td>
<td>0.6</td>
</tr>
<tr>
<td>Inflation rate&lt;sup&gt;b&lt;/sup&gt;</td>
<td>%</td>
<td>2.0</td>
</tr>
<tr>
<td>Interest rate on debt</td>
<td>%</td>
<td>8.0</td>
</tr>
<tr>
<td>Return on equity, before tax</td>
<td>%</td>
<td>15.0</td>
</tr>
<tr>
<td>Weighted Average Cost of Capital&lt;sup&gt;c&lt;/sup&gt;</td>
<td>WACC, %</td>
<td>10.1</td>
</tr>
<tr>
<td>Annuity factor</td>
<td>%</td>
<td>11.1</td>
</tr>
<tr>
<td>Loan fraction, without regard for loan guarantee</td>
<td>%</td>
<td>70</td>
</tr>
<tr>
<td>Equity fraction</td>
<td>%</td>
<td>30</td>
</tr>
<tr>
<td>Effective company tax</td>
<td>%</td>
<td>22</td>
</tr>
<tr>
<td>Project lifetime</td>
<td>Year</td>
<td>25</td>
</tr>
<tr>
<td>Equivalent operating hours</td>
<td>h/year</td>
<td>8 330</td>
</tr>
<tr>
<td>Exchange rates, 2003-11-03</td>
<td>EUR, €1</td>
<td>9.08</td>
</tr>
<tr>
<td>Exchange rates, 2003-11-03</td>
<td>USD, $1</td>
<td>7.85</td>
</tr>
<tr>
<td>Exchange rates, 2003-11-03</td>
<td>GBP, £1</td>
<td>13.27</td>
</tr>
</tbody>
</table>

Notes:

<sup>a</sup> Based on Chemical Engineering Index.
<sup>b</sup> Current (November, 2003) inflation is 1.4%, however the Swedish Riksbank’s Executive Board has set a target of maximum 2.0% inflation on a yearly basis.
<sup>c</sup> Calculated as Return on Equity x Equity fraction + Interest rate on debt x Loan fraction, then used in the calculation of the Annuity factor $A = \frac{r}{1-(1+r)^{-n}}$. 

ALTENER II

December 2003
Table 5.2. Energy input and output balance for each case and respective prices.

<table>
<thead>
<tr>
<th>Products and prices</th>
<th>Reference Mill, Recovery Boiler</th>
<th>BLGMF Methanol</th>
<th>BLGMF DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass export^a</td>
<td>MW 32.0</td>
<td>-129.0</td>
<td>-125.0</td>
</tr>
<tr>
<td>Biomass price^b</td>
<td>EUR/MWh 8.8</td>
<td>11.0</td>
<td>11.0</td>
</tr>
<tr>
<td>Electricity production</td>
<td>MW 45.1</td>
<td>-56.1</td>
<td>-55.4</td>
</tr>
<tr>
<td>Electricity price^c</td>
<td>EUR/MWh 43.6</td>
<td>44.1</td>
<td>44.1</td>
</tr>
<tr>
<td>Methanol/DME production</td>
<td>MW --</td>
<td>272.8</td>
<td>274.8</td>
</tr>
<tr>
<td>- &quot; &quot; -</td>
<td>tonnes/day --</td>
<td>1183</td>
<td>824</td>
</tr>
<tr>
<td>- &quot; &quot; -</td>
<td>tonnes/year --</td>
<td>410 600</td>
<td>285 997</td>
</tr>
<tr>
<td>Methanol/DME price^d</td>
<td>EUR/MWh --</td>
<td>41.7</td>
<td>42.7</td>
</tr>
<tr>
<td>- &quot; &quot; -</td>
<td>EUR/tonne --</td>
<td>230.7</td>
<td>341.4</td>
</tr>
</tbody>
</table>

Notes:

^a In the Reference Mill, certain the biomass will be produced, mainly from falling bark. In the Methanol and DME cases biomass is consumed to balance the mill’s need for power and heat.

^b Based on Swedish prices, SEK 80/MWh (sold biomass) for Reference Mill and SEK 100/MWh (purchased biomass, Exworks) for Methanol and DME, are all consistent with current quarterly listed prices at the Swedish Energy Agency.

^c Based on Swedish prices, SEK 396/MWh (sold electricity) for Reference Mill, which is made up of a long-term average market elspot price at Nordpool of SEK 196/MWh (1996–2003) and a “green” electricity certificate premium (average price since start May 2003 to November, SEK 200/MWh). For the Methanol and DME cases an electricity production cost has been taken which roughly is calculated for a biomass power plant of 40% electric efficiency.

^d Based on Swedish prices (see below in this chapter calculation of petrol and diesel consumer prices and petrol/diesel equivalent prices for methanol and DME).

5.1.4 Price of electricity

The market pulp mill has a surplus of fuel for the recovery boiler. As a basis for comparison all black liquor is used for power and steam generation and the surplus steam is fed to a condensing turbine, resulting in a net excess of power that can be sold to the electric grid. With a BLGMF plant, the energy balance can be shifted either towards a large production of methanol, which causes a demand for purchased biomass and power, or towards a smaller production of methanol, only utilising biomass available at the mill.

The Reference Mill would have to sell the electricity on an open market and today (November, 2003) the market elspot price at Nordpool is about SEK 325/MWh which is historically high. However, the market has fluctuated surprisingly widely since the start of the deregulated electricity market, as shown in Figure 5.1. During this period, several extraordinary events took place. In 1996 the mean temperature was a record low, which followed on record high temperatures next years with record high rainfall and in 2002/2003 a 50-year record low water deposit level at the Nordic hydro plants. This makes it difficult on discussing which electricity-selling price should be used in the calculation.
Figure 5.1. Yearly average Swedish elspot market prices 1996–2003, without taxes or premiums etc (Source: Nordpool).

In addition, the newly established “green” electricity certificate market (May 2003) has fluctuated with the same extreme. The market constitutes of certificates for each generated “green” MWh to be sold at an open market, and where up till end of November 2003 about 1 132 000 certificates have been sold out of a total 2 474 000 issued at an average price SEK of 200/MWh. The prices have varied from SEK 90–320 per certificate.

The BLGMF plant needs additional production of electricity to cover the need from the mill and if the sold product should be biomass based all energy inputs must be biomass based, although the needed electricity could be produced elsewhere. Thus, an estimated cost of produced electricity for a modern biomass power plant has been used with an assumed cost of SEK 400/MWh. However, a sensitivity analysis has been made for purchased electricity should it be seen that this cost would be too high or low.

5.2 Investment cost estimate

The investment cost estimate was based on 3rd quarter 2003 and based on cost information given by respective supplier or vendor. Most costs were assessed using previous estimates with accepted factoring methods as regression exponents, scale-up factors etc. However, the methanol and DME process units and the power boiler unit were based on new budget quotations.

The investment cost includes site preparation, buildings, electrical, piping, instrumentation, engineering, and license fees. Most of the quotations received included some of these off-unit costs and for those, which did not include these costs, these were added to unspecified costs. The Reference Mill case was based on recent sales of complete recovery boilers, thus the unspecified cost was put as a general 5%. The BLGMF cases were added with an additional 5% for excluded costs in the vendor’s budget quotations to a total 10%. In some
cases this may have led to adding twice the same costs, however, the total cost difference would be small.

The net incremental capital investment cost was estimated as EUR 150 million for Methanol and EUR 164 million for DME, based on a pulp mill capacity of 2000 ADt/day. An investment cost breakdown is given in Figure 5.2 below and Table 5.3 summarises the respective process unit’s costs.

![Investment cost, divided on process units](image)

**Figure 5.2. Plant investment cost breakdown, with respective process units.**

Normally for an IGCC plant or for that matter a conventional power plant the gasification unit or power boiler takes up 25% or more of the investment cost. Here, the plant is process based and still the gasification unit is not changed as the dominating process unit. This indicates that there are many common investments such as gas cleaning and auxiliaries.

Interestingly, the power boiler takes up the second largest part and thus opens for possibilities of reduction if the plant would be integrated with combined power and heat production. Three alternatives can be identified for handling the mill’s needs of heat and electric power:

- Firing biofuels in a retrofitted recovery boiler that has been converted to a large “bark” boiler and to purchase the remaining need of power from the grid.
- A modern type of high performance biomass boiler with back-pressure turbines and reheat plus condensing steam turbine in order to manage the remaining need of power for the plants. In reality, this also means an investment in a complete new boiler and also new condensing steam turbines
- In order to further improve the biomass-to-methanol/DME yield the biomass boiler could be replaced with a biomass IGCC, which has a higher power-to-heat ratio. This would further increase the efficiency of the BLGMF plant.
As expected the methanol/DME synthesis unit takes up a major part, as would a combined cycle unit in a power plant.

**Table 5.3. Summary of investment costs.**

<table>
<thead>
<tr>
<th>Investment cost estimate</th>
<th>Reference Mill, Recovery Boiler</th>
<th>BLGMF Methanol</th>
<th>BLGM DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery boiler&lt;sup&gt;a&lt;/sup&gt;</td>
<td>M EUR 93.1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Air separation unit&lt;sup&gt;b&lt;/sup&gt;</td>
<td>M EUR 3.9</td>
<td>27.6</td>
<td>27.6</td>
</tr>
<tr>
<td>Gasification &amp; gas cooling unit&lt;sup&gt;c&lt;/sup&gt;</td>
<td>M EUR --</td>
<td>63.1</td>
<td>63.1</td>
</tr>
<tr>
<td>Gas cleaning unit (pre-wash, CO-shift, Rectisol)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>M EUR --</td>
<td>26.3</td>
<td>26.3</td>
</tr>
<tr>
<td>Sulphur handling (Claus plant)&lt;sup&gt;e&lt;/sup&gt;</td>
<td>M EUR --</td>
<td>6.6</td>
<td>6.6</td>
</tr>
<tr>
<td>Methanol/DME synthesis unit (incl compressor &amp; storage)&lt;sup&gt;f&lt;/sup&gt;</td>
<td>M EUR --</td>
<td>44.6</td>
<td>54.4</td>
</tr>
<tr>
<td>Power boiler incl woodyard and handling&lt;sup&gt;g&lt;/sup&gt;</td>
<td>M EUR --</td>
<td>47.3</td>
<td>49.0</td>
</tr>
<tr>
<td>Steam turbine&lt;sup&gt;h&lt;/sup&gt;</td>
<td>M EUR 20.4</td>
<td>8.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Lime kiln + bark dryer&lt;sup&gt;i&lt;/sup&gt;</td>
<td>M EUR 21.0</td>
<td>25.9</td>
<td>25.9</td>
</tr>
<tr>
<td>Balance of plant&lt;sup&gt;j&lt;/sup&gt;</td>
<td>M EUR --</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td><strong>Equipment and assembly</strong></td>
<td>M EUR 138.3</td>
<td>255.5</td>
<td>267.4</td>
</tr>
<tr>
<td>Site costs incl owner’s cost&lt;sup&gt;k&lt;/sup&gt;</td>
<td>M EUR 0.9</td>
<td>5.2</td>
<td>5.2</td>
</tr>
<tr>
<td>Interest During Construction (IDC)&lt;sup&gt;l&lt;/sup&gt;</td>
<td>M EUR 7.7</td>
<td>17.9</td>
<td>18.7</td>
</tr>
<tr>
<td>Unspecified costs&lt;sup&gt;i&lt;/sup&gt;</td>
<td>M EUR 6.9</td>
<td>25.6</td>
<td>26.7</td>
</tr>
<tr>
<td><strong>Total investment cost</strong></td>
<td>M EUR 153.9</td>
<td>304.1</td>
<td>318.0</td>
</tr>
<tr>
<td><strong>Incremental BLGMF investment</strong></td>
<td>M EUR 150.3</td>
<td>164.2</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

<sup>a</sup> Based on published recent Swedish investment costs for recovery boiler at pulp mills Gruvön and Värö, recalculated.

<sup>b</sup> Based on quotation from Air Products and Chemicals, January 2000, recalculated.

<sup>c</sup> Based on quotation from Chemrec, January 2003, recalculated.

<sup>d</sup> Based on quotation from Linde, 1995, recalculated.

<sup>e</sup> Based on estimation from Ortloff Engineers, January 2000, recalculated.

<sup>f</sup> Based on quotation from Haldor Topsoe, September 2003, storage from Midroc Engineering, November 2003 and KFB, the Swedish Transport and Communications Research Board [31].

<sup>g</sup> Based on quotation from Kvaerner Power, September 2003 plus in-house estimates on woodyard and handling unit as 5% of total quotation cost.

<sup>h</sup> Based on in-house estimates and recalculated.

<sup>i</sup> Based on in-house estimates.

<sup>j</sup> Site costs including foundation based on price estimates and owner’s costs estimated.

<sup>k</sup> Construction time assumed 24 months (Ref Mill) and 30 months (BLGMF) with half cost as credits and calculated with used debt interest rate.

<sup>l</sup> Incl engineering, spare parts, licensing fees, start-up. Calculated generally as 5% (Ref Mill), 10% (BLGMF, general 5% and additional 5% for excluded costs) of Equipment and assembly.
5.3 **Production costs for methanol and DME**

The production cost was calculated with the absolute difference between the operating benefit of the Reference Mill and the operating cost of the BLGMF cases. The resulting net incremental operating cost thus includes the benefit for the sold electricity of the Reference Mill and at the same time, the high cost of purchased electricity for the BLGMF cases.

The resulted production costs were EUR 29¢ per petrol equivalent litre for Methanol (SEK 2.6 per p.e.litre) and EUR 32¢ per diesel equivalent litre for DME (SEK 2.9 per d.e.litre). Table 5.4 and Table 5.5 below summarise the operating costs and production costs.

**Table 5.4. Summary of operating costs and benefits.**

<table>
<thead>
<tr>
<th>Operating costs/benefits</th>
<th>Reference Mill, Recovery Boiler</th>
<th>BLGMF Methanol</th>
<th>BLGMF DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol/DME(^a)</td>
<td>M EUR/year</td>
<td>--</td>
<td>94.7</td>
</tr>
<tr>
<td>Biomass</td>
<td>M EUR/year</td>
<td>2.3</td>
<td>-11.8</td>
</tr>
<tr>
<td>Electricity</td>
<td>M EUR/year</td>
<td>16.4</td>
<td>-20.6</td>
</tr>
<tr>
<td>Chemicals, water etc(^b)</td>
<td>M EUR/year</td>
<td>--</td>
<td>-2.6</td>
</tr>
<tr>
<td>Operation, incremental labour(^c)</td>
<td>M EUR/year</td>
<td>--</td>
<td>-1.4</td>
</tr>
<tr>
<td>Maintenance, insurance, etc(^d)</td>
<td>M EUR/year</td>
<td>-3.5</td>
<td>-6.4</td>
</tr>
<tr>
<td><strong>Total operating benefit</strong></td>
<td>M EUR/year</td>
<td>15.3</td>
<td>51.9</td>
</tr>
<tr>
<td><strong>Incremental BLGMF operating benefit</strong></td>
<td>M EUR/year</td>
<td>36.7</td>
<td>39.8</td>
</tr>
</tbody>
</table>

Notes:

\(^a\) Based on Swedish prices (see below in this chapter calculation of petrol and diesel consumer prices and petrol/diesel equivalent prices for methanol and DME).

\(^b\) Calculated as 1.0% of Equipment and assembly.

\(^c\) Based on four additional operators to the normal staff, five shifts, and a person salary of SEK 30 000 per month plus social benefits of 50% and an overhead of 20%.

\(^d\) Calculated as 2.5% of Equipment and assembly.
Table 5.5. Summary of production costs.

<table>
<thead>
<tr>
<th>Production costs</th>
<th>BLGMF Methanol (M EUR/year)</th>
<th>BLGMF DME (M EUR/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total incremental capital cost</td>
<td>16.7</td>
<td>18.2</td>
</tr>
<tr>
<td>Total incremental operating cost</td>
<td>58.1</td>
<td>57.9</td>
</tr>
<tr>
<td>Total incremental cost</td>
<td>74.8</td>
<td>76.1</td>
</tr>
<tr>
<td>Production cost</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>Production cost</td>
<td>182</td>
<td>266</td>
</tr>
<tr>
<td>Production cost, petrol/diesel eq. litre</td>
<td>28.7</td>
<td>31.8</td>
</tr>
<tr>
<td>Production cost, petrol/diesel eq. litre</td>
<td>2.6</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Notes:

- The methanol production cost was recalculated for the cost of one equivalent litre of petrol, using fuel properties for the specified methanol/DME fuel and petrol properties of 11.626 MWh/tonne, 750 kg/m³ at 20 ºC. Similarly, the DME production cost was recalculated for diesel with properties of 11.750 MWh/tonne, 815 kg/m³ at 20 ºC.

5.4 Production cost sensitivity

The sensitivity of the production cost of methanol was investigated with four parameters and where respective parameter was varied from 75% to 130% (except for availability) of the base case value. The parameters and the base case values were

- Purchased biomass cost (EUR 11 per MWh for 129 MW biomass, balancing the energy need of the pulp mill, not the total amount necessary for same electricity export as the Reference mill),
- Incremental investment cost (EUR 150 million),
- Availability (354 days per year and 98% availability, 8330 hours per year) and
- Purchased electricity cost (EUR 44.1 per MWh for 56.1 MW electricity, calculated as the production cost for the power boiler, balancing the energy need of the pulp mill, not the total amount necessary for same electricity export as the Reference mill).

The base case value is consequently shown in the middle of each diagram and with a vertical line to point at the x-axis for the input value, as shown in Figure 5.3 to Figure 5.6 and with same scales on the primary and secondary y-axes.

The sensitivity analysis yielded a modest sensitivity on the production cost for all parameter changes except availability as seen in Table 5.6 below, only some 5–8% with a 30% change. Availability was as expected most sensitive and biomass as least sensitive on the production cost.
Table 5.6. Sensitivity analysis for different parameters on the production cost of methanol.

<table>
<thead>
<tr>
<th>Sensitivity change</th>
<th>Parameter</th>
<th>Production cost of methanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchased biomass cost</td>
<td>±30%</td>
<td>±4.7%</td>
</tr>
<tr>
<td>Incremental investment cost</td>
<td>±30%</td>
<td>±6.6%</td>
</tr>
<tr>
<td>Availability</td>
<td>±15%</td>
<td>±3.5%</td>
</tr>
<tr>
<td>Purchased electricity cost</td>
<td>±30%</td>
<td>±8.2%</td>
</tr>
</tbody>
</table>
Figure 5.3. Production cost vs. purchased biomass cost, base case EUR 11.0/MWh (EUR 59/tonne dry biomass, SEK 533/tonne dry biomass).

Figure 5.4. Production cost vs. incremental investment cost, base case EUR 150 million.
Figure 5.5. Production cost vs. availability, base case 8330 equivalent operating hours per year.

Figure 5.6. Production cost vs. purchased electricity cost, base case EUR 44/MWh, SEK 400/MWh.
5.5  Return on investment results

5.5.1  Fuel price

To estimate the potential revenue of methanol and DME a price of methanol and DME at the mill gate was calculated by assuming that the cost for the consumer should be the same as for petrol (methanol) and diesel (DME). To calculate DME on petrol equivalent would not be correct as DME is not intended to replace petrol in an otto engine. DME is a diesel fuel only and in analogue with biogas which can not be blended either, however can be used in otto as well as diesel engines it is today used in bi-fuel cars where the price of biogas is fixed at the petrol price with a given absolute discount.

Therefore, DME should be priced as a diesel fuel and related to current diesel price. It should be noted however, that the petrol and diesel consumer prices differ in taxes, distribution costs and markets share, which affects the price in what will certainly positively be different in other European countries. The following are thus based for a Swedish setting and can be recalculated for another country with respective local taxes and prices.

The estimated price is about SEK 2095 (€231) per tonne of methanol, when considering the current Swedish CO\textsubscript{2} tax on petrol and similarly about SEK 3100 (€341) per tonne of DME (see Table 5.7 below). Note that this does not include initial costs for building the infrastructure needed for the distribution systems. DME would have a significantly higher cost, as the fuel would need to be handled similarly to LPG.
Table 5.7. Estimation of selling price for methanol and DME at mill gate (in SEK per litre of petrol/diesel equivalents), to match consumer price of petrol/diesel).

<table>
<thead>
<tr>
<th>Methanol/DME fuel price</th>
<th>Petrol</th>
<th>Methanol</th>
<th>Diesel</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production(^a)</td>
<td>SEK/litre</td>
<td>1.83</td>
<td>3.30</td>
<td>2.41</td>
</tr>
<tr>
<td>Distribution(^b)</td>
<td>SEK/litre</td>
<td>1.05</td>
<td>1.35</td>
<td>1.11</td>
</tr>
<tr>
<td>Energy tax(^c)</td>
<td>SEK/litre</td>
<td>2.94</td>
<td>2.94</td>
<td>1.00</td>
</tr>
<tr>
<td>CO(_2) tax(^c)</td>
<td>SEK/litre</td>
<td>1.77</td>
<td>0.00</td>
<td>2.17</td>
</tr>
<tr>
<td>V.A.T.</td>
<td>SEK/litre</td>
<td>1.90</td>
<td>1.90</td>
<td>1.67</td>
</tr>
<tr>
<td><strong>Consumer price</strong></td>
<td>SEK/litre</td>
<td>9.49</td>
<td>9.49</td>
<td>8.37</td>
</tr>
<tr>
<td><strong>Fuel price</strong>(^d)</td>
<td>SEK/tonne</td>
<td>2 095</td>
<td>3 100</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
\(^a\) The production cost for petrol is given as the average spot market “Rotterdam” price for petrol in 2002, which is also close to a 20-year average. The production cost of diesel is the average cost given by Statoil for 2002.
\(^b\) The distribution cost comprises costs for sea transport, truck, depot storage, station storage and distribution and state addition and includes profit margin before discounts.
\(^c\) Tax rates for 2003.
\(^d\) Corresponds to SEK 3.30 per litre petrol equivalent for methanol and SEK 3.71 per litre diesel equivalent, based on petrol properties of 11.626 MWh/tonne, 750 kg/m\(^3\) at 20 °C and diesel properties of 11.750 MWh/tonne, 815 kg/m\(^3\) at 20 °C.

To calculate the selling price of methanol and DME, firstly, the consumer prices are established for petrol and diesel. Then, the selling price is calculated backwards from the current consumer price, subtracting taxes and estimated distribution costs. The production costs of petrol SEK 1.83, which is the average for 2002 and SEK 2.41 for diesel can be compared with the average Brent crude oil price of USD 25 per barrel for 2002.

### 5.5.2 Internal Rate of Return

A cash flow IRR analysis was carried out for both cases, considering the incremental investment and operating costs for the BLGMF system relative to a new recovery boiler investment. The cash flow analysis did not take into account any yearly differences in consumption, production, depreciation, financing other than stated above, and furthermore rest value of the investment or any levelized prices.

The capital costs in this study have an accuracy of ±30% due to the level of detail included in the cost estimates and to inherent uncertainties in projecting “N\(^{th}\) plant” costs given the pre-commercial status of the BLGMF technology today. Future energy price levels are also uncertain and prices can vary considerably from one region of the country to another.

The incremental investment of EUR 150 million gave an IRR of 26% in both cases with a pay-back of 4.0 years (see Table 5.8).
Table 5.8. Results on return on investment.

<table>
<thead>
<tr>
<th>Results</th>
<th>Methanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback</td>
<td>4.0 years</td>
<td>4.0 years</td>
</tr>
<tr>
<td>Real Return on Total Capital</td>
<td>24%</td>
<td>23%</td>
</tr>
<tr>
<td>IRR</td>
<td>26%</td>
<td>26%</td>
</tr>
</tbody>
</table>

5.6 Indicative case with increased pulp yield

5.6.1 Recausticizing

In the gasifier, a large fraction of the sulphur in the black liquor is converted to hydrogen sulphide. There are three principal routes to convert the concentrated \( \text{H}_2\text{S} \) stream from the acid gas removal system to sulphur in a useful form in the pulping liquor:

- Reabsorption in green or white liquor
- Recirculation to the gasifier
- Conversion to liquid sulphur, which is dissolved to give a polysulphide liquor.

The first two routes will yield a white liquor with essentially the same composition as a conventional liquor, while the third route can be utilised for pulping modifications. The first route does also make it possible to prepare white liquors with different sulphidities, if desired. Although the sulphur split may be put to an advantage in the pulping process, it also leads to an increased load on the lime kiln. The effects on energy efficiency are described in greater detail by Larson et al [15] and Berglin et al [32].

5.6.2 Increased pulp yield

The recovered sulphur may be used in a beneficial way in a newly developed poly-sulphide cooking process to further enhance the yield of fibre from the wood. STFI have reported results with an increased pulp yield of 5–10%. The amount of black liquor would be consequently less than for the conventional cooking process, however as the bottleneck in today’s pulp mills is mostly the recovery boiler this gives an opportunity to increase the overall capacity of the pulp mill without further investment needed.

5.6.3 Economy results

Increasing the overall pulp yield with 5% also means a smaller quantity of black liquor which means less motor fuel production per ton of pulp and thus a smaller BLGMF plant investment. Assuming the change to be rather small in black liquor amount and need for heat and power in the mill, the BLGMF plant investment would be about the same as for the previously estimated Methanol case.

Assuming an increased pulp yield of 5% and with a capacity of 2000 ADt/day, this would give an additional revenue of EUR 16.5 million per year, calculating with an average pulp price of USD 550/ADt. The resulting additional revenue would give a significantly lower production cost and higher return on investment. Table 5.9 below summarises the changed results.
Table 5.9. Summary for indicative case with increased pulp yield.

<table>
<thead>
<tr>
<th>Financial results</th>
<th>BLG MF Methanol Increased pulp yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production cost</td>
<td>EUR ¢/kWh</td>
</tr>
<tr>
<td>Production cost</td>
<td>EUR/tonne</td>
</tr>
<tr>
<td>Production cost, petrol equivalent litre</td>
<td>EUR ¢/equivalent litre</td>
</tr>
<tr>
<td>Production cost, petrol equivalent litre$^a$</td>
<td>SEK/equivalent litre</td>
</tr>
<tr>
<td>Payback</td>
<td>years</td>
</tr>
<tr>
<td>Internal Rate of Return</td>
<td>IRR, %</td>
</tr>
</tbody>
</table>
6 OVERVIEW OF THE MARKET SITUATION

6.1 European market for motor fuels

The demand for transportation fuels in Europe will increase more than the increase in energy efficiency of the vehicles. This is due to the expected rapid increase in transportation intensity. For example, in the White Paper: “European transport policy for 2010: time to decide”, the EU forecasts a transport demand growth by 38% for freight and 24% for passenger transport from 1998 (base year) to 2010.

6.1.1 Heavy-duty vehicles

As mentioned in the White Paper, the increase in transport intensity will be greater for the heavy-duty category of vehicles. Most likely, this will put more focus on fuel substitution in this sector. Today, diesel fuel is more or less the sole fuel for heavy goods vehicles and its market share is increasing for the light commercial vehicles. Alternative fuels for heavy-duty vehicles today are primarily FAME\textsuperscript{1} (RME and other vegetable oils), natural gas (as CNG) and ethanol\textsuperscript{2}. In Sweden, where the natural gas grid covers only a small part of the country, biogas is often used as substitute for natural gas. Petrol is used in small commercial vehicles today. However, it seems as petrol is increasingly being substituted by diesel fuel in this niche, in line with the trend for passenger cars.

Regarding the prospects for alternative fuels in the near future, it can be noted that the use of CNG seems to be increasing, particularly for bus fleets. However, these fleets represent only a small portion of the heavy-duty vehicle population. Thus, it is likely that CNG will remain a niche fuel in the near future. FAME is used both for low-blending and as a neat fuel. The production capacity of FAME is likely to be limited to a few percent of the diesel fuel use in Europe. New fuels, such as dimethyl ether (DME), Fischer-Tropsch fuels and hydrogen is under discussion. However, in the near future, only prototype vehicles for the two latter fuel candidates can be anticipated. Likewise, fuel cells, as the ultimate powertrain candidate for the future, seem to be far from a commercial breakthrough.

6.1.2 Light-duty vehicles

In contrast to the situation for heavy-duty vehicles, two main fuels, petrol and diesel fuel, are used in light-duty vehicles. The market penetration for diesel cars have been increasing in most EU countries during the last years, with the exception of some countries, such as Sweden and Greece, where the share has been decreasing. On the long-term, it is likely that the market penetration for diesel cars, as an average for EU, will increase, unless the policy for fuel and vehicle taxation is changed in favour of petrol. The apparent (recent) success of diesel engines in passenger cars is due to the technology development that has alleviated some of the common drawbacks of diesel engines, such as low power density, greater noise and exhaust emissions. Thus, the customer acceptance for diesel-fuelled cars has increased, although the cost of a diesel car is still substantially higher than its petrol counterpart.

\textsuperscript{1} FAME: Fatty Acid Methyl Esters.

\textsuperscript{2} In Sweden, some 400 heavy-duty vehicles (primarily buses) are running on ethanol. However, Scania, the only manufacturer of ethanol buses has announced that they will terminate the production of these buses in 2003. The use of ethanol in other EU member countries is more or less limited to low-blending in petrol.
Energy converters and fuel types are closely linked together, as petrol can only be used in otto engines and diesel fuel can only be used in diesel engines. A projection of future energy converters in light-duty vehicles was made by Ecotraffic in a project for the Swedish National Road Administration [33]. The results from this estimate are shown in Figure 6.1.

![Future market penetration of engine converters for light-duty vehicles](image)

**Figure 6.1.** Future market penetration of energy converters for LD vehicles.

As can be seen in Figure 6.1, the conventional otto engines with three-way catalysts (TWC) and throttle control for power regulation, will largely be substituted by other technologies. Fully variable valvetrain (VVT), direct injection (DI) and combinations of several concepts (including the concepts mentioned) will have an increased market share. DI diesel engines are likely to increase their market share up to a certain level (slightly above 40%). In some studies, an even higher market share (potentially up to 50% as soon as 2005) has been projected [34], but Ecotraffic’s estimate from 2002 [33] was somewhat more prudent. However, it should be noted that the market penetration of diesel cars was significantly lower in the past.

Therefore, even if the penetration would level off in the future, the diesel share of the population would increase considerably anyway. Limitations in refinery production of middle distillate should eventually curb the market penetration due to the accompanying economical constraints. Fuel trade (import of diesel fuel, export of petrol) with countries outside the EU could perhaps increase the supply of diesel fuel somewhat. Fuel cells are expected to account for only a minor share of the market after 2010. A significant market penetration cannot be expected before 2020.
6.1.3 Other sectors than road transport to consider

In the assessment of potential market penetration of fuels and future powertrains, the energy use in other sectors should also be taken into account. Jet fuel is probably the most important fuel use to be considered. Diesel fuel and jet fuel have overlapping distillation intervals and therefore, an increase in jet fuel demand would put even more pressure on the refinery capacity for diesel fuel production. Although there was a significant decline in air travel after the attack on WTC in New York in September 11, 2001, it is expected that air travel will continue to increase considerably in the future.

6.1.4 Summary of the European fuel market

In summary of the discussion above, the demand for diesel fuel and middle distillate will be increasing in the future. As there will be limitations for the share of these products from crude oil, a shortage of supply of these products could be foreseen in the future. Therefore, a substitute of diesel fuel with alternative fuels would be a desirable solution. International trade with markets having a surplus of diesel fuel could be a temporary solution. To some extent, this is already being done (e.g. USA and Europe).

It should also be noted that substituting diesel fuel with alternative fuels seems to be more difficult than substituting petrol. The reason is that most of the fuel candidates are better suited for spark ignition (SI, or otto) engines. This imposes limitations on the number of fuels suitable for substitution of diesel fuel. It is also obvious that energy converters (engines) and fuels must be developed as a complete system.

6.2 Potential use of methanol/DME in vehicles

6.2.1 Fuel properties

Some relevant fuel properties for petrol (according to EU 2005 specification), diesel fuel (Swedish Environmental Class 1), methanol, DME and propane are shown in Table 6.1. Petrol and diesel fuels are shown as reference. Propane is also included in the table as a comparison for DME, since these fuels have similar physical properties.
### Table 6.1. Fuel properties.

<table>
<thead>
<tr>
<th>Fuel property</th>
<th>Petrol EU 2005</th>
<th>Diesel fuel Swe EC1</th>
<th>Methanol</th>
<th>DME</th>
<th>Propane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal, % C</td>
<td>~86.5</td>
<td>~85.75</td>
<td>37.5</td>
<td>52.1</td>
<td>81.7</td>
</tr>
<tr>
<td>Hydrogen, % H</td>
<td>~13.5</td>
<td>~14.25</td>
<td>12.6</td>
<td>13.1</td>
<td>18.3</td>
</tr>
<tr>
<td>Oxygen, % O</td>
<td>0–2.7</td>
<td>0</td>
<td>49.9</td>
<td>34.7</td>
<td>0</td>
</tr>
<tr>
<td>Mole weight</td>
<td>~100</td>
<td>32.042</td>
<td>46.068</td>
<td>44.094</td>
<td></td>
</tr>
<tr>
<td>Viscosity @ 40°C (cSt)</td>
<td>1.4–4.0</td>
<td>0.60</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (gas) @ 20°C (kg/m³)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1.35</td>
<td>1.92</td>
<td>1.88</td>
</tr>
<tr>
<td>Density (liq.) @ 20°C (kg/m³)</td>
<td>730–770</td>
<td>810–820</td>
<td>795</td>
<td>668</td>
<td>501</td>
</tr>
<tr>
<td>Gas density rel. air (15°C)</td>
<td>3.4–4</td>
<td>4–5</td>
<td>1.11</td>
<td>1.59</td>
<td>1.52</td>
</tr>
<tr>
<td>Vapour pressure @ 20°C (bar)</td>
<td></td>
<td>0.12</td>
<td>5.1</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>RVP at 37.8°C (bar)</td>
<td>0.0007</td>
<td>0.32</td>
<td>8</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>Vapour press. @ 60°C (bar)</td>
<td></td>
<td>0.77</td>
<td>14</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>Boiling point @ 1 bar(a)</td>
<td>30–225</td>
<td>180–300</td>
<td>65</td>
<td>-24.9</td>
<td>-42.1</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>&lt;26</td>
<td>-94</td>
<td>-141</td>
<td>-190</td>
<td></td>
</tr>
<tr>
<td>Flash point</td>
<td>&gt;50</td>
<td>11</td>
<td>-41</td>
<td>-100</td>
<td></td>
</tr>
<tr>
<td>Heat of evaporation (MJ/kg)</td>
<td>0.25</td>
<td>1.17</td>
<td>0.41</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>Heat of comb., LHV (MJ/kg)</td>
<td>42.5</td>
<td>42.3</td>
<td>19.9</td>
<td>28.43</td>
<td>46.4</td>
</tr>
<tr>
<td>LHV (MJ/lit.)</td>
<td>32.0</td>
<td>35.2</td>
<td>15.8</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>CO₂ formation, LHV (g/MJ)</td>
<td>~74.3</td>
<td>~72.3</td>
<td>68.9</td>
<td>67</td>
<td>64.6</td>
</tr>
<tr>
<td>Autoignition temp. (°C)</td>
<td>~250</td>
<td>235–350</td>
<td>470</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flammability limits (% vol)</td>
<td>1.4–7.6</td>
<td>0.6–6.5</td>
<td>6.7–36</td>
<td>3.4–17</td>
<td>2.1–9.4</td>
</tr>
<tr>
<td>Water sol. @ 1 bar, 20°C (% w)</td>
<td>n.a.</td>
<td>5.7</td>
<td>0.39</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water sol. @ 4.8 bar, 20°C (% w)</td>
<td>n.a.</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur content (ppm, mg/kg)</td>
<td>50</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Olefins, max (%)</td>
<td>n.l.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Benzene (%)</td>
<td>&lt;1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Aromatics, max (%)</td>
<td>&lt;42</td>
<td>&lt;5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PAH, tri+ (%)</td>
<td>&lt;0.02</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Cetane number</td>
<td>n.a.</td>
<td>&gt;51</td>
<td>~5</td>
<td>&gt;55</td>
<td>n.a.</td>
</tr>
<tr>
<td>Octane No. (RON)</td>
<td>&gt;95</td>
<td>n.a.</td>
<td>120</td>
<td>n.a.</td>
<td>112</td>
</tr>
</tbody>
</table>

Notes:

n.a.: not applicable
n.l.: not limited
6.2.2 Literature survey

As one of the first tasks of this work, a literature survey was carried out. The first literature search was carried out in the autumn of 2002 and this search was supplemented in September 2003 to obtain the latest references.

The literature search was conducted in the “Global Mobility Database” of SAE (the Society of Automotive Engineers). In this database, more than 120,000 books, papers, biographies, etc. are available from 1906 to date. Not only SAE, but also several worldwide “sister” organisations of SAE as well as many other sources are listed in this database. The literature search was limited to literature published in 1990 and later. It might be of general interest to show how the number of publications on methanol and DME has changed during the past decade. Irrelevant publications have been removed from the literature inventory discussed below.

Due to the limitations of this report, only some selected publications from the literature search are cited. Besides the SAE publications, a literature search was also carried out at the Internet site of the organisations known to be active in this area. Some of these publications are also commented below.

Publications about methanol

The search word “methanol” yielded 599 publications for the period from 1990 to date. Some of the publications were not considered relevant for the area and some were in languages that the authors do not understand (e.g. Japanese and Korean). Books that are collections of many papers, such as, e.g. SAE Special Publications, were not considered either. After the mentioned publications were omitted, 534 relevant publications on methanol remained.

The number of publications on methanol is shown in Figure 6.2. It should be noted that the publications for 2003 were not included in the graph, since this year was not to an end when the literature search was carried out.
Figure 6.2. Methanol publications 1990–2001.

As can be seen in Figure 6.2, the interest in methanol peaked in the early 1990’s. After that a decline in publications is evident but during the last couple of years, a small rise can be noted. Most of the recent interest in methanol is closely linked to the use in fuel cells.

Publications about DME

The search word “DME” yielded 117 publications for the period from 1990 to date. After the publications that were not relevant were omitted, as in the methanol case described above, 101 relevant publications on DME remained.

In Figure 6.3, the number of publications on DME is shown. First, it can be noted that DME was of little interest until 1995. After that, the trend of a steady increase in publications can be noted. However, the number of publications on DME is still lower than on methanol. Virtually all DME publications are linked to the use in diesel engines.
It could be of interest to note that several of the latest publications (2002 and 2003) on DME has been dealing with homogenous charge compression ignition (HCCI) engines. The HCCI combustion is described later (see Section 6.2.6, page 122). DME, possibly mixed with methanol or, dissociated to CO and H\textsubscript{2} could have favourable properties for use in this type of engine.

6.2.3 Energy converters

As this study is focusing on the use of methanol and DME, the main discussion about energy converters is made from this point of view. However, it cannot be neglected that the primary focus of the industry – for the moment anyway – still is on the conventional fuels, i.e. petrol and diesel fuel. Therefore, alternative fuels must make the best use of the development made with regard to conventional fuels. It should also be noted that the views and development potential discussed below is not a forecast but rather a scenario that could take place if fuel efficiency would be the main focus. This does not necessarily imply that scenario will take place.

Methanol and DME could, in principal be used in three energy converters in the near and mid-term future. These are:

- Spark ignition, or otto-cycle, engines
- Compression ignition (CI), or diesel-cycle, engines
- Fuel cells

The rationale for the interest in methanol and DME from biomass is the potential to a high efficiency in a lifecycle perspective. This has previously been shown in a well-to-wheel (WTW) study by Ecotraffic [35]. An example of the results is shown in Figure 6.4. The
figure depicts the best engine converter and drivetrain combination for each of the fuel candidates in a hypothetical passenger car of model year 2012 (i.e. in the timeframe of 2010 to 2015). The efficiency is expressed on a well-to-wheel basis (i.e. higher number is better).

![System efficiency (well-to-wheel) for various fuels and powertrains](image)

**Figure 6.4.** Well-to-wheel efficiency for the best combinations of fuel/powertrain for fuels from biomass.

DME, hydrogen (GH\textsubscript{2} and LH\textsubscript{2}) and methanol had the highest efficiency in the study mentioned above (Figure 6.4). Hydrogen could be of great interest in the long-term future but it is obvious that DME and methanol could be of great interest on a shorter timeframe.

An often-overlooked advantage of methanol is that this fuel can be used in many kinds of energy converters, i.e. otto and diesel engines, as well as fuel cells. It is conceivable that the efficiency is higher in diesel engines and fuel cells than in otto engines. However, the efficiency in an otto engine is not that much lower than the two other energy converters, on the condition that the otto engine has been optimised for methanol.

In Figure 6.5, the relative energy use for the three liquid biofuels with the highest efficiency is depicted (i.e. a lower number is better). The fuels are methanol, ethanol and Fischer-Tropsch diesel fuel. In one case (i.e. FTD) an “impossible” combination is missing in the figure.

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3 In this case, cryogenic liquid fuels, such as LH\textsubscript{2}, are not considered.
Figure 6.5. Well-to-wheel energy use of some liquid biofuels.

As can be seen in Figure 6.5, methanol has a considerably higher efficiency than the other two fuels, regardless of energy converter used. In the literature, the use of FTD has often been promoted with the argument that this fuel enables the use of fuel-efficient diesel engines (instead of otto engines). However, it could be noted that an otto engine optimised for the use of neat methanol could have a higher WTW efficiency than the FTD and diesel engine combination. Furthermore, otto engines are cheaper to manufacture than diesel engines and have a potential for lower exhaust emissions. As mentioned before, DME could provide an even higher efficiency but in this case, a new fuel infrastructure has to be considered.

Other potential energy converters?

Methanol and DME, the two fuels that have received most of the focus in the this project, are primarily of interest in three types of energy converters (“engines”), i.e. otto and diesel engines and fuel cells. Other energy converters, such as gas turbines, stirling and steam engines were of great interest in the 1970’s and have been discussed from time to time since then. The two first energy converters received some attention in the US PNGV\(^4\) programme a couple of years ago and in Europe, as well, but it seems as the interest today is on a relatively low level. Some proponents for steam engines are working on concepts in Germany [36] and Sweden [37]. However, no concept engine of the three mentioned types of engines is close to a production status. Likewise, the interest from the automotive manufacturers has not been high. Therefore, otto and diesel engines, as well as fuel cells remain as the primary energy converters that will be discussed in this report.

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\(^{4}\) PNGV: Partnership for a New Generation of Vehicles. This programme was initiated in 1994 by President Clinton and the three major US car manufacturers but the programme was terminated by the Bush administration in 2002.
Exhaust emissions

In the long-term future, it is likely that maximum efficiency will be the main objective. This bold statement stems from the development record shown during the past century and the promising research results published so far. Presumably, the development trend could be extrapolated for the next 10-year period. Thus, all proposed future emission limits (including USA and California) could in principle, be fulfilled with any of the fuels in discussion. It will only be a matter of cost to meet the emission limits. This will lead to a shift in focus by the end of this decade towards energy efficiency and security of energy supply. Therefore, energy efficiency will become one of the main criteria to take into consideration for the timeframe relevant for a (possible) future erection of a fuel production plant for methanol/DME from biomass.

Although exhaust emissions will be of less importance in the future than today, some aspects on this subject will be discussed for each energy converter and fuel. Emission regulations have been passed for light-duty vehicles for the timeframe to 2005/2006 (Euro IV) and for engines used in heavy-duty vehicles to 2008/2009 (Euro V). The technology options for meeting these emission limits are reasonably well known and are currently being developed. Therefore, no particular analysis of the impact of the emission norms is made here. In general, alternatively fuelled engines have many advantages over conventional fuels regarding exhaust emissions. The primary driving force for the emission development will be to meet the limits for the conventional fuels (petrol and diesel fuel). The routes chosen for engine and aftertreatment development will also have a substantial impact on the adaptation of these engines for alternative fuels. Consequently, the development on the conventional fuels must be taken into account when assessing the potential of future development of the alternative fuels.

Hybrid electric drivetrains

Hybrid electric drivetrains are currently under discussion as a potential means of reducing the energy use. This option is mentioned here only for the sake of making the discussion complete. The biofuels considered here do not provide any particular advantages in hybrid electric drivetrains over petrol and diesel fuels.

Electric hybrid systems of parallel and series types are conceivable for the combustion engines. The parallel hybrid version of hybrids is the concept that has the highest commercial potential in the near and mid-term future. It has also been shown that this system has a greater potential to reduce fuel consumption than the series hybrid. Furthermore, the parallel hybrid does not need a large battery as the series hybrid and consequently, the cost is lower for the former. A special variation of the parallel hybrid system is the system that Toyota uses in the Prius. This system is actually a combination of both systems and has at least the same potential to a reduction of the fuel consumption as the “conventional” parallel hybrid. However, the Prius system seems to be much more expensive than the “simple” parallel hybrid. Part of the fuel improvement with hybrid systems stems from downsizing the engine to maintain the acceleration performance.

Hybrid electric drivetrains for light-duty vehicles are expected to have a breakthrough (large-scale market penetration) on a timeframe of probably less than 10 years. For heavy-duty vehicles, the interest in hybrid drivetrains is not as great as for light-duty vehicles. The potential for reducing the fuel consumption is less for the heavy-duty vehicles, except

5 Note that the cost of meeting the emission limits could vary significantly from fuel to fuel.
in extreme congested traffic. It should also be noted that the introduction of hybrid drivetrains would not facilitate the use of electricity as an energy supply for the road transport sector. This is due to the limited battery capacity in hybrid vehicles due to economical constraints (battery cost). Thus, energy efficiency in the energy converter and drivetrain are essential factors to take into account.

**The strive for increased energy efficiency**

Engine and vehicle development is driven today by a number of partly conflicting requirements. Some of the most important requirements are:

- Crashworthiness and road safety
- Exhaust emissions
- Reduction of climate gases (primarily CO$_2$)

The first issue (safety) is of significant importance for light-duty vehicles (though of somewhat less importance for heavy-duty vehicles) but it is left without further comments here. It should be noted that there is a principal conflict between safety and the two other factors as an increase in vehicle weight also increases fuel consumption and, to a smaller extent, the exhaust emissions. Nonetheless, the two remaining issues on the list are of significant interest to discuss.

In order to reduce climate gases from transportation, the European car manufacturer’s association ACEA and the EU have agreed on voluntary future limits for CO$_2$ emissions for light-duty vehicles. Later, the Japanese (JAMA) and Korean (KAMA) manufacturers agreed on similar commitments but with one year delay. The limits (target and indicative targets) for ACEA are shown in Table 6.2.

**Table 6.2. Voluntary limits for CO$_2$ emissions from passenger cars in Europe**

<table>
<thead>
<tr>
<th>Year</th>
<th>CO$_2$ (g/km)</th>
<th>Red. (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>185</td>
<td>0%</td>
<td>Base level for the comparison</td>
</tr>
<tr>
<td>2003</td>
<td>165–170</td>
<td>-9.9%</td>
<td>Indicative target range</td>
</tr>
<tr>
<td>2008</td>
<td>140</td>
<td>-24.7%</td>
<td>Target for 2008</td>
</tr>
<tr>
<td>2012</td>
<td>120</td>
<td>-35.5%</td>
<td>Indicative target for 2012</td>
</tr>
</tbody>
</table>

It should also be noted that the voluntary agreement mentioned above is for the whole EU and for all ACEA members and it is not applicable to specific markets and/or car manufacturers. It is somewhat unclear how (and if) ACEA will allocate the CO$_2$ emissions between its members, or whether some other procedure to share the burden will be used. However, the means of achieving the goal is of little relevance in this respect if the goal is achieved. Some reservations have been made by ACEA, such as the free penetration of new technology in all member countries. This aspect will most likely be considered in the review process. Regarding heavy-duty vehicles and light commercial vehicles, it has been considered that the driving force for reducing the fuel consumption is great due to customer demands. Therefore, the EU commission has concluded that, at present, no measures are necessary to reduce CO$_2$ emissions and fuel consumption from this category of vehicles.
The description of the powertrain technology used in light-duty vehicle could be completed by drawing the conclusion that a technology shift is currently taking place for both otto and diesel engines. The potential for reductions of fuel consumption and CO₂ is the driving force in both cases. The technology under discussion is direct injection of the fuel – both in the otto and in the diesel case. An alternative technology is to use fully variable valve actuation (both lift and timing) in the otto engine case. The reduction of pumping losses is the primary objective for direct injection, as well as for the fully variable valve actuation. For diesel engines, faster combustion and reduced heat rejection are the main contributing factors to the reduction in fuel consumption that has been shown with direct injection (in comparison to indirect injection). The necessary alterations mentioned are vast regarding the combustion system and the exhaust aftertreatment for both petrol and diesel fuel. However, most of these modifications cannot be seen from the outside the engine.

The technology shift for the diesel-fuelled engines in light-duty vehicles has been proceeding for a couple of years now and it is now about to be completed. This does not necessarily imply that the full potential for a reduction of the fuel consumption is exploited yet, since the concept will presumably be further developed for several years to come. The technology shift for petrol-fuelled otto engines has just recently begun and the authors foresee a transitional period about as long as for the diesel engines also in this case. An assessment of the available data on the vehicles that already have been introduced on the market implies that there is still a vast development potential for this new technology for petrol-fuelled engines. It is likely that this development will lead to that the difference in fuel consumption between cars with diesel and otto engines will decrease in the future (seen as an average consumption for the car population in each case). The slow penetration of low-sulphur petrol and the associated problems with aftertreatment devices might have contributed to the somewhat slower penetration as the record shows today.

During the last couple of years, significant progress has been made on fuel cells. Several light-duty vehicles have been demonstrated by various car manufacturers and technology suppliers. Limited production of vehicles is about to begin within a few years. However, a large-scale introduction of fuel cell cars is not likely during this decade. The best choice of fuel for the fuel cells has not yet been determined. Hydrogen, methanol and reformulated petrol are some of the candidate fuels being discussed. Low or zero emissions is one of the driving forces for the use of fuel cells and the potential for high efficiency is the second primary driving force.

6.2.4 Otto engines

An important question regarding the use of alternative fuels is the level of optimisation of the engines to the fuels and consequently, the question rise whether the alternative fuels have specific advantages that could be utilised in the development. It is plausible that the full potential of these fuels has not been fully exploited today. Some estimations and assumptions are used to elucidate these issues. The assessment is based on the baseline petrol-fuelled engine. Consequently, the development of an engine for this fuel is described first.

The engine technology used for the engine in a conventional drivetrain or a hybrid-electric drivetrain does not differ very much and therefore, the improvements of the otto engine are more or less general for this engine type. The petrol-fuelled otto engine is the base alternative and therefore, it is described first.
**Direct injection**

Today, most otto engines use the three-way catalyst aftertreatment to clean the exhaust. The injection for the new generation of engines will be made directly in the cylinder instead of in the inlet manifold (or inlet port) for the conventional engines. The Japanese manufacturer Mitsubishi introduced this technology first at the Japanese market and subsequently (since 1997); this technology has also been introduced in Europe in several of the car models from this company. The European car manufacturers have also developed similar technology and they have just recently introduced this technology, or else, they will introduce this technology in the near future.

The principal advantage by using direct injection on otto engines is that the fuel consumption is considerably reduced. The primary cause for this is that the so-called pumping losses are reduced due to less throttling (excess air). The consequence of this strategy is that a conventional three-way catalyst cannot be used to reduce the NO\textsubscript{X} emissions and this is the main drawback of the concept. The most technology that seems to have the greatest potential is based on the storage of NO\textsubscript{X} in the catalyst. At a proper interval, the catalyst is regenerated by running the engine in a rich mode for a few seconds so that the stored NO\textsubscript{X} can be reduced in a similar fashion as in the three-way catalyst. The main problem with this type of catalyst is that they need low-sulphur or sulphur-free fuel, since sulphates are adsorbed more easily than nitrogen dioxide in the catalyst.

The emission control concepts for direct injection that are about to be introduced on the market do in fact tolerate a certain level of sulphur in the fuel but it is clear that they could operate better with low sulphur fuel. Furthermore, new catalyst concepts with greater reduction efficiency could be introduced if low-sulphur fuel was available. The sulphur problem has most likely delayed the introduction of the new technology compared to some previous expectations. However, it is likely that several new engine generations will be introduced in the near future, which presumably implies that the technology shift is about to accelerate somewhat.

**Variable valve timing**

The direct injection technology, as described above, is by no means the only possible technology to reduce the fuel consumption from otto engines, although this technology has tended to attract most of the interest lately. Several of the alternatives have almost the same potential as the direct injection technology. Some of the alternatives tend to be too expensive by today’s standards to be realistic, but further development will certainly make these alternatives interesting in the future. One example is that the difference in fuel consumption between the direct injection engine with lean-burn concept and an engine with electrically actuated valves (fully variable valve control) is not great. However, the cost is prohibitively high for this concept.

**Specific advantages of alcohols in otto engines**

It is well known that the alcohols, ethanol and methanol, have specific advantages in otto engines – these fuels are simply “natural” otto engine fuels. First, the octane number is higher than for petrol, which is advantage for an engine where the maximum compression ratio is limited (knocking) by the octane level. Second, the alcohols have a higher latent heat of evaporation than petrol and since the energy content (per litre or per kg) is lower, a total evaporation of the alcohols would give a considerably lower temperature of the air-fuel mixture than petrol. A lower temperature implies a higher volumetric efficiency...
although this is somewhat counteracted by the fact that the alcohol molecules are smaller than the average petrol molecule and therefore they have a greater volume than the latter. However, the air-fuel preparation is not as simple as indicated, since the evaporation is not completed in the inlet manifold (with indirect injection). Nor is it so, that all energy for evaporation is taken from the air. A considerable contribution to the evaporation comes from the hot surfaces in the inlet system (due to evaporation from the walls) and from the hot surfaces surrounding the combustion chamber (fuel impinging on the walls). The result is a lower volumetric efficiency and increased heat transfer. It is notable that alcohol engines have a higher volumetric efficiency than petrol-fuelled engines, which implies that the physical properties of the fuel have an impact. Yet, another advantage for the alcohols is a slightly increased mass flow rate caused by the lower energy density of the fuel. This also gives a small contribution to increased power and efficiency.

**The cold start issue**

The greatest problem with alcohol fuels in otto engines today is the substantial increase in emissions when the engine is cold started at low ambient temperature. This problem should be possible to solve in the future when new engine technology (e.g. direct injection) will be available. In a direct injection otto engine, the injection at higher load is made during the inlet phase. The objective with this strategy is on the one hand to obtain a homogenous charge and on the other hand to utilise the charge cooling effect due to fuel evaporation. In direct injection petrol engines, an increase in power and torque can be obtained with this strategy compared to conventional port injection. With port injection, some heat for evaporation comes from the hot surfaces (before inlet valve closure) and this problem is (partly) avoided by using direct injection, hence the increase in volumetric efficiency in this case. It is plausible that alcohol fuels could have a further advantage in this respect, due to the increase in latent heat of evaporation. The cooling effect of the charge by direct injection also permits a higher compression ratio compared to conventional injection. In early experiments with direct injection of alcohols, several interesting observations of potential advantages with this system have been made. The enhanced cold start ability at low ambient temperatures seems to be the most important feature.

**Fuel flexibility**

Perhaps the most interesting question about future alcohol engines with direct injection is whether these engines can be made fuel flexible (FFV). Even if this concept is a compromise in comparison to a dedicated engine, the concept could be of interest during an introduction phase. It is well known that the injection system and air-fuel preparation in a diesel engine is not suited for FFV operation, since the differences in fuel density (volume) for the fuels in mind (diesel and alcohol) are vast. Furthermore, the time allowed for the injection phase and the air fuel preparation is very short in these engines. Although the similarity between diesel engines and direct injection otto engines might seem far-reaching, the latter engines are also limited by a short period for injection and fuel preparation in the lean-burn stratified charge mode. This is not a particular problem for conventional indirect injection otto engines, since the period for injection and fuel preparation can be longer due to the port injection. No particular study of modern\(^6\) direct injection engines has been made.

---

\(^6\) The development company FEV in Aachen developed a direct injection otto engine in the early 1990’s based on an old VW-concept of an direct injection petrol-fuelled engine. However, this concept was so vastly different from the new direct injection engines that no conclusions can be drawn from that concept that can be directly applied to modern direct injection engines.
Injection systems on an alcohol engine is known to the authors but a recently published study from the Technical University in Zwickau shows the influence of direct injection with methanol fuel [38, 39]. The results from this study, which were performed on petrol, methanol and mixtures of these two fuels, indicated that there should be a fair chance of success for an FFV concept with direct injection. The model tests made showed that the penetration of the spray decreases with methanol, due to the difference in physical properties between methanol and petrol. In general, the penetration should increase when methanol is used but the better atomisation and the enhanced evaporation counteracts this trend. This should be a considerable advantage, since wall-wetting is a particular problem in direct injection engines (especially at cold starts). Another work worth mentioning has been conducted by Michigan State University and US EPA [40]. This engine is spark-ignited and has a compression ratio as high as 19.3:1. As it appears that this work is in its initial phase, it is too early to assess the true potential of this concept. In summary, instead of using M85 and E85 fuels, neat alcohols (besides possible additives), i.e. M100 and E100, could be anticipated to emerge as the preferred solution in the future.

Utilising some specific methanol properties in an unconventional concept

A very interesting new concept of utilising the specific properties of alcohol fuels has been demonstrated in a study by US EPA. The results generated in that project are so promising that a special discussion on this subject is motivated. An SAE paper on this subject was published by the end of 2002 [41].

In the EPA study, a 1.9-litre Volkswagen TDI diesel engine was converted to spark ignition and port injection of the fuel. Some engine parameters are listed in Table 6.3.

A very high level of exhaust gas recirculation (EGR) was used to suppress engine knock. By using this strategy, a compression ratio as high as 19.5:1 could be maintained. The engine could be run at stoichiometric conditions at the greatest part of the engine load and speed map. Only at the lightest load, throttling was required. Due to the use of three-way catalyst (enabled by stoichiometric combustion), very low exhaust emissions could be obtained.

Methanol and ethanol were tested as fuels for the engine. It was concluded that methanol had the greatest potential to utilise this particular concept. One of the fuel properties of methanol that can enable the mentioned concept is the very high tolerance for charge dilution, whether it is utilised as EGR or by increasing the excess air ratio (i.e., a lean-burn concept). High charge dilution enables an increase in the compression ratio (without knock) and this increase in dilution further increases combustion stability, which again enables higher EGR and so on. Ethanol has better properties than petrol in this respect but could not match methanol in the EPA study.

Table 6.3. Engine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type/value/unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>4 cyl., 4-stroke</td>
</tr>
<tr>
<td>Combustion type</td>
<td>PFI, SI</td>
</tr>
<tr>
<td>Valves per cyl.</td>
<td>2</td>
</tr>
<tr>
<td>Displacement</td>
<td>1.9 litre</td>
</tr>
<tr>
<td>Bore</td>
<td>79.5</td>
</tr>
<tr>
<td>Stroke</td>
<td>95.6</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>19.5:1</td>
</tr>
<tr>
<td>Swirl ratio</td>
<td>2.0</td>
</tr>
<tr>
<td>Injectors</td>
<td>Holley, 36 lb/hr, 12-hole nozzle</td>
</tr>
<tr>
<td>Rail pressure</td>
<td>4 bar</td>
</tr>
<tr>
<td>Spark plugs</td>
<td>Champion recessed gap, dual electrode</td>
</tr>
<tr>
<td>Turbocharger type</td>
<td>Variable geometry</td>
</tr>
<tr>
<td>Aftertreatment</td>
<td>Ford FFV 2-stage TWC</td>
</tr>
</tbody>
</table>
In the opinion of the authors of this report, it could be argued whether the engine was an otto or a diesel engine. Although two of the common features of otto engines, i.e. port-injection and spark ignition, are applied, the high compression ratio and throttle-less operation as features of the diesel engine. A glance at the cylinder pressure diagram in the EPA paper also reveals a cycle very similar to a conventional diesel cycle. Therefore, the engine might be considered as a “spark-assisted” diesel engine (i.e. it is still utilising the diesel cycle).

The most interesting results in the study are the very high efficiency obtained. In Figure 6.6, the efficiency for the methanol-fuelled and the diesel-fuelled versions of the engine are compared (the results with ethanol were not as favourable).

![Figure 6.6](image)

**Figure 6.6. Efficiency comparison between diesel fuel and methanol in high CR otto engine (SI). The graphs are adapted from reference [41].**

The results in Figure 6.6 show that the efficiency with methanol was even higher than with diesel fuel. A peak efficiency of 42% was obtained for the methanol-fuelled engine in a relatively large area of the map. The corresponding efficiency for the diesel-fuelled engine in an area of approximately equal size was 40%. The relative improvement is 5%. This advance should be compared to the “normal” yearly improvement of fuel consumption that has been in the order of about 0.5%. Furthermore, it should be noted that a higher efficiency than the diesel cycle has not been demonstrated on any type of combustion engine (internal or external) before.

Due to the throttle-less operation, the efficiency for the methanol engine was also high at very low loads and this is certainly not a feature of conventional otto engines. It remains to be seen what level of fuel consumption that can be achieved at very low load and at idle.

**NO\textsubscript{X} reduction in lean exhaust**

In the future, NO\textsubscript{X} reduction on petrol-fuelled direct injection otto engines will most likely be accomplished by using so-called NO\textsubscript{X} storage catalysts. These catalysts are very sensitive to sulphur poisoning and consequently, as alcohols are sulphur-free, they have a fundamental advantage in this respect over petrol and diesel fuel. A proposal for the
Black Liquor Gasification with Motor Fuels production - BLGMF

reduction of sulphur levels in both these fuels has been put forward in EU for the 2005–2009 timeframe.\(^7\)

A \(\text{NO}_X\) storage catalyst must be regenerated periodically from the stored \(\text{NO}_X\). This is achieved by running the engine under rich condition for a short period (typically a few seconds). During this regeneration, \(\text{NO}_X\) reduction is accomplished by utilising \(\text{CO}\) and \(\text{HC}\) in a similar manner as for “normal” three-way catalysts. This is possible, since there is no oxygen excess during the rich “spike”. It is known that the composition of the \(\text{HC}\) emissions is important to achieve a high \(\text{NO}_X\) reduction (regeneration) and the question arise whether the unburned “\(\text{HC}\)” emissions from alcohol fuels would work as a reductant. Limited results from such catalysts and lean-\(\text{NO}_X\) catalysts indicate that alcohols, and methanol in particular, has better properties than \(\text{HC}\) from petrol and diesel fuel regarding \(\text{NO}_X\) regeneration.

The important properties of methanol as a reducing agent for \(\text{NO}_X\) reduction in lean exhaust have been shown in several studies. Another type of \(\text{NO}_X\) reducing catalyst utilises non-thermal plasma (NTP) to facilitate a selective catalytic reduction of \(\text{NO}_X\) by using hydrocarbons (or their derivatives) in the exhaust as reducing agents. For example, in a recent joint study by the federal laboratory PNNL and Caterpillar it was shown that methanol achieved much higher \(\text{NO}_X\) reduction than any of the other reducing agents tested [42]. It could also be noted that the properties that enable these favourable results probably also play an important role in the regeneration phase for \(\text{NO}_X\) storage catalysts. It is likely that DME has similar properties as methanol in this respect but there are fewer results available in this case.

Another advantage of alcohol fuels in direct injection otto engines would be the foreseen reduction in soot and particulate formation in comparison to petrol. The particulate formation in direct injection petrol engines is a particular problem (especially at low ambient temperatures), since these emissions are approaching those of modern diesel engines without particular filters.

6.2.5 Diesel engines

More than a decade ago, direct injection was introduced in diesel engines for passenger cars but the technology is not new, since it was introduced in a larger scale in engines for heavy-duty vehicles more than 50 years ago. It could be of interest to note that of the three engines that were introduced in the 1988–1989 timeframe (Audi, Rover and Fiat), only one of these (Audi) was a commercial success. Later, the technology of this engine was passed on to other companies within the VW group, thus providing these car manufacturers with a technology lead over their competitors. However, it has not been until the last three years that the development has accelerated and this is attributable to the new high-pressure injection technology (common rail, high-pressure rotary pumps and unit injectors). It is well-known that direct injection for diesel engines demand very high injection pressure to utilise the full potential for reducing emissions and fuel consumption.

Emission control for diesel engines

The greatest obstacle for diesel engines is still the \(\text{NO}_X\) and particulate emissions. Particulate traps are now being commercialised by one car manufacturer (Peugeot-Citroën) while other manufacturers have announced that they are developing filter systems that will

\(^7\) The low-sulphur diesel fuel used in Sweden is below the future EU limit of 10 ppm.
be mature for production in the 2002–2003 timeframe. The technology for reducing the NO\textsubscript{X} emissions will not be introduced in larger scale until low-sulphur fuel is available on several markets in Europe. Although Sweden has a diesel fuel with very low sulphur level (<10 ppm), the market for diesel cars in Sweden probably is too small to motivate the early introduction of this technology here. It could be noted that the most promising technology for NO\textsubscript{X} removal (NO\textsubscript{X} adsorber catalyst) is more or less similar for both Otto and diesel engines in the future. Therefore, the NO\textsubscript{X} emissions will be on a similar level for these engine types in the future.

An elegant solution developed by Toyota is a combination of a particulate filter and a NO\textsubscript{X} storage catalyst. This system, called DPNR or D-Cat is first commercialised this autumn in the new Toyota Avensis model. Other models will probably follow and the technology will be used in light heavy-duty trucks by the Toyota subsidiary Hino, as well.

For heavy-duty vehicles, the use of selective catalytic reduction (SCR) with urea\textsuperscript{8} as a reducing agent seems to be the preferred solution in Europe. This technology seems to be further on in the development path than a NO\textsubscript{X} storage catalyst as the technology has been applied for decades in stationary power plants. Prototype SCR systems are already being tested in several vehicle fleets in Europe. The main problem with SCR is the need for a new infrastructure for urea supply. In the USA, EPA is not in favour of using SCR systems, since these are dependent on the supply of a reducing agent. Apparently, the vehicle could function as well without urea, unless the engine manufacturer uses some programming of the engine control system to reduce its performance if the vehicle is not “refuelled” with urea.

In order to meet future NO\textsubscript{X} emission limits – that are anticipated to be significantly stricter in the future for diesel-fuelled cars, presumably similar to petrol cars – a NO\textsubscript{X} storage catalyst or an SCR system will be necessary. There will be some increase in the fuel consumption associated with the NO\textsubscript{X} regeneration of the storage catalyst (this regeneration could be simultaneous to the regeneration of the particulate filter). Recently published data indicate that this penalty might be reduced to less than 1%, provided that the sulphur content in the fuel is below 10 ppm [43]. For heavy-duty vehicles, the use of SCR is said to enable a reduction of the fuel consumption compared to the contemporary Euro III engines. This is because a higher engine-out NO\textsubscript{X} level than for Euro III can be tolerated with SCR while still meeting the Euro IV and V emission limits. However, the strategy of higher engine-out NO\textsubscript{X} level could also be applied with a NO\textsubscript{X} storage catalyst.

With an even stricter emission level, such as US 2010 for trucks, it is likely that both systems would be plagued with a fuel consumption penalty compared to engines certified for contemporary emission limits. It remains to be seen if future development can reduce this penalty. If not, alternative fuels might have a better chance of success. This would also be the case if the cost for meeting the emission limits would be lower for alternative fuels.

\textit{Fischer-Tropsch diesel fuel}

A synthetic hydrocarbon fuel, such as the Fischer-Tropsch diesel fuel (FTD), has several properties that differ from conventional diesel fuel. The formation of NO\textsubscript{X} and particulate emissions is reduced, although these problems remain as an inherent feature of the diesel engine. The FTD fuel is essentially sulphur-free, which is a considerable advantage

\textsuperscript{8} Other reducing agents, such as ammonia solutions or ammonium carbamate has been proposed instead of urea, but in Europe, it seems as urea has won this contest.
regarding the use of effective exhaust aftertreatment. Furthermore, the cetane number is high for the FTD fuel, which is a considerable advantage for contemporary diesel engines. Since the fuel is also free of polycyclic aromatic hydrocarbons (PAH), olefines and cycloparaffines, the emission components (possibly) causing health hazards should (presumably) be considerably lower than for Swedish Environmental Class 1 diesel fuel (EC1) and European diesel fuel. The density for FTD is lower than for both EC1 and conventional diesel fuel, which would reduce the engine power unless countermeasures are taken. The FTD can be readily mixed with conventional diesel fuel and, possibly, it could have a higher value as a blending component in such use than used separately. Blending could also be interpreted as certain fuel flexibility for the FTD fuel.

**DME as diesel fuel**

DME is a "natural" fuel for diesel engines due to the exceptionally high cetane number. Therefore, the same efficiency as for diesel fuel is possible for a diesel engine adapted for DME. DME is non-toxic and should have an inherent property of significantly reducing the toxic emissions in the exhaust in comparison to conventional diesel fuel. A significant reduction of the NO\(_X\) emissions for DME in comparison to diesel fuel has been found in several studies. Particulate formation is largely avoided with DME in comparison to hydrocarbon fuels. DME also provide the opportunity for using higher rate of EGR, which further reduced the NO\(_X\) emissions compared to diesel fuel. Deducing from the limited number of studies available, it seems that the use of a NO\(_X\) reducing catalyst should be a viable solution for this fuel. Since DME is sulphur-free, the use of effective aftertreatment devices in general is more easily facilitated with DME than with sulphur containing fuels.

A particular problem with DME as a motor fuel is the fuel injection system. Several problems arise from the physical and chemical properties of DME. DME attack most elastomers and therefore, proper seals have to be developed. This problem is also evident in the fuel distribution system. Furthermore, DME has a very low lubricity and thus, one solution would be to develop proper additives to improve the lubricity. Another solution would be to take measures to the injection system itself (surface treatment, etc.) to ensure that a fluid with very low lubricity could be tolerated. Anyway, the long-term durability of the high-pressure injection system has to be secured before an introduction on the market. Recently, new injection systems are being developed with this purpose and the results available so far appear promising [44]. Although emission results also look very promising, much basic research is needed to utilise the full potential for emission reductions compared to diesel fuel. In summary, the large-scale commercial introduction of DME will not happen in the near future.

The next objective might be to aim for a small-scale demonstration fleet with DME. The heavy-duty engine (Figure 6.7) currently being developed by Volvo Truck

![Figure 6.7. Volvo 9-litre D9A engine, to be adopted for DME fuel.](attachment:image.png)
in the EU project AFForDH will probably be one of the first engines to be used in such fleets [45, 46].

A DME engine cannot be made fuel flexible, without too large compromises and at a reasonable cost. This is of course a significant disadvantage during an introduction phase and, in particular, this is of importance for general use of this fuel, as in case of passenger cars.

**Methanol as a diesel fuel**

The experience from heavy-duty vehicles has shown that ethanol and methanol could be used in diesel engines. An external ignition source, such as a glow plug, is foreseen to avoid the use of an ignition improver. Even if the development of glow plugs for diesel-fuelled passenger cars has been rapid, further development will be necessary to increase the reliability and the useful life (i.e. for the life of the engine) for the use in alcohol engines. The necessity to use an external ignition source for the alcohols is a significant disadvantage in comparison to other alternative fuels, such as DME and FTD.

The NO\textsubscript{X} emissions will be lower for the alcohol engines than for diesel fuel and simultaneously the rate of EGR can be increased, which further reduces the NO\textsubscript{X} emissions. In general, the soot and particulate formation is significantly reduced with alcohols, although an increase in particulate formation has been seen with high rates of EGR on a heavy-duty ethanol engine. It is not clear if the same problem will be seen for methanol but, in theory, this molecule should be better in this respect than ethanol due to the absence of carbon-carbon bonds and higher oxygen content. The application of a NO\textsubscript{X} reducing catalyst should be easily facilitated on methanol according to limited test data, due to the excellent properties of methanol as a NO\textsubscript{X} reducing agent.

As in the case with DME, there are no practical opportunities to make alcohol diesel engines fuel flexible.

6.2.6 **Unconventional combustion concepts for otto and diesel engines**

It is interesting to note that new combustion concepts are currently being investigated for both diesel and otto engines. It could be noted that there are several other acronyms to the concepts mentioned below. The authors have used the most common acronyms.

**HCCI**

The HCCI (Homogenous Charge Compression Ignition) concept is of great interest for diesel engines and is probably the most well-known of the two concepts mentioned here. The HCCI system is based on evaporating and premixing the fuel and air before ignition in a somewhat similar manner as in an otto engine. However, contrary to the otto engine, ignition is carried out as compression ignition. HCCI could significantly reduce – or eliminate – NO\textsubscript{X} and particulate emissions, two of the main emission problems for diesel engines.

There are some attempts to utilise the specific properties of alcohol fuels for HCCI combustion. One example is to use flash boiling of methanol as a means of improving mixture preparation and combustion [47]. During the last years, the potential of using DME, mixtures of DME and methanol or reformate from DME and/or methanol in HCCI engines has been investigated. It is well known that DME has a very high cetane number and that methanol and reformate of DME and methanol has very low cetane number. By
using two fuels, the problems of controlling the combustion in a HCCI engine could perhaps be overcome. Japanese universities and institutes in particular have recently tried to exploit these ideas [48–51].

**CAI**

The new concept for otto engines, CAI (Controlled Auto Ignition) is somewhat similar to HCCI, since it also uses premixing and compression ignition. Due to the poor compression-ignition properties for otto engine fuels, ignition must be enhanced in some way. Massive use of hot residual gases is one possibility to promote compression ignition of a fuel with very low cetane number.

It has been shown in a project by the Brunel University and Ford that alcohols, and methanol in particular, could significantly increase the operating area of CAI combustion [52].

**Utilisation of methanol and DME fuel properties in HCCI and CAI engines**

Regarding the fuel demand imposed by the HCCI and CAI concepts, it is notable that different properties than for the conventional petrol and diesel fuels are necessary to fully optimise each concept. Presently, very little is known about the new demands these concepts will impose on fuel specifications. Whether alternative fuels could have significant advantages over conventional fuels is another issue to consider. Very little work has been conducted in this area. Nevertheless, it is worth noting that considerable development efforts are conducted on these combustion concepts and, therefore, bringing alternative fuels and fuel specifications into the optimising process would be a logical next step.

**6.2.7 Fuel cells**

Fuel cell powertrains use a fuel cell stack and an electric drivetrain. PEM fuel cells are of most interest for vehicle applications and, therefore, no other cell technologies are discussed here. Fuel cell drivetrains can be either of the “direct drive” or of series hybrid types. A parallel hybrid system is not possible for a fuel converter that does not produce any mechanical work. Hybridisation of the fuel cell drivetrain is increasingly becoming an important part of the development.

**PEM fuel cells**

PEM fuel cells are the fuel cell concept of main interest for automotive applications. These fuel cells can only use hydrogen as a fuel. All other fuels have to be reformed before being fed to the fuel cell stack. Methanol is the fuels that can be reformed at the lowest temperature (250–270°C) of all fuels. Consequently, besides hydrogen, methanol is one of the fuels of prime interest for PEM fuel cells. However, it should be noted that there is still much work to be carried out on reformers before commercialisation could be initiated. For some reason, it seems as most of the development work on fuel cells has been focused on the fuel cell stack. To date, significantly less work has been conducted on reformers. Therefore, hydrogen appears to have an edge over methanol in this application. It is also likely that the first generation of fuel cells will use hydrogen, simply since it is easier to implement at this stage. However, since the cost of hydrogen infrastructure is prohibitively

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*PEM: Proton Exchange Membrane (fuel cell).*
high, methanol will most certainly have a chance in this competition. The bulkiness of contemporary hydrogen storage limits the vehicle range and this problem could be overcome by using methanol.

Apparently, most of the work on fuel cell vehicles today is carried out on hydrogen. A couple of prototype vehicles have been presented but it seems as most of the field-test vehicles in the near future will be fuelled by hydrogen. In the recent literature, only two publications are worth mentioning. The Korean car manufacturer Hyundai reported at the SAE Congress in March this year about their progress in developing a methanol-fuelled fuel cell SUV [53]. Another paper of interest was the Jeep Commander 2 developed by DaimlerChrysler [54]. The Mercedes part of the company had previously developed the Necar 3 prototype and the fuel cell system and the reformer from this car was installed in the Jeep Commander 2. A methanol reformer has also been tested in the Necar 5 prototype. Albeit the apparent progress in the development mentioned, it seems as the methanol reformer in particular is far from being production ready. Besides from the mentioned work, there are few research and development activities going on in the motor industry on methanol-fuelled fuel cell vehicles.

**The direct methanol fuel cell (DMFC)**

Today, there is little information available about the development potential of direct methanol fuel cells (DMFC). Direct methanol fuel cells (DMFC) could be a possible option in the future, provided that some technical breakthroughs in certain areas are made. Up to now, the reported efficiency has been very low (seldom more than 15%) but it could be expected that a maximum efficiency of more than 40% would be theoretically possible with new technology. Anyway, improvements of the efficiency and power density are crucial for a success. DMFC could vastly simplify the fuel cell drive system in comparison to a PEM fuel cell with reformer. In theory, DME could be used in a direct DME fuel cell similarly to methanol. Today, there is very little documentation available in the public domain database on this subject so most statements here must be based on theoretical considerations. As reforming of DME is somewhat more difficult and less energy efficient than methanol reforming case, it could be expected that the efficiency could be somewhat lower also in the direct DME fuel cell in comparison to its methanol counterpart.

**Direct drive or electric hybrid?**

The direct fuel cell drive system has no large energy storage and therefore, the fuel cell stack has to be sized to correspond to the desired performance level for the vehicle. Furthermore, no regenerative braking can be used (due to the limited battery capacity). Therefore, the total efficiency will be somewhat lower than a hybrid fuel cell system (energy storage). There are also other concerns. If, for example, the start-up period for the fuel cell cannot be sufficiently short, there are no practical possibilities to do without a larger battery capacity. Under these conditions, the direct drive fuel cell system would have to be abandoned in favour of the fuel cell hybrid. As it has been shown that hybrid fuel cells provide higher efficiency than the direct drive systems and therefore, it is likely that the hybrid version will be favoured over the other version. Due to the slow response of the fuel reformer, it is likely that hybrid systems will be preferred for fuel cells with reformers.
6.3 Fuel distribution

6.3.1 Fuel specification

Methanol and DME are chemical commodities on the international market today. For both these fuels, an industrial grade has been used so far in applications as motor fuels. It may be argued that it is would not be necessary to uphold such strict specifications for the use of these chemicals as motor fuels. Thus, the fuel specifications might be more lenient than the specifications for chemical grade. This is on the condition, however, that there is some kind of (economical) gain by changing the specifications by allowing some impurities.

In the following, some issues of methanol and DME dilution are highlighted. In particular, specifications regarding maximum water content are proposed.

*Methanol*

In principal, methanol can be used as a blending component in petrol or as a neat fuel. The use of neat methanol in all the three primary energy converters (engines), such as otto (SI, spark ignition), diesel (CI, compression ignition) and fuel cells, is possible. However, methanol is blended with 15% petrol (M85) for the use in otto engines (FFV, flexible fuel vehicles). This is necessary with contemporary engine technology to ensure that cold start criteria are met\(^\text{10}\). Likewise, the use of ignition improvers is necessary for the use of methanol in diesel engines, unless some positive ignition device (glow plug or spark plug) is used. Several additives (for odour, taste, colour, lubrication, etc.) can be used in methanol intended for petrol and/or diesel engines. The use of such additives might not be permitted for the use in fuel cells due to potential deterioration of the fuel reformer and the fuel cell stack. It would be beneficial if only a single fuel quality could be used in the long-term future. This would simplify the distribution of methanol if only a single grade could be used, as methanol would be a new fuel on the market.

During one of the primary project meetings in this project, the issue of methanol specification was brought up. It was anticipated that methanol would primary be used as a blending component during an early stage. In this respect, fuel separation in the distribution chain was considered a main limiting factor for the water content. Separation in the vehicle tank is not considered an issue as long as the fuel distribution is kept dry. In Sweden, methanol was used in several fleet tests in the 1980’s. As a first guess, the specification used in these field trials did not give any particular problems connected to the fuel quality. Thus, it was considered that this specification could be sufficient today, as well. Two sets of methanol specifications can be found in the documentation from these field trials. One of these specifications is shown in Table 6.4.

\(^\text{10}\) In fact, 15% petrol in ethanol or methanol does not provide similar cold start properties as 100% petrol. However, in warm climate, as in California, it has been quite acceptable.
Table 6.4. Methanol specification in Swedish fleet tests during the 1980’s.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Limit/Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>99.19% w/w</td>
</tr>
<tr>
<td>Water</td>
<td>0.09% w/w</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.59% w/w</td>
</tr>
<tr>
<td>High boiling components</td>
<td>0.13% w/w</td>
</tr>
</tbody>
</table>

As can be seen in Table 6.4, the methanol was almost water-free. Another reference cites a specification that limited the water content to 0.15%. No specific tests were carried out within the programme regarding the maximum permissible water content. Therefore, it is somewhat difficult to draw any firm conclusions from the work on this subject.

When methanol is used as a blending component in petrol, separation might be an issue if the water content is too high. The current EU fuel specification permits the use of up to 3% of methanol in petrol on the condition that a co-solvent (higher alcohol, e.g. ethanol) is also added. Some oil companies claim that higher alcohols might not be needed, since distribution systems generally remain “dry” after the fuel switching has been made. Practically pure methanol is needed to avoid separation in both these cases and special attention has to be paid in the distribution system if no higher alcohol is used. As the current EU fuel specification require the addition of a higher alcohol, the choice is limited for the moment. Further, in the testing of methanol fuelled vehicles in Sweden during the 1980’s, the water content was limited to 0.09% (0.15% has also been mentioned). Acidity was limited to 0.003%. No specific problems related to the water content occurred. There are few data available to support another specification for the use of methanol than the results from the Swedish tests and similar tests in Germany. When methanol is used in FFVs, the methanol content can vary between 85% and 0% in the fuel tank of the car. Therefore, a similar specification is also needed in this case. Note that no higher alcohols are needed if the methanol content is above a certain level (this level is about 15%). One possibility for future use of methanol would be as a blending component in higher percentage. This is on the condition, however, that new vehicles could tolerate higher content of methanol (say, 15%). Due to the condition that older vehicles cannot tolerate this high level of blending (without the increase of some emission components), a new fuel quality would be needed on the market, and this would be somewhat unfortunate. In addition, a new fuel regulation in the EU would be needed that would permit a higher level of blending. Therefore, in the near-term future, only the low blending permitted by the current EU fuel directive should be considered. In any case, water free methanol is required if methanol is to be blended with petrol.

The presence of water in methanol to be used in diesel engines lowers the cetane number of the fuel. However, the cetane number is so low anyway for methanol that this is of no practical importance. Some ignition source or the addition of an ignition improver would have to be used anyway. Today, no (new) diesel engines intended for the use of neat methanol are commercially available in Europe. In general, there is very little activity in this field on an international level. Still this application should be considered in the long-term future, as the energy efficiency is significantly higher for diesel engines than for otto engines. In addition, the possibility of using a fuel specification that would be compatible with fuel cells as well should be considered. This would require a positive ignition source
for diesel engines, as ignition improvers are not compatible with fuel cell reformers intended for methanol (steam reformers).

Water might also be allowed for the use of methanol in fuel cell vehicles, since water is needed anyhow in the steam reforming process. Restrictions on impurities in the methanol might be of more importance in this case compared to the use in Otto and diesel engines. However, very little is known about these issues at the moment. Fuel cell vehicles running on methanol (as well as hydrogen) will be available in small numbers for field testing in 2003/2004. However, commercial scale production of such vehicles cannot be expected before 2010. Possibly, it might last as long as until 2020 before the commercial breakthrough will take place. However, in order to prepare for the investment in fuel infrastructure, it is necessary to conduct studies already today to establish standards for methanol fuel in these applications. In a recent work by Xcellsis, a couple of issues have been identified [55]. Many of the additives under discussion for conventional engines have been shown to degrade the catalyst in the fuel reformer within a very short timeframe in laboratory tests. The current Code of Regulations in California require methanol to have both bitterant and odorant additives. Samples made at several points in the methanol distribution chain were also analysed and it was found that the contamination increased. A project is also conducted by the Methanol Specification Council in the USA where a hazard risk assessment is made of using methanol in fuel cells or in conventional engines. The work by this group is presumed to be of significant importance for future design of methanol specifications regarding safety and health effects. The report was scheduled for publication this fall. However, according to recent information from the American Methanol Institute, the report might not be published due to some difference of opinion between the members of the council. [56].

Based on the discussion above, it can be concluded that the “best” use of methanol on a short-term horizon is as a low blending component or the use in fuel-flexible vehicles. As no new methanol compatible FFV vehicles are available at the moment, the use of methanol for low blending is most likely in the near future. In view of the limited prospects for methanol-fuelled diesel engines and fuel cells on a short-term horizon, new methanol plants should initially focus on the use of methanol as a low blending component.

Based on the considerations above, “raw” methanol is presently not under consideration. Methanol is widely distributed today according to the IMPCA\(^{11}\) specification, which limit water content to 0.1% by weight. The requirements in the federal specification of methanol in the USA limits the water content to 0.15% for grade A and 0.1% for grade AA. Taking the mentioned specifications into consideration, it seems reasonable to limit the water content to 0.1% for the use of methanol in low-blending. Possibly, this limit could be altered when new information is available but it is not likely that the limit will change significantly. By limiting the water content, other impurities are also reduced. The specifications mentioned are listed in Appendix 1.

As the work on this report was finalised, the Methanol Fuel Cell Alliance (MFCA) published a report on the fuel specification for fuel cell vehicles [57]. Although this work was focussed on the use of methanol in fuel cell only, the proposals in the report do not contradict the discussion above.

\(^{11}\) IMPCA: International Methanol Producers and Consumers Association.
**DME**

DME is a fuel that is primarily suitable for diesel engines. Due to the low octane number and the high cetane number, this fuel cannot be used in otto engines. DME is relatively easy to reform in a reformer and consequently, it could be considered for the use in fuel cells, as well. However, methanol can be reformed at an even lower temperature and in addition, methanol can be handled in liquid state at normal pressure. This implies that the use of DME in diesel engines would be the preferred option over the use in fuel cells, as methanol would be the better choice for fuel cells.

Several papers on the use of DME in diesel engines have been presented [58 – 66] but relatively little information is available on the influence of fuel specification. DME is not miscible with other diesel fuels in higher concentration (due to the increase of the vapour pressure) and therefore, it should be considered as a single fuel without fuel flexible properties. In addition, it seems very difficult to envision the use of DME in dual fuel engines, due to the vast difference in fuel properties for the two fuels. The distribution of DME should be considered for the use as a neat fuel. In the near future, DME has to be considered as a niche fuel due to the vast effort needed for building a new fuel infrastructure. However, this also implies that the fuel specification could be chosen more freely than for other fuels (e.g. methanol).

Methanol and water are two of the impurities in “raw” DME. As DME has a very high cetane number (>60), small quantities of methanol and water reduce the cetane number considerably. The significantly lower noise of DME compared to diesel fuel can be attributed to the high cetane number. Likewise, the advantage of a high tolerance to exhaust gas recirculation (EGR), which is often cited, can enable the achievement of lower NO\textsubscript{X} emissions than with diesel fuel. The high EGR tolerance is partly due to the high cetane number. Soot free combustion, a feature that can be derived from the chemical properties of the fuel, is the other cause of the high EGR tolerance. In view of the high cetane number for pure DME, some deterioration in this respect might be tolerated if the production cost of the fuel could be significantly reduced. However, this is on the condition that no other drawbacks than those linked to a reduction of the cetane number will emerge.

In the presence of water, separation (two-phase liquid) occurs at slightly above 5% water content [3]. Increasing content of methanol decreases the risk of separation. With 5% methanol, about 10% water can be tolerated. The ignition property is negatively affected by both methanol and water content. Tests have shown that the combustion characteristics are affected by dilution. At a dilution rate of 20% (10% methanol and 10% water), cylinder pressure data shows a considerably delayed combustion (implying higher noise), indicating that a lower dilution than the mentioned level would be preferable. On the other hand, this rate of dilution has to be considered relatively high. Emission tests show decreasing NO\textsubscript{X} emissions (probably due to the cooling effect of the diluents) and increasing CO and HC emissions with increasing dilution [1]. At 10% dilution (equal parts of water and methanol), CO and HC emissions increase by almost 50%. Although these emission components are not very critical for diesel engines, an increase of these emissions is a clear

12 The knocking resistance (octane number) of DME is far too low for this fuel to be practical in otto engines. High cetane number indicates that the fuel will be ideal for compression ignition, i.e. suitable for a diesel engine. Cetane and octane numbers are generally in state of opposition, e.g. if the cetane number is high, the octane number will be low.
indication of combustion deterioration. At a dilution rate of 5%, the increase is some 10 to 20%, which is of no concern. It is possible that higher dilution than 5% could be tolerated but this level is proposed as a starting point for discussions. It remains to be seen whether a lower production price could motivate a higher dilution level. As dilution also affects power, it could be of interest to note that a power variation by a few per cent could be tolerated for heavy-duty vehicles. Therefore, the situation of having two fuel specifications, i.e. 5% dilution vs. pure DME should not pose any particular problems in this respect.

The type of DME produced today is of chemical grade. Within the framework of the IEA Advanced Motor Fuels, Annex XIV, a proposal for an automotive fuel specification for DME has been prepared [67]. The proposed specification is shown in Table 6.5 below.

**Table 6.5.** Automotive fuel specification for DME.

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Recommended value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>&lt;0.01 [% w/w]</td>
</tr>
<tr>
<td>Methanol</td>
<td>&lt;0.05 [% w/w]</td>
</tr>
<tr>
<td>Methyl Ethyl Ether</td>
<td>&lt;0.20 [% w/w]</td>
</tr>
<tr>
<td>Higher Alcohols</td>
<td>&lt;0.05 [% w/w]</td>
</tr>
<tr>
<td>Higher Ethers</td>
<td>&lt;0.05 [% w/w]</td>
</tr>
<tr>
<td>Ketones</td>
<td>&lt;0.05 [% w/w]</td>
</tr>
<tr>
<td>Odorant (e.g. ethylmercaptane)</td>
<td>20 [ppm]</td>
</tr>
<tr>
<td>Lubricant (e.g. Lubrizol or Hitech)</td>
<td>500–2000 [ppm]</td>
</tr>
</tbody>
</table>

As can be seen in Table 6.5, very low levels of impurities is tolerated in the motor fuel grade of DME. This is in contrast to the engineering considerations discussed above, which indicated that a dilution of up to 5% could be tolerated. Haldor Topsøe has calculated that the incremental cost increase of the specification cited above, in comparison to 98% pure DME, would be about 0.75% in fuel price [67]. Therefore, there is little scope for cost reduction by using lower quality DME.

Note that additives, such as odorants and lubricants, are proposed in the specification above. The addition of odorants might be necessary due to safety concern. Lubricants might also be necessary, as the viscosity and lubricity of DME are very low in comparison to diesel fuel. Although the latter issue might be alleviated by using novel types of injection systems, it would still be an advantage if injection system components (through addition of a lubricant) that are common with systems for diesel fuel could be utilised. An issue that will be of interest to investigate further is whether these additives are compatible with the use of DME in fuel cells. It is known that reformers are very sensitive in this respect and it is likely that the (potential) use in direct DME fuel cells would imply similar constraints on the fuel specification. However, first it should be made clear that DME will be one of the prime fuel candidates for fuel cells. If not, the DME fuel specification could be targeted solely for use in diesel engines.

The (possible) influence of DME dilution on corrosion and lubrication properties has not been considered here. Other impurities than water and methanol might also have to be taken care of but no information on this matter is known to the author. Anyway, it seems
that using the specification shown above would be sufficient for the engineering work to be performed within the framework of this project. As an option, a higher content of methanol and water (up to 5%) could be investigated.

Co-production of methanol and DME is possible and could be a viable solution for a pilot plant. This route of production might also have an influence on the purity of the two fuels.

6.3.2 Environment and health aspects of methanol distribution

Since methanol is toxic, the issues concerning handling and distribution require a specific analysis. Although both petrol and diesel fuel are toxic when ingested, as well, there is a long experience from handling and use of these fuels. Consequently, the number of fatalities is low regarding such effects. There might also be other safety issues, e.g. fire and explosion that have to be taken into account when a new fuel is introduced on the market.

DME is not toxic, as methanol, petrol and diesel fuel but, since this fuel is gaseous under normal pressure and temperature, safety issues concerning fire and explosion have to be addressed.

Health aspects

The knowledge about health effects from methanol are reasonably well understood but the knowledge among laymen is relatively limited, since methanol is not a widespread fuel in any of the EU member countries. Therefore, it is necessary to include a short summary of these effects. In general, the public is only confronted with the problem of the toxicity of methanol when fatal ingestion of methanol has been the case. Usually, people that have been subjected to methanol have thought that they have been drinking ethanol.

Since methanol is a commodity chemical and it is traded worldwide in large quantities, the regulations for this type of handling are well developed. Therefore, it has not been considered necessary to summarise the regulations that govern this handling. Instead, the issues that might arise when methanol is distributed to the public are of main interest in this study. A similar approach has been used for methanol production. As always with technical processes, there might be issues concerning the working environment, but these issues are relatively limited and they are well taken care of today anyway.

Methanol is readily distributed more or less uniformly in the body regardless of the type of exposure. Since methanol is fully soluble in water, the distribution in the organs is directly proportional to their water content. Methanol is also formed in the body by natural metabolic processes and it is present in low concentration in the diet, as well. Consequently, there is a natural “background” level of methanol in the human body. An exposure to methanol – or other substances that can be metabolised to methanol – will increase the methanol content in the body. After exposure and distribution of methanol in the body, methanol is metabolised in the liver and thus eliminated from the body. Methanol is metabolised according to the following metabolic chain: methanol; formaldehyde; formic acid; formate; and finally to CO$_2$. The toxicity of methanol is due to formate. Since the metabolism of formate to CO$_2$ is the limiting process, the accumulation of formate will be the case when exposure levels are high. This will lead to metabolic acidosis, a process that lowers the pH of the blood. Formate can lead to ocular toxicity and metabolic acidosis might be lethal if left untreated. It should be noted that there are several possible treatments available but these methods are not referred to here. In general, it can be concluded that the
mechanisms of the toxicity of methanol and its metabolism are well understood. Methanol is neither mutagenic, nor carcinogenic.

Some typical levels of methanol in the body (calculated for a 70-kg person) due to various routes of exposure is shown in Table 6.6. As can be seen in Table 6.6, minor exposures of methanol seldom lead to any significant increase of methanol concentration in the body. As a comparison, it can be concluded that ingestion of diet that contains the aspartame sweetener also increases the methanol content in the body. A lethal dose of methanol is some 500 times higher than the other exposures shown in the table (50 000 mg compared to 100 mg).

Table 6.6. Exposure of methanol for a 70-kg person (source: Statoil, Methanex).

<table>
<thead>
<tr>
<th>Exposure/dose</th>
<th>Added body burden of methanol (mg)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background level in a 70 kg body</td>
<td>35\textsuperscript{a}</td>
<td>Kavet &amp; Nauss, 1990</td>
</tr>
<tr>
<td>Hand in liquid methanol, 2 min</td>
<td>170</td>
<td>IPCS, 1994</td>
</tr>
<tr>
<td>Inhalation, 40 ppm methanol for 8 hours</td>
<td>170</td>
<td>IPCS, 1994</td>
</tr>
<tr>
<td>Inhalation, 150 ppm for 15 min</td>
<td>42\textsuperscript{b}</td>
<td>Kavet &amp; Nauss, 1990</td>
</tr>
<tr>
<td>Aspartame sweetened products 0.8 litre diet beverage</td>
<td>2 – 77</td>
<td>Stegnik et al., 1984</td>
</tr>
<tr>
<td></td>
<td>42</td>
<td>Kavet &amp; Nauss, 1990</td>
</tr>
<tr>
<td>Ingestion of 0.2 ml of methanol</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Ingestion, 25–90 ml of methanol</td>
<td>~21 000–71 000 (lethal)</td>
<td>IPCS, 1997</td>
</tr>
</tbody>
</table>

Notes:
\textsuperscript{a} Estimated from 0.73 ml/litre in blood
\textsuperscript{b} Assuming 100% absorption in lung (60–85% more likely)

A concluding remark about the levels of exposure is that “normal” exposures hardly could cause a lethal dose of methanol. Some unintended and intended exposure (i.e. ingestion) could result in lethal doses. Statistic information from the USA shows that of the approximately 10 cases of lethal exposure that are registered every year, about 50% are related to suicide [68]. However, in many of the other cases, the reason is unknown, which could render an even higher percentage of suicide. Whether these fatal cases could be influenced (increased or decreased) by an increased use of methanol (i.e. widespread use) is pure speculation.

**Exposure**

Longer exposure to methanol through inhalation and skin penetration will give similar toxic reactions as ingestion, since methanol is readily distributed in the body regardless of type of exposure. The risk of high exposure due to inhalation seems to be limited due to the low concentrations of methanol vapour in the air during normal handling of methanol. This is also a general feature for skin penetration, as only extreme carelessness would lead to high exposure.

Both petrol and methanol penetrate through the skin but the absorption is faster in the methanol case since the methanol molecule is smaller than the (average) petrol molecule.
On the other hand, methanol evaporates faster from the skin, which reduces the total exposure, since the contribution from inhalation will be far less than from skin penetration. Methanol is not considered carcinogenic or mutagenic in skin exposure (or in other types of exposures). On the contrary, petrol is considered as carcinogenic, primarily due to its content of benzene\textsuperscript{13}, a known carcinogen. It should be pointed out that high exposure to petrol poses a risk of almost similar magnitude but in this case, common practice is well developed. Although the risk of “normal” exposure due to skin penetration is small, exposure for liquid methanol for a long period of time, e.g. through the use of gloves or boots soaked with methanol, might lead to high concentrations. It is not likely that the exposed people (e.g. mechanics and technicians) would tolerate such exposure to petrol without taking countermeasures, but in the methanol case, proper information might be necessary to avoid such fates.

Inhalation of methanol is the most common exposure. Exhaust emissions from vehicles, evaporation from the tank and from spill and open containers are examples of exposures due to inhalation. A worst-case calculated exposure of 150 ppm methanol during 15 minutes, as shown in Table 6.6 above, would only slightly increase the dose by 0.6 mg per kg of body weight (42 mg for a 70-kg person). This dose is on a similar level as normal ingestion of fruit, vegetables and alcoholic beverages (0.3–1.1 mg/kg). Most exposures to methanol vapour in the air would result in far lower doses than in the mentioned case.

\textit{Use of methanol in windshield washer fluid}

Canadian report on the use of methanol in windshield washer fluid might be of interest to comment on \cite{69}. Methanol is used in this application in North America, whereas isopropanol, and in some cases ethanol, is used in Sweden and Europe. The use of alcohols in windshield washer fluid is to avoid freezing. There are few alternatives to alcohols if the requirements of primary importance in this application have to be fulfilled.

The use of methanol in windshield washer fluid is an example of widespread use of methanol by the public, although the concentration usually is less than 50\%. This fluid is handled in a similar way as windshield washer fluid in Europe. It may appear obvious that windshield washer fluid should not be ingested, regardless of which alcohol is used as freeze protection, as the fluid contain other substances than methanol and water. It is evident that methanol used in this application can be handled without significant fatalities in Northern America. In addition, it seems as the handling, storage, etc. of this fluid does not pose particular problems regarding the risk of fire or explosion. Health effects of methanol from windshield washer fluid could be expected due to evaporation and inhalation. However, it appears as the concentration of methanol in urban air is very low and therefore, the exposure to methanol from this use seems to be well below a safe level.

In the previously mentioned Canadian report \cite{69}, the possible contribution from methanol from windshield washer fluid to ozone formation was investigated. Ozone is formed by the reaction of volatile organic compounds (VOC) and oxides of nitrogen (NO\textsubscript{X}). Sunlight aids these photochemical reactions, thereby increasing the ozone levels during summertime. Although alcohols are not very reactive compared to hydrocarbons in vehicle exhaust, high concentrations \textit{might} give a contribution to the ozone formation under certain circumstances. According to the mentioned report, windshield washer fluid might

\textsuperscript{13} It should be noted that the benzene content of petrol has been continuously decreased during the past years. However, petrol corresponding to the EU regulation for 2005 still contains benzene.
contribute to the ozone formation. However, the estimations are based on an analytical methodology only, as no direct measurements were available. It is interesting to note that ethanol and isopropanol have higher specific reactivity than methanol. Consequently, the use of methanol instead of these fluids would actually be beneficial regarding ozone formation.

*Methanol spill*

The distribution of methanol in general could include various different transportation modes. In general, methanol of fossil origin is produced at remote sites. Thus, the distribution could include sea, rail and truck transport. Pipeline distribution is not likely other than in rare occasions. During distribution methanol could be spilled to surface water, ground water, soil and evaporate into the atmosphere.

Spill of methanol to land, water and the air evidently occur, since methanol is one of the mostly traded chemicals in the world (No. 3). Calculations have been carried out in the USA to estimate the total release of methanol. Some results for USA have been compiled by AMI (American Methanol Institute) [70] and these results are shown in Table 6.7.

![Table 6.7. Estimated release of methanol in the USA (recalculated in SI units).](image)

<table>
<thead>
<tr>
<th>Release to:</th>
<th>1992a (tonnes/yr)</th>
<th>1993b (tonnes/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere</td>
<td>88 500</td>
<td>77 900</td>
</tr>
<tr>
<td>Underground injection</td>
<td>12 200</td>
<td>12 700</td>
</tr>
<tr>
<td>Land</td>
<td>1 500</td>
<td>800</td>
</tr>
<tr>
<td>Water</td>
<td>7 400</td>
<td>4 500</td>
</tr>
<tr>
<td>Total releases</td>
<td>109 600</td>
<td>95 900</td>
</tr>
</tbody>
</table>

Notes:

a Source: US EPA, 1994


The results in Table 6.7 show that the release to the atmosphere dominates over the other releases. In a spill to land and water, the evaporation will be less and in this case, the distribution of the release is shifted. An increased use of methanol would of course increase the releases of methanol. On the other hand, the release of conventional fuels of fossil origin would decrease if these products were substituted by methanol. As will be shown below, the health- and environmental impact would presumably decrease is this substitution was carried through. The emissions from vehicles are not discussed in this section.
Methanol molecules are ubiquitous (naturally present) in the environment as a result of various biological processes in plants, micro-organisms and animals. Consequently, the biodegradation of methanol is generally faster than for fuels of crude oil origin, as these substances are not naturally present in the nature. In Table 6.8, a comparison between the half-lives for methanol and benzene, a common element in petrol [70]. Since petrol and diesel fuel are mixtures of various hydrocarbons, data on the (average) half-life on these fuels are scarce, so data for benzene are generally used instead. The results in Table 6.8 show that the half-lives in general are significantly shorter for methanol than for benzene in most cases, except for release to air. It should be noted that benzene is a rather reactive chemical compound in the air (i.e. contribution to ozone formation).

Table 6.8. Estimated half-lives for methanol and benzene [70].

<table>
<thead>
<tr>
<th>Medium</th>
<th>Methanol (days)</th>
<th>Benzene (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>3–30</td>
<td>2–20</td>
</tr>
<tr>
<td>Soil</td>
<td>1–7</td>
<td>5–16</td>
</tr>
<tr>
<td>Surface water</td>
<td>1–7</td>
<td>5–16</td>
</tr>
<tr>
<td>Ground water</td>
<td>1–7</td>
<td>10–730</td>
</tr>
</tbody>
</table>

Note:
a. Original source: Howard et al., 1991

The release of crude oil or oil products (such as petrol and diesel fuel) to water and soil generally cause great impact on the environment (at least on a local scale). Catastrophic oil spills are regularly occurring on a smaller or greater scale and the environmental impact is sometimes great, as for a spill in a sensitive area (e.g. Exxon Valdez in Alaska). Accidents with tank trucks and rail cars can happen and in such cases, spill to soil and water is often the case. The question is what the consequences of a methanol spill would be in similar cases, as described previously.

Methanol is readily soluble in water in contrast to oil products that have a very limited solubility in water. Therefore, the acute toxicity will be noted in direct association to the spill area only, but below a certain concentration methanol is not toxic. Instead, some life forms will metabolise methanol, i.e. use the methanol as nutrition. Such an example is that methanol is used today for this particular purpose, i.e. as nutrition for the microorganisms used in wastewater treatment (denitrification, i.e. removal of nitrates).

Spill of methanol to surface water will result in a fast dispersion due to the infinite solubility in water. At a concentration level of less than 1%, it is no longer toxic and therefore, the acute effect is only local. Estimations of a spill of 10 000 tonnes of methanol in the sea show that a concentration would be less than 0.36% within less than one hour [70]. A similar release from a coastal pier would result in a concentration less than 1% after 2 hours and 0.13% after 3 hours. The impact is relatively small and local in both cases. One can easily envision the ecological consequences if similar spills of oil products would occur.

Methanol dissolves very fast in the ground water after a spill on land, and this might be a drawback in comparison to petrol and diesel fuel, where the diffusion is not as fast. In a worst-case situation, this could lead to a faster contamination of water supplies. However, it is not likely that the diffusion would be so fast that precautionary measures could not be taken to avoid the distribution of contaminated drinking water. Again, the advantage of faster biodegradation limits the damage to a local scale. Similar situation might occur for spill in surface water but in this case methanol is dissolved and diluted even faster.
There is always some release (evaporation) of methanol to the air from spill to water and soil. The question is whether this could pose any risk for health and environment. Since the equilibrium between air and water is shifted towards the water, vaporisation is minimal in this case. The vaporisation from spill to (dry) soil tends to be significantly greater than from water and in this case, this is a faster release than for petrol. The vapour pressure is lower than for petrol and likewise, the vapour density is lower for methanol vapour than for petrol vapour. Consequently, methanol vapour is dispersed faster in the atmosphere than petrol vapour. Although methanol vapour most likely has a greater acute toxicity than petrol vapour at the same concentration, this is compensated by the faster diffusion.

In summary, methanol should have significant advantages compared to petrol regarding releases to soil, water and air (and compared to diesel fuel in the two first cases).

### 6.3.3 Environment and health aspects of the distribution of DME

First, it should be noted that (besides fire and explosion hazards) there are no apparent health risks linked to the distribution of DME as a motor fuel. DME is not toxic, nor carcinogenic or mutagenic. DME is commonly used today as an aerosol propellant. Due to this use, comprehensive investigations have been carried out about the potential health effects of DME. As the results from these investigations have been positive, the use of DME as an aerosol propellant has been permitted. In summary, DME has a competitive advantage over many other fuels (including methanol) regarding health effects from fuel distribution and handling.

### 6.3.4 Fire and explosion danger

**Methanol**

Methanol is classified according to a similar class as petrol, i.e. class 1, implying that the flash point is so low (<-21°C) that fire and explosion danger must be considered. Therefore, similar regulations are enforced as for petrol but with different marking [71]. Within the framework of the so-called PNGV programme (Partnership for a New Generation of Vehicles) in the USA, the issues of potential danger with alternative fuels has been studied. These are common issues when widespread introduction of a new fuel is being discussed. In a report by the federal laboratory ANL, the potential fate with various fuels has been investigated [72].

The lower vapour pressure of methanol in comparison to petrol implies that the possibility of reaching a flammable mixture in open areas is lower than for petrol. This advantage is further enhanced by a lower density for methanol vapour (1.1:1) than for petrol vapour (up to 4:1) in relation to air. Still there is a risk for ignition under these circumstances, for example in calm weather, which motivate the fire classification.

If methanol vapour is ignited, the heat release rate is significantly lower than for petrol. The lower heat of combustion and higher heat of evaporation leads to that methanol burns with a speed of only a fourth of the speed of petrol. Consequently, the energy release is only about one-fifth to one-eighth of the level for petrol.

Methanol is combusted with an almost invisible flame in sunlight, in contrast to petrol and diesel fuel that both have a yellow flame. A yellow flame indicates that soot is formed, which is not the case for methanol. The oxygen content an absence of carbon-to-carbon bonds in methanol is the reason for the “clean” burning compared to hydrocarbon fuels. A
lower heat radiation in a methanol fire is the result of the less visible flame. Lower heat radiation is an advantage, since the ignition of other flammable materials near the fire is less likely. Furthermore, fire fighters can approach the fire closer. However, this also poses a certain potential risk due to the almost invisible flame, as fire fighters might be attempted to get too close to the fire. Additives intended to increase the flame luminosity have been discussed, but it is uncertain if such additives are necessary for vehicle applications. In a vehicle fire, there are many other materials that burning simultaneously with methanol will create a visible flame.

Methanol is fully soluble in water and this is of an advantage from a fire fighting point of view. In contrast, petrol and diesel fuel will float on top of water, with the potential for steam explosions and further spread of the fire. Some previously used types of foams were not effective with alcohols. However, new types of multipurpose foams work both with alcohols and petroleum fuels.

The properties of methanol regarding fire hazard have been considered an important feature in motor sports, e.g. in the US CART series, where methanol is the prescribed fuel. The US EPA calculated in a report carried out in 1990 that the substitution of petrol by pure methanol (M100) could give a 95% reduction of the fire hazards [73]. The question remains whether this figure would still be valid for the vehicle fleets we have today.

Petrol storage (tanks, depots, etc.) generally gives such a high vapour pressure (except at very low ambient temperatures) that the mixture is richer than the rich flammable limit. For diesel fuel, the vapour pressure is lower than the lower flammable limit and consequently diesel fuel pose no risk of explosion under these conditions. In contrast to the two other fuels, methanol (as well as ethanol) has a vapour pressure that could cause an explosion in the fuel container at “normal” ambient temperatures. However, since alcohols are more polar fluids than petrol, the risk of ignition by static electricity is considered very small. An explosion initiated by an ignition source outside the tank is possible. Although such explosions have not been shown particularly dangerous in experiments, countermeasures should be taken to avoid such risks. Flame arresters in the pipes to and from tanks are necessary. This technology is well developed and thus, methanol storage can be considered safe regarding the risk of explosion. However, it is essential that countermeasures, as described, be used to avoid public perception of methanol as a dangerous fuel in this respect.

In the ethanol-fuelled city buses used in Sweden (e.g. Stockholm), fires in the engine compartment have been frequent. This is in contrast to the situation for passenger cars where the general opinion is that the risk of fire in a vehicle is less for methanol than for petrol. Without conducting a thorough analysis of the causes of fire in buses, two factors could be of importance to note. First, diesel fuel is the reference in the bus case is diesel fuel and this fuel is generally safer than petrol in such applications. Second, high-pressure fuel pipes for ethanol have been prone to leaks due to cavitation. The hazard for initiating a fire if a high-pressure fuel pipe is leaking is obvious. Consequently, buses are usually equipped with automatic fire extinguishers. However, there is no reason to believe that the experiences from buses are applicable to cars and consequently, the conclusions above that methanol used in passenger cars with otto engines would be safer than petrol are still valid.

It could be hypothesised that methanol-fuelled diesel engines would behave in a similar way as the city buses mentioned above regarding the fire hazard. However, one also has to note that modern high-pressure fuel injection systems have changed dramatically in
comparison to the pump-line-nozzle systems used on the ethanol buses. In the future, common rail injection and unit injectors will replace rotary pumps for diesel cars and in-line pumps for heavy-duty vehicles. These injection systems do not have the problems with cavitation mentioned above. Consequently, there is no reason to believe that methanol-fuelled diesel engines should pose any specific fire hazards in future heavy-duty vehicles.

**DME**

DME has not been investigated thoroughly in this study regarding its hazards for fire and explosion, since no experience is available from widespread public use of this fuel. However, some general comments are nevertheless included. DME has similar physical properties as LPG and consequently, some of the experiences from LPG can be applied to DME as well. DME burns with a visible flame and has less flame radiation than petrol. Containers (tanks) for DME are stronger than petrol tanks and therefore, the risk of leak in a collision and due to other damage is less. The dispersion of DME is faster than petrol due to the low vapour density (1.5:1), but on the other hand, the formation of vapour clouds is faster. Likewise, the persistence of clouds in still-air is more likely than for petrol. DME is likely to have a greater explosion hazard than petrol if it is spilled, due to the wide detonability limits. The flammability risk is higher than for petrol. In summary, it is somewhat difficult to assess whether DME would pose higher or lower risk for explosions and fire compared to petrol. However, *in line with the precautionary principle, it is likely that DME initially should be treated as a more dangerous fuel than petrol (and diesel fuel) in this respect.*

**6.3.5 Cost and handling issues of fuel distribution**

Issues regarding material compatibility and associated cost have been investigated in earlier studies by the author’s organisation. One example is a study by Ecotraffic for the Swedish Governmental Agency KFB (today part of the agency Vinnova) [71]. Another example is a study by the consultant company EA Engineering that was carried out for AMI [74].

The relatively new report by EA Engineering provides an overview of the distribution of methanol and identifies the necessary measures compared to the distribution of petrol [74]. The report concentrates on the cost for upgrading an existing distribution system. The authors concluded that a new refilling unit (replacement of a petrol tank of 10 000 gallon) could be installed for a cost of approximately $10 000. Upgrading of an existing unit could cost $19 000. In both cases, the authors concluded that the incremental cost was relatively low. In Sweden, several oil companies have rebuilt existing tanks to be compatible with motor alcohols. This is now a common procedure in rebuilding tanks (new tank linings, etc.) and when new refilling stations are built, they are made alcohol compatible. However, the policy between companies is slightly varying, since some distributors upgrade to tolerate both ethanol and methanol while others are satisfied with ethanol compatibility alone. The extra investment to be able to tolerate methanol as well is considered small.

A Swedish company of fuel dispensers, Identic, is currently developing a new dispensing system for methanol. In a press release from this company and from the partners in the MFCA, this work is briefly described [75]. In addition to the press release, a leaflet from Identic is available for downloading at the Internet home site of the American Methanol Institute [76]. Besides this information, not very much is known about this development. Within the framework of a contract between MFCA and Identic, the AT-1 dispensing
system currently used for diesel buses and other heavy-duty vehicles will be further developed for the use of methanol. A prototype system has been installed in the Necar 5 prototype fuel cell car by DaimlerChrysler. It is interesting to note that if a fleet test on methanol-fuelled vehicles is initiated in the near future, the proper tank and dispensing system necessary for operation will be available.

It could be of interest to show the potential incremental cost of distributing methanol in comparison to petrol distribution. Evidently, there is an additional cost related to methanol, as the discussion above has indicated. First, this is due to the use of more expensive materials in the methanol case. Second, an increase in the fuel volume has to be taken into account, as methanol has low energy density. In comparison to petrol, the volume increase would be some 40% for ethanol and 85% for methanol. Some of the associated cost is related to the volume increase but some cost in the distribution is independent of the volume and will not be affected by fuel switching. In a previous study by Ecotraffic, the incremental cost of distributing ethanol and methanol was estimated [71]. The cost of DME distribution was calculated in another report by Ecotraffic [77]. Since the first study was completed in 1996 and the second in 1997, the cost was representative for the situation in mid 1990’s. Presumably, the cost would be somewhat higher today, primarily due to inflation. It should also be noted that the cost was estimated for a fully developed system. For rebuilds of old petrol stations and during an initial phase, the cost will most likely be higher but on the other hand, such cost is not relevant on a long-term horizon.

The results from the mentioned study are shown in Table 6.9 but in EUR (€) compared to Swedish crowns (SEK) in the original calculation. The conversion factor from SEK to EUR has been set to 10, i.e. somewhat higher than the exchange rate, to take some inflation into consideration.

As can be noted in Table 6.9, the distribution cost for substituting one litre of petrol is €11.3¢ for methanol and €10.3¢ for ethanol, i.e. an advantage of €1¢ for ethanol. As reference, the cost of distributing petrol was estimated to €8.5¢ per litre. Consequently, the incremental cost of distributing methanol is €2.8¢ per litre petrol substituted. If the fact that the engine efficiency can be increased by using methanol in comparison to petrol would be taken into account, the incremental cost could decrease marginally. A methanol engine would have to utilise direct injection, or else be converted to diesel cycle, to achieve an increase in efficiency. In both cases, it is obvious that a gain in (relative) efficiency in the order of 5–20% cannot fully offset the increase in distribution cost.

The incremental cost of substituting petrol (or diesel fuel) with DME is significantly higher than for methanol simply because DME has to be handled under pressure. Since DME

<table>
<thead>
<tr>
<th>Distribution stage</th>
<th>Petrol</th>
<th>Methanol</th>
<th>Ethanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea transport</td>
<td>0.6</td>
<td>1.1</td>
<td>0.85</td>
<td>1.64</td>
</tr>
<tr>
<td>Depot</td>
<td>0.7</td>
<td>1.7</td>
<td>1.6</td>
<td>1.46</td>
</tr>
<tr>
<td>Land transport</td>
<td>0.7</td>
<td>1.3</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Refuelling station</td>
<td>2.0</td>
<td>2.7</td>
<td>2.35</td>
<td>5.0</td>
</tr>
<tr>
<td>Charge, distributor</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Charge, station</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Total distr. cost</strong></td>
<td><strong>8.5</strong></td>
<td><strong>11.3</strong></td>
<td><strong>10.3</strong></td>
<td><strong>14.6</strong></td>
</tr>
</tbody>
</table>
Black Liquor Gasification with Motor Fuels production - BLGMF

primary is a fuel for diesel engines, the comparison was initially made with diesel fuel. However, as the previous figures for motor alcohols were compared with petrol, the results in the mentioned report have been recalculated for a substitution of petrol (using the conversion factor of 10 between EUR and SEK). The recalculation gives a cost of €14.6¢ per litre of substituted petrol, i.e. a difference of €6.1¢. This is more than €3¢ higher than for methanol and more than twice the difference between methanol and petrol. As diesel engines are more efficient than otto engines, the comparison with petrol would be more favourable if this was taken into account. The comparison with methanol depends on whether the methanol engine is of the otto type or diesel type. As discussed above, diesel engines can also be adapted to methanol.

If the comparison between DME is made with diesel fuel, the difference (€6.5¢) is somewhat higher than in the comparison with petrol. The greater difference in this case is due to the higher energy content of diesel fuel in comparison to petrol. This gives a lower distribution cost per energy unit for diesel fuel compared to petrol and therefore, the comparison between DME is less favourable for DME than the previous comparison with petrol.

6.3.6 Strategy for fuel distribution

Low-level blending in petrol

Current EU fuel specification for petrol allows for blending with alcohols, e.g. 3% of methanol and 5% of ethanol. When methanol is used, a stabilising agent (higher alcohols) must also be added. Ethanol is one of the options for stabilising agents. In total, oxygenates could be added corresponding to an oxygen content of 2.7%. Low-blending of all petrol with 3% methanol could be one option to quickly introduce methanol on the market. During 2001, ethanol was introduced on the Swedish market on a larger scale by low-blending. In the Stockholm area and eastern part of Sweden 5% ethanol is blended in all petrol. Evidently, the same strategy could be used with methanol. One potential problem with this strategy is that low-level blending is one measure to fulfil the EU biofuels directive [78]. According to this directive, which does not set mandatory targets but instead sets “reference” levels, a substitution (on energy basis) by 2% is the reference value for 2005 and similarly 5.75% is set for 2010. It is yet too early to assess the various strategies that the member countries will apply to fulfil the intentions of the directive. However, for example, in Sweden, low-level blending of ethanol in petrol seems to be the preferred solution. In addition, RME will also be used. Since the maximum oxygen content is limited to 2.7%m/m in the contemporary petrol specification, there is little room for additional volumes of methanol if 5%v/v ethanol (corresponding to about 1.8%m/m O) would be used in all distributed petrol. With a small margin to the limit for oxygen content at 2.7%m/m, about 1.5% methanol could be added (corresponding to about 2.6%m/m O) if the petrol already contain 5%v/v ethanol. However, the practical limit may have to be set as low as 1% methanol.

The fuel distribution system for petrol and diesel fuel could be adapted for the distribution of motor alcohols. First, it is possible to upgrade the existing distribution network. Second, when new fuel infrastructure is built, it could be adapted to handle alcohols. In fact, this is already accomplished by several Swedish fuel distributors (e.g. Statoil and OKQ8). In the latter case, the additional cost is marginal. Consequently, it would be possible to switch
from petrol to alcohols in the future without significant additional cost. However, the situation for fuel distribution is not the same in all EU countries.

As an alternative to low-blending, a higher blending rate has been discussed in Sweden. A potential range might be 10–20% methanol\textsuperscript{14}. If this option would prove successful, significantly larger quantities of methanol could be distributed on the market than with low-blending. It would be a logical second step in an introduction strategy. In the USA, “gasohol”, a petrol blend that contains 10% ethanol is marketed in several states. This fuel has a higher oxygen content than normally permitted for US petrol. A potential problem is that the leaning effect of increasing the oxygen content might increase the NO\textsubscript{X} emissions. However, it is likely that new cars with adaptive engine control do not have this problem.

Within a couple of years, a high percentage of the car fleet could probably fulfill this criterion. Eventually, there are other potential problems. First, some cars might be prone to corrosion of metallic components in the fuel system. Methanol might also attack elastomers and polymers in the fuel system. Very little is known about the potential compatibility issues with in-use vehicles, as most of this knowledge is proprietary information of car manufacturers and their suppliers. Second, the fuel flow capacity of the injection system might be a limiting factor on some car models. If the capacity is not sufficient, the mixture will become too lean at rated power.

Although the exhaust temperature will decrease somewhat by adding methanol, it cannot compensate for a flow reduction. Consequently, some engine components and/or some components of the aftertreatment system might overheat. Furthermore, the leaning might increase the NO\textsubscript{X} emissions at full load if the air/fuel ration is leaner than stoichiometric. If a higher blending rate than the currently permitted 3% limit is to be introduced on the market the EU petrol specifications must be amended. Without doubt, such a process would take a long time to carry through. It would also be somewhat counterproductive if a new fuel specification would have to be introduced on the market. It is always desirable to keep the number of different fuel specifications to an absolute limit. Summarising the discussion about higher blending rates it can be concluded that there are several barriers that must be overcome if a higher percentage of methanol that the current EU limit is to be used.

**Fuel flexible vehicles**

Fuel flexible vehicles running on M85 could be the next logical step to introduce methanol on the market. This has already been demonstrated as a feasible technology in the USA. In Sweden some 4 000 ethanol-fuelled E85 cars are now entering. Eventually, the future availability of fuel flexible vehicles could make the interim step of higher blending unnecessary. As several potential problems with a higher blending rate could be expected for contemporary vehicles, fuel flexible vehicles is the preferred solution. As described previously, further development of the fuel flexible vehicles would be to adopt otto engines to direct injection and the ability to run on M100. However, one should note that the interest from the vehicle manufacturers for M85 compatible fuel flexible vehicles is very low at the moment. This lack of interest could be a limiting factor for the possibility to introduce methanol on a larger scale.

\textsuperscript{14} Note that 15% of methanol (M15) was tested fleet tests in Sweden and other European countries (e.g. Germany) during the 1980’s.
For diesel engines in heavy-duty vehicles, methanol could be introduced as a niche fuel using ignition improvers as a fuel additive. As this fuel would have to be “tailored” for a specific engine and the problem that this fuel cannot be used in any other types of engines, it is not likely that this option could create a market. However, M100 could also be used in dedicated diesel engines. As this strategy could enable a common fuel specification for several applications (otto, diesel and FC), this option is much more appalling. The use of emulsified fuel containing methanol and diesel fuel is yet another option. However, no available additive today would enable this fuel to meet long-term stability requirements. Therefore, this is only an option niche applications and is not considered further here.

Distribution of methanol for fuel cells would be significantly simplified if a common fuel specification, i.e. similar fuel for fuel cells and internal combustion engines, could be used. If not (due to the additive issues), a common distribution would still be a simplification. In the distribution chain, some precaution must be taken to avoid contamination. For the use of methanol in internal combustion engines, contamination with low levels (on the ppm level) of petrol and diesel fuel, or other contaminants, is not of too much concern. For fuel cell vehicles, this issue might be crucial. However, it would still be beneficial if a single specification fuel could be distributed, or else if as many steps in the distribution chain as possible could be common for all three energy converters.

The creation of the necessary fuel infrastructure for DME is more costly than for liquid fuels. Partly that cost might be recovered for the customer if the cost of emission control could be reduced in comparison to other fuels for diesel engines. Much knowledge about fuel infrastructure could be derived from solutions used for LPG but improvement of seals and materials is essential, as DME attack most elastomers. This is most likely possible to accomplish but this development will take some time and effort. DME cannot be used in fuel flexible and bi-fuel applications, which makes construction of the fuel infrastructure much more difficult. The overall conclusion is that initially, DME should be used in dedicated fleets with their own fuel infrastructure.

6.4  Handling, distribution and safety of DME

6.4.1  Handling

The physical and chemical similarities between DME and LPG also make the general handling of DME similar. Boiling point, density and vapour pressure are in practice the same for DME and LPG. Accordingly, all transport means available for LPG could be used for DME. Regarding storage, the same equipment and materials could be used as for LPG. Storage tanks approved for propane 95, should according to the Swedish explosives and safety authority “Sprängämnesinspektionen” (now part of Räddningsverket), also be viable for DME. Other material choices should follow the temperature and pressure guidelines available for propane 95. That is, piping and other process parts should be approved for -40 – +40 °C as well as a gauge pressure of 16 bar at 20 °C.

When handling DME, the following differences compared to LPG should be considered: DME could be hazardous when inhaled and weakly toxic, in contrast to LPG. This fact should also be considered when designing equipment for DME handling.

15 For example, a particulate filter might not be needed with DME to meet future particulate limits.
**Naval transport**

Prior to any domestic production of DME, it has to be imported to the country. Currently, the production of DME is located close to natural gas fields, and proposed sources are at the producers in the North Atlantic. Depending on the freight load, two ship types are viable. Smaller loads could be handled with small coastal freighters equipped with pressure tanks. They in general carry between 400 and 5000 tonnes of liquid product. The smaller ships are limited in that they cannot be loaded from all available terminals. There is, however, a good supply of small coastal freighters of this size, although they have to be pre-booked 2–3 months in advance. The cost for transport at sea using small cargo ships has risen the last couple of years with approximately 5% per year, because of the growing demand on this kind of loads.

For larger freights, ships with cooled tanks have to be used. The availability of ships between 10 and 50 000 tonnes is high in the north-west parts of Europe. Analogous to the smaller freighters, these ships are also becoming more expensive to use because of the growing demands. These ships have the advantage that they may be loaded from any terminal. The total number of ships, worldwide, suitable for transporting DME amount to 130. The following price indications may be used as guidelines for further studies:

- Trondheim – Swedish west-coast
  - 5000 tonnage appr. USD 30 per tonne
  - 20 000 tonnage appr. USD 15 per tonne

- Trondheim – Swedish east-coast
  - 5000 tonnage appr. USD 38 per tonne
  - 20 000 tonnage appr. USD 18 per tonne.

Freight rates are approximately the same regardless the specific area in the north Atlantic. A long-term contract may lower the freight rates with 15–20%.

**Harbour terminals and storage**

Storage of DME at harbour terminals may be performed in caverns underground or in spherical tanks. Cylindrical storage tanks may be used as well. Concerning the large amounts of DME considered it is doubtful whether storage above surface would be economically feasible or even approved by local authorities.

To import and store amounts exceeding 100 000 tonnes on an annual basis, a rock cavern corresponding to 50 000 m$^3$ would be required. This size is necessary for freights of 20 000 tonnes. The Swedish competence concerning rock caverns is high. Currently, we have the largest storage capacity for LPG in the world, approximately 1.1 million m$^3$.

The investment cost for a 50 000 m$^3$ rock cavern could be calculated to 76 million SEK. An increase in storage volume would only marginally affect this investment cost, since the largest cost is associated with the entrance tunnel. An increase in storage capacity to 100 000 m$^3$ would only increase the investment with 32 million SEK.

Operating costs for the harbour terminal include personnel and smaller parts from e.g. electricity. The staff requirement should be 3–4 people, whereof one is responsible for the storage in terms of the regulatory acts on explosive and flammable products.
Requirements on potential underground storage areas are a solid rock, i.e. non-porous, a functional harbour, railroad and roads for land transports. This would make it possible to reach practically every large city. Storage should be located as close as possible to the local production site.

6.4.2 Distribution

Distribution from harbour storage is expected to take place by railroad transport to an interim storage, prior to road transport by lorry to the actual filling stations. Interim storages are made up of a number of cylindrical tanks. The volume is determined by the expected consumption in the nearby filling stations, although a minimum storage volume should be 200 m$^3$ to allow for the volume of a railroad car as well as a small reserve for distribution. The interim storage must be located in proximity to both railroad and roads, not further away than 1 km. Physical space required for an interim storage is about 50 x 100 m.

Transport by railroad

Railroad transport is primarily used for transport from harbour terminals to interim storages, alternatively to large single filling stations with sufficient storage capacities. Since the filling stations are located in towns, any large storage tanks must be placed underground for safety reasons.

There is a practically unlimited supply of railroad cars for DME transports available. They are either owned by the railroad administration or rented from French or German counterparts. The normal capacity of a railroad car is 110 m$^3$ corresponding to around 50 tonnes of DME. The rental price for a 110 m$^3$ car is SEK 7020 per month.

Transportation of hazardous cargo is limited to certain areas; for instance, transport of hazardous goods in central Stockholm would be out of the question. The cost for railroad transports are normally negotiable, i.e. fixed determined prices are seldom reported. The cost is also strongly dependent on the volume and distance considered. Increasing competition from road transports has however lowered the cost for railroad transports as well.

Transport by lorry

The transport from interim storage to the filling stations is carried out by lorry. Competition with the railroad has brought about lower costs for transports by lorry as well as the opposite is true. Most of the transport enterprises with suitable tank lorries for DME have some kind of connection to the oil companies. Statoil and Terminalgas use their own lorries. The largest Swedish companies having suitable lorries are POL-Transport and ODAB. Most lorry tankers have loading capacities of approximately 20 tonnes DME.

The price for transportation could be calculated according to:

- Receiving fee, appr SEK 132 per tonne
- Transportation cost, appr. SEK 111 per tonne
- Loading fee, appr. SEK 216 per tonne
To exemplify, the total cost for a lorry transporting 20 tonnes of DME over 150 km, is SEK 4520 or SEK 226 per tonne. As a comparison, the corresponding cost for traditional diesel fuel is SEK 103 per tonne.

The economically feasible transportation distance for road transports is 250 km; a distance exceeding that is more economical and suitable for railroad transportation.

**Filling stations**

There are four different principles for storage and distribution of DME at filling stations.

1) **Filling station with a free laying tank.** The unit consists of a tank within a fenced area. Within the fence, there is also all other auxiliary equipment necessary as well as the pump and safety systems. Regarding this kind of installation, authorities put high demands on safety precautions and the distances to nearby buildings. The installation is, however, the cheapest possible assuming there is physical land area available. The total cost for this installation is SEK 270 000–325 000.

2) **Filling station with concrete building surrounding the tank.** To decrease the necessary safety distance, the tank could be built with this kind of fire technological measures. That is, the tank and the auxiliary equipment must withstand open fire for at least one hour. The total cost for this installation is SEK 380 000–430 000.

3) **Filling station with underground tank.** This installation decreases the land area required for the equipment and it also a safer choice concerning the nearby buildings and the environment. High requirements are, however, put on piping and auxiliary equipment as well as corrosion inhibition. The cost for this installation depends on land conditions and the distance to the filling station, but could be estimated as SEK 540 000.

4) **Filling station with cryogenic tank.** Technically, this is the most advanced type of installation. Since the tank is isolated against fire the installation may be placed in narrow spaces. The unit is pre-fabricated and the setup is performed quickly. The cost for this installation is appr. SEK 1 080 000.

### 6.4.3 Safety

To erect and operate installations using hazardous and flammable goods, the current legislation must be paid attention. The directives regulate the conditions, under which the goods may be shipped and handled. They also regulate the building permits for such activities.

**Risk analysis**

According to the current legislation, industries handling flammable or explosive goods have to make sure a risk analysis, i.e. “What if? analyses”, HAZOP or similar, is performed for their activities. Simply expressed, risk is a function of the consequence for a certain accident and the probability that it will occur.

Fundamental for risk analyses are theoretical methods for indicating the consequences resulting from an accident. The identification of various scenarios put requirements on the cooperating persons, who should have long time experiences from the activity, in question as well as familiarity with risk analyses itself. In general, risk analysis is about making as correct assumptions as possible without having confirmed theories or valid data for the complete process. A risk analysis has to be performed for every harbour terminal, interim
storage and filling station. It should result in identifying the dimensioning scenario and the likely consequences for the dimensioning accident.

**Risks at the harbour terminal**

At harbour terminals, there are two dimensioning handling events: unloading of the cargo ship and the loading of lorry/railroad car.

In case of a rupture on the tubing or a crane failure, relatively large amounts of DME will leak into the harbour basin. Since the harbour area is designed for handling hazardous and flammable goods, no ignition sources should exist and no ignition of the gas will occur. The release should result in a rather lean gas mixture under the lower explosion limit (LEL) within 30 seconds of the release. In this time, the gas may be spread 50–150 m from the release area. The possible ignition of the gas cloud may result in consequences for the surroundings within 100–200 m of the ignition source. These distances are fair approximations and of course have several parameters, which they depend upon.

Analogous to the previous example, the tube rupture is the dimensioning scenario in the loading of railroad car. If the tube ruptures, the leakage will not be as severe as in the previous case, since the constructions are equipped with various safety measurements and valves in case of ruptures. The flammable gas cloud could in “worst case” spread 40 m from the rupture site. In case of ignition, the consequence could be hazardous to people within 50–80 m from the ignition site.

**Risks at interim storage**

In a tank area for interim storage purposes, there are in principle two alternative leakage scenarios: tube rupture at loading/unloading and pump failure. In case of pump failure a small amount of DME will leak during a long time period. The leakage is not hazardous unless there is an ignition source in contact with the leakage. In case of tube rupture, the same conditions as for the loading of railroad cars in the harbour terminal apply. Storage tanks are not considered as a risk, unless they are objects to external damage. Sabotage and similar actions are not dimensioning.

**Risks at filling stations**

At filling stations there are two possible leakage scenarios: loading the tank and the filling of automotives. A leakage during filling is very short term since the filling is continuously supervised and the tube dimensions are small, i.e. the associated volumes are small. Loading the tank from a tank lorry could result in larger leakage of DME in case of a tube rupture. The tube rupture could result in a release of 30–50 kg DME before the pump is stopped. This amount of gas may be ignited 40–70 m from the filling area that is before the gas mixture is leaner than the LEL.

### 6.5 Potential barriers for using methanol/DME as motor fuels

Several barriers for the large-scale introduction of methanol and DME have been identified in the discussion above. At first glance, it seems as all these barriers are possible to break in one way or another. However, further development will certainly be necessary in several areas.
In the following, a summary of the background, conditions and issues is made. The various development paths for energy converters and drivetrains in the future have been discussed. The possibilities for methanol and DME to fit into this picture have been assessed from several different viewpoints. It is likely that the unique properties of methanol and DME could be utilised in future to reduce exhaust emissions and to improve energy efficiency. This is a driving force for the efforts to introduce these fuels. Technical issues regarding fuel distribution and the associated cost have been discussed. Health and environmental impact has been compared with conventional fuels. In neither of the cases mentioned, a real “show-stopper” has been found.

The last part of this chapter, a more systematic summary of the issues discussed is made with short comments when necessary, or in the cases where the issues have not been discussed extensively above.

### 6.5.1 Technical barriers

**Methanol use in fuel-flexible light-duty vehicles**

Fuel flexible cars fuelled by E85 and M85 have been introduced in large numbers in the USA. However, only E85 is used today. Brazil is an emerging market for E85. Sweden will have over 10 000 E85 fuel flexible cars in 2004. The technology for M85 is largely similar to E85. Possibly, some materials in the fuel system would have to be exchanged and the fuel flow (injectors) would have to have a higher flow capacity. It is of importance to note that there are no insurmountable technical problems to overcome to develop a M85 compatible vehicle.

The main problem today is that there is no auto manufacturer is prepared to market light-duty vehicles fuelled by M85 on the European market. Presumably, a market pull and push situation would have to be created. The only alternative today for using M85 in light-duty vehicles would be conversions. However, the preferred solution would be that a vehicle manufacturer is prepared to produce such vehicles.

**Use of neat methanol in light-duty and heavy-duty vehicles**

As for M85, there are no light-duty OEM vehicles available for the use of neat methanol today. However, in the case of spark ignition engines, a technology for direct injection, similar to the direct injection petrol engines, would have to be developed. Compromise solutions to bridge-over this technology gap could be developed, if necessary. For example, the company Zero-m in the UK has converted two vehicles for operation on either neat methanol or a bi-fuel solution for neat methanol and petrol [79]. On a longer term, the results achieved by US EPA could probably also be exploited to obtain an increase in energy efficiency and to reduce the exhaust emissions. In summary, there are several areas where research and development will be necessary if the full potential of methanol-fuelled light-duty vehicles is to be achieved.

Heavy-duty vehicles operating on neat ethanol and methanol have been developed by several manufacturers, e.g. in the USA, Japan and Sweden. Several issues still have to be solved to improve exhaust emissions, reliability and useful engine life. It is proposed that glow-plug ignition, or an alternative positive ignition source, is developed to avoid the use of an expensive ignition improver additive.
**Use of DME in light and heavy-duty vehicles**

Some activities are going on to develop DME-fuelled heavy-duty diesel engines. Within the EU project AFForDH, Volvo Truck is developing a new DME engine. Activities are also going on in Japan and in the USA. DME is an ideal fuel for diesel engines but it has been necessary to develop a new injection system due to the specific physical properties of DME. Furthermore, DME is aggressive on polymer materials implying that further work also might be necessary in this area.

The same basic principles as for heavy-duty engines can also be used on light duty engines. However, for some reason, the interest from vehicle manufacturers has been lower than in the case for heavy-duty vehicles.

**Fuel cell vehicles**

The development of fuel cell vehicles has been a great inspiration for proponents of methanol. However, a somewhat different view on the situation has been developing during the last couple of years. Until recently, high hopes were emerging on the potential availability of methanol-fuelled vehicles among the vehicles in the first generation soon to be ready for field tests. Eventually, this scenario does not seem to manifest itself. Presumably, technical reasons are behind this strategy but it is anticipated that also other strategic decisions lay behind this outcome.

First, it seems that the use of hydrogen provide conditions for a simpler drivetrain. In this case, no reformer is needed. Since the development on reformers is lagging behind the development of the fuel cell stack, it is inevitable that the use of a reformer could have made an already sophisticated drivetrain even more complicated.

Second, the problems with the fuel infrastructure for hydrogen are substantially simplified for fleets. Compressed hydrogen will be used in most cases, and this use of hydrogen can largely rely on the previous experience from refuelling with compressed natural gas. Obviously, there are differences in technology due to the physical and chemical properties of hydrogen, but the similarities are fairly large after all. Since all fuel cell vehicles from the first generation will participate in well-defined vehicle test fleets, the problems of fuel infrastructure will not play a decisive role in these cases.

Third, there has been a considerable hype about hydrogen lately. In other words, the use of hydrogen might be preferred due to public relation benefits. The importance of goodwill for the automotive manufacturers from these test fleets should not be underestimated. If the use of hydrogen can enhance this perception, it will be the preferred fuel by many manufacturers.

Currently, the authors are not aware of any definite plans to introduce methanol-fuelled vehicles on the market. As mentioned above, several activities are going on (e.g. Necar 5, Jeep Commander and Hyundai), but it is obvious that hydrogen is leading the race at this moment.

The most important component in a methanol-fuelled fuel cell drivetrain is the fuel reformer. It is unfortunate that considerably less effort has been spent on the reformer than the fuel cell stack. There is a considerable need for much more research and development in this area.
Production of methanol and DME

The fuel production of methanol and DME from biomass is the main focus of this report so there is not much more to be said in this case. One can simply conclude that there are several areas in this field where further research and development activities are necessary. The main problem is that the capital cost of research and pilot plants is so high. In addition, only a few industrial stakeholders are interested in such investments today.

The use of fossil methanol and DME could bridge over the period until biomass can be used as feedstock. In the methanol case, the production technology for methanol from natural gas is more or less mature but in the DME case, additional development is necessary.

Fuel distribution

Today, there is considerable experience of distributing methanol for motor vehicles. Furthermore, methanol is a commodity on the chemical market today and it is transported and stored in large quantities. No technical breakthroughs are necessary in this field. However, the refuelling has to be addressed to avoid unintended exposure and misuse of methanol. Similar solutions as the one developed by Identic, can solve this problem.

For DME, the fuel infrastructure issues pose one of the toughest barriers. Since DME cannot be used in fuel flexible engines, vehicle fleets and fuel infrastructure is linked together. The short-term option for DME is to be used as niche application in dedicated fleets. A whole new fuel infrastructure has to be built for DME. Lessons learned from LPG and the current distribution of DME for special purpose can probably be adapted to some extent.

6.5.2 Legal barriers

Regulations for methanol

One of the most difficult questions to handle regarding a large-scale introduction of methanol is the acute toxicity. However, there are no legal problems to introduce methanol. Contacts have been made with the two leading Swedish Governmental Authorities in this field, i.e. the Swedish Work Environment Authority and the National Chemicals Inspectorate. None of these authorities could see any particular problems with a widespread use of methanol in the transportation sector. Petrol and diesel are also toxic fuels. Methanol is handled as a chemical commodity today but the handling is made by educated people. Precaution must be taken both at the refuelling station and in the vehicle to avoid unintended exposure to methanol.

Future fuel specifications for low-blending must be developed. In the “world-wide fuel charter” document by the organisations of the car and engine manufacturers new fuel specifications are proposed [80]. Regarding methanol, it is stated that: “Methanol is not permitted”. Furthermore, it is concluded that: “Methanol is an aggressive material, which can cause corrosion of metallic components of fuel systems and the degradation of plastics and elastomers”. No reference is given for background information. Discussion with industry representatives has not revealed any more information. If future petrol specifications would be changed in line with this demand, the possibility of using methanol for low-blending would be impossible. Therefore, it is of utmost importance for the stakeholders to follow and to exert influence on this issue.
The need for and compatibility with additives for fuel cell vehicles must be further investigated. Legislation in this area could also be a potential problem. Internal combustion engines could tolerate most of the proposed additives to methanol.

**Regulations for DME**

A standard for fuel-grade DME has been proposed. Toxicity is not an issue in the DME case as for methanol. A lubricity additive might have to be used. If DME is to be used in fuel cell vehicles, this additive could pose similar potential problems as in the methanol case. This could necessitate the adoption of two different standards. However, the interest for using DME in fuel cells has not been manifested yet so this potential problem is not urgent.

DME is a new fuel on the market. The safety hazards regarding fire and explosion have to be taken seriously. New regulations both for fuel distribution and the fuel system in the vehicles have to be developed.

### 6.5.3 Economical barriers

**Fuel production cost**

The incremental cost of an alternative fuel could be prohibitive, in general. This is also a crucial issue for biomethanol and bio-DME. Therefore, the use of fossil natural gas, or the cheapest biomass feedstock, during an initial phase are two possible options to create a market opportunity. Reducing the cost of methanol and DME from biomass has been one of the primary objectives of the BLGMF project. The results for black liquor are very encouraging but for other biomass feedstocks, the cost is significantly higher.

The fuel production cost is presumably the most significant economical barrier.

**Fuel infrastructure cost**

In the methanol case, the incremental cost for erecting new refuelling stations is marginal compared to petrol and diesel fuels. This barrier is often referred to as a prohibitive cost, but it is only a small fraction of the cost for gaseous (e.g. CNG and GH₂) and cryogenic (e.g. LNG and LH₂) fuels. Therefore, the infrastructure cost is not a particular problem for methanol. In fact, some oil companies in Sweden (OKQ8 and Statoil) are already designing new petrol stations to be both ethanol and methanol compatible. This is said to be at a marginal incremental cost.

The fuel infrastructure cost for DME will be significantly higher than for methanol. However, also in this case, the cost will be lower than for gaseous and cryogenic fuels. A parallel to the cost for distributing LPG can be made.

**Fuel tax**

First, it might be of interest to start with kind of a principal discussion about fuel taxation. The fuel tax should ideally correspond to some, or most, of the external costs caused by the use of motor fuels. This could be external cost as road tax, accidents, noise, environmental impact and so on. Value-added tax (VAT) is usually also added on motor fuels but is not considered here. The socio-environmental damages from electricity production and the use of motor fuels are studied by the European Commission. A recent report from this project has been published by the Commission [81].
The emissions of greenhouse gases are (usually) considerably lower for biofuels than for fossil fuels. Therefore, the CO\textsubscript{2} tax should be significantly reduced – or omitted – for biofuels. This conclusion is based on the assumption that the societal cost from the global warming is equal to the CO\textsubscript{2} tax fossil fuels. The level of CO\textsubscript{2} tax could be discussed and this kind of tax is used by only a few countries today. Sweden is one of them and some conclusions can be drawn from this experience.

In the near or mid-term future, it is conceivable that the exhaust emissions from vehicles fuelled with any fuel will be reduced to a very low level. Therefore, the societal impact from vehicle emissions could be more or less omitted in evaluations of biofuels in the future. The remaining difference in societal cost between biofuels and fossil fuels will be the greenhouse gases, i.e. CO\textsubscript{2}.

During an introductory phase, a CO\textsubscript{2} tax incentive alone will not be sufficient to reach a substantial market penetration of biofuels. Costs are always higher during an introductory phase. Therefore, incentives will be necessary. However, such tax incentives cannot be maintained eternally. Therefore, it is conceivable that the long-term tax incentive should be reduced to the level of the CO\textsubscript{2} tax as soon as the introductory phase has been completed.

There are different ways of setting a level for the tax exemption and a strategy on how to gradually reduce this level. An example of a linear reduction of the tax exemption is shown in Figure 6.8. All units and levels shown in the figure are arbitrary; e.g., it is likely that the timeframe should be longer than shown in the figure. Another method could be to set a fixed level for a certain period. This is shown in Figure 6.9. A number of potential strategies could be used but are not discussed further here.

The objective of including the discussion above was to show that a reasonable long-term target for production cost for biofuels could be a similar cost as for conventional fossil fuels (w/o taxes) plus the CO\textsubscript{2} tax. This was the target adopted as a goal in this project, using the contemporary level of CO\textsubscript{2} tax in Sweden (SEK 1.77 per litre, or about €20¢ per litre for petrol). Compared to current production costs for biofuels, this target is very though. Eventually, a change in CO\textsubscript{2} tax and/or an increase in the price of crude oil might provide better opportunities for biofuels in the
It is likely that the cost of fuel production will be the most severe barrier of all for methanol and DME, as well as for all other biofuels.

Vehicle cost for methanol-fuelled vehicles

The incremental vehicle cost for a fuel flexible car is relatively low today. Little or no extra hardware is needed. An extra fuel sensor might be necessary. Some materials in the fuel system have to be changed for slightly more expensive materials. The Ford Focus Flexifuel is an example that an E85 car can be sold at approximately the same cost as a conventional model of the same car. It is likely that also an advanced concept of a spark ignition engine using neat methanol could be produced at only a marginal incremental cost.

Heavy-duty methanol-fuelled diesel engines are likely to be somewhat more expensive than their diesel-fuelled counterparts. As in the previous case, some changes in material quality will be necessary in the fuel system. Additional hardware will be needed for a glow-plug system, if such system is to be used. However, this hardware is relatively inexpensive. An interesting area is the emission control. Future diesel engines will have to be equipped with particulate filters and some kind of a NO\textsubscript{X} reducing catalyst. There is some scope of reducing the cost for methanol-fuelled engines in this area.

Vehicle cost for DME-fuelled vehicles

Besides the fuel injection system, there will be only minor differences between diesel engines fuelled with DME and diesel fuel. Today, one could anticipate that the injection system will be more expensive for DME engines, but on the other hand, it seems as DME engines might not need the extremely high injection pressure projected for future diesel-fuelled engines. Thus, savings in some areas might counteract the expected more expensive solutions in other areas. Different materials have to be used in the fuel system.

As in the methanol case, it is likely that the exhaust gas aftertreatment will be less expensive in the future than for diesel-fuelled engines. The technology used in light-duty and heavy-duty engines will be more or less similar so the same conclusions apply to both categories of engines.

Cost of fuel cell drivetrains

The projections of the driveline cost for fuel cell vehicles are very high today. For fuel cell vehicles to become commercially attractive in the future, the cost would have to be reduced by at least one order of magnitude compared to the projected cost for (imaginary) mass-produced vehicles using the technology available today. It is impossible to say, based on present knowledge, whether the cost for vehicles fuelled by methanol and DME will more favourable than for hydrogen-fuelled vehicles.

6.5.4 Market barriers

Public perception of methanol

Today, the public perception of methanol is very “bad” today. Several vehicle manufacturers and oil companies are certainly not in favour of methanol. The toxicity is mentioned frequently. In order to create a market for methanol as a motor fuel, this reputation has to be altered. The necessary efforts to change this perception cannot be overestimated.
**Public perception of DME**

One of the main problems with DME is that it is a “new” fuel. The knowledge about DME is not widespread. Other alternative fuels are reasonably well known (in most cases anyway). Therefore, there is always a small risk that there might be some issues with public perception in the DME case. Information activities might solve this potential problem.

**Competition with other “clean” fuels**

Several alternative fuels have been commercialised during the last decade in the EU. Although the market penetration still is very limited, fuels such as, natural gas, ethanol and RME have gained some customer acceptance. Methanol and DME will have to compete on the market with these fuels. As the target would be similar categories of customers, this would favour the established fuels. A similar situation might be the case regarding governmental support for research, development and demonstration.

**Governmental programmes**

Both on the member state level and on the EU level financial support is of great importance for “new” fuels. Some programmes are dedicated to certain fuels and some are “open”. Within the 6th and 7th framework programmes, some activities could be possible. If methanol and DME should have a chance to develop, more support will be necessary.

**Stakeholders**

A particular problem for “new” fuels is that there are relatively few stakeholders in this area. Most of the automotive and oil companies have a different focus. The companies producing methanol and DME have other markets (chemicals) as their main targets. In order to develop the use of methanol and DME as motor fuels, stakeholders have to be identified and organised.

### 6.6 Introduction strategy

Based on the collected results and the discussion above, an introduction strategy for methanol and DME is proposed. This strategy has its main focus on the fuel production from a first major demonstration plant and should not necessarily be considered applicable for later stages.

**6.6.1 Implications by the EU “biofuels” directive**

The biofuels directive is both a threat and an incentive. The directive will most certainly promote the use of renewable fuels. The particular problem for methanol and DME is that the production technology is not fully developed yet. Therefore, other fuels will gain a competitive edge in this respect. On the other hand, some of the fuels under discussion will be very expensive and are plagued with problems (i.e. herbicides, pesticides and energy use) in the feedstock production chain. It is hoped that national strategies with the objective to implement the directive will consider such issues.

**6.6.2 Proposed introduction strategy**

Based on the discussion and conclusions in the sections above a proposal for the introduction of methanol and DME has been made. The following priorities are proposed.
1. Use of methanol in fuel cell vehicles and DME in dedicated vehicle fleets
2. Low-blending of methanol in petrol, M3
3. Fuel-flexible light-duty vehicles, M85
4. Dedicated and fuel-flexible light-duty vehicles, M100
5. Dedicated heavy-duty vehicles, M100 and DME

**Priority #1**

Methanol was one of the first alternative fuels of considerable interest. Due to the lack of fuel infrastructure for light-duty vehicles and certain technical problems on heavy-duty buses in the USA, the market interest in methanol dropped considerably. Methanol is toxic, which is an issue that must be handled with care. Use of a safe fuel dispensing technology is one of the precautionary measures that must be taken. Thus, there is a need to regain confidence in methanol. Using methanol in fuel cells that have very low or zero emissions would be one step to achieve this goal. Therefore, the highest priority is to use methanol in fuel cell vehicles. This will not provide for any large volumes in the near future but it would be essential to regain the customer acceptance.

Initially, DME should be used in dedicated fleet applications. The high cost for fuel infrastructure is somewhat prohibitive for a broad use of DME in the near future. Engine and vehicle manufacturers must develop the necessary technology to utilise DME. In the mid-term future, potential savings in emission aftertreatment technology should be investigated in order to assess if these savings could offset the incremental cost for fuel distribution.

**Priority #2**

Low-blending of methanol in petrol (M3) is the easiest and most cost-effective way to enter the market. The use of methanol in ordinary cars could for an increase in customer acceptance for methanol. As mentioned above, one problem could be that the introduction of ethanol will limit the market for (additional) use of methanol with the current limitations for oxygen content in petrol.

If possible, the use of higher blending levels (e.g. M15) could be an option to increase the use of methanol in a second step.

**Priority #3 and 4**

Fuel flexible vehicles could bridge the gap between the use of methanol in small volumes and larger quantities. The availability of fuel flexible vehicles is essential. Development of vehicles able to use M100 (and petrol) would be the second stage in the use of fuel flexible vehicles. Engine development on direct injection methanol engines must be initiated. The vehicle manufacturers are important stakeholders in this area.

**Priority #5**

When the fuel infrastructure is increasingly becoming available, the use of methanol and DME in heavy-duty vehicles will be possible. In an earlier stage, both fuels could be used in dedicated fleets if vehicles are available. Engine development will be necessary to avoid the use of ignition improvers. The use of emulsified fuel can only be considered for niche applications.
A vision for the future fuel distribution of methanol

In Figure 6.10, a vision for the distribution of methanol in the future (2010 and beyond) is shown. This vision is based on the strategy that the number of different fuel specifications should be kept as low as possible.

All petrol could contain 3% methanol or else the blending could be made at the pump using dedicated equipment. Vapour pressure is an issue that must be handled in these cases. Fuel flexible M85 and M100 vehicles could be refuelled from a pump that could blend the appropriate fuel quality. Fuel cell vehicles, fuel flexible M100 vehicles and dedicated heavy-duty M100 vehicles could use the same fuel dispenser. The possibilities of using similar fuel specification for Otto and diesel engines and, possibly, also for fuel cells is an issue that should be investigated. If this cannot be accomplished in the fuel cell vehicle case, potential synergies in fuel production and fuel distribution should be investigated.

Figure 6.10. Vision for future methanol distribution (2010 and beyond).
7 GASIFICATION AND FUEL MARKET POTENTIAL

7.1 Pulp and paper industry

7.1.1 World paper market

The world market for paper is estimated to increase by 2.7% per year to year 2010, adding an average 9.3 million tonnes per year paper consumption. The highest growth is expected in Asia, but European growth forecasted at 2.4% annually will add 1.9 million tonnes per year and North American growth at 1.7% annually will add 1.8 million tonnes per year. (Source: Jaakko Pöyry).

During the last 10–20 years the use of recycled fibres has increased and is approaching the point where half the pulp produced comes from recycled fibres. This offsets black liquor production since it is not necessary to pulp wood to obtain these fibres. However, the use of recycled fibres is not expected to increase further, so future increases in pulp production will generate associated increases in black liquor production.

Chemrec’s technology is used in the production of virgin chemical pulp in sulphate-based (kraft) pulp mills. Global annual virgin chemical pulp production since 1965 is shown in Figure 7.1, along with a forecast until 2025. Lines indicating the production if the rate of increase is ±20% of the projected rate are included in the figure. The increase in bleached pulp production is greater than that of unbleached pulp. Production of bleached pulp generates more black liquor per tonne of pulp than production of unbleached pulp, which contributes to the global increase in black liquor production.

![Figure 7.1. Global virgin chemical pulp production and forecast.](image)

Global black liquor production is shown in Figure 7.2. The figure shows both historical production since 1965 and projected production to 2025. North America will continue to be the largest market, accounting for over half the global black liquor production. In the
next 25 years, it is projected that North American black liquor production will increase by roughly 50 million tonnes per year. This additional black liquor is enough to feed 55 new recovery units each having a capacity of 2500 tDS/day.

**Figure 7.2. Global black liquor production and forecast.**

### 7.1.2 Recovery boiler age and capacity

A number of groups have analysed the global market potential for black liquor gasification. A recent such study was conducted in June 1999 by Jaakko Pöyry for Vattenfall in Sweden. Their analysis included a survey of the world’s sulphate mills and recovery boilers, an assessment of current and future capacity requirements and an indication of the number of recovery boilers, which will require renovation or replacement in the near future.

In the United States, the majority of the Tomlinson boilers currently operating were built beginning in the late 1960s through the 1970s (Figure 7.3) with a majority rebuilt from the mid-1980s to the late 1990s. With lifetimes of 30 to 40 years, many of these units are approaching the time at which they will need to be rebuilt or replaced. Thus, over the next 10 to 20 years, there will be strong demand for replacement black liquor energy and chemical recovery systems. The considerable progress in the development of gasification technologies with a near commercialisation gives a turning point where the next investment may be a shift to the new technology. Thus, there is a wide and large market for potential for black liquor gasification.
7.1.3 Market for Chemrec BLGMF system

The Chemrec BLGMF system would be targeted as a replacement for the conventional recovery boiler. Very few greenfield mills are expected to be built in the foreseeable future, so there will be little opportunity for installation of a Chemrec BLGMF system in a new mill. Instead, the primary application of the Chemrec BLGMF system in the near future will be as a replacement for existing boilers that have become outdated.

Recovery boilers have a useful service life of roughly 20 years, after which they either need to be extensively renovated or replaced. This is where the major market for the Chemrec BLGMF system lies — mills that have recovery boilers that have not been rebuilt or extensively renovated in the past 20 years.

Current market

According to the Jaakko Pöyry study, there are 236 recovery boilers in the world that fit this description. However, as seen in Figure 7.4, the majority of these boilers have quite low capacities, less than 500–600 tDS/day. Many of the smaller recovery boilers have been due to significant modifications during the years such as increasing the dry solids content of the black liquor, rebuilding of the boiler and other debottlenecking actions. Nevertheless, Chemrec BLGMF system would not be a realistic replacement alternative for small boilers.

One can assume that a mill, which is replacing an outdated recovery boiler, would desire somewhat more capacity (perhaps 25%) than the old boiler provided. A Chemrec BLGMF system is a competitive alternative for capacities of roughly 1000 tDS/day and higher. Hence, the actual market is for replacement of boilers with a capacity of 800 tDS/day or
more, and which have not been built or extensively renovated in the last 20 years. There are 57 such boilers in the world today, about half of which are in the United States. The majority of the remainder is located either in Canada or in Japan.

**Figure 7.4.** World recovery boilers constructed or last renovated before 1980.

**Future market**

The market for the Chemrec BLGMF system will expand in the future due to the obsolescence of more and larger recovery boilers. As seen in Figure 7.5, the average size of new recovery boilers has increased over the years. While the current market includes those boilers built prior to 1980, the market ten years from now will include those boilers built prior to 1990. A much larger proportion of those boilers is larger than 800 tDS/day.

The above analysis implies that those recovery boilers will not undergo renovation to extend their service life. This is of course not the case for many, and perhaps most of those boilers. However, when the time comes to decide whether, or not to renovate, an alternative will be to install a BLGMF system instead. Nevertheless, eventually the usefulness of the renovated boiler will diminish, and it will again be a candidate for replacement by a BLGCC system. In short, each of the world’s 327 recovery boilers with a capacity of more than 800 tDS/day can be considered a candidate for eventual replacement by a Chemrec BLGMF system.

The above analysis assumes that these mills have only one recovery boiler. But it is common for sulphate mills to have several smaller recovery boilers. World-wide, the average number of recovery boilers per mill is 1.5 and in the United States, the average is 1.7. The recovery boilers in these mills are relatively small by today’s standards, generally 400–700 tDS/day in North America and Japan, and 200–500 tDS/day in southeast Asian countries. Boilers of this size are not included in the market figures presented above. It is becoming common for mills with multiple recovery boilers to replace several or all with one unit having a capacity of 2000 tDS/day or more. A Chemrec BLGMF
Black Liquor Gasification with Motor Fuels production - BLGMF

System is clearly an alternative for these mills, so the market is actually larger than suggested in Figure 7.6.

Figure 7.5. Increase in capacity of recovery boilers erected in the US, Canada, Scandinavia and Japan. The line shows the average size of all recovery boilers built in that year.

Figure 7.6. World recovery boilers with capacity of 800 tDS/day or more.
7.2 Availability of black liquor

7.2.1 World

The estimated black liquor production with projections to 2025 based on previous 35 years yearly production records is given in Figure 7.7 for the world and in Figure 7.8 for the European Union according to FAOSTAT [82]. The total world production of black liquor is about 175 million tDS per year or some 600 TWh.

Main world producer is North America with more than half of the total world production. Second largest producer is Europe with Sweden (39 TWh) and Finland (40 TWh) as main producers. Asia is third largest producer equalling Sweden and Finland together, with Japan as largest producer (50 TWh).

![Estimated world black liquor production](image)

*Figure 7.7. Estimated world black liquor production, year 2000. Source: FAOSTAT 2001.*

The total production has shown a steady increase, with on average about 3.5%/year from 1965 to present with largest absolute increase in North America. It is likely that the demand for pulp & paper will grow in the future as it has in the past. Thus, the availability of black liquor will ever more show an increase. Especially for new developing production markets, like South America (Chile, Brazil) and Asia (India, China, Indonesia, Malaysia).
7.2.2 European Union

The total production of black liquor in the European Union totals some 33 million tDS per year or 120 TWh. The production is shared three-ways with Sweden, Finland and the remainder Europe in equal parts of about 40 TWh each. The total production has shown a steady increase, with on average about 3.8%/year from 1965 to present.

Although Europe is a developed market it is likely that the production will grow here as well. As an example, the Swedish forest growth currently totals about 100 million wood m$^3$ per year, however the yearly outtake of forest is just 70 million wood m$^3$ per year. Thus, the Swedish forest has never been larger before and the current production has only been taken from the “interest”, not the wood “capital”.

Without endangering protected forests and forests of social and ecological value there is a possibility to maintain forests with an increase in production. Sustained forest management is key if such outtake should occur to further keep the rich capital and a productive forest.

![Estimated EU black liquor production](image)

*Figure 7.8. Estimated kraft black liquor production in the European Union. Source: FAOSTAT 2001.*

As to the smaller production countries like Spain, Portugal and France it is unclear whether they can increase their production. It is more likely that a significant contribution would come from the neighbouring European countries with a production today and which will become EU countries in 2004. There lies maybe the largest potential.
7.3 Methanol and DME fuel production

7.3.1 European Union

From the material and energy balances, various pulp mill cases have been calculated for the energy efficiency of biomass to methanol. In the KAM2 pulp mill (2000 ADt/day) the methanol yield from black liquor is 1183 t/d (or 824 t/d DME), which is equivalent to 56.1%. The theoretical maximum production of methanol (or similarly for DME) can thus be calculated for countries in the European Union with black liquor production. As described in previous section the availability of black liquor in Europe is some 120 TWh and using aforementioned method of calculation results for possible methanol production can be calculated, shown in Table 7.1.

Note that the BLGMF concept is using additional biomass to balance the incremental power export from the pulp mill, when compared with a modern recovery boiler. Normally this would not be a governing limiting factor for the market potential to produce methanol or DME as the pulp mill would not have incentive to co-produce power for export but only to cover its own consumption. However for comparison purposes this could be possibly important. For the market KAM2 pulp mill about 129 MW additional biomass need to be purchased or about 0.11 MW biomass per each t/d of methanol produced.

For the whole European Union as much as 61 TWh or some 11 million tonnes of methanol could be produced each year. This may be compared with current total consumption of motor fuels for the road transport sector and a calculated maximum replacement percentage (on energy basis) for each country [83]. Finland could replace more than 50% of all transport fuels consumed, Sweden and Portugal nearly 30% and 10% respectively.
Table 7.1. European Union: Annual motor fuel consumption and black liquor production with estimated percentage of potential methanol production replacement.

<table>
<thead>
<tr>
<th>EU (15) Countries</th>
<th>Fuel consumption (1999, LHV)a</th>
<th>Black liquor production (2000, LHV)b</th>
<th>Produced methanol replacement percentagec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M toe PJ TWh</td>
<td>PJ TWh PJ TWh</td>
<td>%</td>
</tr>
<tr>
<td>Austria</td>
<td>5.4 226.1 62.8</td>
<td>13.4 3.7 7.5</td>
<td>3.3%</td>
</tr>
<tr>
<td>Belgium</td>
<td>7.6 318.2 88.4</td>
<td>4.8 1.3 2.7</td>
<td>0.84%</td>
</tr>
<tr>
<td>Denmark</td>
<td>3.8 159.1 44.2</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Finland</td>
<td>3.7 154.9 43.0</td>
<td>141.4 39.3 78.8</td>
<td>50.9%</td>
</tr>
<tr>
<td>France</td>
<td>41.8 1 750.2 486.1</td>
<td>32.3 9.0 18.0</td>
<td>1.0%</td>
</tr>
<tr>
<td>Germany</td>
<td>57.5 2 407.5 668.7</td>
<td>0.1 0.0 0.1</td>
<td>0.0%</td>
</tr>
<tr>
<td>Greece</td>
<td>5.3 221.9 61.6</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Ireland</td>
<td>3.0 125.6 34.9</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Italy</td>
<td>36.7 1 536.6 426.8</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>1.4 58.6 16.3</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Portugal</td>
<td>5.2 217.7 60.5</td>
<td>32.9 9.1 18.3</td>
<td>8.4%</td>
</tr>
<tr>
<td>Spain</td>
<td>25.3 1 059.3 294.2</td>
<td>32.1 8.9 17.9</td>
<td>1.7%</td>
</tr>
<tr>
<td>Sweden</td>
<td>6.4 268.0 74.4</td>
<td>138.1 38.4 76.9</td>
<td>28.7%</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>9.5 397.8 110.5</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>38.0 1 591.1 441.9</td>
<td>0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td><strong>EU Total</strong></td>
<td><strong>251</strong> <strong>10 493</strong> <strong>2 914</strong></td>
<td><strong>395</strong> <strong>110</strong> <strong>220</strong> <strong>61</strong></td>
<td><strong>61</strong>%</td>
</tr>
</tbody>
</table>

Notes:

- a Taken from European Commission’s Energy and Transport Statistics [83].
- b Based on the Food and Agriculture Organisation (FAO) database.
- c Based on KAM2 case with black liquor to methanol efficiency of 56.1% (calculated as LHV energy of the methanol fuel product divided with LHV of the black liquor).

As can be seen in Figure 7.9, France, Portugal and Spain have the potential to produce nearly 1 million tonnes of methanol per year. Although the same quantity, Portugal could replace as much as 8% and Spain merely nearly 2%. Sweden and Finland could produce about 4 million tonnes each, a substantial amount. Thus, the production potential in the European Union is concentrated to a few countries, which have a large potential and for Sweden and Finland extremely high replacement potential.
7.3.2 Sweden

As a study example, if all black liquor produced in Sweden were used for methanol production, 29 TWh/yr biofuel would be needed to cover the fuel needs of the pulp mills – provided that the mills need all of the heat value of the black liquor. However, there is a trend of decreased energy need in market pulp mills, due to better process integration. On the other hand, if integration with paper mills and other energy intensive industry grows, this will increase the internal energy demand.

Sweden uses about 52 TWh forest fuel per year, 45 TWh of which from domestic forests (1999). It is estimated that an additional 30 TWh biofuel can be utilised ecologically sustainably, and at the same, or only moderately higher, cost (below EUR 1.1¢/kW h). Another 30 TWh is also ecologically available, but at higher costs (above EUR 1.4¢/kW h) \[84\]. This means that within the pulp mills of today, approximately 40 TWh black liquor production in Sweden could be available for methanol production, from a wood fuel supply point of view. The corresponding methanol production potential is thus about 21 TWh/year or nearly 4 million tonnes.

A theoretical example for an existing kraft mill in mid-east Sweden shows that with an annual production of 185 000 ADt of kraft pulp, the mill would need a forest area of approximately 180 000 hectares for its pulpwod supply. That area can at the same time produce 1040 GWh forest fuel per year sustainably. The black liquor production would need to be replaced by approximately 1250 GWh biofuel. The difference could be covered by the additional production of biofuels within the region \[85, 86\].

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**Figure 7.9.** Methanol (or similarly DME) production potential from biomass via black liquor for some European countries.
7.3.3 Outside Europe

The world production of black liquor comprises some 600 TWh/year (2160 PJ/year, 2001), however a few countries dominate the production – USA, Canada, Japan, Brazil and in Europe, Finland and Sweden. As can be seen in Table 7.2, these countries have a substantial potential for possible biomass-based methanol or DME production to be utilised at the mills. Although ready available, however today with considerable capital already invested in existing recovery boilers. Nevertheless, the market potential is ample and credible as the pulp & paper industry is capital-strong and structured around large concentrated plants simplifying logistics and gaining scale-economics.

Economically, the industry comprises mainly nationally-based companies although with a merger trend for internationalisation and globalisation as new markets appear. Technically, in principle, all plants could be fitted with a BLGMF plant when the process technology has become successfully demonstrated and commercially available.

From the Food and Agriculture Organisation (FAO) database bleached and unbleached pulp production statistics have been used to calculate the black liquor production for the dominating countries outside the European Union. With the BLGMF concept calculated for material and energy balances the following potential of biomass-based methanol or DME production is presented.

Table 7.2. World: Annual production of black liquor with estimated percentage of potential methanol production replacement.

<table>
<thead>
<tr>
<th>Countries</th>
<th>Black liquor production/year (2001, LHV)(^a)</th>
<th>Potential methanol production/year(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PJ</td>
<td>TWh</td>
</tr>
<tr>
<td>Brazil</td>
<td>106.0</td>
<td>29.5</td>
</tr>
<tr>
<td>Canada</td>
<td>252.0</td>
<td>70.1</td>
</tr>
<tr>
<td>Chile</td>
<td>36.0</td>
<td>10.0</td>
</tr>
<tr>
<td>China</td>
<td>30.3</td>
<td>8.4</td>
</tr>
<tr>
<td>India</td>
<td>21.2</td>
<td>5.9</td>
</tr>
<tr>
<td>Indonesia</td>
<td>73.4</td>
<td>20.4</td>
</tr>
<tr>
<td>Japan</td>
<td>192.4</td>
<td>53.5</td>
</tr>
<tr>
<td>USA</td>
<td>1007</td>
<td>279.9</td>
</tr>
<tr>
<td>Total</td>
<td>1,718</td>
<td>478</td>
</tr>
</tbody>
</table>

Notes:
\(^a\) Based on the Food and Agriculture Organisation (FAO) database.
\(^b\) Based on KAM2 case with black liquor to methanol efficiency of 56.1% (calculated as LHV energy of the methanol fuel product divided with LHV of the black liquor).

Canada has a potential of more than 7 million tonnes of methanol to be produced, also shown in Figure 7.10. This can be compared with a reported consumption of petrol and diesel fuel oil for road transport of 1953 PJ (2000). Thus, the calculated potential replacement is 7.2%, which is of course substantial and, not before noticed, offers great help in the commitment to the Kyoto protocol cut down on use of fossil fuels.
USA has the world’s largest methanol potential by amount, but not with replacement percentage. Potentially, a staggering 28 million tonnes of methanol could be produced. Astonishingly, this already equals today’s world methanol production from mainly natural gas based plants, which are all commercial and can be of 5000 tonnes per day or more. However, just the US national petrol consumption totals the equivalent of 1000 million tonnes of methanol or 21 500 PJ. The resulting possible potential replacement is about 2.2% if also the diesel fuel oil consumption would be accounted for.

![Figure 7.10. Methanol (or similarly DME) production potential from biomass via black liquor for some countries outside Europe.](image)

### 7.4 Greenhouse emissions and possible reductions

#### 7.4.1 Emission development in EU

Stabilisation in the concentration of greenhouse gases in the atmosphere is necessary to ensure that biological diversity, food production and other goals of sustainable development are not jeopardised. Carbon dioxide emissions must be limited in order to pass on a climate in balance to coming generations.

Climate change is a global problem that the EU alone cannot solve, as all countries emit greenhouse gases. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was agreed. At present, 186 nations have ratified this convention and are legally bound by it. This Convention explicitly recognises the problems posed by climate change, and sets an “ultimate objective” of stabilising “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced)
interference with the climate system”. However, the text does not specify precisely what this level should be – it remains a subject of scientific research and political debate.

The Kyoto Protocol to the UNFCCC, agreed in 1997, was an important additional step, committing developed countries to emission reduction and limitation targets for greenhouse gases. The EU agreed to cut emissions by 8% relative to 1990 levels by the years 2008–2012. However, the Kyoto Protocol has not yet been ratified by most signatories, and in particular none of the industrialised countries, and is therefore not yet legally binding. Moreover, the Intergovernmental Panel on Climate Change estimates that to stabilise CO$_2$ concentrations at even around twice the pre-industrial atmospheric concentration would require cuts in JOREDO emissions of around 50 to 70% over the next 100 years. This implies that implementing the Kyoto Protocol will only be a first step.

Carbon dioxide is the most significant greenhouse gas; it contributes about 80% of total EU greenhouse gas emissions. The developments of carbon dioxide emissions for the EU (15) countries are shown in Figure 7.11. Emissions fell between 1990 and 1994, mainly because of relatively slow economic growth, increases in energy efficiency, economic restructuring of the new Länder in Germany and the switch from coal to natural gas, mainly in the United Kingdom. Emissions then increased by 3% between 1994 and 1998 and furthermore by 2000 because of increased economic growth. Particularly Spain has increased their emissions by a large extent with no showing of slowing down or taking countermeasures.

![Development of CO$_2$ emissions in EU (15) during 1990 - 1998](image)

*Figure 7.11. Development of carbon dioxide emissions for the EU(15) countries between 1990 and 1998.*
7.4.2 National emission targets

Total EU emissions in 2000 were little lower to those in 1990. The EU target of stabilisation of carbon dioxide emissions at the 1990 level by 1998 was reached and by year 2000 the emission index was 96, which can be compared with the targeted agreed Kyoto Protocol emission index of decrease to 92.

Figure 7.12 shows the total greenhouse gases emissions as percentage increase, based in carbon dioxide equivalents, in year 2000 compared with emissions in 1990. The figure also shows as a comparison the national target indices for 2008–2012, indicated with black bars and black box values. On a national basis some EU countries have significantly increased their emissions, compared with 1990 levels, by as much as 25–35% e.g. Greece, Ireland, Portugal and Spain. On the opposite, Germany, Luxembourg and United Kingdom have made large cuts in their total greenhouse gases emissions. Others have maintained or made a small decrease in their emissions.

However, with EU distributed national targets some countries were allowed increases. Instead, those countries, which are today far from reaching their targets, are Austria, Belgium, Denmark, Ireland, Italy, Netherlands and Spain. They will not likely fulfil their Kyoto Protocol agreements, unless some drastic measures are taken. All other EU countries will most likely fulfil their promises to the Kyoto Protocol.

There is an upward trend in carbon dioxide emissions from transport, largely due to growing traffic volumes, as there has been very little change in average energy use per vehicle kilometre. In the future, policies such as the voluntary agreements with the car
industry are expected to bring average energy use down. The first annual report on the effectiveness of this agreement shows a reduction of almost 6% in carbon dioxide emissions from new passenger cars between 1995 and 1999. However, in order to meet the final target, more effort by European and non-European car manufacturers is needed.

7.4.3 Swedish relevance

More than 80% of the emissions of greenhouse gases in Sweden can be accounted to carbon dioxide. According to the Kyoto Protocol, the EU and all of its member states shall have reduced their greenhouse gases emissions by 8% from 1990 levels by the time 2008–2012. Emission quotas in the EU are distributed in such a way that Sweden is permitted to increase its emissions by 4%. However, the Swedish parliament has decided that the emissions should be cut by 4% from 1990 levels as an average during 2008–2012. The emissions levels will be adjusted to temperature and downpour variations.

Nevertheless, the Swedish parliamentary commission concluded in 2000 in an assessment study that greenhouse gases need to be reduced by 50% from 1990 levels by 2050. In 2000 total Swedish emissions had decreased compared with 1990 by 2%. However, scenarios from the Government Commission of Measures against Climate Change indicate that there will be an increase of carbon dioxide emissions by 5% between 1990 and 2010 if further measures are not introduced.

Carbon dioxide emissions fell significantly in Sweden during the 1980s, mainly due to the expansion of nuclear power and greater energy efficiency. The use of fossil fuels has increased during the 1990’s, especially because of increased transport demand. The tax system, and particularly the carbon dioxide tax on fossil fuels that was introduced in 1991, has played a major role in limiting carbon dioxide emissions. The most obvious effect of the carbon dioxide tax has been the expansion of biomass use in the district heating system, from 10 TWh/year to 25 TWh/year. Since 1990, biomass use has also increased in industry, although to a lesser extent, from 45 TWh/year to 54 TWh/year.

7.4.4 Potential carbon dioxide reduction with BLGMF

In a scenario where all major recovery boilers would be replaced with a BLGMF concept, all black liquor would be used to produce methanol or DME. To replace needed power and heat in the mill some biomass would be additionally needed. The amount of biomass would depend on the situation and if the mill would like to be a net producer of electricity as well. The base case would be a zero net importer.

Nevertheless, with the potential of black liquor in the EU and the results here presented some key numbers for theoretical possible carbon dioxide reduction can be calculated. For each tonne of methanol produced about 1.5 tonnes of carbon dioxide could be saved, with an average value of 85% carbon in 1 tonne petrol and with energy content of 11.626 MWh. Thus, the potential carbon dioxide reduction in EU if fully implemented is 16.4 million tonnes per year.

Table 7.3 below shows for selected EU countries national targets of total greenhouse gases emissions in carbon dioxide equivalents according to the Kyoto Protocol and carbon dioxide (only) emissions for year 2000 and the calculated potential carbon dioxide reduction. Finland and Sweden already fulfils the Kyoto target but have potential of reducing current emissions with 5.9 and 5.7 million tonnes of carbon dioxide or 11% and 12% of year 2000 emissions, respectively.
Table 7.3. Carbon dioxide emissions for selected EU countries and targets according to the Kyoto Protocol with potential carbon dioxide reduction with BLGMF.

<table>
<thead>
<tr>
<th>EU Countries</th>
<th>Targeted total greenhouse gases emissions(^a)</th>
<th>Carbon dioxide emissions (2000)(^b)</th>
<th>Potential carbon dioxide reduction(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO(_2) equivalents, M tonnes/year</td>
<td>M tonnes/year</td>
<td>M tonnes/year</td>
</tr>
<tr>
<td>Austria</td>
<td>52</td>
<td>57</td>
<td>0.56</td>
</tr>
<tr>
<td>Belgium</td>
<td>105</td>
<td>116</td>
<td>0.20</td>
</tr>
<tr>
<td>Finland</td>
<td>54</td>
<td>55</td>
<td>5.9</td>
</tr>
<tr>
<td>France</td>
<td>367</td>
<td>370</td>
<td>1.3</td>
</tr>
<tr>
<td>Portugal</td>
<td>54</td>
<td>59</td>
<td>1.4</td>
</tr>
<tr>
<td>Spain</td>
<td>300</td>
<td>284</td>
<td>1.3</td>
</tr>
<tr>
<td>Sweden</td>
<td>59</td>
<td>48</td>
<td>5.7</td>
</tr>
<tr>
<td>Total EU (15)</td>
<td>3060</td>
<td>3127</td>
<td>16.4</td>
</tr>
</tbody>
</table>

Notes:

\(^a\) Total carbon dioxide emissions (all GHG included, biomass sources excluded), Kyoto Protocol.

\(^b\) Based on EUROSTAT, European Commission (excludes maritime bunker oil and other greenhouse gases, which may account for another +25% carbon dioxide equivalents).

\(^c\) Possible carbon dioxide reduction to be compared with dioxide emissions in 2000.
8 DISCUSSION AND CONCLUSIONS

8.1 Comparing the BLGMF plant with the Reference Mill

8.1.1 Processes and equipment

The wood handling stage and the fibre line do not differ from the Reference Mill. Also the evaporation plant is the same, generating final black liquor with a dry solids content of 80%.

The gasification process that has been chosen for this comparison is very similar to the patented Chemrec concept, which uses an oxygen-blown, entrained-flow gasifier. The gasifier can be either ceramic-lined or have water-cooled walls.

The alkali smelt, with a relatively low content of sulphide, from the gasification plant is dissolved and forms green liquor. The green liquor is causticized in the conventional manner before the separately recovered \( \text{H}_2\text{S} \) sulphur is returned to the white liquor. Hydrogen sulphide removal from the gas is preferably done by physical absorption in a conventional acid gas treatment plant. Some \( \text{CO}_2 \) is absorbed both when the gas and smelt are quenched with weak wash and when the \( \text{H}_2\text{S} \) is reabsorbed in the white liquor. The causticizing plant is of a conventional type, but it requires a larger amount of lime from the lime kiln due to the higher fraction of alkali present as carbonate in the green liquor. A more detailed description is given in Berglin et al. [30].

The cleaned pressurised gas is used in a synthesis unit. The methanol synthesis unit is of conventional technology and is commercial currently being used with natural gas-derived synthesis gas. There is considerable experience from operating these in the petrochemical industry.

The expanded flue gas is cooled in a boiler producing HP, MP, LP, and LLP steam. The high-pressure steam is passed through a back-pressure steam turbine before it is used by mill consumers. The steam turbine is smaller than the one in the Reference Mill because the steam production is lower and a large fraction of the MP and LP steam is generated directly in the gasification plant.

The incineration of malodorous weak gases calls for another solution than in the Reference Mill, where they are destroyed in the recovery boiler. The strong (LVHC) gases can be burned in a dedicated incinerator or in the lime kiln. Between 2 and 3 percent of the sulphur captured in the gas cleaning unit will also leave with tail gases from the sulphur recovery unit, adding to the amount of LVHC gases.

Since precipitator ash is not generated, purging of potassium and chloride would call for another process, e.g., evaporation and crystallization of a part of a green or white liquor stream. On the other hand, control of the sodium and sulphur balances would be facilitated by the fact that Na and S are enriched in separate streams.

8.1.2 Results

Product quality

If the \( \text{H}_2\text{S} \) is reabsorbed to make a conventional green liquor there is no effect on the pulp properties. However, there is a potential to use modified cooking liquors with different
sulphide contents, in particular a polysulfide liquor. Polysulfide impregnation improves yield by retaining more hemicellulose. Pulps rich in hemicellulose sometimes exhibit lower tear strength than conventional kraft pulps.

**Environmental impact**

The physical absorption system used to remove H₂S is designed so that SO₂ emissions are on par with those from the recovery boiler. Higher removal efficiencies can be achieved but at a higher cost. To minimize CO₂ absorption, some H₂S will be allowed to slip through the reabsorption system. These gases are burned with the LVHC gases. Weak (HVLC) gases, which in the reference mill are burned in the recovery boiler, may increase emissions by 0.6 kg SO₂/ADt unless a suitable solution is developed.

**Investment and operating costs**

The extra investment for the gasification plant, including air separation, gas clean-up and the synthesis unit, in comparison with a recovery boiler, is estimated to be about EUR 150 million for the case with conventional pulping. The plant incorporates some redundancy in the gasifier island (4 x 33% gasifiers) to ensure an availability equal to that of a recovery boiler. The extra investment also includes a higher capacity lime kiln and some changes to the size of the equipment on the turbine and steam side.

The obvious operating benefit is the increased methanol surplus. Differences in operating costs are primarily due to increased maintenance. In order to determine when these schemes could be profitable, a production cost of electricity was calculated. All extra capital costs and operating costs (including changes in wood consumption) were thus allocated to the methanol produced.

**8.1.3 Potential of generating polysulfide**

The extracted hydrogen sulphide increases the flexibility of sulphur usage. For example, it is easier to divide the sulphur between different white liquor streams for modified cooking. It is also easy to produce elemental sulphur from the H₂S gas if the plant is integrated with a Claus reactor. Sulphur can be mixed with cooking liquors to produce polysulfide and then returned for use in impregnation.

**8.2 CHEMREC® technology and market status**

**8.2.1 Reference and demonstration plants**

Reference and demo plants is key to demonstrate the technology to the market and the first commercial reference plant has been applied to the CHEMREC® Booster technology. The upgrading work on the CHEMREC® Booster plant installation at the Weyerhaeuser pulp mill at New Bern was completed in June 2003. The work essentially comprised the installation of a new reactor vessel with the most recent CHEMREC® booster design features, introduced in cooperation with technical staffs of the host mill.

In addition work has commenced for plants for commercial demonstration of pressurised technology at Piteå, Sweden. A two-step approach towards the full commercialisation of the pressurised technology in support of the “electricity case” and the “green motor fuel case” is being affected. This approach includes the construction and operation of first a design verification plant, DP-1, based on experience gained from Chemrec’s original
pressurised and oxygen-driven pilot plant at Skoghall, and then, as a scale-up of DP-1, a demonstration plant for commercial operation. The first facility does not require any additional funding from Chemrec AB. The second facility will be built for a commercial operator/owner, also contributing Chemrec’s remaining funds for the development initiative.

An accelerated timetable for the commercialisation is possible; such an approach would require substantial additional up-front funding for Chemrec AB and an explicit sharing of the deemed technical risk between the plant owner, the EPC contractor, Chemrec AB, and public bodies taking an interest in the new technology.

8.2.2 Development plant in Piteå, Sweden

The oxygen-fed pressurised pilot facility which Chemrec built and operated as a development tool at the Skoghall pulp mill, Sweden, showed that the real life CHEMREC® pressurised process in its industrial version is consistent with simulations and theoretically documented results. However, the pressurised CHEMREC® BLGCC system proves a number of technical challenges, mostly related to materials of construction and process chemistry. A comprehensive development programme has therefore been implemented to address these issues in order to secure the design of the commercial demonstration system.

The platform for this work is Chemrec’s latest entity, the new Development Plant (DP-1) in Piteå, Sweden. The plant is currently under construction with 50% funding under a grant from the Swedish Energy Agency and located adjacent to the Kappa Kraftliner Mill and wall-to-wall with the ETC laboratory (EnergiTekniskt Centrum), a research facility for wood related sciences (see Figure 8.1).

![Figure 8.1. Site location: Kappa Kraftliner mill / ETC, Piteå, Sweden. Black liquor capacity: 20 tDS/24 h. Operating period: expected start second half 2004.](image-url)
The DP-1 plant will develop the oxygen blown, pressurised black liquor gasification concept enabling the realisation of commercial systems such as BLGCC, BLGMF and BLGH2. The plant is planned to be in operation during the second half of 2004.

The new plant will differ from the Skoghall plant in a number of respects, the most significant being that it will operate at 30 bar, double that of the previous Skoghall pilot-plant and in addition to a refractory lined reactor a cooled wall reactor, design based on BBP Power Plants proprietary technology, will be tested under real process conditions with different types of protection methods for the cooled wall.

The objective of the Chemrec participation in the formation of the Piteå BLG (Black Liquor Gasification) Core Competence Center and DP-1 is in the near term to secure the execution of the design verification programme to be carried out using DP-1. In the longer term the objective is to share in the production of new knowledge and insights in general in the gasification field. There is a comprehensive research programme connected to the DP-1, jointly operated by three national universities, the forestry industry, the Swedish Energy Agency, and by Chemrec AB.

Chemrec has at its disposal, via Chemrec Kraftliner in Piteå KB, the remaining €22 million of the initial Swedish Energy Agency grant, which is intended for the first large scale pressurised facilities in Sweden, DP-2, to be commercially operated and owned by Kappa Kraftliner and/or Södra Cell.

8.2.3 RENEW project

Project objective

Within the EU 6th Framework Program a proposal for a project, RENEW, has been sent by Volkswagen, where Chemrec is the leader of subproject 3. The subproject aims at increasing the conversion efficiency of the produced black liquor within the pulp and paper industry, and to simultaneously produce high-quality energy products such as renewable DME/methanol for automotive uses. The BLGMF system has the potential of increasing the Community’s use of renewable energy through replacement of fossil motor fuels. Hence, the project aims to:

- Integrate renewable energy into the energy system and increase use of renewable energy thereby reduce greenhouse gases and pollutant emissions
- Improve energy efficiency with optimal utilisation of alternative fuels in new concepts
- Introduce “polygeneration” in the mature and well functioning pulp & paper industry and will be able to quickly demonstrate the concept
- Enhance competitiveness of European industry (Chemrec has the only well protected high temperature BLG technology in the world and draws a lot of attention from USA)
- Secure energy supply from within EU.

The following main objectives for the project are identified:

- To study the technical and economical feasibility of a commercial demonstration plant of 45 MWth black liquor (300 t/d) gasification integrated with DME/methanol production as CO2 neutral motor fuels for automotive uses. The process plant would be integrated with an existing pulp mill of Södra Cell. The study would constitute input to
the decision to construct a demonstration plant creating added value for the parties involved.

- To study novel ways of pulp cooking with aim to enhance the product yield and the process integration with the black liquor gasification process and the mill.
- Carry out heavy duty engine tests with DME as the fuel to establish a DME fuel specification.

Based on the achievement of these objectives the overall dissemination and implementation plan is:

- To develop a broad interest in the European pulp and paper industry to actively support the development of such a proposed system
- To interact with the stakeholder group for implementation of investment decisions for erection of BLGMF production plants.

**Potential impact**

The critical mass for the overall programme outlined in the proposal is assured by the active involvement of the participating companies and networking and co-operation with leading research institutions in relevant disciplines. There is also a demonstrated global linkage of this effort with the US programme principally directed towards the R&D and demonstration of pressurised black liquor gasification for increased generation of green electricity and green automotive fuels.

The scale of ambition is very significant. If all primary energy available in the current global output of spent cooking liquids from the pulp industry would be commercially accessible for the new technology, some 325 TWh per year (28 million toe) of sustainable fuel supplies for combustion engines and fuel cells would be assured on a global basis. The black liquor to fuels route would add a highly significant new revenue stream to the pulp industry.

Europe has for many years been leading the development and commercialisation of pulp and paper production technologies. The change from combustion to gasification in chemical and energy recovery is a new, powerful technology shift in a mature industry. Europe is leading on a world scale with the CHEMREC® technology and there is currently no competing technology for replacement of recovery boilers. US pulp & paper industry shows big interest and with this project the market potential is large. A large number of the North American recovery boilers are approaching the end of their technical and economic life and need to be replaced. The investment for replacing a recovery boiler is in the order of $100 million; North America alone has about 250 recovery boilers.

Gasification also brings other important advantages to the pulp mill. Black liquor gasification brings a potential for a considerable pulp to wood yield increase by facilitating the introduction of more efficient cooking methods and/or sulphur free cooking chemicals. BLG also enables better environmental performance and the elimination of explosion hazards intrinsic to the use of conventional recovery boilers. The impacts on the proposed project actions on a short- and long-term basis with outcomes/results/benefits have been estimated and are summarised below:
a) Direct outcomes: Project feasibility to commercialise the technology, with project report, interim report and one final report. The result would be a planning document for the development & engineering of a BLGMF plant at a Swedish pulp mill.

b) Potential impacts: A medium-sized pulp mill could host a black liquor gasification integrated motor fuel production plant that would produce e.g. 210 000 tonnes/year of methanol, which is equivalent to about 1.2 TWh/year. Replacing the recovery boiler, this would decrease CO₂-emissions by more than 90% and NOₓ is expected to be reduced by about 50%. There would also be a decrease of negative environmental and health effects by about 50% when using methanol/DME instead of fossil energy carriers in vehicles.

The benefits described above can be available 5 years from today when commercial supply of BLGMF plants is expected and when the demand for cleaner biofuels for transport is expected to be a growing factor in sustainable development. Market penetration of the BLGMF system is linked to pulp mill capacity expansions and replacement of obsolete recovery boilers after 25–40 years service. Currently there are 23 pulp mill sites in Sweden and 23 in Finland, together producing two-thirds of all European black liquor but also a large number of pulp mills on the European continent. BLGMF plants will be an attractive option for a major part of all these mills.

8.2.4 Black liquor gasification market perspectives

With many years of under-investment, recovery plants at many sites are approaching the ultimate end of their useful life also having exhausted the possibilities for retrofits. This results in “must do” investments in recovery capacity to either supplement overloaded capacity and prolong life or to replace the capacity outright at the end of its technical/economic life.

The age distribution of conventional recovery plants in the pulp industry is described in previous section and as can be seen North American mills have the highest average age for recovery plants, followed by Sweden. The high average age for the existing conventional equipment results in reduced availability prolonged loss of capacity, lower efficiency, safety problems and environmental permit conflicts.

Increasing power prices – in particular for “green power” with CO₂ emissions certificate trading. Price projections for green electricity have since 2002 increased from USD 3¢/kWh to USD 4 or 5¢/kWh. The current CO₂ certificate programme in Sweden is trading at USD 2¢/kWh for green power, potentially adding USD 0.2¢/kWh to the totality of the electricity supply of the country. Similar programs are in effect in most of the countries where the CHEMREC® process will have markets.

Large international programs mandate the inclusion of “green automotive fuels” in the national energy supplies and the European Commission has called for the inclusion by 2010 of “green automotive fuels” for up to 6% of the total automotive fuel use in the individual member countries. In summary, current market values for green motor fuels make the use of spent cooking liquids for production of motor fuels a financially more attractive case than the case for maximum electricity production.
8.2.5 Public endorsements of CHEMREC® technology

The US pulp and paper industry joint strategy document, Agenda 2020, identifies on a consensus basis the preferred practices to be adopted by the US pulp and paper industry for the longer term. In this document the industry-wide adoption of recovery technologies based on black liquor gasification, as embodied in the CHEMREC® systems, is a key theme for the industry to meet environmental, financial, and other targets.

The Swedish Pulp and Paper Research Institute has made black liquor gasification, as embodied in the CHEMREC® systems, a key component in the perspective planning and concept development for a new benchmark pulp and paper mill concept, featuring maximum energy efficiency and minimum environmental impact.

The European Union funding programme for new energy technologies awarded the Chemrec funding application the highest point score in the July 2002 screening round. The funding given to Chemrec through this initiative was to support Chemrec’s work related to the production of green automotive fuels through black liquor gasification at the pulp mills. Chemrec has extensive co-operation within EU-funded projects with the international automotive industry regarding “green” automotive fuels.

The US Department of Energy (DOE) is expected to allocate major grant funds in support of a US pulp industry consortium, which will engage for the first commercial demonstration plant for high pressure black liquor gasification in the US. DOE has launched the visionary concept of the “bio-refinery” for the pulp mills of the future. The CHEMREC® technology to produce green motor fuels out of spent cooking liquids provides the necessary technology base required for such plant concepts. DOE has together with the US forestry industry commissioned a major study effort, recently completed by the Princeton University assisted by Larson et al [87]. This study demonstrates very attractive proforma economics for the production of green automotive fuels from spent cooking liquids with the CHEMREC® processes.

The Swedish Energy Agency has committed major grant funds in support of the first Chemrec commercial demonstration plant for high-pressure black liquor gasification in Sweden. Two world-class pulp industry leaders, SCA and Weyerhaeuser, are leading the establishment of industry user groups, in Scandinavia and North America respectively, in support of the demonstration of the high pressure CHEMREC® black liquor gasification technology.

External organizations such as Princeton University, the Swedish Pulp and Paper Research Institute, Vattenfall, and Southern Company have all made comparative studies on black liquor gasification economics with enhanced electricity production or the production of green automotive fuels. These organizations have concluded favourably on the potential of the technology embodied in the CHEMREC® pressurised systems. Their various sets of data have been found to be consistent with Chemrec’s in-house work. BOC, (British industrial gases supplier) in a recent conference publication concluded that pressurised oxygen-blown black liquor gasification, as embodied in the Chemrec systems, will be the recovery technology of choice for the pulp mill, opening new doors also for other gas applications in the pulping process.

Several internationally recognized EPC (engineering, procurement, and construction) firms serving the pulp industry have recognized the potential of the Chemrec systems and are now seeking to obtain engineering licensing agreements with Chemrec AB.
8.3 Technology and market considerations

The purpose of this section is to account for the state of the requisite technologies and the pulp industry’s perspectives on the technology and the commercial prospects for the production of green motor fuels based on the pulp industry’s spent cooking liquids.

8.3.1 The requisite core technology

The case for production of synthetic motor fuels, i.e. methanol, DME, FT diesel or hydrogen from spent cooking liquids in the pulp and paper industry is entirely contingent on the new oxygen blown pressurised entrained flow gasification technology to be referred to as the core technology. The core technology, which thus is a key requisite for the route to green motor fuels from spent cooking liquids, as described in this report, has been developed by Chemrec AB and was first demonstrated in pilot operations concluded in 2000 at the Skoghall pulp mill in central Sweden.

Investments in the development of the core technology to date has been in excess of €22 million. The technology is backed by some 100 patents. Another €26 million have been committed to the ongoing design verification and first commercial demonstration of the core technology.

8.3.2 Continuing support

A new competence centre focusing entirely on issues related to black liquor gasification, in support of the core technology, is being established in a joint effort by leading Swedish universities and Nordic forestry and energy companies with a proposed earmarked budget of some €11 million for an initial three year period. The new centre, sited at the coastal town of Piteå in northern Sweden, in the heart land of the Nordic pulp industry, is organized around a new process verification plant built by Chemrec adjacent to the Kappa Kraftliner pulp mill.

The planning for the first commercial demonstration for the pressurised oxygen driven black liquor gasification is also in progress. The two new Chemrec plants will be of great significance to demonstrate that there is a relevant technology base for green motor fuels from black liquor. Subsequent fully commercial installations of the CHEMREC® gasification technology are expected to be on offer by 2005.

8.3.3 Green motor fuels or electricity

The choice between electricity and motor fuels as the ultimate end product resulting from the application of the core technology is partly an economic optimization, partly a strategic choice for the host pulp mill considering the adoption of black liquor high pressure gasification as part of its recovery cycle. Given the current market valuation in Europe and the US for electricity and for motor fuels, electricity will give attractive returns back to the investor. But the alternative of producing green motor fuels in regions, which have a significant forestry industry, may give even better investment returns. Carbon dioxide credits will of course produce even quicker financial pay back for the investment in black liquor gasification for both cases.
8.3.4 The pulp industry perspective

The pulping industry produces pulp with an annual market value of some $45 billion per year. The CHEMREC® core technology will provide up to 5% incremental output of pulp, at the same time, it may add an additional 20% of profitable revenues for the mill, with the additional output of green motor fuels. The technology, producing green automotive fuels, valued at today’s international market prices, thus potentially adds profitable revenues to the global installed base of pulp mills of some $14 billion per year. It also makes very substantial contributions towards the reduction of carbon dioxide emissions.

In total the annual flow of primary energy in the recovery processes of the global pulp industry is some 600 TWh. Typically only an average of some 7% of this energy is recovered as electricity by the existing technology in the global pulp industry. Pressurized black liquor gasification systems, as embodied in the pressurised CHEMREC® processes, however, can profitably convert some 22% of this energy flow into electricity, equivalent to profitable incremental industry revenues of $4 billion or an increment to the pulp revenue of 9%.

The initial investment is higher than for installing traditional recovery technology for the pulp mill. But the pay-back for the incremental investment providing both the recovery capacity and the capacity to produce green automotive fuels from spent cooking liquids is very attractive. The adoption of the new technology by the pulp industry may be greatly accelerated should a carbon dioxide credit programme give additional impetus to the new process option.

8.3.5 Pulp and paper industry drivers

Recovery of energy and regeneration of pulping chemicals from spent cooking liquids, black liquor, is a critical operation for the manufacture of chemical pulp in the pulp and paper industry. The recovery boilers used are the single largest investment component in a pulp mill. The conventional technology, the Tomlinson boiler, has been around for about 70 years. Recent studies commissioned by the US Department of Energy together with a joint body of the US forestry industry conclude that the new pressurised black liquor gasification technology, as embodied by the CHEMREC® processes, will ultimately replace the Tomlinson boilers because of higher thermal efficiency and cash flow and return considerations, taking into account the additional production of saleable energy commodities based on a given amount of spent cooking liquids.

The pressurised CHEMREC® process in either of the two versions – enhanced electricity generation or production of green automotive fuels – allows enhancement of the pulping process to increase the output of pulp by up to 5% based on the same wood intake. The full-scale adoption of the CHEMREC® core technology can therefore profitably add between 20% (all electricity case) and 30% (all green motor fuels case) to global pulp industry net revenue.

The case for the core technology for the world’s pulp mills is characterized by the following factors:

- Many years of under-investment now result in “must do” replacement investments for recovery capacity.
• In the short-term one third of the 442 recovery boilers currently in operation are fully loaded and cannot be retrofitted – immediate market prospects for the basic CHEMREC® technology.

• Some 60 Tomlinson boiler units are up for complete replacement over the next 10 years. In the 20 year perspective the whole world-wide fleet of 442 Tomlinson boilers, will likely become technically obsolete because of age and/or economically obsolete due to competitive pressures from mills with supplemental production of electricity and/or green motor fuels.

• Increasing power prices – in particular for “green power”.

• Multilateral and national programs mandating “green” automotive fuels.

• Drive to increase pulp yield through application of improved cooking methods.

• The pulp industry rationalizes and wants to purchase comprehensive production processes, possibly outsourcing the recovery cycle to operators of the new technology, e.g. suppliers of electricity or motor fuels.

8.3.6 Specific industry perspectives

The pressurised CHEMREC® technology makes a proper sodium and sulphur split in the recovery cycle. This allows the introduction of modified more efficient cooking processes using enhanced cooking liquids. Yields and/or product properties are substantially improved. According to tests carried out by the Swedish Pulp and Paper Research Institute and by the industry itself an improvement of 5% in the output of pulp for a given quantity of wood is feasible.

Prime raw materials for fibres from forestry are especially essentially spoken for in Scandinavia. Wood biomass fractions from forestry, which are not primarily useful as raw materials for the production of paper fibres, may constitute the starting point for totally new products for the pulp mill in the form of synthesis products and/or green electricity. The technology which is cost-wise most competitive, actually currently the only economically viable technology, to implement such concepts for the existing pulp mills (DOE’s concept is “biorefineries”) to produce mainstream revenue generators such as green motor fuels/fuel additives etc. is offered by the pressurised Chemrec system. The pressurised Chemrec system will not add to the demand for the prime raw materials. The Chemrec concept will instead create good use for secondary raw materials from the forests, “forestry waste”, used to balance energy needs for the mill when green fuels etc are extracted.

To put things in perspective – production of green motor fuels using the CHEMREC® pressurised systems will add some 20% to the net revenue for a typical Swedish pulp mill, assuming that the product value is equal to the current cargo import price for methanol, without tax and without CO2 credits.

As a final example, if all Swedish pulp mills in the future would replace the existing Tomlinson recovery boilers with the pressurised Chemrec systems for enhanced power production, an additional production of green electricity of 13 TWh would be possible in 20 years time. This would also give an increase in revenues for the Swedish pulp industry of SEK 4 billion or €440 million per year in today’s prices.
8.4 Considerations among fuel distributors

In the last five years, the oil companies have tried to change their image externally, from pure oil companies to energy companies, and they are also engaged in different projects within alternative energy sources. Eventually the oil will cease to exist and the transformation to other energy resources is thereby inevitable. The question is when the willingness to change appears. The fuel distributors have many different reasons for either supporting or interfering in this introduction of a biofuel plant. Their starting point in general is to distribute as few fuels as possible in their distribution network, which from a cost perspective is sound. On the other hand a good product or a positive image may attract customers to the petrol station and thereby buy other products with a better profitability. In competition with other alternative fuels, low ratio blend in petrol is a way to avoid investments in the petrol stations.

Today’s distributors of fuel can be divided in two categories:

1. Companies with own refinery capacity. These are bound to their previous large investments in the production plants and are thereby less inclined to make that rapid changes into new fuels. Methanex belongs to this category, in regards to methanol.

2. Companies without own refineries that purchase the fuel they supply the market with. These companies are not bound to large investments and hence are able to more rapid adapt and offer other fuels. OK-Q8 belongs to this category.

8.4.1 Methanex

Methanex Corporation is a Vancouver based, publicly traded company engaged in the world-wide production and marketing of methanol. Methanex is the largest supplier of methanol to each of the major international markets, accounting for roughly 24% of the total world market for methanol. As such, Methanex are active in methanol marketing, logistics and sales, including taking a principal role in maintaining existing markets and in developing new applications for methanol and participating in industry restructuring and consolidation.

Production plants are located in North America, Chile and New Zealand. In addition to these manufacturing facilities they also have marketing offices in the United States, Chile, New Zealand, Belgium, the United Kingdom and Korea. Although Methanex has no production facilities in Europe, Methanex use storage terminals, which serve as “virtual plants” for the region. The amount of methanol delivered from their 150 000 tonnes storage facility in Rotterdam exceeds the production capacity of many world-scale plants. Methanex also have a number of smaller terminals in the Mediterranean and in Northern Europe.

Transport are structured around their 3 000 000 tonnes per year production hub in Chile to Rotterdam with the use of the Millennium Explorer, a new 100 000 tonnes DWT vessel, and then trans-ship the product by ship, barge, rail and truck to the customers. Methanex has formed alliances with BP, Statoil, DaimlerChrysler, BASF and XCellsis in Europe and Mitsui and Mitsubishi in Japan to evaluate what is needed to commercialise methanol fuel cell vehicles. Methanex is an associated member of the California Fuel Cell Partnership, an important multi-stakeholder group promoting the commercialisation of fuel cell electric vehicles and founding member of Fuel Cells Canada.
8.4.2 OK-Q8

OK-Q8 AB is the largest distribution company in Sweden regarding the amount of delivered petrol and number of petrol stations. OK-Q8 has been strongly engaged in the introduction of E85 (85% ethanol and 15% petrol) on the Swedish market and they continuously increase this development.

OK-Q8 is not bound to any owned refineries and is therefore considered to have the possibilities to relatively quickly make a change in their offer to the market. A change to other fuels is dependent on long-term market conditions, which according to OK-Q8 are not fulfilled today. Relevant biofuels are too expensive and the profit margins are too small in order to give enough good return. The price cannot be higher than the price on petrol if biofuel should reach a broad acceptance by the general public.

The offering of biofuel can however render a positive environmental image that can attract customers to the petrol stations. A strong environmental image is important for OK-Q8. The profit margins on fuels are presently low and an increasing proportion of the receipts comes from automotive spare parts and other daily commodities that are part of the overall offer from the petrol stations. The investments in larger petrol stations enabling the sales of other items thus are of higher priority than investment on biofuels.

The technical solutions for methanol and DME are according to OK-Q8 not a problem. They have a long experience of alcohol and the technique for handling DME is similar to the handling techniques for LPG. All new stations that are being built are adapted for alcohol fuels and the fuel tanks are in practice adapted for alcohol. When it comes to pumps and pipes they are not to the same extent adapted as the fuels tanks, but this renewal is less expensive.

Decisive for the introduction of a new fuel are the long term economic conditions and in this respect the authorities plays a central role for which fuels that will succeed and thereby existing on the market in the future. The industry has in general a lower engagement in alternative fuels arguing that profitability is weak and that technical solutions now are available. Now is the time for incentives from authorities in order to enable a positive development for alternative fuels. The single most important question is the reduction of CO₂-emissions in a cost-effective way. Trading with emission rights may play an important role in this development.

OK-Q8 advocates a low ratio blend as the most suitable way of introducing alternative fuels. That introduction can start within a year and solves the hen and egg problem that cars for biofuel will not be developed without fuel and vice versa. As the largest distribution company of biofuels in Sweden OK-Q8 are willing to act on their own if the market conditions exists. A mutual commitment from distributors is a more likely scenario.

In the same way as the E5 petrol was introduced in the region of Mälardalen, with a binding agreement by all distributors to buy the ethanol being produced by Agroetanol in Norrköping, a similar approach for other fuels could give a market opportunity and hence secure the production of fuels. OK-Q8:s strategy is presently to follow the development closely on a broad basis in order to prepare for a rapid change and are for example involved in the project to produce fuels by thermal gasification. They are however not prepared to join as a part owner in a production plant or as an operational part of the plant. That is beyond OK-Q8: s business concept. Q8 International on the contrary could possibly run or own biofuel plants.
8.5 Views and activities of Volvo

Volvo considers DME to be the major candidate as future energy carrier including fuel for heavy-duty transports. Since the early 90’s Volvo has been studying energy sources and carriers issues with a holistic perspective. A holistic perspective regarding energy carriers is essential in the long-term energy scenario.

DME is a fuel, which is well suited for compression ignition engines (diesel process). The diesel engine has a comparatively high efficiency, which today can reach 45% at the best. There should be possibilities to increase the engine efficiency to approximately 50% in ten to fifteen years. Buses for urban transport may also be hybridised and this can further increase the efficiency by 20%, thus it might be possible to reach 60% in such applications. DME has a high cetane number and ignites more readily than most conventional diesel fuels. This implies possibilities for even more improvements in energy efficiency compared to today’s diesel fuels.

Volvo has been active in developing a system for using DME is heavy-duty vehicles since 1996. In 1999 Volvo Bus presented the first DME-powered heavy-duty bus in the world, see Figure 8.2. This first generation demonstrator achieved significant reductions in NO\textsubscript{X} by 60 % and 90 % for particulates.

The second generation will be demonstrated during 2004. The demonstrator will be a Volvo FM9 truck which has been developed within the EU-project AFFORHD, see Figure 8.3. The Volvo D9A (nine litres 6 cylinders) engine which is adapted to use of DME can be fitted to trucks and buses, primarily for urban transports. The AFFORHD project has evolved well and the results will be a good platform for further development.

Figure 8.2. Volvo DME bus in 1999.
DME has the potential to significantly reduce regulated emissions without using advanced exhaust after treatment systems. There are virtually no particulate emissions linked to the combustion of DME. This is due to the absence of carbon-to-carbon bonds in the DME molecule.

The emissions of NOX from a conventional diesel engine running on DME can be reduced using high levels of exhaust gas recirculation (EGR) without increasing emissions of particulates. Advanced exhaust after treatment systems are expensive and will be needed on diesel engines running on conventional or synthetic diesel. The price of a DME driveline compared to a conventional diesel fuel driveline will therefore be on approximately the same level when complying with the suggested legislation in 2008/2009 (Euro V).

Reductions in noise levels from the combustion of DME were identified in recent rig tests. The low noise level is linked to the low injection pressure in the engine. Low external noise levels will be one of the drivers in a future scenario with increasing urbanisation and congestion.

Energy efficiency is one of the most important parameters for a future fuel candidate. Adding up the high energy efficiency figures for the production and use of DME in heavy-duty vehicles leads to a high energy efficiency from “well-to-wheels”. With hybridisation DME even exceeds the energy efficiency of a fuel cell with hydrogen produced from biomass. Efficient use of energy resources will be focused and is an essential key to the success of future alternative fuels.

The combination of a diesel engine and DME has a far-reaching potential when it comes to achieving an environmentally sound propulsion system. The CO2 emissions from biomass
derived DME does contribute very little to the greenhouse effect and the impact on global warming is much lower than when using conventional diesel. DME produced from black liquor is close to CO₂ neutral and the most efficient and environmentally sound way to introduce biomass based fuels in the heavy-duty vehicle sector.

DME can be used as a hydrogen carrier for fuel cells either directly or via reforming. The Solid Oxide Fuel Cell (SOFC) can be fed with DME without using a reformer. The SOFC has larger potentials for energy efficiency gains than the more investigated and developed Proton Exchange Membrane fuel cell (PEM).

### 8.6 Conclusions

#### 8.6.1 Driving forces

Emissions from the transport sector are growing at an alarming rate. Road transport in particular generates 85% of the transport sector’s emissions. Furthermore, 98% of the European transport market is dependent upon oil. The external energy dependence has passed 50% and will increase to more than 70% and 90% for oil in particular, in 20–30 years if nothing is done. This is viewed as economically and strategically unacceptable.

Therefore, the European Parliament and the Council of the European Union has issued a Council Directive (2003/30/EC) on the promotion of the use of biofuels for transport. The Directive sets a minimum percentage of biofuels to replace diesel or petrol for transport purposes in each Member State. By end of 2005 a 2% minimum proportion of biofuels of all petrol and diesel fuels sold on their market must be ensured with a 0.75 percentage point yearly increase to 5.75% by 2010 with a target of 20% by 2020. In addition, a Council Directive has recently been issued modifying Directive 92/81 on excise duties on mineral oils with main products eligible to differentiated excises duties until 2010.

In the long term, conversion to hydrogen is an attractive route, but this requires far greater changes to distribution systems and vehicles. Furthermore, as long as fuel cells will be much more expensive than current engines per kilowatt it is unlikely that the gain in energy efficiency or lower emissions will be enough as argument for replacement.

On the other hand, methanol can and is transported today easily at large volumes with little energy needed for the transportation work compared with the methanol energy transported. DME can be easily pressurised and handled as a liquid. Both methanol and DME show promising features as fuel candidates with the Otto and the diesel engine and comparing with other fuels from an LCA point of view, these fuels show highest energy efficiency from “well-to-wheel”.

#### 8.6.2 Benefits of black liquor

A mill that produces bleached kraft pulp generates 1.7–1.8 tonnes of black liquor (measured as dry content) per tonne of pulp. Black liquor thus represents a potential energy source of 250–500 MW per mill. As modern kraft pulp mills have a surplus of energy, they could become key suppliers of renewable fuels in the future energy system. Today, black liquor is the most important source of energy from biomass in countries such as Sweden and Finland with a large pulp and paper industry. There is growing attention to forest biofuels due to the penalty taxation of using fossil fuels for heating and electricity.
generation. It is thus of great interest to convert the primary energy in the black liquor to an energy carrier of high value.

World-wide, the pulp and paper industry currently processes about 170 million tonnes of black liquor (measured as dry solids) per year, with a total energy content of about 2 EJ, making black liquor a very significant biomass fuel. In comparison with other potential biomass sources for chemicals production, black liquor has the great advantage that it is already partially processed and exists in a pumpable, liquid form. Using black liquor as a raw material for methanol/DME production would have the following advantages:

- Biomass logistics are extremely simplified as the raw material for fuel making is handled within the ordinary operations of the pulp & paper plant
- The process is easily pressurised, which enhances fuel production efficiency
- The produced syngas has a low methane content, which optimises fuel yield
- Pulp mill economics becomes less sensitive to pulp prices as the economics are diversified with another product
- Gasification capital cost is shared between recovery of inorganic chemicals, steam production and syngas production.

### 8.6.3 Energy efficiency and economy

The BLGMF concept shows very high biomass to methanol efficiency of about 66%. From the summarising performance estimates for the two BLGMF cases, i.e. mass and energy flows, it could be seen that the requirement on external power purchase is 56.1 and 55.4 MW, respectively for the methanol and DME case. The total power generated amounts to 41.0 and 43.1 MW, respectively, electricity that is solely consumed by internal plant units.

The energy streams passing the boundary of the various plant configurations are given below in Table 8.1. At the bottom of the table, the efficiencies for the respective fuel are given divided on the two feedstocks, i.e. biomass and black liquor.

#### Table 8.1. Summary of consumed and produced energy products.

<table>
<thead>
<tr>
<th>Fuel options</th>
<th>Methanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass consumption</td>
<td>414 MW</td>
<td>408 MW</td>
</tr>
<tr>
<td>Black liquor</td>
<td>487 MW</td>
<td>487 MW</td>
</tr>
<tr>
<td>Fuel production</td>
<td>273 MW</td>
<td>275 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy efficiency (LHV)</th>
<th>56%</th>
<th>56%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black liquor to fuel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass to fuel</td>
<td>66%</td>
<td>67%</td>
</tr>
</tbody>
</table>

The results are based on a comparison with a Reference mill with a modern recovery boiler producing electricity for export. The above configurations are thus equally based and calculated on the same black liquor capacity.
It should be noted that the biomass to fuel efficiency could be significantly larger if a biomass IGCC should be used instead of the calculated power boiler with a condensing steam turbine. Nevertheless, the BLGMF plant shows, as it is a very efficient use of biomass energy to produce motor fuels.

To assess the performance economics of the BLGMF technology at the mill level an investment cost assessment was done both for a modern recovery boiler and a BLGMF plant based on the KAM2 mill at 2000 ADt/day of pulp. The net incremental capital investment cost to the Reference Mill was estimated as EUR 150 million for the BLGMF Methanol case and EUR 164 million for the BLGMF DME case, based on a pulp mill capacity of 2000 ADt/day.

The resulted production costs were EUR 29¢ per petrol equivalent litre for Methanol (SEK 2.6 per p.e.litre) and EUR 32¢ per diesel equivalent litre for DME (SEK 2.9 per d.e.litre).

Table 8.2 below summarises the production costs.

<table>
<thead>
<tr>
<th>Production costs</th>
<th>BLGMF Methanol</th>
<th>BLGMF DME</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Incremental BLGMF operating benefit</strong></td>
<td>M EUR/year</td>
<td>36.7</td>
</tr>
<tr>
<td>Production cost</td>
<td>EUR ¢/kWh</td>
<td>3.3</td>
</tr>
<tr>
<td>Production cost</td>
<td>EUR/tonne</td>
<td>182</td>
</tr>
<tr>
<td><strong>Production cost, petrol/diesel eq. litre</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>EUR ¢/equivalent litre</td>
<td>28.7</td>
</tr>
<tr>
<td><strong>Production cost, petrol/diesel eq. litre</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td>SEK/equivalent litre</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Notes:

<sup>a</sup> The methanol production cost was recalculated for the cost of one equivalent litre of petrol, using fuel properties for the specified methanol/DME fuel and petrol properties of 11.626 MWh/tonne, 750 kg/m³ at 20 °C. Similarly, the DME production cost was recalculated for diesel with properties of 11.750 MWh/tonne, 815 kg/m³ at 20 °C.

The sensitivity analysis yielded a modest sensitivity on the production cost for all parameter changes (purchased biomass, purchased electricity and incremental investment cost) except availability.

To estimate the potential revenue of methanol and DME a selling price of methanol and DME at the mill gate was calculated by assuming that the cost for the consumer should be the same as for petrol (methanol) and diesel (DME). The estimated price is about SEK 2095 (€231) per tonne of methanol, when considering the current Swedish CO₂ tax on petrol and similarly about SEK 3100 (€341) per tonne of DME.

To calculate the selling price of methanol and DME, firstly, the consumer prices are established for petrol and diesel. Then, the selling price is calculated backwards from the current consumer price, subtracting taxes and estimated distribution costs. The production costs of petrol SEK 1.83, which is the average for 2002 and SEK 2.41 for diesel can be compared with the average Brent crude oil price of USD 25 per barrel for 2002.

A cash flow Internal Rate of Return (IRR) analysis was carried out for both cases, considering the incremental investment and operating costs for the BLGMF system relative
to a new recovery boiler investment. The capital costs in this study have an accuracy of ±30% due to the level of detail included in the cost estimates and to inherent uncertainties in projecting “Nth plant” costs given the pre-commercial status of the BLGMF technology today. Future energy price levels are also uncertain and prices can vary considerably from one region of the country to another.

The incremental investment gave an IRR of 26% with a pay-back of 4.0 years for both the Methanol and the DME case (see Table 8.3).

Table 8.3. Results on return on investment.

<table>
<thead>
<tr>
<th>Results</th>
<th>Methanol</th>
<th>DME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback</td>
<td>4.0 years</td>
<td>4.0 years</td>
</tr>
<tr>
<td>Real Return on Total Capital</td>
<td>24%</td>
<td>23%</td>
</tr>
<tr>
<td>IRR</td>
<td>26%</td>
<td>26%</td>
</tr>
</tbody>
</table>

The recovered sulphur may be used in a beneficial way in a newly developed poly-sulphide cooking process to further enhance the yield of fibre from the wood. Assuming an increased pulp yield of 5% and with a capacity of 2000 ADt/day, this would give an additional revenue of EUR 16.5 million per year, calculating with an average pulp price of USD 550/ADt. The resulting additional revenue gives a significantly lower production cost, EUR 22.3¢/petrol equivalent litre (SEK 2.0 per p.e.litre) and higher returns on investment, 37% and a pay-back of 3.2 years.

8.6.4 Fuel market and possible distribution strategy

The demand for transportation fuels in Europe will increase more than the increase in energy efficiency of the vehicles. In particular, the demand for diesel fuel and middle distillate will be increasing in the future. As there will be limitations for the share of these products from crude oil, a shortage of supply of these products could be foreseen in the future. Therefore, a substitute of diesel fuel with alternative fuels would be a desirable solution. International trade with markets having a surplus of diesel fuel could be a temporary solution. To some extent, this is already being done (e.g. USA and Europe).

It should also be noted that substituting diesel fuel with alternative fuels seems to be more difficult than substituting petrol. The reason is that most of the fuel candidates are better suited for spark ignition (SI, or otto) engines. This imposes limitations on the number of fuels suitable for substitution of diesel fuel. It is also obvious that energy converters (engines) and fuels must be developed as a complete system.

DME, hydrogen (GH$_2$ and LH$_2$) and methanol had the highest efficiency, when analysed from “Well-to-Wheel”. Hydrogen could be of great interest in the long-term future but it is obvious that DME and methanol could be of great interest on a shorter timeframe. It could be noted that an otto engine optimised for the use of neat methanol could have a higher WTW efficiency than the FTD and diesel engine combination. Furthermore, otto engines are cheaper to manufacture than diesel engines and have a potential for lower exhaust emissions. DME could provide an even higher efficiency but in this case, a new fuel infrastructure has to be considered.
It can be concluded that the “best” use of methanol on a short-term horizon is as a low blending component or the use in fuel-flexible vehicles. As no new methanol compatible FFV vehicles are available at the moment, the use of methanol for low blending is most likely in the near future. In view of the limited prospects for methanol-fuelled diesel engines and fuel cells on a short-term horizon, new methanol plants should initially focus on the use of methanol as a low blending component. In addition, DME should initially be used in dedicated fleets with their own fuel infrastructure.

8.6.5 Market opportunity

There are 236 recovery boilers in the world that have not been rebuilt during the last 20 years and thus can be suitable for replacement with gasification technology. However, the majority of these boilers have quite low capacities, less than 500–600 tDS/day. Many of the smaller recovery boilers have been due to significant modifications during the years such as increasing the dry solids content of the black liquor, rebuilding of the boiler and other debottlenecking actions. Nevertheless, Chemrec BLGMF system would not be a realistic replacement alternative for small boilers.

One can assume that a mill, which is replacing an outdated recovery boiler, would desire somewhat more capacity (perhaps 25%) than the old boiler provided. A Chemrec BLGMF system is a competitive alternative for capacities of roughly 1000 tDS/day and higher. Hence, the actual market is for replacement of boilers with a capacity of 800 tDS/day or more, and which have not been built or extensively renovated in the last 20 years. There are 57 such boilers in the world today, about half of which are in the United States. The majority of the remainder is located either in Canada or in Japan.

The market for the Chemrec BLGMF system will expand in the future due to the obsolescence of more and larger recovery boilers. In short, each of the world’s 327 recovery boilers with a capacity of more than 800 tDS/day can be considered a candidate for eventual replacement by a Chemrec BLGMF system. It is becoming common for mills with multiple recovery boilers to replace several or all with one unit having a capacity of 2000 tDS/day or more. A Chemrec BLGMF system is clearly an alternative for these mills, so the market is actually larger than earlier suggested.

8.6.6 Potential fuel production and carbon dioxide reduction

From the material and energy balances, various pulp mill cases have been calculated for the energy efficiency of biomass to methanol. In the KAM2 pulp mill (2000 ADt/day) the methanol yield from black liquor is 1183 t/d (or 824 t/d DME), which is equivalent to 56.1%. The theoretical maximum production of methanol (or similarly for DME) can thus be calculated for countries in the European Union with black liquor production.

For the whole European Union as much as 61 TWh or some 11 million tonnes of methanol could be produced each year. This may be compared with current total consumption of motor fuels for the road transport sector and a calculated maximum replacement percentage (on energy basis) for each country. Finland could replace more than 50% of all transport fuels consumed, Sweden and Portugal nearly 30% and 10% respectively.

In absolute terms, Sweden and Finland could produce about 4 million tonnes each, a substantial amount. Thus, the production potential in the European Union is concentrated to a few countries, which have a large potential and for Sweden and Finland extremely high replacement potential.
For each tonne of methanol produced about 1.5 tonnes of carbon dioxide could be saved, with an average value of 85% carbon in 1 tonne petrol and with energy content of 11.626 MWh. Thus, the potential carbon dioxide reduction in EU if fully implemented is 16.4 million tonnes per year.

Finland and Sweden already fulfils the Kyoto target but have potential of reducing current emissions with 5.9 and 5.7 million tonnes of carbon dioxide or 11% and 12% of year 2000 emissions, respectively.

Outside Europe, Canada has a potential of more than 7 million tonnes of methanol to be produced. With the reported consumption of petrol and diesel fuel oil for road transport the calculated potential replacement is 7.2%, which is of course substantial and, not before noticed, offers great help in the commitment to the Kyoto protocol cut down on use of fossil fuels.

USA has the world’s largest methanol potential by amount, but not with replacement percentage. Potentially, a staggering 28 million tonnes of methanol could be produced. Astonishingly, this already equals today’s world methanol production from mainly natural gas based plants, which are all commercial and can be of 5000 tonnes per day or more. However, just the US national petrol consumption totals the equivalent of 1000 million tonnes of methanol or 21 500 PJ. The resulting possible potential replacement is about 2.2% if also the diesel fuel oil consumption would be accounted for.
9  ACKNOWLEDGEMENTS

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The authors also acknowledge Mr. J-E Kignell, who in collaboration with Mr. Ingemar Croon made the initial CHEMREC® invention, a process for chemicals and energy recovery from black liquor based on entrained flow gasification. Mr. J-E Kignell was consequently awarded a Gold Medal by the Swedish Royal Academy of Engineering Sciences for his invention.
10  ABBREVIATIONS AND ACRONYMS

ADt  Air Dry Tonne (of paper pulp)
AFPA  American Forest and Paper Association
AGR  Acid Gas Removal system
AMI  American Methanol Institute
ASU  Air Separation Unit
BFW  Boiler Feed Water
BLGCC  Integrated Black Liquor Gasification with Combined Cycle
BLGMF  Black Liquor Gasification with Motor Fuels Production
CAA  Clean Air Act
CAI  Controlled Auto Ignition
CDM  Clean Development Mechanism
CFB  Circulating Fluidised Bed
CI  Compression Ignition
DI  Direct Injection
DME  Di-Methyl Ether
DMFC  Direct Methanol Fuel Cell
DOE  U.S. Department of Energy
ECF  Elementary Chlorine Free
EGR  Exhaust Gas Recirculation
EPA  U.S. Environmental Protection Agency
ETBE  Ethyl Tertiary-Butyl Ether
EUR  Euro
FAME  Fatty Acid Methyl Esters
FAO  Food and Agriculture Organisation
FFV  Flexible Fuel Vehicle
FTD  Fischer-Tropsch Diesel
GHG  Green House Gases
GH₂  Gaseous Hydrogen
HCCI  Homogeneous Charge Compression Ignition
HRSG  Heat Recovery Steam Generator
IGCC  Integrated Gasification with Combined Cycle
IMPCA  International Methanol Producers and Consumers Association
ISAF  International Symposium on Alcohol Fuels
KAM  Ecocyclic Pulp Mill (Kretsloppsanpassat Massabruk)
LCV  Low Calorific Value
LH₂  Liquid Hydrogen
LHV  Lower Heating Value
LPG  Liquid Petroleum Gas
LVHC  Low Volume High Concentration gas systems
MFCA  Methanol Fuel Cell Alliance
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>NTP</td>
<td>Non-Thermal Plasma</td>
</tr>
<tr>
<td>PAH</td>
<td>Polycyclic Aromatic Hydrocarbons</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton Exchange Membrane Fuel Cell</td>
</tr>
<tr>
<td>PNGV</td>
<td>Partnership for a New Generation of Vehicles</td>
</tr>
<tr>
<td>PSA</td>
<td>Pressure Swing Adsorption</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Source of Energy</td>
</tr>
<tr>
<td>RME</td>
<td>Rape Methyl Ester</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reforming</td>
</tr>
<tr>
<td>SEK</td>
<td>Swedish monetary unit</td>
</tr>
<tr>
<td>SI</td>
<td>Spark Ignition</td>
</tr>
<tr>
<td>SNCR</td>
<td>Selective Non-Catalytic Reforming</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Oxide Fuel Cell</td>
</tr>
<tr>
<td>SRU</td>
<td>Sulphur Recovery Unit</td>
</tr>
<tr>
<td>STFI</td>
<td>Pulp and Paper Research Institute (Skogsindustriernas Tekniska Forskningsinstitut)</td>
</tr>
<tr>
<td>TCF</td>
<td>Totally Chlorine Free</td>
</tr>
<tr>
<td>tDS</td>
<td>Tonne Dry Substance (of black liquor)</td>
</tr>
<tr>
<td>TWC</td>
<td>Three Way Catalyst</td>
</tr>
<tr>
<td>USD</td>
<td>US Dollar</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile Organic Compounds</td>
</tr>
<tr>
<td>VVT</td>
<td>Variable ValveTrain</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-To-Wheel</td>
</tr>
</tbody>
</table>
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Technical and Commercial Feasibility Study of Black Liquor Gasification with Methanol/DME Production as Motor Fuels for Automotive Uses – BLGMF

**FINAL REPORT - APPENDICES**

Contract No. 4.1030/Z/01-087/2001

Tomas Ekbom
Mats Lindblom
Niklas Berglin
Peter Ahlvik

December 2003
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APPENDIX 2: Paper I — Efficient Production of Methanol from Biomass via Black Liquor Gasification (*Prepared for TAPPI Engineering Conference, San Diego, USA, 8–12 September, 2002*)


APPENDIX 5: Paper IV — Preliminary Economics of Black Liquor Gasification with Motor Fuels Production (*Prepared for the Colloquium on Black Liquor Combustion and Gasification, Park City, Utah, USA, 13–16 May, 2003*)
APPENDIX 1.

CHEMREC – BLACK LIQUOR GASIFICATION

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1. Background

1.1 The kraft recovery cycle

Recovery of energy and chemicals from black liquor is an essential part of the kraft pulping process. The primary chemical cycle for a typical kraft mill is depicted in Figure 1. In this process, wood chips are fed into the top of a cooking vessel, the digester. An aqueous solution of sodium hydroxide and sodium sulphide, so-called white liquor, flows upwards through the digester, counter-current to the wood chips. The white liquor neutralises the organic acids in the chemical matrix of the wood. Approximately half the dry mass of the wood, containing lignin and other organic material, dissolves into the white liquor. The remaining part, containing the wood fibres, is separated and exits the digester as pulp, which in turn eventually becomes paper.

The solution exiting the top of the digester, the black liquor contains both the dissolved organic material from the wood and the residual pulping chemicals. At this point, the black liquor is approximately 15% solids by weight, too low to sustain combustion. The solution is therefore sent through a series of evaporators to raise its solids content to 65-80% so that sustained combustion is possible.

This strong black liquor is a very viscous, dark brown liquid with the typical odour of a sulphate mill. The solid (non-water) material in the liquor contains about 21% sodium, 4% sulphur and 34% carbon. Inorganic salts, primarily sodium carbonate and sodium sulphate, account for about half the dry mass. These salts are valuable, and need to be recycled to the process.

The concentrated black liquor is burned in a large unit called a recovery boiler. The recovery boiler is the largest, single most expensive piece of equipment in a modern pulp mill. The purpose of the recovery boiler is twofold. As the black liquor burns it releases heat...
which is used to generate steam for mill processes and power production. The amount of energy produced is by no means trivial. In Scandinavian paper making countries as much as 9% of the non-nuclear energy production comes from black liquor production. Globally, the black liquor generation rate is roughly 66 000 MW.

The other function of a recovery boiler is to recover the pulping chemicals contained in the liquor. The inorganic material falls to the bottom of the boiler to form a smelt pool. This smelt flows into a dissolving tank and forms so-called green liquor, comprising primarily sodium carbonate. The green liquor undergoes a causticizing process to regenerate white liquor, thus completing the chemical cycle.

1.2 Black liquor gasification development

Kraft chemical recovery technology is a mature, fairly standardized technology. The last major innovation was the introduction of the Tomlinson recovery boiler in the 1930’s. In spite of considerable improvements over the years, the Tomlinson recovery boiler with steam cycles still has some significant drawbacks:

- Expensive equipment
- Odorous and acid gas emissions
- Risk of smelt-water explosion
- Complicated maintenance under corrosive conditions
- Low power to heat ratio
- Inflexibility in chemicals output composition.

These and other areas of concern have been the driving forces for development of new methods for recovering chemicals and energy from black liquor. One of the more promising solutions to these problems is black liquor gasification in an entrained bed. The principles of gasification are not new. A great amount of research in this area has been conducted over the years, which has resulted in a few processes implemented at commercial scale.

Work in this area performed during the late fifties and sixties by Stora Kopparberg, Svenska Cellulosa Aktiebolaget and Billerud is of particular significance for the development of modern entrained bed gasifiers for black liquor. In a departure from the AST process developed by PPRIC in Canada, scientists at SCA and Billerud developed a sulfite recovery process based on incomplete combustion of spent liquor in a down draft gasifier in the presence of oxygen (air) under reducing conditions.

In the AST and SCA-Billerud gasification concepts, direct combustion of the liquor particles was deliberately avoided. Through shock pyrolysis in hot flue gases, which contained an excess of air, the concentrated liquor was transformed into a combustible gas and solid particles, which contained essentially sodium carbonate and carbon. The reactor operating temperature was kept at 700–750 °C. All sulfurs were converted into H₂S except for the small quantities of sulfate and sulfur bound in the carbon residue. Leaching of solid residue yielded a soda solution, which was practically free of sulfide and thiosulfate.

The first SCA-Billerud pilot plant was installed in October 1959 at Jössefors in, Sweden. The plant had a capacity of around 150 kg dry solids per hour. A second larger pilot plant with a capacity of 1500 kg DS/hour was erected at the SCA mill in Östrund. The plant was
put in operation in early 1961. Findings from these early pilot plants indicated that to obtain a high carbon conversion, the gasification temperature had be close to the point where sodium salts are molten.

The rate of gasification rapidly increased over 750 °C, and at temperatures above 900 °C, the rate was very fast. In all temperature ranges, the rate of gasification was highly dependent on the size of the black liquor droplets.

Combustion of the lean gas was carried out in standard gas boilers and raw cooking acid was prepared by washing the flue gases with a soda solution. The SCA-Billerud process was never intended for kraft liquor recovery, although some process schemes were suggested and tested at pilot scale.

The second development of particular importance for the CHEMREC® process originated in process developments in the steel industry, an industry with more than a hundred years of experience in coal gasification and handling of reducing gases. In 1972, SKF Steel in Sweden started developing new metallurgical processes based on plasma technology.

The plasma technology was used for conversion of electrical energy into a high-energy density gas. As a spin-off of these metallurgical process developments, the use of plasma gas technology was considered as applicable to recovery of cooking chemicals from spent cellulose liquors.

The basic idea was that at temperatures above 1250–1300 °C, sodium carbonate would not form. Sodium carbonate added through the black liquor would decompose into sodium oxide and sodium fumes. By separating the smelt from the fuel gas and freezing the equilibrium by rapid cooling, liquor with a high content of sodium hydroxide for direct use in the digesters could be obtained.

A black liquor plasma gasification unit with gas clean up and a gas-fired boiler was targeted to replace the recovery boiler, the lime kiln and the causticizing system in a conventional kraft mill. A black liquor plasma gasifier pilot plant with a capacity of 100 kg black liquor DS/hour was erected in the Hofors steel mill in Sweden in 1985. The trials in this plant confirmed the general assumption and calculations for the new process:

- Complete gasification of the organic compounds to CO, H₂, CO₂ and H₂O occurred in a fraction of a second. The gas composition was close to the calculated equilibrium.
- Reduction efficiency was very high and almost all sulfurs were bound into sodium sulfide.
- Less than 20% of the sodium calculated on total alkali was recovered from the gasifier smelt as carbonate.

The excessive carry-over of alkali from the gasifier and a reformation of sodium carbonate during cooling in additional to the very high level of electricity consumption in the plasma generator forced the choice of a less ambitious approach in 1986.

A new pilot plant gasifier, based on recovery of standard green liquor, was erected in early 1987 at the same site. This gasifier operated in the temperature range of 900–1000 °C and at a pressure slightly above 1 bar a. Air and oxygen were used as oxidants and plasma was eliminated.
1.3 CHEMREC® kraft recovery boosters

Many recovery boilers are presently operating beyond their design capacity, often with a decreased availability and poor performance consequently. Based on the experiences from the pilot studies a black liquor capacity booster commercial concept was developed to enable pulp mills to expand recovery capacity and relieve overloaded recovery boilers.

In 1991, a commercially sized CHEMREC® black liquor gasifier was started up at the Frövifors kraft mill in Sweden. The capacity of this plant was 75 ton DS/day. Data and experience from this operation has been presented extensively in technical conference proceedings.

When Weyerhaeuser’s New Bern pulp mill began planning for its Production Optimization Project in 1992, it was natural that black liquor gasification be considered to provide the required incremental black liquor processing capacity. Pulp production would increase by about 20% and a recent retrofit of the recovery boiler had brought its production performance to the top of company and industry benchmarks.

Weyerhaeuser had been tracking the development of the CHEMREC® gasifier since its inception in 1986. Between 1988 and 1996 numerous visits were made to both the pilot plant at SKF Hofors and the demonstration plant at Frövifors. The process simplicity and ease of operation impressed mill operators and engineers. Business planners were impressed by the ability to provide incremental production capacity independent of the recovery boiler. The lack of an extended recovery boiler outage and associated learning curve for a new firing strategy were also key considerations.

The gasifier project was released on June 29, 1995 and construction began the following November. The first black liquor was fired on Dec. 12, 1996 and the first green liquor was sent to production five days later. Nine months were built into the schedule between startup of the gasifier and the new digester. This time was allotted in part to give operations a chance to learn how to operate the new technology.

The New Bern gasifier is over four times larger than the Frövifors plant. The unit is sized for a capacity of 330 metric tons of dry solids/day or (734 000 lbs. of dry solids/day). This is equivalent to an incremental pulp production rate of 188 ADMT/day of finished pulp. For the most part, the gasifier reactor vessel at New Bern was a straight geometric scale-up of the Frövifors reactor.

Three notable process changes were made between the New Bern and Frövifors systems.

At New Bern steam is used to atomize the black liquor instead of air. This has reduced the plugging tendency of the liquor nozzle. A separately fired indirect air heater is used instead of the flue gas heat exchanger employed at Frövifors. This was done to improve process reliability. Gasifier product gas is fired in a multifuel power boiler rather than a small dedicated fire tube boiler. This package boiler was designed to produce high pressure superheated steam from a combination of gasifier product gas, high and low volume NCG gases, and #6 fuel oil. Combining the process needs of incinerating NCG gases and the flexibility to burn fossil fuel helped the project economics.
1.4 Pressurized gasifier pilot plant

Encouraged by the significant interest in black liquor gasification throughout the pulp & paper industry and experiences gained in pilot and commercial gasification operations the black liquor gasification commercialization efforts were advanced towards full scale oxygen blown black liquor gasification combined cycle (BLGCC) schemes. The first step in this advancement was the erection of a pressurized pilot plant black liquor gasifier and gas clean up system at the STORA Skoghall kraft mill near Karlstad, Sweden in 1994.

Experiences and data from this pilot plant support and confirm the most of the theoretical BLGCC modeling work well documented in literature. Some of the results however, show encouraging and potentially beneficial deviation from theoretical predictions in past literature. Some of the most important findings from this pilot plant work include:

1. Confirmation that fuel gas of adequate energy value (>200 BTU/SCF) required for reliable operation of gas turbines can be produced with a pressurized, oxygen blown gasifier.
2. Demonstration of fuel gas clean-up processes employed at the pilot plant that can remove impurities, particularly alkaline carryover, to levels sufficiently low for use in modern gas turbines.
3. Demonstration of carbon conversion efficiencies >99% contrary to some earlier projections of reduced carbon conversion efficiency at elevated gasification pressure.
4. H$_2$S content in the fuel gas below that predicted by equilibrium modeling.

2. The kraft pulping cycle with black liquor gasification

From the standpoint of black liquor processing, a black liquor gasification system is analogous to a recovery boiler. It consumes black liquor and produces green liquor. Consequently, the mill requires very few modifications to other systems when a black liquor gasification system is installed.

Chemrec has developed two black liquor gasification systems suited to fulfil different needs of the host pulp mill: (1) a Booster system which operates in parallel with an existing recovery boiler to increase total black liquor processing capacity and (2) a black liquor gasification combined cycle (BLGCC) system designed to replace a recovery boiler.

2.1 Booster system

Chemrec’s Booster system is designed to relieve overloaded recovery boilers or to provide additional black liquor processing capacity. The technology involves air-blown gasification of the black liquor near atmospheric pressure. Chemrec has installed Booster units in the range 75–350 tDS/day. While there appears to be no upper limit on the size of a Booster unit from a technological point of view, practical physical limitations on reactor size restrict Booster units to a maximum of roughly 500 tDS/day.
The Booster system is installed in parallel with the mill’s existing recovery boiler (Figure 2), sharing common black liquor feed and green liquor return lines. A significant benefit of this system is that it can be installed while the recovery boiler continues to operate, thus avoiding downtime and lost production. The combustible fuel gas produced is typically burned in an auxiliary boiler for steam generation.

2.2 Black Liquor Gasification Combined Cycle (BLGCC)

Chemrec’s BLGCC system is targeted as an alternative to replace the conventional recovery boiler. The BLGCC technology is based on oxygen-blown gasification at high pressure, roughly 30 atmospheres. The high pressure and lack of dead load nitrogen associated with air gasification result in more black liquor throughput per unit volume. Consequently, the gasifier and associated equipment are relatively small, which helps keep capital costs low.

Unlike the Booster system, the BLGCC system will have several gasification reactors (e.g. 2 x 100% or 3 x 50%). This redundancy not only ensures high availability, but also provides flexibility in handling capacity. If desired, capacity can be expanded by installing additional reactors.

The BLGCC system is designed to replace the recovery boiler (Figure 3). For mills with an existing recovery boiler, the BLGCC system can be installed in parallel. When the system has been installed and proven reliable, the recovery boiler can be taken off line. This approach avoids any period of downtime associated with installation of the BLGCC system.

A Chemrec BLGCC system has several advantages over a recovery boiler; the most significant being improved energy production. With the incorporation of both gas and steam turbines, a BLGCC system can produce approximately twice as much electricity per ton of black liquor as a recovery boiler. Overall thermal efficiency is higher, as well (80% for a BLGCC system versus 70% for a recovery boiler).

Due to the natural split of sodium and sulphur in pressurised gasification, a BLGCC system opens up opportunities for advanced pulping methods that increase pulp yield and production rate. A gasification system has no risk of a smelt-water explosion like a recovery boiler.
3 Chemrec Booster technology

Chemrec’s Booster technology can be used to provide incremental recovery capacity for pulp mills, or it can be used to relieve overloaded recovery boilers and remove bottlenecks in the recovery process. The Chemrec Booster has been proven on a commercial scale and is in the process of being introduced to the marketplace.

3.1 Technical description

The CHEMREC® Booster technology is based on atmospheric air-blown gasification of black liquor in an entrained-flow reactor. Each Booster unit can provide up to roughly 500 tons dry solids (tDS)/day black liquor handling capacity, providing an additional 25% capacity for a typical 2000 tDS/day recovery boiler.

In the Booster concept (Figure 4), black liquor, air and atomising steam are fed to a burner located atop a vertically-oriented gasification reactor. The black liquor is partially oxidised to produce a combustible fuel gas comprising mostly hydrogen, carbon monoxide, carbon dioxide and nitrogen with smaller amounts of methane and hydrogen sulphide. The inorganic salts in the black liquor form a molten smelt that exits with the gas from the bottom of the gasification reactor.
The gas and smelt are rapidly cooled in the quench section by water sprays. The smelt solidifies and falls into a bath fed by weak wash in the bottom of the quench vessel where it dissolves to form green liquor. The green liquor is processed with the green liquor from the recovery boiler in the mill’s existing green liquor handling system. The cooled gas is saturated with water vapour and upon exiting the quench it passes through a venturi scrubber to remove alkali particles.

The gas is fed to a combined tray and packed scrubber system, where it is cooled and water vapour condenses. The condensate is collected in a bath at the bottom of the scrubber, and from there it is pumped to the venturi scrubber and quench sprays. Hydrogen sulphide in the gas is absorbed into weak wash in the scrubber part of the unit. Alternatively, $\text{H}_2\text{S}$ will be removed in the form of sulphur dioxide downstream of the boiler burning the Chemrec gas.

The cooled fuel gas can be fired in a power boiler for steam production. Alternately, the gas may be co-fired in the lime kiln, offsetting the fuel demands there. The overall energy efficiency of the Booster concept is not exceptional, but the Booster is designed primarily to increase black liquor handling capacity in a simplistic manner with a minimum of operator attendance.

### 4 Chemrec BLGCC technology

Chemrec black liquor gasification combined cycle (BLGCC) technology is an advanced system for black liquor gasification which is ultimately targeted as a replacement technology for the conventional recovery boiler. Development of the BLGCC technology is into the design verification phase, with construction of the first commercial demonstration unit planned for the near future.
4.1 Technical description

The Chemrec black liquor gasification combined cycle (BLGCC) concept (Figure 5) is a pressurised, oxygen-blown gasification system which incorporates a combined cycle including a gas turbine for electricity generation. Compared to conventional technology, the Chemrec BLGCC system doubles the electrical output while maintaining thermal (steam) output.

![Figure 5. Schematic diagram of Chemrec BLGCC system.](image)

The gasifier reactor and quench systems are pressurised counterparts to those in the Booster system. Instead of air as an oxidant, the BLGCC system uses oxygen supplied by an on-site air separation unit.

The quench in the BLGCC system functions similarly to that in the Booster concept. The gasifier gas and smelt are cooled by water sprays and the smelt solidifies. The smelt falls into a quench bath fed with weak wash to produce green liquor. The quench bath is at a higher temperature than in the Booster concept due to the higher steam saturation temperature. Upon leaving the quench the syngas is saturated with water vapour.

The syngas next passes through a gas cooler. Water vapour in the gas condenses in the cooler and falls to the bottom to form a sump. The condensate is recirculated back to the quench. A suitable gas cooler design is the so-called counter-current condenser, in which water vapour condenses and flows downwards against the upwards-flowing gas. This action efficiently cleans the gas from alkali and other particulates.

The cooled gas is sent to a gas cleaning system to remove sulphurous gases, primarily hydrogen sulphide. In the absorber column, hydrogen sulphide is selectively absorbed into an absorption solvent. The solvent is collected and fed to a stripping unit, where the absorbed gases are released, thus forming an off-gas stream rich in hydrogen sulphide. The hydrogen sulphide-rich gas can be treated in a number of ways. It can be fed to a Claus oven to pro-
duce elemental sulphur or it can be absorbed into white or green liquor in special short-time contacting units.

The sulphur-cleaned fuel gas is fed to a gas turbine for electricity production. The hot exhaust gas from the gas turbine passes through a heat recovery steam generator (HRSG) for steam production. High pressure steam from the HRSG can be fed to a steam turbine for additional electricity production.

4.2 Gas turbine technology

Gas turbines are key to designing an efficient combined heat and power system with a high power-to-heat ratio. Modern aeroderivative gas turbines show power generating efficiencies close to, and in some cases above, 40%. Industrial gas turbines have lower pressure ratios and slightly lower efficiencies, but are more efficient in combined heat and power generation because of the higher exhaust temperatures and smaller stack losses. Both types of gas turbines are considered for BLGCC.

Key issues for the use of gas turbines in the BLGCC concept are (1) the availability of suitable burners and modified fuel systems, (2) adequate compressor margins, and (3) the removal of alkali compounds from the black liquor.

Fortunately, BLGCC can draw on burner development for other gasification applications (coal, residual oil and biomass). To date, at least five manufacturers have developed burner and fuel systems for low and medium heating value gases.

Experience from other IGCC applications shows that sufficient compressor surge margin can be maintained throughout the operating range despite a significant increase of power output from the turbine stage.

The high temperatures experienced by the first turbine stages make them susceptible to alkali induced corrosion. Manufacturers specify lower than ppm levels of Na and K in the fuel gas as a requirement. In the Chemrec BLGCC this is achieved by removing alkali from the gas in the quench, counter-current condensing cooler and low temperature gas clean-up stages. Data from Chemrec’s pilot plant indicates that alkali concentrations in the fuel gas produced in the full-scale BLGCC system will be within turbine specifications.

4.3 Chemrec BLGCC pilot plant operations

4.3.1 Skoghall pressurised pilot plant 1994–2000

Between 1994 and spring 2000, Chemrec operated a pressurised pilot plant for gasification of black liquor. The plant was located at the STORA Skoghall paper mill near Karlstad, Sweden. The plant consisted of a refractory-lined entrained flow reactor, quench system and counter-current gas cooler/condenser. A gas cleaning system was also present on site, and consisted of an absorber/stripper arrangement which used green or white liquor to absorb hydrogen sulphide from the fuel gas. The gas cleaning system was used during the early stages of the pilot program. The fuel gas produced during gasification was flared.

The pilot plant operated at 15 bar pressure. It was originally built as an air-blown unit with a capacity of approximately 6 tDS/day black liquor. In 1997 the pilot was rebuilt to an oxygen-blown unit. The corresponding lack of nitrogen in the gas resulted in a capacity increase to 10 tDS/day.
The Skoghall pilot demonstrated that it is possible to achieve good carbon conversion during pressurised gasification while producing good quality green liquor. The fuel gas produced in the pilot has low concentrations of alkali particles. Measurements of sodium and potassium in the raw gas after the counter-current condenser give total alkali concentrations (Na+K) in the range 0.14–0.37 ppmw. This is somewhat higher than gas turbine specifications, which typically require alkali concentrations in the fuel gas to be less than 0.1 ppmw. In a full-scale BLGCC plant, the fuel gas will be further cleaned in the gas cleaning and sulphur removal stages, so the final cleaned gas will be suitably clean for the gas turbine.

More recently, the pilot was used for quench system development. Minimising carbon dioxide absorption into the green liquor is necessary in order to avoid overloading the mill’s causticising system, as described below. Great advances were made in quench design and understanding of quench chemistry.

**Advances in minimising causticising load increase**

Due to the natural increase in carbonate production that results from gasification chemistry, the Chemrec BLGCC system will always increase the causticising demand for the mill. The very best case, assuming no carbon dioxide absorption, will result in a causticising load increase of 18–20% compared to a recovery boiler. Excessive CO\textsubscript{2} absorption into the green liquor has the potential to increase the causticising load by 200–300%. Chemrec’s aim is to develop a system that increases the causticising load by less than 25%.

During the final year of operation at Skoghall, great advances were made in understanding quench chemistry and controlling CO\textsubscript{2} absorption. Tests were conducted to identify which zones of the quench and gas cooling system are most responsible for CO\textsubscript{2} absorption. Through a combination of design improvements and careful control in these zones, it was possible to improve the quality of the green liquor so that the associated increase in causticising demand dropped from 110% to 45%.

Pilot plants generally perform more poorly than their full-scale counterparts due to exaggerated boundary influences and area-to-volume ratios. It is expected that Chemrec will be able to achieve its goal of max 25% causticising load increase in a full-scale system with an advanced quench design based on experience from the pilot operations.

**4.4 BLGCC research and development program**

Chemrec has a broad research and development program aimed at resolving the technical issues, which threaten the commercial viability of the system. Most of the research focuses on issues relating to the pressurised BLGCC concept, but some of the areas concern the Booster concept as well. Much of the research is carried out in Chemrec’s DP-1 unit while other work is performed on a contract basis with universities or research institutions.

Based on the experience of the Skoghall pilot plant for pressurised black liquor gasification, operated from 1994 to 2000, a new Development Plant (DP-1) is currently under construction at the Energy Technology Centre (ETC) next door to the Kappa Kraftliner pulp and paper mill in Piteå, Sweden.

The Piteå DP-1 agreements, including the SEK 237.5 million (EUR 26 million) Swedish government grant, for 50% funding of DP-1 and the remaining balance for the following DP-2, with scale up of the gasification step and addition of remaining process units, are
vested in the limited liability company Chemrec Kraftliner in Piteå KB, created for the purpose and owned by Chemrec AB.

The Municipality of Piteå has provided approx. EUR 0.8 million funding for the new building, which Chemrec has agreed to repay through a 10 year lease agreement. The building was completed in January 2002.

The DP-1 long delivery items, the gasification reactor & quench and the refractory lining have been ordered and start up is currently planned for the fourth quarter 2004.

4.4.1 Work Programme

Chemrec’s R&D program currently has nine major areas of focus.

1. Cooled wall reactor endurance

Noell’s cooled membrane wall reactor technology has been identified as the most suitable reactor concept for the Chemrec gasification system. The very aggressive process conditions in the gasifier reactor make it necessary to test the reactor concept under real process conditions with different types of protection methods for the cooled wall. Tests will be performed in the design verification facility DP-1 using black liquor from a nearby pulp mill. When the optimum method has been identified, its endurance will be tested in long term tests followed by material analysis to confirm its suitability and integrity in the environment.

2. Burner and gasifier modelling and optimisation.

Efficient conversion of black liquor in the gasifier reactor requires optimal droplet size distribution, flow patterns and gas and smelt residence times. Synergy between the burner design, the shape of the resulting flame and the reactor geometry is necessary for optimal conversion. Burner testing, computerised fluid dynamic (CFD) modelling and pilot testing will be used to identify the optimal design for the gasifier reactor and burner.

3. Quench system design.

The quench system located below the gasifier reactor must simultaneously separate the smelt and product gas, cool the gas stream and dissolve the smelt to form green liquor, all while minimising CO₂ absorption into the green liquor. Optimisation of the quench design will be performed with the aid of CFD modelling. Quench designs will be tested in the DP-1 design verification plant.

4. Quench construction material

The quench and green liquor systems will operate at roughly 220 °C, giving rise to a much more corrosive environment than is experienced in conventional liquor recovery systems. The construction materials for these systems must tolerate the corrosive environment through many years of operation. The aim of this project is to perform long term testing of the most suitable material for construction of the quench and green liquor systems identified and pre-tested in an earlier work. A small system suitable for long term testing of materials will be built into the new DP-1 unit.
5. Green liquor chemistry at elevated temperatures

No data exists for solubility of salts in green liquor at high temperatures. Therefore, a fundamental study will be made to obtain such data up to 230 °C in the laboratory of STFI. This will require design and construction of lab scale testing equipment for operation at high temperature and pressure. In addition, the long-term manageability of the green liquor will be tested and optimised as part of the test program at the DP-1 plant.

6. Tar and trace species evolution and management

Trace species generated during gasification, including tars, nitrogen and sulphur species, may cause operational problems in a full-scale black liquor gasification system. Trace species in both gaseous and liquid streams in the new design verification plant DP-1 will be identified and quantified. The formation of significant species will be examined and schemes for their minimisation and management will be developed.

7. Selective $H_2S$ absorption in short-time contactors

The black liquor gasification process would benefit if a system for selective sulphur recovery system based on absorption of $H_2S$ by green liquor could be developed. Published reports based on laboratory work suggests that it should be possible. By keeping the contact time between gas and liquid short co-absorption of $CO_2$ can be minimised. This project aims to demonstrate such a short-time contacting device as sulphur removal step in the DP-1 plant.

8. Black liquor viscosity reduction and control

Viscosity of the black liquor is an important parameter for gasification, influencing burner operation, atomisation and conversion of the fuel in the gasifier. Low viscosity as well as stable and predictable viscosity are essential for stable operation. This program aims to develop a system for reducing and controlling black liquor viscosity through chemical and/or mechanical means.

9. Refractory material development

Identifying a refractory material which can withstand the black liquor gasification environment has been a serious challenge, and much progress has been made. But research into this area will continue, with the goal of finding a material, which can provide a service life of at least three years
APPENDIX 2.

EFFICIENT PRODUCTION OF METHANOL FROM BIOMASS VIA BLACK LIQUOR GASIFICATION
EFFICIENT PRODUCTION OF METHANOL
FROM BIOMASS VIA BLACK LIQUOR GASIFICATION

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ABSTRACT
Results are presented from a European Union research project (under the Altener II program) that investigates the technical and commercial feasibility of producing renewable motor fuels, such as methanol or dimethyl ether (DME), via oxygen-blown high-pressure black liquor gasification. Mass and energy balances are based on a comprehensive process simulation model of a kraft mill recovery system developed in the software HYSYS. Several alternatives are investigated, ranging from the conversion of the energy surplus of a modern kraft mill to complete utilization of black liquor for chemicals production and consequent biomass replacement for steam and power production. The estimated maximum potential for fossil-fuel replacement in the Swedish transport sector with black liquor-based fuels is about 25%, 20 TWh, or 3.6 million tonnes of methanol annually.

INTRODUCTION
There is a growing interest in finding ways to produce CO₂-neutral automotive fuels, by using biomass as the raw material. Many countries have committed themselves to reducing carbon dioxide emissions considerably, according to the Kyoto protocol. For example, the European Union has a target of 8% CO₂ reduction compared to 1990 levels. As one means to approach this target, the EU is in the process of adopting a directive that aims to require 2% of all motor fuel to come from renewables by 2005 (EU 2002). This fraction is then suggested to increase to 5.75% by 2010.

The primary route to produce CO₂-neutral motor fuels is through conversion of agricultural and forestry residues and organic wastes to gas (biogas), hydrocarbons (biodiesel), alcohols (methanol and ethanol), or dimethyl ether (DME). These fuels, except DME, can all be blended into gasoline or diesel to facilitate distribution. In the long term, conversion to hydrogen is an attractive route, but this requires far greater changes to distribution systems and vehicles.

A modern kraft pulp mill has a surplus of energy. Pulp mills could thus become important suppliers of renewable fuels in the future energy system. It is of great interest to convert the primary energy in the biomass to an energy carrier of high value.

In the present study, methods to convert black liquor to methanol or DME are evaluated. The conversion of other biomass feedstocks to renewable fuels has been investigated in a large number of studies, some of which discuss methanol production (Brandberg et al 1997, Bain 1992, Elam et al 1994, Ekström and Kopp 1992, Katofsky 1993, Browne 1996). Meanwhile, the pulp and paper industry is turning its attention to black liquor gasification as a possible means of improving the economic and environmental performance of the chemical pulp mill. Pressurized gasification of the black liquor has a potential to improve the mill energy efficiency, while generating conventional or modified cooking liquors and a synthesis gas (syngas). Previous concepts have mainly aimed to use the syngas in a gas turbine as part of an integrated black liquor gasification combined cycle, BLGCC, for electricity generation (Fogelholm 1993, Stigsson 1998, Larson et al 1998). A few studies have investigated the manufacture of renewable fuels from black liquor syngas (Kelleher 1983, Isaksson et al 2000).
Altener II Study – Black Liquor Gasification with Motor Fuels Production (BLGMF)

The present project to investigate black liquor gasification with motor fuels production was initiated within the EU Altener II program in 2001 and started up in February of 2002. The work is carried out by a consortium including Nykomb Synergetics (process engineering consultant), STFI (pulp and paper research company), Babcock Borsig Power (engineering company), Ecotraffic ERD\(^3\) (automotive and environmental consultant), Volvo Group (automotive producer), OK-Q8 (national fuel company) and Methanex (world-wide methanol company). The project spans over 15 months.

In the short term, the goal is to establish the preliminary engineering and a cost estimate for calculating the economic performance of a BLGMF system. In addition, the proposed actions will lead to a checklist of necessary conditions for a market introduction of renewable fuels. The long-term goal is to form a broad interest group in the European pulp and paper industry to support the development of such a system. The project comprises six main phases:

**Phase 1.** Technology selection (gas cleaning and methanol/DME synthesis) and engineering design information. Here the process plant units will be specified and battery limits be identified. The acquired engineering design information will form the basis for Phase 3 of engineering and cost estimation.

**Phase 2.** Overview of product market situation, competitive economic strategy to implementation. Here the market is analyzed and barriers identified for a market introduction of renewable transport fuels. Specifically, discussions will be held with biomass resource owners (such as pulp and paper companies) and their interest organizations, trade and development industries and engineering companies related to motor fuels production, oil companies (distributors), and motor industry companies.

**Phase 3.** Engineering design work on process units with conceptual and basic plant design establishing battery limit specifications and cost data. Here the obtained engineering design information from Phase 1 will be used as base for performing preliminary engineering of the process plant with attention to process integration with the mill’s energy and chemicals system. The release of a process package will be taken to Phase 5 for investment quotations.

**Phase 4.** Necessary conditions for implementation of a system using motor alcohols/ethers are identified. A potential stakeholder group is formed with local community representatives and entrepreneurs, national and regional energy authorities/companies, auto and oil companies. Strategic economic solutions will be sought to any technical, environmental, organizational, legal and economic barriers.

**Phase 5.** Investment estimation with capital investment cost and operating costs for the plant financial modeling.

**Phase 6.** Dissemination of project results.

In the following, results from the work in Phase 1 are presented.

### Table 1. Process heat consumption in the studied mills.

<table>
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<th>Mill Type</th>
<th>Heat Consumption (GJ/ADt)</th>
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<td>-</td>
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</tr>
<tr>
<td>MP STEAM</td>
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<td></td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>Digester</td>
<td>0.29</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Bleach Plant</td>
<td>0.27</td>
<td>0.27</td>
<td></td>
</tr>
<tr>
<td>Black Liquor Evaporation</td>
<td>2.71</td>
<td>2.71</td>
<td></td>
</tr>
<tr>
<td>Pulp Dryer</td>
<td>2.21</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Other (incl. losses)</td>
<td>0.20</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Paper Mill</td>
<td>-</td>
<td>4.82</td>
<td></td>
</tr>
<tr>
<td><strong>Total Heat from LP Steam</strong></td>
<td>5.68</td>
<td>8.30</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL PROCESS CONSUMPTION</strong></td>
<td>9.99</td>
<td>15.81</td>
<td></td>
</tr>
</tbody>
</table>

*Heat consumption internal to the cogeneration systems, e.g. in air preheaters and soot-blowers, is not included here. It is deducted from the generation side for each case.

### Table 2. Electricity consumption in the studied mills.

<table>
<thead>
<tr>
<th>Mill Type</th>
<th>Electricity Cons. (kWh/ADt)</th>
<th>Market</th>
<th>Integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>MP STEAM</td>
<td></td>
<td>-</td>
<td>100%</td>
</tr>
<tr>
<td>Digester</td>
<td></td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Bleach Plant</td>
<td></td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Oxygen Delignification</td>
<td></td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Black Liquor Evaporation</td>
<td></td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Bleach Plant</td>
<td></td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Final Screening</td>
<td></td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>Pulp Dryer</td>
<td></td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>Black Liquor Evaporation</td>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Recausticizing *</td>
<td></td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Cooling Towers *</td>
<td></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Raw Water Treatment</td>
<td></td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Waste Water Treatment</td>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Bleaching Chemicals</td>
<td></td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Other (incl. losses)</td>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Paper Mill</td>
<td></td>
<td>790</td>
<td></td>
</tr>
<tr>
<td><strong>Total Process Consumption</strong></td>
<td>761</td>
<td>1331</td>
<td></td>
</tr>
</tbody>
</table>

* Electricity consumption in these departments varies for different black liquor gasification schemes. The changes are accounted for on the generation side.

** prepared for Tappi Engineering Conference, San Diego, U.S.A., September 8-12, 2002
Figure 1. Process flow diagram for black liquor gasification combined cycle system (BLGCC) with air separation unit (ASU), acid gas removal system (AGR), Claus plant sulfur recovery, gas turbine (GT), heat recovery steam generator (HRSG), and steam turbine (ST). In a BLGMF system the GT and HRSG are replaced by a methanol plant (see Fig. 2). Note that the calculations in the present paper are based on reabsorption of $\text{H}_2\text{S}$ in green liquor rather than conversion in a Claus plant.

BASIS FOR CALCULATIONS

Reference Pulp Mill

System performance was calculated for a mill used as a reference mill in the ”Ecocyclic Pulp Mill” program, a large ongoing research effort in the Swedish pulp and paper industry. The process equipment, mode of operation and material and energy balances have been well defined for the reference mill (Jönsson et al 1998, Delin 1998) which is assumed to employ late 1990s state-of-the-art technology in all process units. Although the actual reference mill has not been built, its characteristics well match those of mills that have been built or rebuilt in the last few years. Except for the black liquor gasification systems, all the equipment assumed to be used in the reference mill is in operation in existing mills.

Data for the reference mill are presented in Tables 1 and 2. Out of the four cases defined by Jönsson et al, the ”TCF, Summer” case was used here, mainly because the steam consumption approximately corresponded to the average of the four cases. Note that process consumption has been separated from steam and power consumption inside the powerhouse, since the latter figures will vary depending on the studied configuration. The results are all based on a pulp mill capacity of 1000 ADt of pulp per day.

Recovery boilers. Background data for the reference mill include calculations for one recovery boiler, generating steam at 79 bar(a), 485°C. Recovery boiler performance was calculated with a model derived from the one used for the black liquor gasifier.

Black liquor gasification systems. The studied systems are centered around a high-temperature, oxygen-blown gasifier, and are implied to approximate the systems being developed by Chemrec and Babcock Borsig Power (Stigsson 1998, Lorson 1997). Gasifier performance was estimated with GIBBSGAS, a chemical equilibrium model based on Gibbs energy minimization (Berglin & Berntsson, 1999). The remaining systems –
Recausticizing. In the gasifier, a large fraction of the sulfur in the black liquor is converted to hydrogen sulfide. There are three principal routes to convert the concentrated H₂S stream from the acid gas removal system to sulfur in a useful form in the pulping liquor:

- reabsorption in green or white liquor
- recirculation to the gasifier
- conversion to liquid sulfur, which is dissolved to give a polysulfide liquor.

The first two routes will yield a white liquor with essentially the same composition as a conventional liquor, while the third route can be utilized for pulping modifications. The first route does also make it possible to prepare white liquors with different sulfidities, if desired. Although the sulfur split may be put to an advantage in the pulping process, it also leads to an increased load on the lime kiln. The effects on energy efficiency are described in greater detail by Larson et al (1998) and Berglin et al (1999).

Process Concept for BLGMF

Instead of burning the black liquor in the recovery boiler producing power and heat, the calorific energy of black liquor is utilized for producing liquid motor fuels. Concentrated black liquor from the pulp mill is sent to the gasification process where it is gasified with 99% oxygen in an entrained flow reactor at 32 bar, 950°C. The process produces an energy-rich synthesis gas, which is then further upgraded to Motor Fuels (MF) such as methanol, DME or hydrogen.

The black liquor gasification, as well as the synthesis steps according to the BLGMF process, is carried out under pressurized conditions. Gasification and gas cooling are preferably carried out at pressures around or above 25 bar, since a high pressure increases the temperature at which heat evolved in the gasifier can be recovered, and thus leads to an increase in steam production. On the other hand, technical conditions constrain the upper limit for the pressure. The synthesis step, such as e.g. methanol synthesis, is preferably car-
ried out in the range from about 60 bar up to about 80 bar, mainly because a high pressure favors the chemical equilibrium.

The presented gasification unit process is shown in Fig. 1 and comprises pressurized oxygen-blown black liquor gasification in an entrained flow reactor with a quench primary cooler, green liquor handling and gas cooling in a countercurrent condenser. These units are identical in the power generation and the methanol production schemes.

It is well known from many methanol production schemes where the feedstock is a sulfur-rich heavy-oil fraction or coal that the gas cleaning step must be of advanced nature in order to protect the sensitive methanol catalyst in the methanol reactor from poisoning and degradation. The synthesis gas from the black liquor gasification step contains sulfur components in the form of hydrogen sulfide and carbonyl sulfide and it also contains carbon dioxide, traces of higher hydrocarbons and possibly other traces that can be harmful for the methanol synthesis step. Technology suited to meet the high quality demand for methanol synthesis gas is available and commercially proven.

The new part of the BLGMF process begins at the outlet of the gas cooler from which the raw gas will be sent to a gas cleaning unit. The gas cleaning unit selected here is a Rectisol plant since there are stringent demands on a highly purified cleaned gas, free from H\textsubscript{2}S, COS and low in CO\textsubscript{2}, HCN and NH\textsubscript{3} will also be removed. Absorption is carried out in methanol at low temperatures. The raw syngas from the gas cooler enters a pre-wash unit using methanol for removal of tar components such as benzene, toluene, naphthalene. The removed tars are recycled to the gasifier.

Within the gas cleaning unit a CO-shift catalyst bed is included, preferably of “clean” type. The CO-shift feed is first warmed up with a small portion of IP steam in a heat exchanger, and then a sufficient amount of steam is added to reach a steam-to-dry-gas ratio of 0.9. Approximately 75% of the CO is used in the conversion of H\textsubscript{2}O to H\textsubscript{2}, so that about 50% of the whole clean gas flow needs to be shifted to reach the desired H\textsubscript{2}:CO ratio of about 2 required for the methanol synthesis. The remaining part of the clean gas flow is bypassed the CO-shift unit and the second CO\textsubscript{2} absorption unit. After CO-shifting, the gas stream is cooled down to ambient temperature via steam generation. The shifted gas then needs to be further adjusted in CO\textsubscript{2} content, and the cooled, shifted and cleaned gas is mixed to the clean by-pass stream. The cleaned outlet gas is then compressed to about 60 bar in a centrifugal compressor prior to the methanol synthesis loop. The gas cleaning unit will produce a concentrated H\textsubscript{2}S-rich gas, which is treated as described under causticizing above. In addition, the advanced type of gas cleaning selected allows extraction of a concentrated CO\textsubscript{2} stream at a few bar pressure which can be used for blanketing purposes within the pulp mill as well as purging gas if needed within the gasification unit.

Methanol synthesis. In the presented preliminary calculations, the methanol streams are considered as energy streams on LHV-basis, based on in-house data from previous projects. Part from methanol, the by-product streams from the methanol synthesis loop are the combustible purge gas and the flash gas streams. Cooling of the methanol reactor results in generation of IP steam of 30 bar. The raw methanol contains water and fusel oil that are removed as a combustible fusel oil stream and a waste water stream, and finally after distillation the purified methanol stream with water-free methanol.

Methanol distillation. The standard type methanol distillation uses a significant amount of LP-steam, which normally is of 4-5 bar. In the BLGMF plant LLP-steam of 1.4 bar is available and can be used to replace some of the LP-steam. The LP- and MP-steam from the boilers and the BLGMF plant is sent to the pulp mill.

Dimethyl Ether Production. Direct DME manufacture is very similar to the methanol synthesis loop. DME can also be efficiently manufactured from methanol. No detailed calculations were made for DME production in the present phase of the study.
The lime kiln is fired with dried pulverized bark. A fraction of the bark is used to heat the bark dryer.

Based on the lower heating value of each fuel:

<table>
<thead>
<tr>
<th>Description</th>
<th>Mill Consumers</th>
<th>Producers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electric Power</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Million (MW)</td>
<td>Million (MW)</td>
</tr>
<tr>
<td>HE Gas Turbine</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Condensing Steam</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>N2 Compressor</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>LP Compressor</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>BFW Pumps</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Liquor Pumps</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>ASU</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Syngas Compressor</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Methanol Synthesis</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Condenser</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Diesel heater</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Excess Power</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Excess Power</td>
<td>20.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Summary:

- **Power Generated, Gross (MW)**
  - Mill: 55.8 (Rb), 52.1 (BLGCC), 12.7 (BLGMF)
  - Producers: 92.3 (Rb), 76.7 (BLGCC), 5.6 (BLGMF)

- **Power Consumed in Mill (MW)**
  - Mill: -29.2 (Rb), -32.0 (BLGCC), -32.0 (BLGMF)

- **Electric Power (MW)**
  - Mill: 23.9 (Rb), 46.2 (BLGCC), 5.3 (BLGMF)

- **Total Incremental Biomass (MW)**
  - Mill: 50.3 (Rb), 111.4 (BLGCC), 219.0 (BLGMF)

- **Imported Power Efficiency (Biomass) (%)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

- **Imported Power Efficiency (Mill) (%)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

- **Feeder Efficiency (MW)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

- **Feeder Efficiency (Mill) (%)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

Table 3. Calculated performance for the BLGMF systems (with BLGCC and RB included for comparison) at 100 ADt/d.

<table>
<thead>
<tr>
<th>Description</th>
<th>Market Pulp Mill</th>
<th>Integrated Pulp &amp; Paper Mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasifier Temperature °C</td>
<td>950</td>
<td>950</td>
</tr>
<tr>
<td>HZS Processing</td>
<td>Reats</td>
<td>Reats</td>
</tr>
<tr>
<td>Reactor Gas Turbine</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Condensing Steam Turbine</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>N2 Compressor</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>LP Compressor</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>BFW Pumps</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Liquor Pumps</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>ASU</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Syngas Compressor</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Methanol Synthesis</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Condenser</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Diesel heater</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Excess Power</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Excess Power</td>
<td>20.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Summary:

- **Power Generated, Gross (MW) (Mill)**
  - Mill: 55.8 (Rb), 52.1 (BLGCC), 12.7 (BLGMF)
  - Producers: 92.3 (Rb), 76.7 (BLGCC), 5.6 (BLGMF)

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  - Mill: -29.2 (Rb), -32.0 (BLGCC), -32.0 (BLGMF)

- **Electric Power (MW) (Mill)**
  - Mill: 23.9 (Rb), 46.2 (BLGCC), 5.3 (BLGMF)

- **Total Incremental Biomass (MW) (Mill)**
  - Mill: 50.3 (Rb), 111.4 (BLGCC), 219.0 (BLGMF)

- **Imported Power Efficiency (Biomass) (%)(Mill)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

- **Imported Power Efficiency (Mill) (%)(Mill)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

- **Feeder Efficiency (Mill) (%)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

- **Feeder Efficiency (Mill) (%)**
  - Mill: 35% (Rb), 35% (BLGCC), 35% (BLGMF)

**Prepared for Tappi Engineering Conference, San Diego, U.S.A., September 8-12, 2002**
RESULTS

Calculations are presented for nine different BLGMF cases (Table 3). Cases 5-7 (market pulp mill) and 10-12 (integrated mill) assume that 100% of the black liquor is used for methanol production, and that make-up steam requirements are met by firing purchased biomass in a biomass boiler, while make-up electric power is bought from the grid. Cases 3 and 4 assume that only some of the energy surplus of the market pulp mill is used for methanol production. Incremental biomass and power requirements (bottom of Table 3) are in reference to the recovery boiler cases (#1, market pulp; #8, integrated). Also included are calculations for two BLGCC cases (Berglin et al 1999).

Market Pulp Mill

The market pulp mill has a surplus of fuel for the recovery boiler and BLGCC systems. As a basis for comparison, all black liquor and bark is used for power and steam generation and the surplus steam is fed to a condensing turbine, resulting in a net excess of power that can be sold to the grid. With a BLGMF plant, the energy balance can be shifted either towards a large production of methanol, which gives a demand for purchased biomass and power, or towards a smaller production of methanol, only utilizing biomass available at the mill.

Using surplus energy for methanol production. One approach for a BLGMF plant connected to a market pulp mill is to primarily secure the mill heat demand via the conventional recovery boiler and then to use only the surplus energy for production of motor fuels. When 25% of the black liquor is used for methanol production, there is still a power surplus (case #3). The calculations show that if 50-55% of the black liquor is used for production of methanol while the remaining black liquor is burnt in the recovery boiler, there is no need for purchased biomass. At 53%, there is no need for a bark boiler (case #4), and a small amount of falling bark can be sold. In this case about two thirds of the electric power needed for the mill must be purchased from the grid. Fig. 3 illustrates the energy flows for this case.

Full scale concept. The next step would be to allow the gasification unit to fully replace the recovery boiler and convert all black liquor to motor fuels. This means that the loss of energy in the withdrawn black liquor has to be replaced by another fuel resource or compensated in another way. Indeed, the BLGMF plant will have a much higher overall efficiency than a recovery boiler, because of reduced or eliminated losses from sootblowing, smelt cooling, and flue gas.

In the full-scale case the existing recovery boiler is either converted to a large-scale bark boiler or replaced with a new biomass-fired boiler. The new combination of processes creates a large year-around heat sink, and the mill’s need of continuous process heat makes a pulp mill a suitable location for a large-scale biofuel boiler. Figure 4 illustrates the energy flows within and around this type of case.

Integrated Pulp and Paper Mill

The base case for comparison is the recovery boiler case (#8) for an integrated pulp and paper mill. In an analogue to the full-scale concept for the market pulp mill above, using all black liquor for production of motor fuels in an integrated pulp and paper mill will require a significant amount of purchased bark. The base case recovery boiler system, (case #8) is with a slight marginal surplus, producing the required amount of steam needed but only if the tall oil is used as a internal boiler fuel or in the lime kiln. The electric power need is higher than for a market mill and there will be a demand of purchasing power of about 15 MW.

Three alternatives can be identified for handling the mill’s needs of heat and electric power:

- Firing biofuels in a retrofitted recovery boiler that has been converted to a large “bark” boiler and to purchase the remaining need of power from the grid.
- A modern type of high performance biomass boiler with back pressure turbines and reheat plus condensing steam turbine in order to manage the remaining need of power for the plants.
- Introduce a biomass IGCC with a high power-to-heat ratio, in order to improve the power-to-heat balance needed.
**Figure 3.** Energy flows for case #4.

**Figure 4.** Energy flows for case #5.
The first alternative can be attractive for mills that desire to change to BLGMF technology but still make use of an existing investment - the recovery boiler, which, is modified to use solid biofuels, and goes on to provide the mill’s need of heat and some of its need of power. A large portion of power will then have to be purchased and such a scenario is of interest for regions with a large surplus of biofuels or waste fuels and where the price of electricity is low.

The second alternative shows the potential efficiency gain for a new biomass boiler. In reality, this also means an investment in a complete new boiler and also new condensing steam turbines.

The last alternative has not yet been evaluated in detail. The heat required by the mill is 15.8 GJ/ADt, and the BLGMF plant will produce approximately 5.4 GJ/ADt (72.5 MW). Thus, to meet the entire energy need the biomass IGCC plant requires a power-to-heat ratio of 0.6. Since a biomass IGCC has the potential of reaching a power-to-heat ratio of 1.0, even the integrated mill combined with BLGMF and biomass IGCC has the potential of becoming a net exporter of power.

DISCUSSION

Costs and Benefits
Case #6 for the market pulp mill above could describe a demonstration plant for BLGMF producing some 324 tpd of methanol from biomass. Taking account of today’s market price of methanol and the Swedish CO\textsubscript{2}-tax for fossil fuels, the net value of the produced methanol (after deduction of the required power purchase) is 17.4 million USD/yr. As a comparison, the corresponding value of renewable electricity (using 4 US ¢/kWh) produced from the extra available steam put through the condensing turbine in case #1 represents about 8 million USD/yr. A detailed cost estimate will be made in Phase 3 of the project.

Availability of Biomass for Methanol Production
If all black liquor produced in Sweden were used for methanol production, 29 TWh/yr biofuel would be needed to cover the fuel needs of the pulp mills – provided that the mills need all of the heat value of the black liquor. However, there is a trend of decreased energy need in market pulp mills, due to better process integration. On the other hand, if integration with paper mills and other energy intensive industry grows, this will increase the internal energy demand.

Sweden uses about 52 TWh forest fuel per year, 45 TWh of which from domestic forests (1999). It is estimated that an additional 30 TWh biofuel can be utilized ecologically sustainably, and at the same, or only moderately higher, cost (below 1.1 US ¢/kWh). Another 30 TWh is also ecologically available, but at higher costs (>1.4 US ¢/kWh) (Lönner 1998). This means that with the pulp mills of today, the approximately 40 TWh black liquor production in Sweden could be available for methanol production, from a wood fuel supply point of view. The corresponding methanol production potential is 20 TWh/yr.

A theoretical example for an existing kraft mill in mid-east Sweden shows that with an annual production of 185,000 ADt of kraft pulp, the mill needs a forest area of approximately 180,000 hectares for its pulpwod supply. That area can at the same time produce 1040 GWh forest fuel/yr sustainably. The black liquor production needs to be replaced by approximately 1250 GWh biofuel. The difference could be covered by the additional production of biofuels within the region (Backlund 2002, Ahlgren 2001).

Other Methods of Producing Motor Fuels from Biomass
The conversion efficiency from raw biomass to methanol is, with reference to previous studies approximately 50% and may reach a few percentage points higher when further optimized (Brandberg et al 1997, Bain 1992, Elam et al 1994, Ekström and Kopp 1992, Katofsky 1993, Browne 1996). State-of-the-art biomass to methanol production comprises the following process steps: Biomass feedstock preparation involves wood storage, handling size reduction and drying, air separation to produce pure oxygen, pressurized gasification with oxygen to produce a synthesis gas, syngas cooling, purification, conditioning and methanol synthesis. However, pressurized gasification of solid biomass has some challenging features, which need further development to reach commercial status.
With a liquid biomass residual feedstock such as black liquor, the pressurization step of the gasifier feedstock stream can be performed by a simple pump instead of a lock hopper system that is necessary for solid fuel feeding systems according to state-of-the-art processes and systems for production of e.g. methanol. The burner system of the gasifier reactor can also be simplified when fed with a pumpable liquid instead of a solid feedstock.

CONCLUSIONS

Worldwide, the pulp and paper industry currently processes about 170 million tonnes of black liquor (measured as dry solids) per year, with a total energy content of about 2 EJ, making black liquor a very significant biomass fuel. In comparison with other potential biomass sources for chemicals production, black liquor has the great advantage that it is already partially processed and exists in a pumpable, liquid form. Using black liquor as a raw material for methanol production would have the following advantages:

- biomass logistics are extremely simplified as the raw material for fuel making is handled within the ordinary operations of the pulp & paper plant
- the process is easily pressurized, which enhances fuel production efficiency
- the syngas has a low methane content, which optimizes fuel yield
- pulp mill economics becomes less sensitive to pulp prices as the economics are diversified with another product
- gasification capital cost is shared between recovery of inorganic chemicals, steam production and syngas production.

ACKNOWLEDGMENTS

The European Commission, the Swedish National Energy Administration (STEM), and the Swedish Agency for Innovation Systems (VINNOVA) have sponsored the study within the Altener II program. This study is also part of the “Ecocyclic pulp mill” research program financed by MISTRA, the Swedish “Foundation for Strategic Environmental Research”.

REFERENCES


20. Backlund, B., STFI, personal communication, 2002

APPENDIX 3.

FEASIBILITY AND MARKET POTENTIAL OF BLACK LIQUOR GASIFICATION WITH METHANOL/DME PRODUCTION AS RENEWABLE CO₂ NEUTRAL MOTOR FUELS

Prepared for the ISAF XIV (International Symposium on Alcohol Fuels) Conference
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FEASIBILITY AND MARKET POTENTIAL OF BLACK LIQUOR
GASIFICATION WITH METHANOL/DME PRODUCTION AS
RENEWABLE CO₂ NEUTRAL MOTOR FUELS

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ABSTRACT

Results are presented from a European Union research project (under the Altener II program) that investigates the technical and commercial feasibility of producing renewable motor fuels, such as methanol or dimethyl ether (DME), via oxygen-blown high-pressure black liquor gasification. Several alternatives are investigated, ranging from the conversion of the energy surplus of a modern kraft mill to complete utilization of black liquor for chemicals production and consequent biomass replacement for steam and power production. A reference case shows a biomass to methanol efficiency of 64%. Estimated potential for fossil-fuel replacement in the Swedish transport sector with black liquor-based fuels is about 25%, 20 TWh, or about 4 million tonnes of methanol. For the European Union, the potential is 62 TWh or 11.5 million tonnes of methanol.

INTRODUCTION

There is a growing interest in finding ways to produce CO₂-neutral automotive fuels, by using biomass as the raw material as CO₂ is the main gas responsible for climate change. One reason is that the European Union committed at the UN’s climate conference in Kyoto in December 1997 to lower its CO₂ emissions with 8% from the level in 1990 measured as the average value of emissions during the years 2008-2012. However, emissions from the transport sector are still growing. Road transport in particular generates 85% of the transport sector’s emissions. Furthermore, 98% of the European transport market is dependent upon oil. The external energy dependence has passed 50% and will increase to more than 70%, and 90% for oil in particular, in 20-30 years if nothing is done (EC, 2000). This is viewed as economically and strategically unacceptable.

Since 1970, the number of passenger-kilometre (pkm) for cars and lorries has increased by 140% to 3800 billion pkm and goods transport tonne-kilometre (tkm) has increased by 215% to 1300 billion tkm. During same time the number of cars in the European Community trebled from 62.5 million to nearly 175 million. This trend seems to be slowing down now, but the number of private cars in the European Community is still rising by more than 3 million every year (EC, 2001). With current increase of 3% per year, it is projected that by 2020 transportation will account for a third of EU final energy carrier consumption (EC, 1999).
Therefore, the European Commission has proposed a draft European Parliament and Council Directive on the promotion of the use of biofuels for transport. The Directive sets a minimum percentage of biofuels to replace diesel or gasoline for transport purposes in each Member State. Member States must ensure by end of 2005 a 2% minimum proportion of biofuels of all gasoline and diesel fuels sold on their market with a 0.75% points increase to 5.75% by 2010 with a target of 20% by 2020 (EC, 2001). In addition, a draft council Directive has been issued modifying Directive 92/81 on excise duties on mineral oils with main products eligible to differentiated excises duties until 2010.

The primary route to produce CO₂-neutral motor fuels is through conversion of agricultural and forestry residues and organic wastes to gas (biogas), hydrocarbons (biodiesel), alcohols (methanol and ethanol), or dimethyl ether (DME). The hydrocarbons and the alcohols can be blended into gasoline or diesel to facilitate market introduction and distribution. For example, 18% of the gasoline in Sweden is today blended by 5% with ethanol (e5) without adjustments needed for the vehicles (Agroetanol, 2002). The infrastructure could likewise accommodate methanol without much change. In the long term, conversion to hydrogen is an attractive route, but this requires far greater changes to distribution systems and vehicles.

In the present study, methods to convert black liquor to methanol or Di-Methyl Ether (DME) are evaluated. The conversion of other biomass feedstocks to renewable fuels has been investigated in a large number of studies, some of which discuss methanol production (Brandberg et al 1997, Bain 1992, Elam et al 1994, Ekström and Kopp 1992, Katofsky 1993, Browne 1996). Meanwhile, the pulp and paper industry is turning its attention to black liquor gasification as a possible means of improving the economic and environmental performance of the chemical pulp mill. Pressurized gasification of the black liquor has a potential to improve the mill energy efficiency, while generating conventional or modified cooking liquors and a synthesis gas (syngas). Previous concepts have mainly aimed to use the syngas in a gas turbine as part of an integrated black liquor gasification combined cycle, BLGCC, for electricity generation (Fogelholm 1993, Stigsson 1998, Larson et al 1998). A few studies have investigated the manufacture of renewable fuels from black liquor syngas (Kelleher 1983, Isaksson et al 2000).

**KRAFT PULPING PROCESS**

The dominant route for production of pulp is the sulfur-based chemical process known as “kraft pulping”. In Fig. 1 a schematic is shown for a modern plant with the main process unit being the digester where wood chips are transformed into pulp by cooking at high temperature and pressure in a caustic solution called white liquor, which consists primarily of sodium hydroxide and sodium sulphide. The white liquor breaks down the lignin, or "glue", that holds the wood fibres together, and this lignin dissolves into the liquor. For each ton of chips that are processed, about ½ ton consists of fibres that become pulp. The other ½ ton is made up of lignin and carbohydrate residues which dissolve into the liquor. The pulp exiting the digester is washed and often bleached, and is then sent to the paper machine to form paper, or dried and sold as market pulp.

The spent cooking liquor exiting the digester, known as black liquor, contains roughly 15% solids consisting of dissolved organics from the wood and spent pulping chemicals. A typical pulp mill uses several hundred tons of chemicals per day. For both environmental and economic reasons, it is desirable to recover and recycle these chemicals. Black liquor has a high organic content from the dissolved lignin, and in concentrated form it burns in a manner similar to a heavy oil. In a modern pulp mill, the black liquor is usually concentrated to 70-80% dry solids.

Pulp mills today burn the black liquor in large recovery boilers, which are similar in principle to other large-scale boilers such as pulverised coal boilers. In the recovery boiler, the energy released from black liquor is recovered and used to generate steam to provide heat and power for the mill. In a modern pulp mill, 10-15% of the lower heating value of the black liquor can be re-
covered as electricity, with an additional 55-65% available in the form of steam for the mill, giving a total efficiency of 70-80%.

A typical modern pulp mill produces about 1800 tons of black liquor (measured as dry content) per day. This corresponds to a potential energy source of 250 MW per mill. As modern kraft pulp mill have a surplus of energy they could become important suppliers of renewable fuels in the future energy system. It is of great interest to convert the primary energy in the biomass to an energy carrier of high value. World-wide, the energy contained in black liquor fuel could be estimated to about 66,000 MW.

Figure 1. Schematic of a modern kraft pulp mill with its process units. In a BLGMF system only the recovery boiler (marked with red dotted box) has to be replaced. Note that the logistics of the biomass feedstock and distribution of the produced methanol can easily be handled at the plant.

ALTENER II STUDY

The present project to investigate Black Liquor Gasification with Motor Fuels (BLGMF) production was initiated within the EU Altener II program in 2001 and started up in February of 2002. The work is carried out by a consortium including Nykomb Synergetics (process engineering consultant), STFI (pulp and paper research company), Babcock Borsig Power (engineering company), Ecotraffic ERD³ (automotive and environmental consultant), Volvo Group (automotive producer), OK-Q8 (national fuel company) and Methanex (world-wide methanol company). The project spans over 15 months.

In the short term, the goal is to establish the preliminary engineering and a cost estimate for calculating the economic performance of a BLGMF system. In addition, the proposed actions will lead to a checklist of necessary conditions for a market introduction of renewable fuels. The long-term goal is to form a broad interest group in the European pulp and paper industry to support the development of such a system. The project comprises six main phases:

Phase 1. Technology selection (gas cleaning and methanol/DME synthesis) and engineering design information. Here the process plant units will be specified and battery limits be identified. The acquired engineering design information will form the basis for Phase 3 of engineering and cost estimation.
Phase 2. Overview of product market situation, competitive economic strategy to implementation. Here the market is analyzed and barriers identified for a market introduction of renewable transport fuels. Specifically, discussions will be held with biomass resource owners (such as pulp and paper companies) and their interest organizations, trade and development industries and engineering companies related to motor fuels production, oil companies (distributors), and motor industry companies.

Phase 3. Engineering design work on process units with conceptual and basic plant design establishing battery limit specifications and cost data. Here the obtained engineering design information from Phase 1 will be used as base for performing preliminary engineering of the process plant with attention to process integration with the mill’s energy and chemicals system. The release of a process package will be taken to Phase 5 for investment quotations.

Phase 4. Necessary conditions for implementation of a system using motor alcohols/ethers are identified. A potential stakeholder group is formed with local community representatives and entrepreneurs, national and regional energy authorities/companies, auto and oil companies. Strategic economic solutions will be sought to any technical, environmental, organizational, legal and economic barriers.

Phase 5. Investment estimation with capital investment cost and operating costs for the plant financial modeling.

Phase 6. Dissemination of project results.

In the following, results from the work in Phase 1-3 are presented.

**BASIS FOR CALCULATIONS**

**Reference Pulp Mill**

System performance was calculated for a mill used as a reference mill in the "Ecocyclic Pulp Mill" program, a large ongoing research effort in the Swedish pulp and paper industry. The process equipment, mode of operation and material and energy balances have been well defined for the reference mill (Jönsson et al 1998, Delin 1998) which is assumed to employ late 1990s state-of-the-art technology in all process units. Although the actual reference mill has not been built, its characteristics well match those of mills that have been built or rebuilt in the last few years. Except for the black liquor gasification systems, all the equipment assumed to be used in the reference mill is in operation in existing mills. The results presented in Table 1 (see Appendix) are all based on a pulp mill capacity of 1000 ADt of pulp per day.

**Recovery Boilers**

Background data for the reference mill include calculations for one recovery boiler, generating steam at 79 bar(a), 485°C. Recovery boiler performance was calculated with a model derived from the one used for the black liquor gasifier.

**Black Liquor Gasification Systems**

The studied systems are centered on a high-temperature, oxygen-blown gasifier, and are implied to approximate the systems being developed by Chemrec and Babcock Borsig Power (Stigsson 1998, Lorson 1997). Gasifier performance was estimated with GIBBSGAS, a chemical equilibrium model based on Gibbs energy minimization (Berglin & Berntsson, 1999b). The remaining systems – air separation, gas and smelt cooling, acid gas removal and recovery, methanol synthesis, combined cycle – were modeled either in the process simulator HYSYS or in spreadsheet models. Heat losses and pressure drops were estimated for each unit operation.
Recalcitrizing
In the gasifier, a large fraction of the sulfur in the black liquor is converted to hydrogen sulfide. There are three principal routes to convert the concentrated H$_2$S stream from the acid gas removal system to sulfur in a useful form in the pulping liquor:

- reabsorption in green or white liquor
- recirculation to the gasifier
- conversion to liquid sulfur, which is dissolved to give a polysulfide liquor.

The first two routes will yield white liquor with essentially the same composition as conventional liquor, while the third route can be utilized for pulping modifications. The first route does also make it possible to prepare white liquors with different sulfidivities, if desired. Although the sulfur split may be put to advantage in the pulping process, it also leads to an increased load on the lime kiln. The effects on energy efficiency are described in greater detail by Larson et al (1998) and Berglin et al (1999a).

Process Concept for BLGMF
Instead of burning the black liquor in the recovery boiler producing power and heat, the calorific energy of black liquor is utilized for producing motor fuels. Concentrated black liquor from the pulp mill is sent to the gasification process where it is gasified with 99% oxygen in an entrained flow reactor at 32 bar, 950°C. The process produces an energy-rich synthesis gas, which is then further upgraded to motor fuels, such as methanol, DME or hydrogen (see Fig. 2).

![Process flow diagram for black liquor gasification with motor fuels production](image)

Figure 2. Process flow diagram for black liquor gasification with motor fuels production. Note that to produce DME essentially only the catalyst is changed in the methanol synthesis unit.

The new part of the BLGMF process begins at the outlet of the gas cooler from which the raw gas will be sent to a gas cleaning unit. The gas cleaning unit selected here is a Rectisol plant since there are stringent demands on a highly purified cleaned gas, free from H$_2$S, COS and low in CO$_2$. HCN and NH$_3$ will also be removed. Absorption is carried out in methanol at low temperatures. The raw syngas from the gas cooler enters a pre-wash unit using methanol for removal of tar components such as benzene, toluene, naphthalene. The removed tars are recycled to the gasifier.

Within the gas cleaning unit a CO-shift catalyst bed is included, preferably of “clean” type. The CO-shift feed is first warmed up and then a sufficient amount of steam is added to reach a steam-
to-dry-gas ratio of 0.9. Approximately 75% of the CO is used in the conversion of H₂O to H₂, so that about 50% of the whole clean gas flow needs to be shifted to reach the desired H₂:CO ratio of about 2.4 required for the methanol synthesis. The remaining part of the clean gas flow is bypassed the CO-shift unit and the second CO₂ absorption unit. After CO-shifting, the gas stream is cooled down to ambient temperature via steam generation. The shifted gas then needs to be further adjusted in CO₂ content, and the cooled, shifted and cleaned gas is mixed to the clean by-pass stream. The cleaned outlet gas is then compressed to about 60 bar in a centrifugal compressor prior to the methanol synthesis loop. The gas cleaning unit will produce a concentrated H₂S-rich gas, which is treated as described under causticizing above. In addition, the advanced type of gas cleaning selected allows extraction of a concentrated CO₂ stream at a few bar pressure which can be used for blanketing purposes within the pulp mill as well as purging gas if needed within the gasification unit.

**Methanol Synthesis and Dimethyl Ether Production**

In the presented preliminary calculations, the methanol streams are considered as energy streams on LHV-basis, based on in-house data from previous projects. Part from methanol, the by-product streams from the methanol synthesis loop are the combustible purge gas and the flash gas streams. Cooling of the methanol reactor results in generation of IP steam of 30 bar. The raw methanol contains water and fusel oil that are removed as a combustible fusel oil stream and a waste water stream, and finally after distillation the purified methanol stream with water-free methanol.

Direct DME manufacture is very similar to the methanol synthesis loop. DME can also be efficiently manufactured from methanol. No detailed calculations were made for DME production in the present phase of the study.

**AVAILABILITY OF BLACK LIQUOR**

The estimated black liquor production with projections to 2025 based on previous 35 years yearly production records is given in Fig. 3 for the world and in Fig. 4 for the European Union. Main world producer is North America with more than half of the total world production.

![Estimated Black Liquor Production (World)](image)

*Figure 3. Estimated black liquor production in the world (2000). Source: FAOSTAT, 2001.*
Second largest producer is Europe with Sweden (39 TWh) and Finland (40 TWh) as main producers. Asia is third largest producer equalling Sweden and Finland together, with Japan as largest producer (50 TWh).

If all black liquor produced in Sweden were used for methanol production, 29 TWh/yr biofuel would be needed to cover the fuel needs of the pulp mills – provided that the mills need all of the heat value of the black liquor. However, there is a trend of decreased energy need in market pulp mills, due to better process integration. On the other hand, if integration with paper mills and other energy intensive industry grows, this will increase the internal energy demand.

Sweden uses about 52 TWh forest fuel per year, 45 TWh of which from domestic forests (1999). It is estimated that an additional 30 TWh biofuel can be utilized ecologically sustainably, and at the same, or only moderately higher, cost (below 1.1 US ¢/kWh). Another 30 TWh is also ecologically available, but at higher costs (>1.4 US ¢/kWh) (Lönner 1998). This means that with the pulp mills of today, the approximately 40 TWh black liquor production in Sweden could be available for methanol production, from a wood fuel supply point of view. The corresponding methanol production potential is about 21 TWh/yr.

A theoretical example for an existing kraft mill in mid-east Sweden shows that with an annual production of 185,000 ADt of kraft pulp, the mill needs a forest area of approximately 180,000 hectares for its pulpwood supply. That area can at the same time produce 1040 GWh forest fuel/yr sustainably. The black liquor production needs to be replaced by approximately 1250 GWh biofuel. The difference could be covered by the additional production of biofuels within the region (Backlund 2002, Ahlgren 2001).

**RESULTS**

Calculations are presented for nine different BLGMF cases (see Appendix). Cases 5-7 (market pulp mill) and 10-12 (integrated mill) assume that 100% of the black liquor is used for methanol production, and that make-up steam requirements are met by firing purchased biomass in a bio-

*Prepared for the ISAF XIV (International Symposium on Alcohol Fuels) Conference Phuket, Thailand, 12 – 15 November, 2002*
mass boiler, while make-up electric power is bought from the grid. Cases 3 and 4 assume that only some of the energy surplus of the market pulp mill is used for methanol production. Incremental biomass and power requirements (bottom of Table 2) are in reference to the recovery boiler cases (#1, market pulp; #8, integrated). Also included are calculations for two BLGCC cases (Berglin et al 1999).

Market Pulp Mill
The market pulp mill has a surplus of fuel for the recovery boiler and BLGCC systems. As a basis for comparison, all black liquor and bark is used for power and steam generation and the surplus steam is fed to a condensing turbine, resulting in a net excess of power that can be sold to the grid. With a BLGMF plant, the energy balance can be shifted either towards a large production of methanol, which gives a demand for purchased biomass and power, or towards a smaller production of methanol, only utilizing biomass available at the mill.

The next step would be to allow the gasification unit to fully replace the recovery boiler and convert all black liquor to motor fuels. This means that the loss of energy in the withdrawn black liquor has to be replaced by another fuel resource or compensated in another way. Indeed, the BLGMF plant will have a much higher overall efficiency than a recovery boiler, because of reduced or eliminated losses from sootblowing, smelt cooling, and flue gas.

In the full-scale case the existing recovery boiler is either converted to a large-scale bark boiler or replaced with a new biomass-fired boiler. The new combination of processes creates a large year-around heat sink, and the mill’s need of continuous process heat makes a pulp mill a suitable location for a large-scale biofuel boiler. Figure 5 illustrates the energy flows within and around this type of case.

Energy Efficiency
A Sankey diagram of the BLGMF system based on case #5 is presented in Figure 5. The pulp and paper processing plant have the same energy demand still in the form of power and heat, but as the black liquor is withdrawn from the mill additional biomass has to be added to a biomass boiler in order to provide the necessary energy. Therefore the energy in the black liquor is practically substituted with the extra biomass energy converted into power and heat. Additional power is needed and supplied from an external source (e.g. a biomass boiler plant with an assumed electrical efficiency of 35%).

The biomass to methanol efficiency, designated as $\eta_{\text{methanol}}$, can be expressed as the ratio of produced methanol and consumed biomass, black liquor, incremental electricity (calculated as equivalent needed biomass at 35%) minus exported steam (with case #5 values).

$$\eta_{\text{methanol}} = \frac{\text{methanol}}{\text{biomass} + \text{black liquor} - \text{steam}} = 64.5\%$$

The black liquor to methanol efficiency, designated as $\varphi_{\text{methanol}}$, can be expressed as the ratio of produced methanol and consumed black liquor (with case #5 values).

$$\varphi_{\text{methanol}} = \frac{\text{methanol}}{\text{black liquor}} = 55.6\%$$
The energy efficiency of biomass to methanol varies for the different cases with 64-71% with case #5 (64.5%) as the most the probable commercialisation case in the near future (reference case). The energy efficiency of the BLGMF concept is probably that of the highest noted in the literature for conversion of biomass to a motor fuel. The black liquor to methanol efficiency is likewise high and 55.6% for case #5.
Using $\varphi_{\text{methanol}}$ for case #5 on the estimated black liquor production in the European Union (Fig. 4) theoretical values of methanol production is given in Table 2, with as much as 62 TWh for the whole European Union. This may be compared with current total consumption of motor fuels (EC, 2002) for the road transport sector and percentages are given for maximum percentage replacement (on energy basis).

Table 2. European Union: Motor Fuel Consumption and Black Liquor Production with Estimated Methanol Replacement

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>M toe</td>
<td>PJ</td>
<td>TWh</td>
</tr>
<tr>
<td>Austria</td>
<td>5.4</td>
<td>226.1</td>
</tr>
<tr>
<td>Belgium</td>
<td>7.6</td>
<td>318.2</td>
</tr>
<tr>
<td>Denmark</td>
<td>3.8</td>
<td>159.1</td>
</tr>
<tr>
<td>Finland</td>
<td>3.7</td>
<td>154.9</td>
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<tr>
<td>France</td>
<td>41.8</td>
<td>1,750.2</td>
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<tr>
<td>Germany</td>
<td>57.5</td>
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<tr>
<td>Greece</td>
<td>5.3</td>
<td>221.9</td>
</tr>
<tr>
<td>Ireland</td>
<td>3.0</td>
<td>125.6</td>
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<td>Italy</td>
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<td>Luxembourg</td>
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<tr>
<td>Portugal</td>
<td>5.2</td>
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</tr>
<tr>
<td>Spain</td>
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</tr>
<tr>
<td>Sweden</td>
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</tr>
<tr>
<td>The Netherlands</td>
<td>9.5</td>
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<tr>
<td>United Kingdom</td>
<td>38.0</td>
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<tr>
<td><strong>EU (15)</strong></td>
<td>251</td>
<td>10,493</td>
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* Taken from European Commission's Energy and Transport Statistics (EC, 2002)
** Based on case #5 with black liquor to methanol efficiency of 55.6%

DISCUSSION

Costs and Benefits
Case #4 for the market pulp mill above could describe a demonstration plant for BLGMF producing some 324 tpd of methanol from biomass. Taking account of today’s market price of methanol and the Swedish CO\textsubscript{2}-tax for fossil fuels, the net value of the produced methanol (after deduction of the required power purchase) is 17.4 million USD/yr. As a comparison, the corresponding value of renewable electricity (using 4 US¢/kWh) produced from the extra available steam put through the condensing turbine in case #1 represents about 8 million USD/yr. A detailed cost analysis will be made in Phase 5 of the project.

CONCLUSIONS

World-wide, the pulp and paper industry currently processes about 170 million tonnes of black liquor (measured as dry solids) per year, with a total energy content of about 2 EJ, making black liquor a very significant biomass fuel. In comparison with other potential biomass sources for chemicals production, black liquor has the great advantage that it is already partially processed and exists in a pumpable, liquid form. Using black liquor as a raw material for methanol production would have the following advantages:

- biomass logistics are extremely simplified as the raw material for fuel making is handled within the ordinary operations of the pulp & paper plant
- the process is easily pressurized, which enhances fuel production efficiency
- the syngas has a low methane content, which optimizes fuel yield
- pulp mill economics becomes less sensitive to pulp prices as the economics are diversified with another product
- gasification capital cost is shared between recovery of inorganic chemicals, steam production and syngas production.

The BLGMF concept shows very high biomass to methanol efficiency of about 64% and of the European countries Sweden and Finland have largest potential to produce motor fuels from black liquor and replace current fossil fuel consumption.

ACKNOWLEDGMENTS

The European Commission, the Swedish National Energy Administration (STEM), and the Swedish Agency for Innovation Systems (VINNOVA) have sponsored the study within the Alte ner II program. This study is also part of the “Ecocyclic pulp mill” research program financed by MISTRA, the Swedish “Foundation for Strategic Environmental Research”.

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### Table 1. Calculated performance for the BLGMF systems (with BLGCC and RB included for comparison) at 1000 ADt/d.

<table>
<thead>
<tr>
<th>Description</th>
<th>Market Pulp Mill</th>
<th>Integrated Pulp &amp; Paper Mill</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>BLGCC</td>
</tr>
<tr>
<td>Case No.</td>
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<td>2</td>
</tr>
<tr>
<td>Gasifier Temperature °C</td>
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<td>950</td>
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<tr>
<td>Gasifier Pressure bar(a)</td>
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</tr>
<tr>
<td>KJ Processing Rate Kg/h</td>
<td>Reads</td>
<td>Reads</td>
</tr>
<tr>
<td>Fraction of BSL to BLGMF %</td>
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<td>0%</td>
</tr>
<tr>
<td>Integration</td>
<td>Integr</td>
<td>Integr</td>
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<tr>
<td>准备</td>
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<tr>
<td>HP Steam Temperature °C</td>
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#### ELECTRIC POWER

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<td>Steam flashed</td>
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<tr>
<td>MWe</td>
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<td>Gasification</td>
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<tr>
<td>Condenser Steam</td>
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<td>-</td>
</tr>
<tr>
<td>CO</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Produced</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ASU</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LL</td>
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<td>-</td>
</tr>
<tr>
<td>RP</td>
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<tr>
<td>Misc</td>
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</tr>
<tr>
<td>Summary</td>
<td>Power Generated, Gross</td>
<td>55.8</td>
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<tr>
<td>Power Consumed in Mill</td>
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<td>Excess Power</td>
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<td>Excess Power kMW/kADE</td>
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<td>Total</td>
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#### Production

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#### Note

- The lime kiln is fired with dried pulverized bark. A fraction of the bark is used to heat the bark dryer.
- Based on the lower heating value of each fuel:
- The calculations were done for a gas turbine of fixed size (the General Electric 6FA); the results in the table have been scaled to the generic 1000 ADt/d mill.
APPENDIX 4.

BLACK LIQUOR GASIFICATION WITH METHANOL/DME PRODUCTION AS RENEWABLE CO₂ NEUTRAL MOTOR FUELS
BLACK LIQUOR GASIFICATION WITH METHANOL/DME PRODUCTION AS RENEWABLE CO$_2$ NEUTRAL MOTOR FUELS

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ABSTRACT

Results are presented from a European Union research project (under the Altener II program) that investigates the technical and commercial feasibility of producing renewable motor fuels, such as methanol or dimethyl ether (DME), via oxygen-blown high-pressure black liquor gasification. Several alternatives are investigated, ranging from the conversion of the energy surplus of a modern kraft mill to complete utilization of black liquor for chemicals production and consequent biomass replacement for steam and power production. A reference case shows a biomass to methanol efficiency of 64%. Estimated potential for fossil-fuel replacement in the Swedish transport sector with black liquor-based fuels is about 25%, 20 TWh, or about 4 million tonnes of methanol. For the European Union, the potential is 62 TWh or 11.5 million tonnes of methanol.

INTRODUCTION

There is a growing interest in finding ways to produce CO$_2$-neutral automotive fuels, by using biomass as the raw material as CO$_2$ is the main gas responsible for climate change. One reason is that the European Union committed at the UN’s climate conference in Kyoto in December 1997 to lower its CO$_2$ emissions with 8% from the level in 1990 measured as the average value of emissions during the years 2008-2012. However, emissions from the transport sector are still growing. Road transport in particular generates 85% of the transport sector’s emissions. Furthermore, 98% of the European transport market is dependent upon oil. The external energy dependence has passed 50% and will increase to more than 70%, and 90% for oil in particular, in 20-30 years if nothing is done (EC, 2000). This is viewed as economically and strategically unacceptable.

Since 1970, the number of passenger-kilometre (pkm) for cars and lorries has increased by 140% to 3800 billion pkm and goods transport tonne-kilometre (tkm) has increased by 215% to 1300 billion tkm. During same time the number of cars in the European Community trebled from 62.5 million to nearly 175 million. This trend seems to be slowing down now, but the number of private cars in the European Community is still rising by more than 3 million every year (EC, 2001). With current increase of 3% per year, it is projected that by 2020 transportation will account for a third of EU final energy carrier consumption (EC, 1999).
KRAFTE PULPING PROCESS

The dominant route for production of pulp is the sulfur-based chemical process known as “kraft pulping”. In Fig. 1 a schematic is shown for a modern plant with the main process unit being the digester where wood chips are transformed into pulp by cooking at high temperature and pressure in a caustic solution called white liquor, which consists primarily of sodium hydroxide and sodium sulphide. The white liquor breaks down the lignin, or "glue", that holds the wood fibres together, and this lignin dissolves into the liquor. For each ton of chips that are processed, about ½ ton consists of fibres that become pulp. The other ½ ton is made up of lignin and carbohydrate residues which dissolve into the liquor. The pulp exiting the digester is washed and often bleached, and is then sent to the paper machine to form paper, or dried and sold as market pulp.

The spent cooking liquor exiting the digester, known as black liquor, contains roughly 15% solids consisting of dissolved organics from the wood and spent pulping chemicals. A typical pulp mill uses several hundred tons of chemicals per day. For both environmental and economic reasons, it is desirable to recover and recycle these chemicals. Black liquor has a high organic content from the dissolved lignin, and in concentrated form it burns in a manner similar to a heavy oil. In a modern pulp mill, the black liquor is usually concentrated to 70-80% dry solids.

Pulp mills today burn the black liquor in large recovery boilers, which are similar in principle to other large-scale boilers such as pulverised coal boilers. In the recovery boiler, the energy released from black liquor is recovered and used to generate steam to provide heat and power for the mill. In a modern pulp mill, 10-15% of the lower heating value of the black liquor can be recovered as electricity, with an additional 55-65% available in the form of steam for the mill, giving a total efficiency of 70-80%.

A typical modern pulp mill produces about 1800 tons of black liquor (measured as dry content) per day. This corresponds to a potential energy source of 250 MW per mill. As modern kraft pulp mill have a surplus of energy they could become important suppliers of renewable fuels in the future energy system. It is of great interest to convert the primary energy in the biomass to an energy carrier of high value. World-wide, the energy contained in black liquor fuel could be estimated to about 66,000 MW.

Figure 1. Schematic of a modern kraft pulp mill with its process units. In a BLGMF system only the recovery boiler (marked with red dotted box) has to be replaced. Note that the logistics of the biomass feedstock and distribution of the produced methanol can easily be handled at the plant.
ALTENER II STUDY

The present project to investigate Black Liquor Gasification with Motor Fuels (BLGMF) production was initiated within the EU Altener II program in 2001 and started up in February of 2002. The work is carried out by a consortium including Nykomb Synergetics (process engineering consultant), STFI (pulp and paper research company), Babcock Borsig Power (engineering company), Ecotraffic ERD (automotive and environmental consultant), Volvo Group (automotive producer), OK-Q8 (national fuel company) and Methanex (world-wide methanol company). The project spans over 15 months.

In the short term, the goal is to establish the preliminary engineering and a cost estimate for calculating the economic performance of a BLGMF system. In addition, the proposed actions will lead to a checklist of necessary conditions for a market introduction of renewable fuels. The long-term goal is to form a broad interest group in the European pulp and paper industry to support the development of such a system. The project is ongoing.

RESULTS

Market Pulp Mill
The market pulp mill has a surplus of fuel for the recovery boiler and BLGCC systems. As a basis for comparison, all black liquor and bark is used for power and steam generation and the surplus steam is fed to a condensing turbine, resulting in a net excess of power that can be sold to the grid. With a BLGMF plant, the energy balance can be shifted either towards a large production of methanol, which gives a demand for purchased biomass and power, or towards a smaller production of methanol, only utilizing biomass available at the mill.

The next step would be to allow the gasification unit to fully replace the recovery boiler and convert all black liquor to motor fuels. In the full-scale case the existing recovery boiler is either converted to a large-scale bark boiler or replaced with a new biomass-fired boiler. The new combination of processes creates a large year-around heat sink, and the mill’s need of continuous process heat makes a pulp mill a suitable location for a large-scale biofuel boiler. Figure 5 illustrates the energy flows within and around this type of case.

Energy Efficiency
A Sankey diagram of the BLGMF system based on case #5 is presented in Figure 2. The pulp and paper processing plant have the same energy demand still in the form of power and heat, but as the black liquor is withdrawn from the mill additional biomass has to be added to a biomass boiler in order to provide the necessary energy. Therefore the energy in the black liquor is practically substituted with the extra biomass energy converted into power and heat. Additional power supplied from an external source (e.g. a biomass boiler plant).

The biomass to methanol efficiency, designated as $\eta_{methanol}$, can be expressed as the ratio of produced methanol and consumed biomass, black liquor, incremental electricity (calculated as equivalent needed biomass at 35%) minus exported steam (with case #5 values).

$$\eta_{methanol} = \frac{\text{methanol}}{\text{biomass + black liquor - steam}} = 64.5\%$$

The energy efficiency of biomass to methanol varies for the different cases with 64-71% with case #5 (64.5%) as the most probable commercialisation case in the near future (reference case). The energy efficiency of the BLGMF concept is probably that of the highest noted in the literature for conversion of biomass to a motor fuel. The black liquor to methanol efficiency is likewise high and 55.6% for case #5.

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Eskilstuna, Sweden, 11 – 12 March, 2003
Figure 2. Sankey diagram of the BLGMF system with respective energy streams based on case #5. The system needs additional power (from an external biomass boiler).

Using calculated values and black liquor production in the European Union theoretical values of methanol production is given in Table 2, with as much as 62 TWh for the whole European Union. This may be compared with current total consumption of motor fuels for the road transport sector and percentages are given for maximum percentage replacement (on energy basis).

Table 2. European Union: Motor Fuel Consumption and Black Liquor Production with Estimated Methanol Replacement

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>M toe PJ TWh</td>
<td>PJ PJ TWh</td>
<td>PJ PJ TWh %</td>
</tr>
<tr>
<td>Austria</td>
<td>5.4 226.1 62.8 13.5 3.8 7.5 2.1</td>
<td>3.3%</td>
</tr>
<tr>
<td>Belgium</td>
<td>7.6 318.2 88.4 4.8 1.3 2.7 0.7</td>
<td>0.8%</td>
</tr>
<tr>
<td>Denmark</td>
<td>3.8 159.1 44.2 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Finland</td>
<td>3.7 154.9 43.0 142.6 39.6 79.3 22.1</td>
<td>51.2%</td>
</tr>
<tr>
<td>France</td>
<td>41.8 1 750.2 486.1 32.6 9.1 18.1 5.0</td>
<td>1.0%</td>
</tr>
<tr>
<td>Germany</td>
<td>57.5 2 407.5 668.7 0.1 0.0 0.1 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Greece</td>
<td>5.3 221.9 61.6 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Ireland</td>
<td>3.0 125.6 34.9 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Italy</td>
<td>36.7 1 536.6 426.8 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>1.4 58.6 16.3 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Portugal</td>
<td>5.2 217.7 60.5 33.2 9.2 18.4 5.1</td>
<td>8.5%</td>
</tr>
<tr>
<td>Spain</td>
<td>25.3 1 059.3 294.2 32.3 9.0 18.0 5.0</td>
<td>1.7%</td>
</tr>
<tr>
<td>Sweden</td>
<td>6.4 268.0 74.4 139.3 38.7 77.5 21.5</td>
<td>28.9%</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>9.5 397.8 110.5 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>38.0 1 591.1 441.9 0.0 0.0 0.0 0.0</td>
<td>0.0%</td>
</tr>
<tr>
<td><strong>EU (15)</strong></td>
<td>251 10 493 2 914 398 111 222 62</td>
<td></td>
</tr>
</tbody>
</table>

* Taken from European Commission's Energy and Transport Statistics (EC, 2002)

** Based on case #5 with black liquor to methanol efficiency of 55.6%
CONCLUSIONS

World-wide, the pulp and paper industry currently processes about 170 million tonnes of black liquor (measured as dry solids) per year, with a total energy content of about 2 EJ, making black liquor a very significant biomass fuel. In comparison with other potential biomass sources for chemicals production, black liquor has the great advantage that it is already partially processed and exists in a pumpable, liquid form. Using black liquor as a raw material for methanol production would have the following advantages:

- biomass logistics are extremely simplified as the raw material for fuel making is handled within the ordinary operations of the pulp & paper plant
- the process is easily pressurized, which enhances fuel production efficiency
- the syngas has a low methane content, which optimizes fuel yield
- pulp mill economics becomes less sensitive to pulp prices as the economics are diversified with another product
- gasification capital cost is shared between recovery of inorganic chemicals, steam production and syngas production.

The BLGMF concept shows very high biomass to methanol efficiency of about 64% and of the European countries Sweden and Finland have largest potential to produce motor fuels from black liquor and replace current fossil fuel consumption.

ACKNOWLEDGMENTS

The European Commission, the Swedish National Energy Administration (STEM), and the Swedish Agency for Innovation Systems (VINNOVA) have sponsored the study within the Altener II program. This study is also part of the “Ecocyclic pulp mill” research program financed by MISTRA, the Swedish “Foundation for Strategic Environmental Research”.

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Eskilstuna, Sweden, 11 – 12 March, 2003
APPENDIX 5.

PRELIMINARY ECONOMICS OF BLACK LIQUOR GASIFICATION WITH MOTOR FUELS PRODUCTION
PRELIMINARY ECONOMICS OF BLACK LIQUOR GASIFICATION
WITH MOTOR FUELS PRODUCTION

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ABSTRACT
Results are presented from a European Union research project (under the Altener II program) that investigates the technical and commercial feasibility of producing renewable motor fuels, such as methanol or dimethyl ether (DME), via oxygen-blown high-pressure black liquor gasification. A preliminary cost estimate for a greenfield 2000 ADt/d market pulp mill shows that the production cost of methanol from black liquor could be low compared to that of other renewable fuels, and even be competitive with that of fossil fuels. A simplified cost-benefit assessment for a theoretical mill operating in Sweden shows that, with current and foreseeable Swedish energy prices and taxes, renewable motor fuels could represent a revenue stream that would be significant also in relation to the pulp production. Several alternatives are investigated, ranging from the conversion of the energy surplus of a modern kraft mill to complete utilization of black liquor for chemicals production and consequent biomass replacement for steam and power production. The estimated maximum potential for fossil-fuel replacement in the Swedish transport sector with black liquor-based fuels is about 25%, 20 TWh, or 3.6 million tonnes of methanol annually.

INTRODUCTION
There is a growing interest in finding ways to produce CO$_2$-neutral automotive fuels, by using biomass as the raw material. Many countries have committed themselves to reducing carbon dioxide emissions considerably, according to the Kyoto protocol. For example, the European Union has a target of 8% CO$_2$ reduction compared to 1990 levels. As one means to approach this target, the EU is in the process of adopting a directive that aims to require 2% of all motor fuel to come from renewables by 2005 (EU 2002). This fraction is then suggested to increase to 5.75% by 2010.

The primary route to produce CO$_2$-neutral motor fuels is through conversion of agricultural and forestry residues and organic wastes to gas (biogas), hydrocarbons (biodiesel), alcohols (methanol and ethanol), or dimethyl ether (DME). These fuels, except DME, can all be blended into gasoline or diesel to facilitate distribution. In the long term, conversion to hydrogen is an attractive route, but this requires far greater changes to distribution systems and vehicles.
A modern kraft pulp mill has a surplus of energy. Pulp mills could thus become important suppliers of renewable fuels in the future energy system. It is of great interest to convert the primary energy in the biomass to an energy carrier of high value.

In the present study, methods to convert black liquor to methanol or DME are evaluated. The conversion of other biomass feedstocks to renewable fuels has been investigated in a large number of studies, some of which discuss methanol production (Brandberg et al. 1997, Bain 1992, Elam et al. 1994, Ekström & Kopp 1992, Katofsky 1993, Browne 1996). Meanwhile, the pulp and paper industry is turning its attention to black liquor gasification as a possible means of improving the economic and environmental performance of the chemical pulp mill. Pressurized gasification of the black liquor has a potential to improve the mill energy efficiency, while generating conventional or modified cooking liquors and a synthesis gas (syngas). Previous concepts have mainly aimed to use the syngas in a gas turbine as part of an integrated black liquor gasification combined cycle, BLGCC, for electricity generation (Fogelholm 1993, Stigsson 1998, Larson et al. 1998). A few studies have investigated the manufacture of renewable fuels from black liquor syngas (Kelleher 1983, Isaksson et al. 2000).

**Altener II Study – Black Liquor Gasification with Motor Fuels Production (BLGMF)**

The present project to investigate black liquor gasification with motor fuels production was initiated within the EU Altener II program in 2001 and started up in February of 2002, by a consortium including Nykomb Synergetics (process engineering consultant), STFI (pulp and paper research company), Babcock Borsig Power (engineering company), Chemrec (supplier of black liquor gasification technology), Ecotraffic ERD (automotive and environmental consultant), Volvo Group (automotive producer), OK-Q8 (national fuel company) and Methanex (world-wide methanol company).

In the short term, the goal is to establish the preliminary engineering and a cost estimate for calculating the economic performance of a BLGMF system. In addition, the proposed actions will lead to a checklist of necessary conditions for a market introduction of renewable fuels. The long-term goal is to form a broad interest group in the European pulp and paper industry to support the development of such a system.

The present paper is an update of the paper by Berglin et al. (2002), where we have added material and energy balances for a second reference mill, as well as preliminary economic calculations. A more detailed economic assessment will be made in the final phase of the project.

### Table 1. Process heat consumption in the studied mills.

<table>
<thead>
<tr>
<th>Mill Type</th>
<th>HEAT CONSUMPTION (GJ/ADt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Market</td>
</tr>
<tr>
<td>Fraction of Pulp to Paper Mill</td>
<td>-</td>
</tr>
<tr>
<td><strong>MP STEAM</strong></td>
<td></td>
</tr>
<tr>
<td>Digester</td>
<td>1.39</td>
</tr>
<tr>
<td>Bleach Plant</td>
<td>1.43</td>
</tr>
<tr>
<td>Oxygen Delignification</td>
<td>0.38</td>
</tr>
<tr>
<td>Black Liquor Evaporation</td>
<td>0.95</td>
</tr>
<tr>
<td>Other (incl. losses)</td>
<td>0.15</td>
</tr>
<tr>
<td>Paper Mill</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Heat from MP Steam</strong></td>
<td>4.30</td>
</tr>
</tbody>
</table>

| **LP STEAM** |         |          |
| Digester  | 0.29   | 0.29      |
| Bleach Plant | 0.27   | 0.27      |
| Black Liquor Evaporation | 2.71  | 2.71      |
| Pulp Dryer | 2.21  | -         |
| Other (incl. losses) | 0.20  | 0.20      |
| Paper Mill | -     | 4.82      |
| **Total Heat from LP Steam** | 5.68  | 8.30      |
| **TOTAL PROCESS CONSUMPTION*** | 9.99  | 15.81     |

* Heat consumption internal to the cogeneration systems, e.g. in air preheaters and scot-blowers, is not included here. It is deducted from the generation side for each case.

### Table 2. Electricity consumption in the studied mills.

<table>
<thead>
<tr>
<th>ELECTRICITY CONS. (kWh/ADt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ELECTRICITY CONS.</strong></td>
</tr>
<tr>
<td>Market</td>
</tr>
<tr>
<td>Fraction of Pulp to Paper Mill</td>
</tr>
<tr>
<td>Pulping Scheme</td>
</tr>
<tr>
<td>Woodyard *</td>
</tr>
<tr>
<td>Digester *</td>
</tr>
<tr>
<td>Brown Stock Washing</td>
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<td>Oxygen Delignification</td>
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<td>Bleach Plant</td>
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<tr>
<td>Final Screening</td>
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<tr>
<td>Pulp Dryer</td>
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<tr>
<td>Black Liquor Evaporation *</td>
</tr>
<tr>
<td>Recausticizing *</td>
</tr>
<tr>
<td>Cooling Towers *</td>
</tr>
<tr>
<td>Raw Water Treatment</td>
</tr>
<tr>
<td>Waste Water Treatment</td>
</tr>
<tr>
<td>Bleaching Chemicals</td>
</tr>
<tr>
<td>Other (incl. losses)</td>
</tr>
<tr>
<td>Paper Mill</td>
</tr>
<tr>
<td><strong>TOTAL PROCESS CONSUMPTION</strong></td>
</tr>
</tbody>
</table>

* Electricity consumption in these departments varies for different black liquor gasification schemes. The changes are accounted for on the generation side.

** Excludes electricity consumed in the powerhouse (90 kWh/ADt in the reference pulp mill). Powerhouse consumption is calculated for each case.
BASIS FOR CALCULATIONS

Reference Pulp Mill

System performance was calculated for a mill used as a reference mill in the "Ecocyclic Pulp Mill" program (also referred to by the Swedish acronym, KAM), a large research effort in the Swedish pulp and paper industry. The process equipment, the mode of operation, and material and energy balances have been well defined for the reference mill (Jönsson et al 1998, Delin 1998, Ledung et al 2000) which is assumed to employ late 1990s state-of-the-art technology in all process units. Although the actual reference mill has not been built, its characteristics well match those of mills that have been built or rebuilt in the last few years. Except for the black liquor gasification systems, all the equipment assumed to be used in the reference mill is in operation in existing mills.

The research program has been carried out in two program periods: KAM1, 1996-1999 and KAM2, 2000-2002. There has therefore been some development in the definition of the reference mill. Material and energy balances presented here are based on the 1000 ADt/d KAM1 TCF mill and the 2000 ADt/d KAM2 ECF mill. The preliminary cost estimate was carried out for the KAM2 mill only.

Data for the KAM1 reference mill are presented in Tables 1 and 2. Out of the four cases defined by Jönsson et al, the "TCF, Summer" case was used here, mainly because the steam consumption approximately corresponded to the average of the four cases. Note that process consumption has been separated from steam and power consumption inside the powerhouse, since the latter figures will vary depending on the studied configuration. The major difference between the KAM1 and KAM2 mills is the production capacity, resulting in a lower specific investment cost.
for the 2000 ADt/d KAM2 mill. From an energy perspective, the major difference between the TCF and ECF cases is the pulp yield and therefore the specific amount of black liquor solids recovered per tonne of pulp, 1.8 tDS/ADt in the TCF case, 1.71 tDS/ADt in the ECF case. Bleach plant steam consumption is slightly higher in the TCF case (“Totally Chlorine Free”), where more of the bleaching is carried out in pressurized hydrogen peroxide stages, than in the ECF case (“Elemental Chlorine Free”), where chlorine dioxide is used in one of the bleaching stages.

**Recovery boilers.** Background data for the reference mill include calculations for one recovery boiler, generating steam at 79 bar(a), 485°C (KAM1) or 81 bar(a), 490°C (KAM2). Recovery boiler performance was calculated with a model derived from the one used for the black liquor gasifier to ensure thermodynamic consistency between the models.

**Black liquor gasification systems.** The studied systems are centered around a high-temperature, oxygen-blown gasifier, and are implied to approximate the systems being developed by Chemrec (Stögsson 1998, Lorson 1997). Gasifier performance was estimated with GIBBSGAS, a chemical equilibrium model based on Gibbs energy minimization (Berglin & Berntsson, 1999). The remaining systems – air separation, gas and smelt cooling, acid gas removal and recovery, methanol plant, gas turbine, and steam cycle – were modeled either in the process simulator HYSYS or in spreadsheet models according to the flowsheet in Fig. 1. Specifically, for the methanol plant, product yields, utility consumptions, etc., were based on calculations from a supplier for a plant of similar size. Heat losses and pressure drops were estimated for each unit operation. Auxiliary calculations for the chemical recovery cycle and the bark boiler were carried out in a spreadsheet model.

**Recausticizing.** In the gasifier, a large fraction of the sulfur in the black liquor is converted to hydrogen sulfide. There are three principal routes to convert the concentrated H₂S stream from the acid gas removal system to sulfur in a useful form in the pulping liquor:

- reabsorption in green or white liquor
- recirculation to the gasifier
- conversion to liquid sulfur, which is dissolved to give a polysulfide liquor.

The first two routes will yield a white liquor with essentially the same composition as a conventional liquor, while the third route can be utilized for pulping modifications. The first route does also make it possible to prepare white liquors with different sulfidities, if desired. Although the sulfur split may be put to an advantage in the pulping process, it also leads to an increased load on the lime kiln. The effects on energy efficiency are described in greater detail by Larson *et al* (1998) and Berglin *et al* (1999a).

**Process Concept for BLGMF**

Instead of burning the black liquor in the recovery boiler producing power and heat, the calorific energy of black liquor is utilized for producing liquid motor fuels. Concentrated black liquor from the pulp mill is sent to the gasification process where it is gasified with 99% oxygen in an entrained flow reactor at 32 bar, 950°C. The process produces an energy-rich synthesis gas, which is then further upgraded to motor fuels (MF), such as methanol, DME or hydrogen.

The black liquor gasification, as well as the synthesis steps according to the BLGMF process, is carried out under pressurized conditions. Gasification and gas cooling are preferably carried out at pressures around or above 25 bar, since a high pressure increases the temperature at which heat evolved in the gasifier can be recovered, and thus leads to an increase in steam production. On the other hand, technical conditions constrain the upper limit for the pressure. The synthesis step, such as e.g. methanol synthesis, is preferably carried out in the range from about 60 bar up to about 80 bar, mainly because a high pressure favors the chemical equilibrium.

The presented gasification unit process is shown in Fig. 1 and comprises pressurized oxygen-blown black liquor gasification in an entrained flow reactor with a quench primary cooler, green liquor handling and gas cooling in a countercurrent condenser. These units are identical in the power generation and the methanol production schemes.

It is well known from many methanol production schemes where the feedstock is a sulfur-rich heavy-oil fraction or coal that the gas cleaning step must be of advanced nature in order to protect the sensitive methanol catalyst in the
methanol reactor from poisoning and degradation. The synthesis gas from the black liquor gasification step contains sulfur components in the form of hydrogen sulfide and carbonyl sulfide and it also contains carbon dioxide, traces of higher hydrocarbons and possibly other traces that can be harmful for the methanol synthesis step. Technology suited to meet the high quality demand for methanol synthesis gas is available and commercially proven.

The new part of the BLGMF process begins at the outlet of the gas cooler from which the raw gas will be sent to a gas cleaning unit. The gas cleaning unit selected here is a Rectisol plant since there are stringent demands on a highly purified cleaned gas, free from H₂S, COS and low in CO₂. HCN and NH₃ will also be removed. Absorption is carried out in methanol at low temperatures. The raw syngas from the gas cooler enters a pre-wash unit using methanol for removal of tar components such as benzene, toluene, naphthalene. The removed tars are recycled to the gasifier.

Within the gas cleaning unit a CO-shift catalyst bed is included, preferably of “clean” type. The CO-shift feed is first warmed up with a small portion of IP steam in a heat exchanger, and then a sufficient amount of steam is added to reach a steam-to-dry-gas ratio of 0.9. Approximately 75% of the CO is used in the conversion of H₂O to H₂ so that about 50% of the whole clean gas flow needs to be shifted to reach the desired H₂:CO ratio required for the methanol synthesis. The remaining part of the clean gas flow is by-passed the CO-shift unit and the second CO₂ absorption unit. After CO-shifting, the gas stream is cooled down to ambient temperature via steam generation. The shifted gas then needs to be further adjusted in CO₂ content, and the cooled, shifted and cleaned gas is mixed to the clean bypass stream. The cleaned outlet gas is then compressed to about 60 bar in a centrifugal compressor prior to the methanol synthesis loop. The gas cleaning unit will produce a concentrated H₂S-rich gas, which is treated as described under recausticizing above. In addition, the advanced type of gas cleaning selected allows extraction of a concentrated CO₂ stream, which can be used for blanketing purposes within the pulp mill as well as purging gas if needed within the gasification unit.

**Methanol synthesis.** In the presented preliminary calculations, the methanol streams are considered as energy streams on LHV-basis, based on in-house data from previous projects. Part from methanol, the by-product streams from the methanol synthesis loop are the combustible purge gas and the flash gas streams. Cooling of the methanol reactor results in generation of IP steam of 30 bar. The raw methanol contains water and fusel oil that are removed as a combustible fusel oil stream and a waste water stream, and finally after distillation the purified methanol stream with water-free methanol.

**Methanol distillation.** The standard type methanol distillation uses a significant amount of LP-steam, which normally is of 4 -5 bar. In the BLGMF plant LLP-steam of 1.4 bar is available and can be used to replace some of the LP-steam. The LP- and MP-steam from the boilers and the BLGMF plant is sent to the pulp mill.

**Dimethyl ether production.** Direct DME manufacture is very similar to the methanol synthesis loop. DME can also be efficiently manufactured from methanol. No detailed calculations were made for DME production in the present phase of the study.

**Assumptions for the Economic Study**

The estimated investment cost for the black liquor gasification system with auxiliaries was scaled from information in Griffis (2002). Costs for the Rectisol plant, shift reactor and methanol plant were estimated from in-house data for a plant using syngas from another raw material than black liquor, but of similar size to the plant considered here. Fuel and electricity prices were chosen to correspond to those used in the KAM program: 250 SEK/MWh for electricity, 100 SEK/MWh for purchased wood residues, and 80 SEK/MWh for sold bark. Note that costs and benefits are expressed in Swedish currency (SEK) to emphasize that the results of the study are valid foremost under Swedish conditions. At the time of writing (May 2003), the exchange rate was approximately 8 SEK/USD.
### Table 3. Calculated performance for the BLG MF systems (with BLGCC and RB included for comparison).

<table>
<thead>
<tr>
<th>Description</th>
<th>Market Pulp Mill, KAM1 TCF, 1999 ADt</th>
<th>Market Pulp Mill, KAM2 ECF, 2000 ADt</th>
<th>Integrated, KAM1 TCF, 1999 ADt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Consumers</strong></td>
<td><strong>Producers</strong></td>
<td><strong>Consumers</strong></td>
<td><strong>Producers</strong></td>
</tr>
<tr>
<td>HP Steam Temperature °C</td>
<td>222.6</td>
<td>475.5</td>
<td>222.6</td>
</tr>
<tr>
<td>Gasifier Pressure bar(a)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>HP Steam Pressure bar(a)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Mill</td>
<td>950</td>
<td>950</td>
<td>950</td>
</tr>
<tr>
<td>Internal Consumers</td>
<td>950</td>
<td>950</td>
<td>950</td>
</tr>
<tr>
<td>Excess Power GJ/ADt</td>
<td>1.93</td>
<td>1.93</td>
<td>1.93</td>
</tr>
<tr>
<td><strong>Energy Management</strong></td>
<td><strong>Energy Management</strong></td>
<td><strong>Energy Management</strong></td>
<td><strong>Energy Management</strong></td>
</tr>
<tr>
<td>Gas Turbine*** MWe</td>
<td>-0.4</td>
<td>-0.4</td>
<td>-0.4</td>
</tr>
<tr>
<td>Steam Turbine MWe</td>
<td>-1.7</td>
<td>-1.7</td>
<td>-1.7</td>
</tr>
<tr>
<td><strong>Summary</strong></td>
<td><strong>Summary</strong></td>
<td><strong>Summary</strong></td>
<td><strong>Summary</strong></td>
</tr>
<tr>
<td>Power Generated, Gross MWe</td>
<td>124.9</td>
<td>750</td>
<td>124.9</td>
</tr>
<tr>
<td>Power Generated, Net MWe</td>
<td>21.0</td>
<td>21.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Power Consumed in Mill MWe</td>
<td>-101.4</td>
<td>-101.4</td>
<td>-101.4</td>
</tr>
<tr>
<td>Excess Power GJ/ADt</td>
<td>1.93</td>
<td>1.93</td>
<td>1.93</td>
</tr>
<tr>
<td><strong>Emissions</strong></td>
<td><strong>Emissions</strong></td>
<td><strong>Emissions</strong></td>
<td><strong>Emissions</strong></td>
</tr>
<tr>
<td>Black Liquor</td>
<td>611</td>
<td>611</td>
<td>611</td>
</tr>
</tbody>
</table>

*Based on the lower heating value of each fuel: Black liquor (reduced sulfur), 12.1 MJ/kg; Black, 16.0 MJ/kg (55% moisture); Tar, 38 MJ/kg; Methanol, 19.9 MJ/kg.

**The lime kiln is fired with gasified bark. A fraction of the bark is used to heat the bark dryer.

*** The calculations were done for a gas turbine of fixed size (the General Electric 6FA); the results in the table have been scaled to the generic 1000 ADt/d or 2000 ADt/d mill.

**** Estimated fuel requirement in a biomass-fired condensing power plant (35% LHV efficiency) to meet the power deficit on the line above.

---

RESULTS

Calculations are presented for eight different BLGMF cases (Table 3). Cases 4-5, 10-11 (market pulp mill) and 14-15 (integrated mill) assume that 100% of the black liquor is used for methanol production, and that make-up steam requirements are met by firing purchased biomass in a biomass boiler, while make-up electric power is bought from the grid. Cases 3 and 9 assume that only some of the energy surplus of the market pulp mill is used for methanol production. Incremental biomass and power requirements (bottom of Table 3) are in reference to the recovery boiler cases (#1, #7, and #12). Also included are calculations for three BLGCC cases (Berglin et al. 1999).

Market Pulp Mill

The market pulp mill has a surplus of fuel for the recovery boiler and BLGCC systems. As a basis for comparison, all black liquor and bark is used for power and steam generation and the surplus steam is fed to a condensing turbine, resulting in a net excess of power that can be sold to the grid. With a BLGMF plant, the energy balance can be shifted either towards a large production of methanol, which gives a demand for purchased biomass and power, or towards a smaller production of methanol, only utilizing biomass available at the mill.

Using surplus energy for methanol production. One approach for a BLGMF plant connected to a market pulp mill is to primarily secure the mill heat demand via the conventional recovery boiler and then to use only the surplus energy for production of motor fuels. The calculations show that if 50-55% of the black liquor is used for production of methanol while the remaining black liquor is burnt in the recovery boiler, there is no need for purchased biomass. At 53%, there is no need for a bark boiler (case #3), and a small amount of falling bark can be sold. In this case

Black Liquor (BL) to MeOH plant using surplus of BL energy for production of green motorfuels.

Figure 2. Energy flows for the KAM1 mill (case #3) when approximately half of the black liquor is used for methanol synthesis.
about two thirds of the electric power needed for the mill must be purchased from the grid. Fig. 2 illustrates the energy flows for this case.

**Full scale concept.** The next step would be to allow the gasification unit to fully replace the recovery boiler and convert all black liquor to motor fuels. This means that the loss of energy in the withdrawn black liquor has to be replaced by another fuel resource or compensated in another way. Indeed, the BLGMF plant will have a much higher overall efficiency than a recovery boiler, because of reduced or eliminated losses from sootblowing, smelt cooling, and flue gas.

In the full-scale case the existing recovery boiler is either converted to a large-scale bark boiler or replaced with a new biomass-fired boiler. The new combination of processes creates a large year-around heat sink, and the mill’s need of continuous process heat makes a pulp mill a suitable location for a large-scale biofuel boiler. As shown in Fig. 3, when 100% of the black liquor is used for methanol production about 5.4 GJ/ADt of wood residues need to be fired in a biomass boiler to meet the mill’s steam demand while producing some back-pressure power. The specific consumption numbers, as compared to the reference mill, are only marginally affected, except for the increased need for bark in the lime kiln.

**Integrated Pulp and Paper Mill**

The base case for comparison is the recovery boiler case (#12) for an integrated pulp and paper mill. In an analogue to the full-scale concept for the market pulp mill above, using all black liquor for production of motor fuels in an integrated pulp and paper mill will require a significant amount of purchased bark. The base case recovery boiler

*Figure 3. Energy flows (GJ/ADt) in the KAM2 mill when 100% of the black liquor is used to produce methanol. Wood residues are purchased to produce steam in order to meet the mill’s steam demand (9.7 GJ/ADt). Back-pressure power generation leaves only a small amount of power for the mill (0.4 GJ/ADt or 122 kWh/ADt) when internal power consumption in the gasification and methanol plants has been deducted. Remaining electric power (551 kWh/ADt) must be purchased, or generated in a larger on-site system for power generation.*
system produces the required amount of steam needed, if the tall oil is used as a boiler fuel or in the lime kiln. The electric power need is higher than for a market mill and there will be a demand for purchased power of about 15 MW.

Three alternatives can be identified for handling the mill’s needs of heat and electric power:

- Firing biofuels in a retrofitted recovery boiler that has been converted to a large “bark” boiler and to purchase the remaining need of power from the grid.
- A modern type of high performance biomass boiler with back pressure turbines and reheat plus condensing steam turbine in order to manage the remaining need of power for the plants. In reality, this also means an investment in a complete new boiler and also new condensing steam turbines.
- In order to further improve the biomass-to-methanol yield the biomass boiler could be replaced with a biomass IGCC, which has a higher power-to-heat ratio. This would further increase the efficiency of the BLGMF plant.

DISCUSSION

Costs and Benefits

The market pulp mill has a surplus of fuel for the recovery boiler and BLGCC systems. As a basis for comparison, all black liquor and bark is used for power and steam generation and the surplus steam is fed to a condensing turbine, resulting in a net excess of power that can be sold to the grid. With a BLGMF plant, the energy balance can be shifted either towards a large production of methanol, which causes a demand for purchased biomass and power, or towards a smaller production of methanol, only utilizing biomass available at the mill.

The investment cost for the gasification plant integrated with methanol synthesis is estimated to be about 980 MSEK higher than for the recovery boiler in the case when 100% of the black liquor is used for methanol synthesis (Table 5). This extra investment includes the costs for a large biomass boiler, a higher capacity causticizing plant, and some changes to the size of the equipment on the turbine and steam side.

The operating costs increase considerably due to the requirements for purchased biofuels and electric power. Maintenance costs can also be expected to be higher. On the other hand, the increased revenues are substantial, because of the high value that can be assigned to carbon-neutral methanol. To estimate the potential revenues, a price of methanol at the mill gate was calculated (Table 4), by assuming that the cost for the consumer should be the same as for gasoline. The estimated price is about 2000 SEK per tonne of methanol, when considering the current Swedish CO₂ tax on gasoline. Approximately 0.6 tonnes of methanol can be produced per tonne of pulp, giving a potential net operating benefit of close to 700 SEK/ADt (Table 5).

<table>
<thead>
<tr>
<th>Table 4. Estimation of competitive selling price for methanol at mill gate (in SEK per liter of gasoline equivalent), to match consumer price of gasoline.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasoline (typical Swedish costs &amp; taxes)</strong></td>
</tr>
<tr>
<td>Production*</td>
</tr>
<tr>
<td>Distribution**</td>
</tr>
<tr>
<td>Energy tax***</td>
</tr>
<tr>
<td>CO₂ tax***</td>
</tr>
<tr>
<td>V.A.T.</td>
</tr>
<tr>
<td>Consumer price</td>
</tr>
<tr>
<td><strong>Methanol</strong></td>
</tr>
<tr>
<td>Consumer price</td>
</tr>
<tr>
<td>V.A.T.</td>
</tr>
<tr>
<td>CO₂ tax***</td>
</tr>
<tr>
<td>Energy tax***</td>
</tr>
<tr>
<td>Distribution**</td>
</tr>
<tr>
<td>**Equivalent price of product methanol ****</td>
</tr>
</tbody>
</table>

* average spot market ("Rotterdam") price for gasoline in 2002, also close to 20 yr average
** includes profit margin before discounts
*** tax rates for 2003
**** 3.30 SEK/l.g.e. corresponds to 1.62 SEK/l MeOH or 2040 SEK/tonne MeOH.

Prepared for the Colloquium on Black Liquor Combustion and Gasification, Park City, Utah, May 13-16, 2003
For comparison with other methods of producing carbon-neutral motor fuels, a production cost of methanol was calculated by allocating the incremental capital and operating costs for the BLGMF model mill to the methanol produced. The calculated cost, expressed as SEK per liter of gasoline equivalent, is similar to that of gasoline, indicating that methanol from black liquor could be competitive with gasoline even if the CO\textsubscript{2} tax were lower. A sensitivity analysis indicate that the production cost is likely to be in the range of 1.8 to 2.2 SEK per liter of gasoline equivalent.

**Availability of Biomass for Methanol Production**

If all black liquor produced in Sweden were used for methanol production, 29 TWh/yr biofuel would be needed to cover the fuel needs of the pulp mills – provided that the mills need all of the heat value of the black liquor. However, there is a trend of decreased energy need in market pulp mills, due to better process integration. On the other hand, if integration with paper mills and other energy intensive industry grows, this will increase the internal energy demand.

**Table 5.** Comparison of investment and operating costs for the BLGMF model mills and the reference mill. In the “100 %” case, all the black liquor is used to produce methanol, and wood residues are purchased to meet the steam requirements. In the “54%” case, approximately half of the black liquor is fired in the recovery boiler and half is taken to the BLGMF plant. In this case there is no need for purchased wood residues. In both cases some of the electric power used in the mill must be purchased.

<table>
<thead>
<tr>
<th>INVESTMENT (Total installed cost, TIC) *</th>
<th>Reference Mill</th>
<th>BLGMF 54%</th>
<th>BLGMF 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case 7</td>
<td>Case 9</td>
<td>Case 10</td>
</tr>
<tr>
<td>Air separation unit</td>
<td>MSEK</td>
<td>35</td>
<td>183</td>
</tr>
<tr>
<td>Gasification &amp; gas cooling</td>
<td>MSEK</td>
<td>--</td>
<td>351</td>
</tr>
<tr>
<td>Gas clean-up (Rectisol), shift reactor &amp; compressor</td>
<td>MSEK</td>
<td>--</td>
<td>170</td>
</tr>
<tr>
<td>Sulfur handling (H2S Reabsorption)</td>
<td>MSEK</td>
<td>--</td>
<td>55</td>
</tr>
<tr>
<td>Methanol synthesis and distillation</td>
<td>MSEK</td>
<td>--</td>
<td>172</td>
</tr>
<tr>
<td>Balance of plant</td>
<td>MSEK</td>
<td>--</td>
<td>35</td>
</tr>
<tr>
<td>Recovery boiler</td>
<td>MSEK</td>
<td>845</td>
<td>565</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td>MSEK</td>
<td>880</td>
<td>1531</td>
</tr>
<tr>
<td>Biomass boiler</td>
<td>MSEK</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Steam turbine</td>
<td>MSEK</td>
<td>185</td>
<td>76</td>
</tr>
<tr>
<td>Lime kiln + bark dryer</td>
<td>MSEK</td>
<td>191</td>
<td>215</td>
</tr>
<tr>
<td>Other equipment in the mill according to table 7.xx</td>
<td>MSEK</td>
<td>5444</td>
<td>5444</td>
</tr>
<tr>
<td><strong>TOTAL INVESTMENT</strong></td>
<td>MSEK</td>
<td>6700</td>
<td>7266</td>
</tr>
<tr>
<td>Incremental Investment for BLGMF Model Mill</td>
<td>MSEK</td>
<td>566</td>
<td>982</td>
</tr>
</tbody>
</table>

**OPERATING COSTS/BENEFITS**

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>BLGMF 54%</th>
<th>BLGMF 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>2040 SEK/t</td>
<td>MSEK/a</td>
<td>411</td>
</tr>
<tr>
<td>Electricity</td>
<td>250 SEK/MWh</td>
<td>MSEK/a</td>
<td>-59</td>
</tr>
<tr>
<td>Biofuels **</td>
<td>80/100 SEK/MWh</td>
<td>MSEK/a</td>
<td>22</td>
</tr>
<tr>
<td>Catalyst</td>
<td>MSEK/a</td>
<td>-5</td>
<td>-10</td>
</tr>
<tr>
<td>Maintenance</td>
<td>2% of TIC annually</td>
<td>MSEK/a</td>
<td>-134</td>
</tr>
<tr>
<td>Incremental Labor</td>
<td>2 operators per shift</td>
<td>MSEK/a</td>
<td>-4</td>
</tr>
<tr>
<td><strong>NET OPERATING BENEFIT</strong></td>
<td>MSEK/a</td>
<td>-26</td>
<td>215</td>
</tr>
<tr>
<td>Incremental Net Operating Benefit for BLGMF Model Mill</td>
<td>MSEK/a</td>
<td>241</td>
<td>438</td>
</tr>
</tbody>
</table>

|                          | SEK/ADt      | 383       | 695        |

* Includes site preparation, buildings, electrical, piping, instrumentation, engineering, license fees and contingencies. Estimated costs have been scaled from several sources with an initial accuracy of +/- 30%. Scaling adds an additional uncertainty of +/- 10%.

** low price for sold bark, high price for purchased wood residues

Prepared for the Colloquium on Black Liquor Combustion and Gasification, Park City, Utah, May 13-16, 2003
Sweden uses about 52 TWh forest fuel per year, 45 TWh of which from domestic forests (1999). It is estimated that an additional 30 TWh biofuel can be utilized ecologically sustainably, and at the same, or only moderately higher, cost (below 1.1 US ¢/kWh). Another 30 TWh is also ecologically available, but at higher costs (>1.4 US ¢/kWh) (Lönner 1998). This means that with the pulp mills of today, the approximately 40 TWh black liquor production in Sweden could be available for methanol production, from a wood fuel supply point of view. The corresponding methanol production potential is 20 TWh/yr.

A theoretical example for an existing kraft mill in mid-east Sweden shows that with an annual production of 185,000 ADt of kraft pulp, the mill needs a forest area of approximately 180,000 hectares for its pulpwood supply. That area can at the same time produce 1040 GWh forest fuel/yr sustainably. The black liquor production needs to be replaced by approximately 1250 GWh biofuel. The difference could be covered by the additional production of biofuels within the region (Backlund 2002, Ahlgren 2001).

**Comparison with Other Methods of Producing Motor Fuels from Biomass**

The conversion efficiency from raw biomass to methanol is, with reference to previous studies approximately 50% and may reach a few percentage points higher when further optimized (Brandberg et al 1997, Bain 1992, Elam et al 1994, Ekström and Kopp 1992, Katofsky 1993, Browne 1996). State-of-the-art biomass to methanol production comprises the following process steps: Biomass feedstock preparation involves wood storage, handling size reduction and drying, air separation to produce pure oxygen, pressurized gasification with oxygen to produce a synthesis gas, syngas cooling, purification, conditioning and methanol synthesis. However, pressurized gasification of solid biomass has some challenging features, which need further development to reach commercial status.

With a liquid biomass residual feedstock such as black liquor, the pressurization step of the gasifier feedstock stream can be performed by a simple pump instead of a lock hopper system that is necessary for solid fuel feeding systems according to state-of-the-art processes and systems for production of e.g. methanol. The burner system of the gasifier reactor can also be simplified when fed with a pumpable liquid instead of a solid feedstock.

Costs to produce renewable fuels are generally much higher than for fossil fuels, as shown in Fig. 4. The results from this preliminary study show that methanol could potentially be produced from black liquor at a surprisingly low cost, on par with that of gasoline. Note, however, that this is based on incremental costs for a BLGMF system compared to a modern recovery boiler. This comparison is, of course, only valid when the mill is considering a recovery boiler replacement.

---

**Table 6. Estimated production cost for methanol, calculated as the incremental capital and operating costs to produce methanol in a BLGMF plant compared to the capital and operating costs for a mill with a recovery boiler. Investment and operating costs according to Table 5.**

<table>
<thead>
<tr>
<th>METHANOL PRODUCTION COST</th>
<th>BLGMF 54%</th>
<th>BLGMF 100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incremental Capital Cost</td>
<td>MSEK/a</td>
<td>57</td>
</tr>
<tr>
<td>Incremental Operating Cost</td>
<td>MSEK/a</td>
<td>169</td>
</tr>
<tr>
<td>Incremental Cost, Total</td>
<td>MSEK/a</td>
<td>226</td>
</tr>
<tr>
<td>Methanol produced</td>
<td>ktonnes/a</td>
<td>201</td>
</tr>
<tr>
<td>Cost of methanol produced</td>
<td>SEK/tonne</td>
<td>1123</td>
</tr>
<tr>
<td>SEK/l</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>SEK/l gasoline eq.</td>
<td>1.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>
**CONCLUSIONS**

Worldwide, the pulp and paper industry currently processes about 170 million tonnes of black liquor (measured as dry solids) per year, with a total energy content of about 2 EJ, making black liquor a very significant biomass fuel. In comparison with other potential biomass sources for chemicals production, black liquor has the great advantage that it is already partially processed and exists in a pumpable, liquid form. Using black liquor as a raw material for methanol production would have the following advantages:

- biomass logistics are extremely simplified as the raw material for fuel making is handled within the ordinary operations of the pulp & paper plant
- the process is easily pressurized, which enhances fuel production efficiency
- the syngas has a low methane content, which optimizes fuel yield
- pulp mill economics becomes less sensitive to pulp prices as the economics are diversified with another product
- gasification capital cost is shared between recovery of inorganic chemicals, steam production and syngas production.

A preliminary cost estimate for a greenfield 2000 ADt/d market pulp mill has shown that the production cost of methanol from black liquor could be on the order of 2 SEK per liter gasoline equivalent, which is low compared to that of other renewable fuels, and even competitive with that of fossil fuels.

A simplified cost-benefit assessment for a theoretical mill operating in Sweden has shown that, with current and foreseeable Swedish energy prices and taxes, renewable motor fuels could represent a revenue stream that would be significant also in relation to the pulp production.

It should be noted that the economic assessment is preliminary and needs to be verified. A more detailed assessment will be part of the final phase of the project.

**ACKNOWLEDGMENTS**

The European Commission, the Swedish National Energy Administration (STEM), and the Swedish Agency for Innovation Systems (VINNOVA) have sponsored the study within the Altener II program. This study is also part of...
the “Ecocyclic pulp mill” research program financed by MISTRA, the Swedish “Foundation for Strategic Environmental Research”.

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