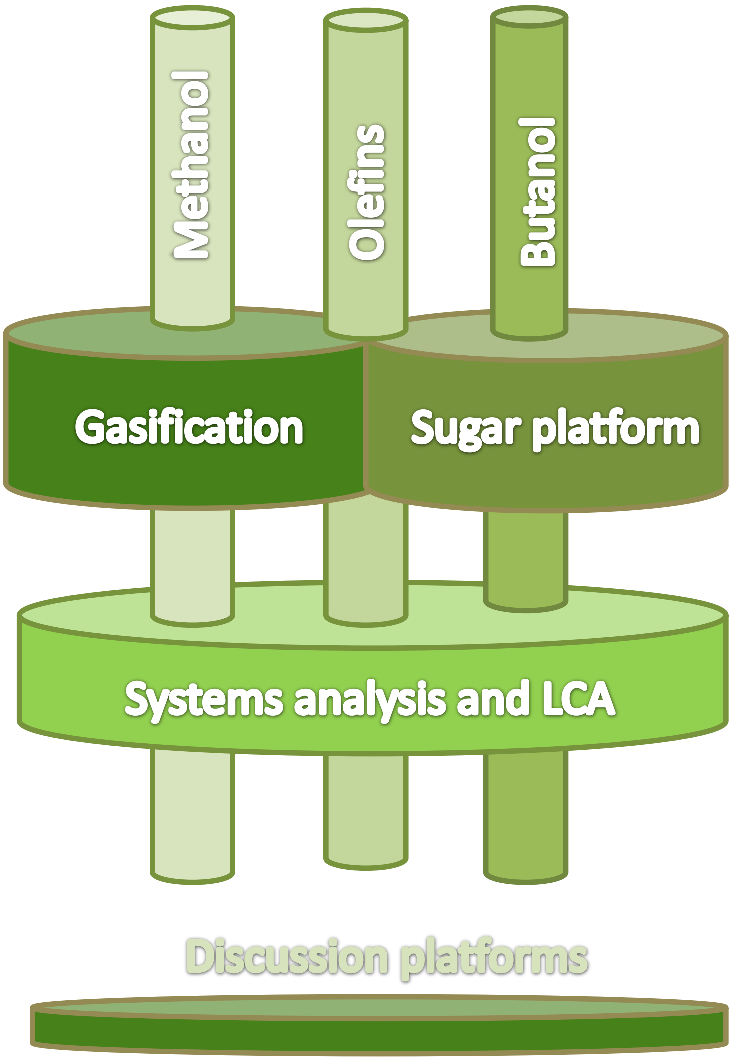
SKOGSKEMI – FINAL REPORT



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Skogskemi project leaders

Clas Engström (project leader), Lena Heuts (co-project leader)

Final report editor

Jonas M. Joelsson

NB! This report is forthcoming in the Vinnova report series (www.vinnova.se). The present version is preilminary.

SP Processum AB
Box 70
891 22 ÖRNSKÖLDSVIK
www.processum.se

1 EXECUTIVE SUMMARY

The aim of the Skogskemi innovation development project has been to lay the foundation for a sustainable and competitive production of forest-based bulk chemicals through the cooperation between the forest industry and the chemical industry. Two large Swedish clusters have been participating in Skogskemi: The chemistry cluster in Stenungsund and the biorefinery cluster of Processum. Three value chains with potential to be scaled up to demonstrators in Sweden were selected: Butanol, Methanol and Olefins. Large market volumes providing for bulk production potential and the ability of the chemicals to fit into existing infrastructure – so called drop-in chemicals – were important selection criteria. The project has performed detailed technical studies of the three value chains and preliminary front-end engineering designs (pre-FEED) have been delivered. The project has also delivered extensive knowledge regarding two technology platforms for the conversion of Swedish lignocellulosic feedstock: a sugar platform with production of ethanol and a gasification platform with production of methanol. Ethanol and methanol are important intermediates in the butanol and olefins value chains.

A dedicated systems analysis sub-project has contributed with environmental assessments in the form of life cycle assessment (LCA) for the full chain from forest to chemical products. Innovation system analysis and policy analysis have provided insights into potential risks and barriers in the process of developing new biorefinery industries and a review of the present policy landscape have been performed. Finally, the project has provided for a discussion platform - a forum for forest industry, chemical industry and other stakeholders in the bioeconomy, realized in the form of a number of seminars. A total of approximately 300 participants from a large number of companies attended the five events.

1.1 SUMMARY AND RECOMMENDATIONS

We conclude that the technologies for production of butanol and olefins from ethanol and methanol are mature, and the construction of such plants could start today. The step from forest feedstock to methanol and ethanol still carries uncertainties with respect to upscaling of the processes. Large-scale demonstration projects are, however, under way, which is likely to reduce uncertainties in the near future.

The economic assessments show that some of the projects appear feasible if the product is to be sold on the transportation fuel market with the current tax exemption policy, while production for the chemicals markets is less promising. Although there are important synergies between renewable transportation fuels and renewable chemicals markets, it is apparent that use of the studied chemicals for non-fuel purposes will be difficult to realize unless this is given similar conditions as their use for biofuel purposes. A rough estimate is that a long-term, stable green premium on forest methanol and ethanol as well as the value chain end products in the vicinity of 20-50% would create sufficient impetus to start realizing investments. The LCA results show a significantly lower contribution to global warming with forest-based chemicals than with fossil-based chemicals. For other environmental impact categories the picture is more diverse.

Apart from the more technical and economic results of the extensive work done in Skogskemi, some very important but more intangible results are worth mentioning: personal trust has been built and new collaboration and networks have been set up. An important example is the representation of the chemical industry and the forest industry in the Bioinnovation Strategic Innovation Area.

Wood is the feedstock for a range of products today, and there are several pathways to new forest-based products. This project has focused on specific value chains for bulk production of drop-in chemicals and their feasibility. Based on the project results, three broad conclusions are delivered on what would be needed to realize the studied value chains:

1. **A policy for deployment of new technology is needed**
   To further develop the Skogskemi value chains, we argue that projects for deployment of the new technologies are needed, as well as policy to support such projects. A deployment project, in contrast to technology verification projects, serves to develop the full value chain. The technologies have to be implemented at a relevant, industrial scale and be intended for continuous production, to allow for learning by doing and incremental technical improvements. Deployment projects, although with a focus on production, are not likely to be economically feasible without policy support to reduce market risks.

2. **Policies should be designed for long-term stability**
   Long-term stability is essential if a policy should be efficient in reducing risks to the stakeholders developing a value chain. Policies also need to be designed with care, so that they are efficient in achieving their intended purpose. A policy for renewable chemicals should include the option to co-process renewable and fossil feedstock to be able to utilize existing industry investments. In practice, the options studied in the Skogskemi project will not be possible to realize without blend-in solutions.

3. **New value chains may require new business models**
   It is our conclusion that the studied value chains must be built in cooperation with several stakeholders. However, there is a complexity in forming such cooperation that should not be underestimated and we recommend the industry to be proactive and start to develop the required networks, partnerships and new business models that will be required. The Skogskemi project has increased the awareness among stakeholders to start building new value chains and joint ventures and a couple of such endeavors are already underway.

2 PREFACE

The project "Skogskemi – Hållbara kemikalier och material" (Forestchemistry – Sustainable Chemistry and Materials) ran 2012-2014. It was funded by the Swedish Innovation Agency (Vinnova) as part of their Challenge Driven Innovation program ("Utmaningsdriven innovation", UDI) and by the project partners. The project consortium consisted of forest- and chemical industry companies and research organizations. It was coordinated by SP Processum AB.

The present document is the synthesis report of the project. It is based on the individual reports of the subprojects within Skogskemi. The subproject reports, listed below, can be obtained on request to SP Processum AB.

- Skogskemi – Gasification platform.
- Skogskemi – Sugar platform.
- Skogskemi – Olefins value chain.
- Skogskemi – Butanol value chain.
- Skogskemi – Methanol value chain.
- Skogskemi – Systems analysis.

For the Skogskemi Project. Umeå and Gothenburg, October 2014.

Clas Engström, SP Processum AB. Project leader.

Lena Heuts, Chalmers University of Technology. Co-project leader.

Jonas Joelsson, SP Processum AB. Editor of the synthesis report.

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LIST OF ABBREVIATIONS AND ACRONYMS

BAT	Best available technology
CFB	Circulating fluidized bed
DME	Dimethyl ether
E2E	Ethanol-to-olefins
EF	Entrained flow
EUR	Euro
FEED	Front end engineering design
IG	Indirect gasification
IRR	Internal rate of return
kt	Thousand metric tons
LCA	Life cycle assessment
MTO	Methanol-to-olefins
PE	Polyethylene
PFD	Process flow diagram
PP	Polypropylene
PVC	Polyvinyl chloride
RME	Rape methyl ester
SEK	Swedish krona
SIO	"Strategiskt innovationsområde" (Strategic innovation area)
SNG	Synthetic natural gas
t	Metric ton
tpa	Metric tons per annum (year)
UDI	"Utmaningsdriven innovation" (Challenge-driven innovation)

1 INTRODUCTION

Petro-chemistry and forest industry are important Swedish industry sectors. They both face challenges, but of different nature. The petro-chemical industry is based on the exploitation of finite, fossil resources, and is seeking ways to move towards a sustainable development based on renewable resources. The forest industry, on the other hand, has a long tradition of utilizing the vast forest resources that exist in Sweden. The Swedish forest biomass stock is increasing and residues from forest industries and forests are underutilized today. Markets for lumber, pulp and paper are mature, and in some segments stagnant or declining. The forest industry is seeking to develop new products for new markets to increase its competitiveness and to widen the range of renewable products in the economy.

What if these two interests could meet? What if the forest industry could be the supplier of the renewable feedstock desired from the chemical industry? We think that this is possible, and we call it Skogskemi – Forest Chemistry. The serious commitment of the industry in this project is apparent. The techniques to bring it about on different levels are also there, for sure, but are they viable in the present market settings, in combination, and in the present policy context? Can we get the chemical industry and the forest industry to start working closer together, and what can we achieve by that?

The aim of this innovation development project has been to lay the foundation for a sustainable and competitive production of forest-based bulk chemicals through the cooperation between the forest industry and the chemical industry. Two large Swedish clusters have been participating in Skogskemi. The chemistry cluster in Stenungssund and the biorefinery cluster of Processum. Together, we explore pathways, where available technologies and the existing industrial structures are utilized, to produce green bulk chemicals from Swedish forests that would fit directly into the current production facilities and markets of the Stenungsund chemical industries.

1.1 THE STENUNGSUND CLUSTER

Several large chemical industries are located at an industry park in Stenungsund. The chemistry is based on fossil feedstock, with a steam cracker for production of ethylene as a central component. Within this chemical cluster there is a common vision that "in 2030 Stenungsund Industry Park will be the hub for the manufacturing of sustainable products within the Swedish chemical industry". A major challenge in this vision is to shift towards renewable feedstock and energy carriers. There are also possibilities for energy efficiency and energy integration within the cluster.

1.2 THE PROCESSUM CLUSTER

The Processum cluster brings together companies, universities and society functions in a common work with biorefinery development. The major part of the activities consists of support and initiatives concerning research and development in the areas of biotechnology, energy technology, inorganic chemistry, organic chemistry and raw materials with focus on sustainability. The cluster has its geographical focus along the northern coast of Sweden and focus on feed-stock from the Swedish forest. Processum is also a VINNVÄXT-initiative.

1.3 PARTNERS OF THE SKOGSKEMI PROJECTS

Partners in the Skogskemi projects come from our two clusters. They decided to join the project after an in-depth discussion in a so called UDI, phase A-project within the VINNOVA framework.

Figure 1. Partners of the Skogskemi project.

1.4 PROJECT ACTIVITIES

The project goal has been to develop forest based value chains for production of commodity chemicals. This is exemplified by three value chains that are considered to have great potential to be scaled up to demonstrators in Sweden: Butanol, Methanol and Olefins. The value chains were chosen as a part of the UDI A projects since they were judged to be low hanging fruits, going from forest to chemicals. Large market volumes providing for bulk production potential and the ability of the chemicals to fit into existing infrastructure – so called drop-in chemicals – were important selection criteria. The project has performed detailed technical studies of the three value chains and preliminary front-end engineering designs (pre-FEED) have been delivered. The pre-FEED is the point in a project where the possibilities are narrowed down into a single development concept on a given location. Feasibility studies are conducted for cost and schedule estimates, as well as analyses of other relevant factors that could impact the final outcome.

The project has also delivered extensive knowledge regarding two different raw material platforms, which form the basis for these three value chains: a sugar platform and a gasification platform based on Swedish lignocellulosic feed-stock for further processing into methanol and ethanol, respectively. Methanol and ethanol are important commodity chemicals in the value chains. The platforms give an overview of the most promising pathways to get to biomethanol and bioethanol from Swedish forest. Concrete locations and technologies are analyzed but cost estimations carry larger uncertainties for the platforms than for the value chains, since the platforms contain more elements which are not yet commercially available. In a first implementation step, biomass-based input of ethanol and methanol could be derived from other sources than forest feedstock to feed the value chains.

Figure 1 gives an overview of the platforms and value chains considered in the project. Several routes from biomass to methanol exist. Four of them are studied in the Skogskemi project: methanol production via three biomass gasification techniques and methanol recovery from kraft pulping processes. Forest-based ethanol is a key intermediate chemical in the butanol and olefins value chains and methanol, besides being one of the studied end products, is also an intermediate in the olefins value chain.

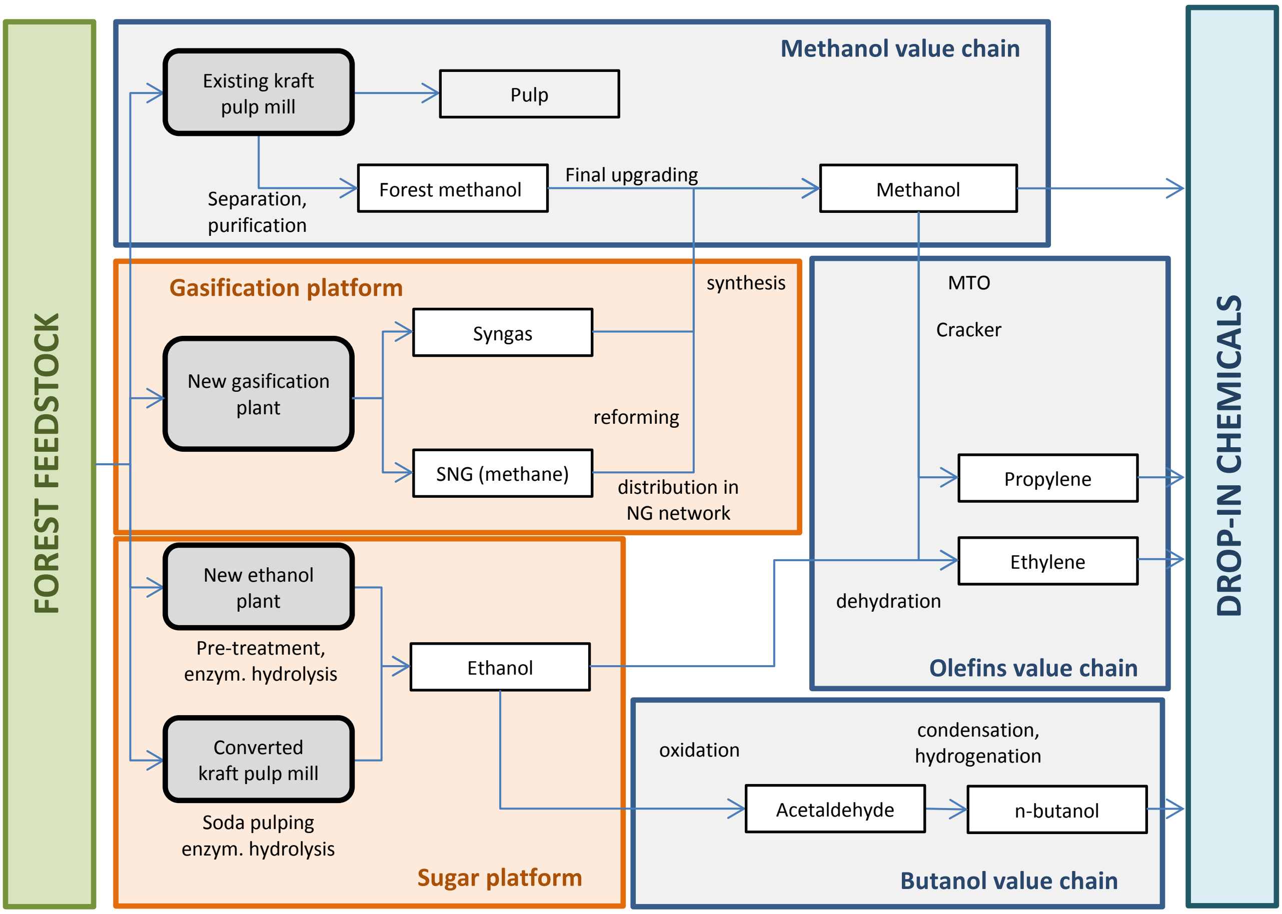

Figure 2. Overview of Skogskemi platforms and value chains

The systems analysis sub-project has contributed with environmental assessments in the form of LCA for the full chain – from forest to chemical product. Innovation system analysis and policy analysis have provided insights into potential risks and barriers in the process of developing new biorefinery industries and a review of the present policy landscape have been performed. This has formed an important foundation for the policy recommendations formulated in the final sections of this report.

Finally, the project has provided for a discussion platform - a forum for forest industry, chemical industry and other stakeholders in the bioeconomy, realized in the form of a number of seminars. This network is one of the most important outcomes of the project –the forest and chemical industry have been brought closer and started to find common interests and forms of cooperation. A total of approximately 300 persons from a large number of companies participated in five events.

1.5 VALUE CHAIN EVALUATION

The objective of the project was to explore several specific value chains and examine possibilities for up-scaling or commercialization including business modelling, economic analyses, environmental assessments and technical assessments. The objective was not to compare the studied value chains, to decide which are better or more promising than others. Rather, opportunities and barriers in realizing each of the studied value chains were identified and discussed, with a focus on the industry's perspective. The selected value chains were specified with respect to technology, location and integration with existing structures. Hence, all value chains were considered in site-specific, integrated cases and general conclusions cannot be drawn when it comes to comparing the efficiency of different technologies.

1.5.1 ECONOMIC EVALUATION WITH MARKET SCENARIOS

To ensure a certain degree of consistency in the economic evaluation, two scenarios where created for the market price development of key input and output products within the project.

- The *Current Policy Scenario* reflects an energy market under the current global climate ambitions, and with the current Swedish energy- and CO_2 taxes.
- The *450 Scenario* reflects a situation where a globally harmonized CO_2 charge is the only policy incentive for promotion of renewable energy and materials, and energy markets are harmonized. The CO_2 charge is set to reflect an ambition to limit global warming to 2°C. A gradual transformation over 10 years from the Current Policy to the 450 scenario is included.

As starting point for the scenarios we used market prices of the Skogskemi products, based on historical market data (Table 1). The future development of the market prices was modelled using energy market scenarios created with a tool called ENPAC. ENPAC is a tool for generating consistent future scenarios of energy market prices and prices on carbon dioxide emissions, which has been developed by Chalmers University of Technology. The ENPAC scenarios were not used directly. Instead the prices of the Skogskemi products were assumed to be linked to the ENPAC energy prices. The Skogskemi market scenarios and their linkage to the ENPAC model are described in greater detail in the systems analysis subproject report.

The prices applied as a base case for the chemical products in our calculations represent the market price on the international chemicals market without any subsidies or premiums. Different price levels and the impact of subsidies or premiums for renewable chemicals were explored in sensitivity analyses. For chemicals that could be used as transportation fuel (ethanol, methanol, butanol), we also considered a price corresponding to the willingness-to-pay for renewable fuels on the Swedish transportation fuel market. Thus, the price as transportation fuel was set to be equal, on an energy basis, to the price of the fossil fuel (gasoline or diesel) it would replace. The gasoline and diesel prices used included energy and CO_2 tax, from which renewable fuels are exempted, at present. This gives a comparatively high value for ethanol, methanol and butanol as transportation fuels.

In general, price predictions are uncertain. Some of the prices may be case specific and depend on the type of contract, transportation costs etc. Forest feedstock markets are to some extent regional, since long transports may entail high costs. In line with the purpose of the project, the market price scenarios are intended as guidelines, and the view on the actual market development and pricing in each value chain is discussed in the sub project reports.

The projects were analyzed over a timeframe of 20 years. The net present value (NPV) over this time frame was calculated using a real discount rate (weighted average cost of capital) of 10%. For sensitivity analysis, 5% and 15% were also applied. Also, the internal rate of return (IRR) was calculated.

Table 1. Heating values and initial prices applied for key products in the Skogskemi project.

Product	Heating value MWh/t	International bulk price SEK/t	Swedish transportation fuel price SEK/t
Gasoline	12		15270
Diesel	12		12790
Ethanol	7.5	4420	9500
Methanol	5.5	2465	7010
Butanol	10	9175	10650
Ethylene		10840	
Propylene		9790	
		Swedish market price SEK/MWh	
Biomass		192	

1.5.2 *ENVIRONMENTAL ASSESSMENT*

An environmental evaluation of the full pathways from forest to methanol, butanol and olefins was performed by means of a life cycle assessment (LCA). In the LCA study, environmental strengths and weaknesses are highlighted within each value chain. LCA is a tool designed to assess environmental impacts in a holistic manner. However, similar to the economic analyses, the LCA study has only considered a limited number of the large range of alternative options. Other configurations or assumptions may give other results and conclusions should be drawn with care. The study was not designed to compare different chemicals or biomass-based production routes, but rather to compare the different value chains to a fossil reference case.

2 PLATFORMS – METHANOL AND ETHANOL FROM WOOD

The aim of the gasification platform and sugar platform subprojects has been to deliver knowledge on these two feedstock platforms, which could supply key platform molecules from forest feedstock: Methanol from biomass gasification and ethanol from sugar platform technologies based on lignocellulosic feedstock. Green ethanol and methanol are in turn raw materials for butanol and olefins value chains.

Both these technology platforms have been extensively researched during the past decades. They have been implemented on pilot-scale demonstrators and the first industrial-scale demonstration units are planned or in construction. However, the technologies are yet unproven at the scale envisioned in the Skogskemi project. After an in-depth review of the state-of-the-art, a selection of technologies for further evaluation was made based on their feasibility for the Skogskemi project and the availability of sufficiently detailed data about the process.

2.1 METHANOL VIA THE GASIFICATION PLATFORM

The largest use of methanol is in making other chemicals, such as formaldehyde. Methanol is a potential alternative transportation fuel and is applied in conventional internal combustion engines to a limited extent today. Currently, methanol is mainly produced from natural gas. Methanol is the feedstock for the methanol-to-olefins (MTO) process investigated within the olefin value chain, proposed to be built by Borealis in Stenungsund. It is also an important feedstock for Perstorp AB in their current production of, for example, biodiesel – rape methyl ester (RME).

Methanol production via gasification of biomass is one of the main, large-scale, pathways considered in the discussion on alternative fuels and chemicals. This pathway is explored in the gasification platform. By gasification, lignocellulosic biomass is transformed to a gas. Hydrogen, carbon monoxide and methane are typically key components of the gas, which could be combusted for heat and power generation or cleaned and conditioned to be used for the synthesis of a large number of hydrocarbon compounds. In the latter case, the gas is called a syngas. Methanol is one of the products that could be synthesized from the syngas. Down-stream processes where syngas is synthesized into methanol are commercially available processes and exist in large scale plants where fossil raw material is used.

The gasification platform subproject has delivered

- Descriptions of possible methanol production cases, built on current knowledge
- Quantitative estimates for the technical and economic performance
- Analysis of different location options
- Brief review of the technology maturity and potential for improvements

Three main types of gasification technologies were chosen for further studies within the project:

- Indirect gasifier (IG)
- Circulating fluidized bed gasifier (CFB)
- Pressurized entrained flow gasifier (EF)

Based on these technologies, three specific cases where designed and studied in-depth within the platform:

1. 350 MW_{LHV} of indirect gasification. Thereof 200 MW_{LHV} for synthetic natural gas (SNG) production located in proximity of the Värö pulp mill in the Swedish West Coast, and 150 MW_{LHV} for production of syngas located in Stenungsund. The SNG is reformed to syngas in Stenungsund, and the syngas is used for methanol synthesis.
2. 450 MW_{LHV} Direct oxygen-blown pressurized gasification and methanol synthesis located in proximity of the Iggesund pulp mill on the Swedish East Coast.
3. 450 MW_{LHV} entrained flow gasification located in Stenungsund. The feedstock to the entrained flow gasifiers is torrefied biomass produced in three torrefaction plants each with an input of 150 MW_{LHV} biomass; two located in northern Sweden and one located in Stenungsund.

A detailed description of each of the three cases is given in the gasification platform report for Skogskemi. The choice of technologies was based on their feasibility for the Skogskemi project and the availability of sufficiently detailed data about the process. In all cases, the feedstock has been wood chips. In case three, torrefied wood was used as an intermediate product. Torrefaction is a thermal pre-treatment process especially well-suited for employment early in the supply chain of biomass conversion systems to improve storage, logistical, handling, transport, and feeding properties. Another biomass that can be used for gasification is black liquor, a stream at chemical pulping plants consisting mainly of dissolved lignin and which contains approximately half of the energy introduced to the plant with the pulp wood. Gasification of black liquor has been proven in a pilot plant, using entrained flow gasification and with production of dimethyl ether (DME) or methanol. We decided not to evaluate the black liquor gasification route in detail as it has already been well documented. However, data from a proposed plant at the Domsjö mill in Örnsköldsvik have been updated and included in the gasification platform subproject report, for comparison.

The performance of each of the cases was modelled using existing models and process integration studies were performed to identify energy integration options with existing industries at the considered locations. A profitability analysis was performed based on the technical performance of the plants and on estimated capital costs. In summary, the results show that in all three cases the investment cost is huge, and the major risk is the methanol price. It might be possible to reduce the total investment cost, and perhaps there will be some long-term policies to support the methanol production. The economic evaluation is presented in greater detail in the gasification platform subproject report.

Partnership will be essential to realize these projects; and partnerships with several companies involved will be necessary in these cases. In Case 1 the companies involved would probably be Södra, Perstorp, one or more technology providers, gas distributor and biomass supplier to the Stenungsund site. Case 2 would probably involve partners like Holmen, Borealis (if they are the user of methanol), additional biomass supplier to Iggesund and some technology providers. In Case 3 several companies will have to start some torrefaction units at more or less the same time. This set-up is not easy and requires commitment from many companies. Financing as well as off-take agreements will be inevitable to discuss in future business models, since investments of some 5 billion SEK or more will require either strong partnerships or sufficient financing opportunities.

Table 2. Summary of key data and results for the gasification cases.

	Case 1	Case 2	Case 3
Investment [MSEK]	5736	4782	4842*
Production [tpa MeOH]	274 000	427 000	367 000
Premium required on fossil methanol price	91%	35%	70%

* Excluding investment in torrefaction plants. This investment is included in the calculation of the cost for torrefied feedstock.

None of these three major investments can be profitable by themselves based on the current methanol price, and a chemical industry would have to pay a considerable premium on the forest-based methanol in order to make the production feasible. Under the applied assumptions, the required methanol price for the methanol plant to break even (at 10% discount rate) is 35-91% above the market price in the "Current Policy" scenario. With the higher price estimated on the Swedish transportation market, it appears more attractive to sell methanol as a biofuel for the transportation sector. The potential market volume for methanol as transportation fuel is, however, limited at present.

The alternative with the highest economic return seems to be Case 2 (direct pressurized gasifier in Iggesund). This may not have to do with the choice of gasifier, as much as the total set-up of the system, with scale, integration, logistics etc. An entrained flow gasifier, or an indirect fluidized bed gasifier could have shown the same result and conclusion should not be that this particular technology is the most promising. The investment for Case 2 is 4782 MSEK and with methanol being sold as biofuel the internal rate of return (IRR) is 38 %; and the payback time is only 5 years. A 50 % increase in investment (€834 million in total) gives a 27% IRR and payback time of 6 years.

What affect profitability most are two factors; methanol price and total investment. The biomass price will not differ very much depending on location, type of biomass and time. Integration with existing industry can give a contribution to positive cash flow. However, since the gasification plants are huge a minor error in estimation of investment has a significant effect.

2.1.1 CONCLUSION

A chemical company wanting to obtain renewable methanol from the projected plants would have to pay a significant premium compared to the methanol market. With a high willingness-to-pay for renewable transportation fuel, the use of methanol for the transportation fuel market looks more profitable, if acceptance can be found for large volumes of methanol in the transportation sector.

The envisaged projects represent huge investments, and none of the gasification technologies are operated in this scale. The technologies are at different stages of development and since the technology is one of the great risk factors, this development must be closely followed and included in any decision on how to progress with the gasification projects studied in Skogskemi.

2.2 ETHANOL VIA THE SUGAR PLATFORM

Forest-based ethanol is a key intermediate in the Skogskemi project. Ethanol is presently produced mainly through fermentation processes using starch- and sugar-based feedstock. A smaller amount of ethanol is also produced synthetically from ethylene. Industrial ethanol production from wood has been performed historically, but new technologies are, however, expected to have superior performance. These new technologies, which utilize lignocellulosic feedstock such as wood, and enzymatic treatments are currently in the phase of large-scale demonstration on several sites globally. A key step in the processes is saccharification – the conversion of feedstock into fermentable sugars. Saccharification of lignocellulosic feedstock requires pretreatment. The chemistry based on the further conversion of the sugar molecules into a range of chemicals and materials is collectively called the sugar platform.

The sugar platform sub project within Skogskemi has focused on the pretreatment and saccharification of wood with the aim of evaluating the technical and economic feasibility for the production of cellulosic ethanol that can be utilized by the chemical industry for further conversion into butanol and/or ethylene.

The sugar platform subproject has delivered

- Review of state-of-the art for pre-treatment, hydrolysis, fermentation, ethanol dewatering and purification
- Descriptions of two alternative production technologies in three defined cases
- Quantitative estimates for the technical and economic performance

After a review of the state-of-the art of cellulosic ethanol production, two different process concepts were selected for the evaluation in three cases. The first process concept, applied in case 1 and 2, uses the SEKAB CelluAPP technology, which is based on an acid pretreatment. The second process concept used in case 3 is based on an alkaline soda pulping process carried out in a converted pulp mill. The choice of process concepts was made from the assumption that the two selected concepts are among the most suitable ones for forest-based feedstock. Three different locations (Örnsköldsvik, Stenungsund, and Piteå) were selected as potential sites for the evaluation. Most of the current efforts to produce ethanol from lignocellulosic feedstocks in industrial scale are within the range 50,000-100,000 metric tons per year (tpa). An output of 50,000 tpa was assumed to be close to the minimum production scale that can be profitable. Softwood from Swedish forestry was selected as the feedstock that should be prioritized in the case studies. The three cases considered for economic evaluation was:

- Case 1: 50 000 or 100 000 tpa ethanol plant located in Örnsköldsvik. Acid pretreatment and enzymatic hydrolysis. Solid lignin, biogas and carbon dioxide are key byproducts.
- Case 2: 50 000 or 100 000 tpa ethanol plant located in Stenungsund. Acid pretreatment and enzymatic hydrolysis. Solid lignin, biogas and carbon dioxide are key byproducts.
- Case 3: 100 000 tpa ethanol produced in a converted pulp mill located in Munksund, Piteå. This concept applies soda pulping pretreatment and enzymatic hydrolysis. Black liquor for heat and power generation and lignin extraction, biogas and carbon dioxide are key co-products.

All three cases are described in detail in the report of the sugar platform subproject.

An economic evaluation of the three cases was made based on investment costs and operations cost. The investment cost estimates included the main machinery within each process unit and auxiliary equipment such as piping, instrumentation, insulation, electrical, civil etc. For Case 1 and 2, the most capital intensive process units are pretreatment, a simultaneous saccharification and fermentation process and waste water treatment. The investment cost was estimated to 895

MSEK and 1470 MSEK for a 50 000 and 100 000 tpa plant, respectively. For Case 3, the cost for acquiring a closed-down pulp mill was set to 1500 MSEK, based on a previous study performed by the Innventia research institute. The total investment for Case 3 was estimated to 2415 MSEK. The economic evaluation is presented in greater detail in the sugar platform subproject report.

Table 3. Summary of key data and results for the sugar platform cases.

	Case 1	Case 2	Case 3
	SEKAB technology, 50 000 tpa	SEKAB technology, 100 000 tpa	Converted pulp mill 100 000 tpa
Investment [MSEK]	895	1470	2415
Production [tpa EtOH]	50 000	100 000	100 000
Premium required on ethanol market price*	**	14%	61%

* This price refers to an international price for ethanol as a bulk chemical. There are, however, several markets with different prices. The price for ethanol as a transportation fuel in Sweden could, for example, be higher.

** Profitability analysis was performed for the 100 000 case only

Under the applied assumptions, the required ethanol price for the ethanol plant to break even (at a 10% discount rate) is 14-61% above the international market price in the "Current Policy" scenario. However, with the higher price estimated on the Swedish transportation fuel market, it appears to be possible to reach a payback time of about 5-10 years if ethanol is valued as a transport fuel. If ethanol is valued as a feedstock for chemicals it will not be feasible in any of the scenarios unless policies directed towards this use for ethanol are introduced. In the 450 scenario, the relation between the feedstock price and the ethanol price develop in a less favorable direction, and the economics appears more challenging.

The ethanol price and its relation to the biomass feedstock price are the important factors in the analysis. However, sales of lignin and biogas may account for more than half of the revenues in the present evaluation and the development of these markets will therefore have an important impact on the overall results. Compared to the methanol production described in the gasification platform, investments for the ethanol projects are relatively small – in absolute numbers and as share of total production costs. In Case 3, the price of a closed-down Kraft pulp mill is very uncertain, and could affect the profitability in both a positive and a negative direction.

2.2.1 CONCLUSION

The main conclusion that can be drawn from this study is that to produce ethanol from wood-based biomass is technologically feasible and that the profitability of an ethanol plant is dependent on the price obtainable for the ethanol, but also on by-product prices. With a high willingness-to-pay for renewable transportation fuel, the studied concepts could have a payback time of some 5-10 years if ethanol is sold to the transportation fuel market. Compared to current markets for ethanol as a bulk chemical, a premium of at least 14% would be needed on the forest-based ethanol, according to the profitability analysis. However, in order to get a better picture of the economic performance of the considered ethanol projects, more detailed studies are required with regards to markets, subsides and technological aspects.

3 VALUE CHAIN 1 – OLEFINS FROM WOOD VIA METHANOL OR ETHANOL

Ethylene and propylene, also referred to as light olefins, are important building blocks used for producing, for example, polyethylene (PE), polypropylene (PP) and polyvinyl chloride (PVC), which are the three most widely produced polymers and the main components of common plastic products. Ethylene is one of the most consumed commodity chemicals by volume, and is mostly used as a feedstock in the manufacturing of plastics, fibers, and other organic chemicals. Borealis is a large user and producer of ethylene in Stenungsund, and also supplies ethylene to other industries within the Stenungsund industrial park. Propylene is also an important feedstock for industrial derivatives such as polypropylene, acrylonitrile, propylene-oxide and phenol. Propylene usage spans over various industries, from automotive and construction to packaging, medical and electronics. Perstorp AB is a user of propylene feedstock at the Stenungsund site.

Currently most olefins are produced via thermal cracking of naphtha or other light fractions of petroleum with steam, which is often referred to as steam cracking. The process is very energy intense. The resulting product mix from the cracking process must be separated into the desired products by using a sequence of operations, consisting mainly of distillation processes. The Borealis steam cracker plant is the heart of the Stenungsund cluster. In 2011, some 770 kt of olefins (ethylene and propylene), were produced in the Stenungsund cracker.

At least four routes exist for production of olefins from forest feedstock. One route is to utilize forest-based methanol in the methanol-to-olefins (MTO) process, producing a mixture of ethylene, propylene and butylenes, or the methanol-to-propylene process. Another route is via ethanol and the ethanol to ethylene (E2E) process. These two pathways have been studied in the Skogskemi project. Olefins can also be synthesized directly via biomass gasification using the Fischer-Tropsch process and cracking or via a process utilizing forest-based methane and oxygen.

The MTO and E2E processes were selected because they were proven, readily available and could fit well into the existing production in Stenungsund. In the studied concept, methanol and ethanol would be supplied via the concepts developed within the gasification platform and sugar platforms, respectively, and converted into olefins via the MTO and E2E processes by Borealis in Stenungsund.

The aim of the Olefin project was to investigate opportunities of producing bioolefins (ethylene, propylene and butylenes) from forest-based ethanol and methanol. One requirement in this project was that a production of at least 200kt of bioolefins should be studied.

The following studies have been performed as part of the olefins project of Skogskemi:

MTO pathway:

- MTO Process Technical information package
- MTO process description
- Storage study, methanol in existing rock caverns; screening and engineering
- Constructability study of the MTO plant
- Mass balance study including the steam cracker
- Business case development

- Impact study for co-feeding of methanol and ethanol in the MTO process
- Pursued the mass balance methodology in the on-going EU standardization work for bio-products

E2E pathway:

- Engineering study for a 60 000 tpa E2E process
- Constructability study of the E2E plant
- Business case development

The scales of the processes were selected based on available demonstration projects of this size, on their complexity and economies of scales benefits and on site-specific factors at the Borealis facilities in Stenungsund. The processes were evaluated with respect to e.g. profitability, availability, synergies with existing processes, process related aspects, environmental aspects, safety aspect, storage possibilities etc.

3.1 DESCRIPTION

The process route for the production of green olefins from ethanol and methanol are commercially available, i.e. proven technologies. Chematur Engineering was chosen as technology licensor for the ethanol route to green olefins. For the methanol route to green olefins, the MTO process licensed by UOP was chosen.

3.1.1 WOOD TO METHANOL

Forest-based methanol would be supplied from a gasification unit, as described in the gasification platform section of this report. The production cost of the gasification-based methanol was estimated to about 35% above the fossil methanol market price, in the best of the three cases considered.

Difficulties in reaching a certain quality specification and small available volumes of the pulp-mill based methanol described in the methanol value chain could limit its usability for production of olefins. It has therefore not been investigated further in the olefins value chain.

3.1.2 WOOD TO ETHANOL

Forest-based ethanol would be supplied from a second-generation ethanol plant, as described in the sugar platform section of this report. The production cost of the forest-based ethanol was estimated to about 14% above the international ethanol market price in the best case. The largest ethanol volumes on the market are produced from sugar- and starch-based crops. This 1st generation ethanol could be the initial feedstock for the ethanol-to-olefins process.

3.1.3 METHANOL TO OLEFINS (MTO)

In the MTO process methanol is converted, mostly, into light olefins such as ethylene, propylene and butylenes, and water. Methanol is heated and vaporized utilizing internal heat exchanging to reach appropriate temperature for the MTO process before it is fed to the MTO reactor. The MTO process is a catalytically driven exothermic process. The reaction mechanism of the MTO process is not fully understood, but a proposed chemical reaction for the MTO process over the catalyst consists of three steps:

1. Dehydration of methanol to dimethyl ether (DME)
2. Formation of intermediate species [CH2]

3. Formation of olefins and other hydrocarbons

$$2CH_3OH \leftrightarrow CH_3OCH_3(+H_2O) \rightarrow [CH_2] \rightarrow \text{Olefins}$$

After the MTO reactor, the product gas is fed to a quench scheme to purify it and quench the reaction. The product gas is then directed to the oxygenate recovery scheme before it is being fed to the existing system at the cracker plant.

Within the Skogskemi project, the possibility of co-feeding ethanol in the MTO-process has been studied. The idea is to use the exothermic methanol-to olefin (MTO) reaction to supply heat to the endothermic ethanol dehydration reaction. Preliminary evaluation of the heat balance suggests that about 20% ethanol can be added to the methanol feed and lab-scale experiments have been performed to study the impact of co-feeding 10% and 20% ethanol to a methanol feed on the MTO yields. The MTO process is thus possible to connect with both the sugar platform and the gasification platform.

3.1.4 ETHANOL TO ETHYLENE (E2E)

The E2E process is based on a license from Chematur Engineering. Ethanol is vaporized and heated in a gas fired furnace to reaction temperature (about 425-450°C). The vaporized ethanol is fed to the first bed of a multi bed reactor (typically 4 beds in series) in which it is catalytically dehydrated to produce ethylene. About 60% of the ethanol is converted to ethylene in the first bed.

$$C_2H_5OH \rightarrow C_2H_4 + H_2O$$

The reaction stops as the gas cools down by about 100°C due to the endothermic nature of the reaction. The effluent from the first bed is then fed back to the gas fired furnace and reheated to reaction temperature and fed to the second bed for an additional 20-30% conversion. The gas cools down and is reheated in the furnace a third time for another 10% conversion. The fourth and final bed is to ensure a conversion of over 99% of the incoming ethanol to ethylene. The effluent from the multi bed reactor containing ethylene, water, unconverted ethanol and by products, such as acetaldehyde, C3's and C4's, is fed to the quench column. In the quench column water and heavier hydrocarbons are removed. The quenched raw ethylene gas is then sent to downstream processing for purification to achieve the desired ethylene quality (crude, intermediate or polymer grade).

The reaction is endothermic requiring about 1630 kJ/kg ethylene produced. As recovery of unconverted ethanol for recycling is energy and capital intensive, reaction conditions enabling 99% conversion of ethanol, or more, are usually preferred in the Chematur process. The conversion of ethanol is highly selective with the reaction product containing essentially only ethylene and water.

3.2 IMPLEMENTATION

Both of the new process plants, MTO and E2E, are planned to be located at Borealis facilities in Stenungsund. Methanol and ethanol are assumed to be imported by ship. The MTO plant will be designed to produce 300 kt olefins (C2, C3 and C4) per year from bio-based methanol. The plant will use approximate 100 t dry methanol per hour as feedstock into the plant. Methanol is assumed to be supplied from offsite storage in two underground caverns. The E2E plant will be designed for production of 60 kt of ethylene, and use approximate 14 t of ethanol per hour as feedstock into the plant. The plant would be constructed on a former process area. The reason why this area is chosen is the old plant was closed at the end of 2013 and the area is an excellent industrial estate released for new enterprises. All necessary utilities are accessible on the site, such as steam, electricity, cooling water and natural gas. Ethanol is supplied from an offsite storage tankage. The MTO process is intended to replace olefins produced from naphtha, butane and propane, while the E2E process is intended to be an addition, which increases the olefins production capacity at the site.

3.3 BUSINESS MODEL

The new plants would be built by Borealis at their facilities in Stenungsund. Biomass-based ethanol and methanol would be bought on the open market. In an initial phase, co-feeding of the fossil methanol with biomethanol in the MTO unit is a possible option to get started. Also, already available 1st generation bioethanol could be used to feed the E2E process until sufficient volumes of forest-based ethanol are available.

3.4 ECONOMIC EVALUATION

The economic evaluation is performed based on estimated market prices for conventional methanol and ethanol, and we also discuss the impact of the higher production costs estimated by the gasification platform and the sugar platform. The MTO case is built on the assumption that the produced olefins would replace some of the olefins today produced from fossil feedstock in the Borealis cracker. Hence, the feasibility of the project depends also on the current process and projected prices for conventional feedstock. The E2E process, on the other hand, is assumed to add olefin production capacity to the existing production. The economic evaluation is presented in greater detail in the olefin subproject report.

3.4.1 MTO

The investment cost for the MTO plant, including storage of methanol in underground caverns, was estimated to 2864 MSEK, with a ±40% accuracy. A maintenance cost corresponding to 2% of the total investment cost was assumed and a personnel cost of 1 050 000 SEK per year and personnel.

Table 4. Summary of key data and results for the MTO plant

	Base case	Alt. 1	Alt. 2
Description		30% higher product price	30% higher product price and 30% higher methanol cost
Investment [MSEK]	2864	2864	2864
Production [tpa olefins]	270 000	270 000	270 000
IRR	-5%	24%	6%

The profitability of the MTO process is highly dependent on the methanol price in relation to conventional cracker feeds. Affecting the profitability is also the assumed green premium price that can be obtained for green olefins and the price of green methanol feedstock compared to conventional methanol. The basic ethane price will not affect the result, only the premium obtainable on green ethylene, as the same amount of ethane is assumed to be cracked in both the present production and the envisioned MTO case. The results show that an incentive in the form of policy instruments or green premiums would be required for profitability. However, the production cost for forest methanol was estimated in the gasification platform to be 35% above the methanol market price. At this high methanol price, the return on the MTO investment will be low also if a green premium of 30% can be obtained on the olefin products..

3.4.2 E2E

The investment cost for the E2E plant was estimated to 636 MSEK, with ±40% accuracy. As for the MTO plant, a maintenance cost corresponding to 2% of the total investment cost was assumed and a personnel cost of 1 050 000 SEK per year and personnel.

Table 5. Summary of key data and results for the E2E plant

	Base case	Alt. 1
Description		30% higher product price
Investment [MSEK]	636	636
Production [tpa olefins]	60 000	60 000
IRR	**7%**	**26%**

In comparison to the MTO business case, the E2E business case implies an increase in production capacity. The profitability of the different scenarios is therefore only dependent upon the prices of the raw materials and products in the E2E process. The product price is to a great extent affected of implementing the green premium price. As for the MTO process, an incentive in the form of policy instruments or green premiums is likely to be needed to achieve a sufficient return on investments. It should also be taken into account that the lowest production cost for forest-based ethanol was estimated to be 14% above the current market price for ethanol as a bulk chemical.

3.5 ENVIRONMENTAL EVALUATION

The analysis of the change in environmental impact is carried out for the entire cluster in Stenungsund. The current production in the cluster today (base case) is compared with a future production where part, 200 kt, of the olefins is produced from forest-based methanol in an MTO plant and 30 kt ethylene is produced from forest-based ethanol in a dehydration plant. The forest-based olefins production would account for approximately 30% of the total olefins production.

Switching to partly produce olefins from renewable methanol and ethanol will reduce the environmental impact of the products from the cluster. The total amount of energy used along the value chain will be higher when the olefins are partly produced from renewable methanol/ethanol, but since a significant part of this energy will be from renewable sources the total dependency on fossil resources will be lower compared to the current situation. The impact on global warming (cradle to grave) will decrease with 19% when 25% of the olefins used in the cluster are produced from forest feedstock. Heat integration between the gasification/methanol synthesis plants and the cracker is of high importance for the results as well as what kind of fuel that is replaced

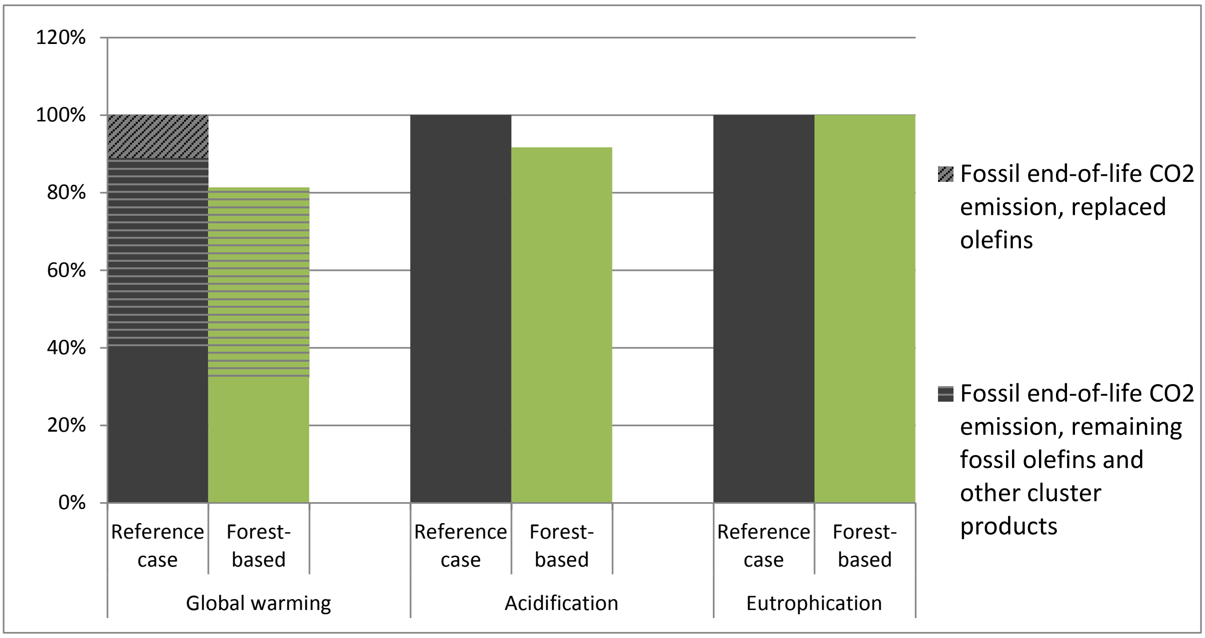

Figure 3. Environmental impacts of the entire Stenungsund cluster in the Skogskemi case, where approximately 30% of the olefins are produced from forest feedstock, compared to the today's production in the Stenungsund cluster.

The reduced CO_2 emission in the cradle to gate activities is mainly due to two things:

- The reduced use of natural gas in the cracker plant due to that the surplus heat generated in the gasification and methanol synthesis could be used in the cracker.
- The production of the renewable raw materials, methanol and ethanol, have lower net CO_2 emission than the production of the fossil raw materials (ethane, propane and butane) used in the base case.

The impact on acidification is also lower for the forest-based case while there is no difference with respect to eutrophication[a] potential.

3.6 OPPORTUNITIES AND BARRIERS

In 2009 the MTO process was still unproven at commercial scale. However, a first commercial scale installation of the UOP/Hydro MTO process was announced in 2011 and started up in September 2013. The technology can therefore be considered to be proven on a commercial scale.

The E2E process is a relatively low-investment option to increase the ethylene production capacity at the Stenungsund site. The project has also indicated that it is possible to co-feed ethanol and methanol into the MTO process. The process itself can be tuned towards higher or lower propylene production and has a relatively large turndown ratio. The setup would therefore have a high degree of flexibility.

To produce green olefins, a green premium, or policy incentives, for the olefins is essential for the profitability of the project. At the same time, the economics is sensitive to feedstock ethanol and methanol prices. These prices are difficult to predict. Fossil methanol prices have

[a] Eutrophication is the excessive supply of nutrients to, for example, a lake or sea, where it causes rapid growth of algae and subsequent oxygen depletion.

historically been very volatile, fluctuating between 147 and 525 EUR/t between 2006 and 2014, for example. Prices for biomass-based ethanol and methanol is subject to market uncertainties, but also very much to policy uncertainties regarding, for example import tolls and tax exemptions and other incentives for their use in the transportation sector.

3.7 CONCLUSION

With forest methanol production costs estimated at some 35% to 65% above current market price levels, the economics of the full chain from forest to olefins via methanol are challenging without proper policy incentives. Given the present results, the E2E pathway shows better economic performance but green premiums or other incentives would be required for profitability. Production could be started with first-generation ethanol already available on the market. However, import duties levied on ethanol could present an important barrier.

Future work would include further evaluation of existing E2E pathways, studies on raw material markets as well as product markets. This could include investigation into the possibilities to make agreements with raw material suppliers, producers and with potential customers to identify their willingness-to-pay a green premium price.

4 VALUE CHAIN 2 – BUTANOL FROM WOOD VIA ETHANOL

Butanol is a chemical used in both water-based and oil-based paints today. The global production is about 3 000 000 tpa. Today butanol is produced from the fossil feedstock natural gas and propylene at Perstorp Oxo in Stenungsund. Perstorp is producing about 100 000 tpa of butanol. Biobutanol can also be used as a biofuel to replace diesel. Both car engine manufacturers and oil companies are today interested in biobutanol as a diesel component blended in up to 30 % in diesel.

Butanol could be produced from biomass directly via fermentation or via catalytic processes. The pathway pursued in Skogskemi is to produce butanol via biomass-based ethanol, a process for which there is well proven technology. Conversion of forest feedstock is studied in the sugar platform of the project. Initially it is possible to start production of biobutanol from bioethanol derived from other feedstock, which is already on the market.

The pathway studied includes conversion of ethanol to acetaldehyde at SEKAB in Örnsköldsvik, for transport to Perstorp AB in Stenungsund and further conversion into butanol. Except for butanol this also gives the possibility to produce other heavy alcohols, organic acids and polyols in already existing plants within Perstorp, only by co-feeding bio based feed stock. Furthermore, development of new production of other bio based downstream products of higher value like 1,3 butandiol, sorbic acid, crotonic acid etc. is made possible.

The goal of the biobutanol project has been to do a Pre-FEED to evaluate and describe a demo plant for production of 20 000 tpa biobutanol at the Perstorp Oxo site in Stenungsund. The project has produced the following deliverables, which are detailed in the butanol subproject report:

- Localization study of the new plant (Örnsköldsvik or Stenungsund)
- Process flow diagrams (PFD)
- Layout and 3D-model
- Mass balance
- Equipment lists
- Investment cost ±30 % accuracy
- Profitability calculations and analysis

A complete pre-FEED with the above deliveries has been made for the new biobutanol plant which comprehends:

- The new biobutanol process plant itself
- Connection of utilities like steam, cooling water etc. and connection to feed stock
- Storage tanks
- Control system
- Logistics of the feed stock and product

The full pre-FEED study was made for a new plant for production of biobutanol from acetaldehyde. An increase in the acetaldehyde production in Örnsköldsvik is necessary to be able to supply the new biobutanol plant. The capacity increase was outside of the scope for the pre-FEED, but an investment estimate and a profitability analysis was made for this part. Also, increased capacity in possible downstream products, such as octanol, octanoic acid and polyols, was studied within the project but not included in the pre-FEED scope.

4.1 DESCRIPTION

4.1.1 WOOD TO ETHANOL

Forest-based ethanol would be supplied from a second-generation ethanol plant, as described in the sugar platform section of this report. The production cost of the forest-based ethanol was estimated to about 14% above the international ethanol market price in the best case. The largest ethanol volumes on the market are produced from sugar- and starch-based crops. This 1st generation ethanol could be the initial feedstock for the butanol value chain, with a gradual shift to forest-based ethanol as this becomes available.

4.1.2 ETHANOL TO ACETALDEHYDE

SEKAB produces bio-based acetaldehyde in a catalytic oxidation process that uses bioethanol, oxygen from the air and bioenergy to produce acetaldehyde. The process is efficient, both in terms of energy and material consumption. An increased production capacity for acetaldehyde production at SEKAB in Örnsköldsvik would be needed to be able to supply the new biobutanol plant.

4.1.3 ACETALDEHYDE TO BIOBUTANOL

The process of chemically converting acetaldehyde to biobutanol consists of two steps:

1. Production of crotonaldehyde from acetaldehyde
2. Hydration of the crotonaldehyde to biobutanol

A known process from SEKAB has been chosen for producing crotonaldehyde from acetaldehyde whereas the process design for the hydration to biobutanol has been developed within the project.

The SEKAB crotonaldehyde process was used in Örnsköldsvik in 1960-1970, before cheaper products from the developing petro-chemical industry made it obsolete. It is a process that is known and documented at SEKAB but also a process that had severe problems with fouling in one of the columns. To handle the fouling a lot of fresh water was used which in turn created a large stream of waste water. During the project several potential improvements to the croton process have been identified. It is recommended that the next step would be to evaluate the technology to ensure the use of best available technology (BAT) both in terms of energy use and reaction efficiency. The problem of fouling by-products has in processes available today been reduced by replacing one column with a tube reactor. This is believed to, in addition to increase conversion rate, reduce the need of excessive water in the process and thereby reduce the environmental impact even further.

In the process two acetaldehyde molecules combine to form acetaldol:

$$2\ CH_3CHO \rightarrow CH_3CH(OH)CH_2CHO$$

The reaction is highly exothermic leading to vaporization of products and reactants inside the column. The heat is removed thorough condensation of the vapors in a condenser. Acetic acid neutralizes the stream before it is pumped into the croton column where an aldol condensation occurs, forming crotonaldehyde and water.

$$CH_3CH(OH)CH_2CHO \rightarrow CH_3CH{=}CHCHO + H_2O$$

Crotonaldehyde is separated and purified in a sequence of steps before it is recovered as a liquid side stream from the purification column at an estimated purity of >99%.

The product stream is then pumped to 25 bar and mixed with a circulation stream from the butanol reactor. In the butanol reactor both double bonds of crotonaldehyde are hydrated according to the formula

$$CH_3CH{=}CHCH{=}O + 2H_2 \rightarrow CH_3CH_2CH_2CH_2OH$$

The hydration reaction occurs in a hydrogen atmosphere in four beds of Ni catalyst. The reaction is highly exothermic, thus a large side stream needs to be taken out after the first bed for cooling. Suitable reaction temperatures are between 120 °C and 140 °C and should not increase above 150 °C not to damage the catalyst. The product stream is cooled and depressurized to 20 °C and 2.5 bar in a flash vessel which separates dissolved hydrogen. The butanol product is then pumped to storage.

4.2 IMPLEMENTATION

The biobutanol plant will be located at a designated plot at Perstorp Oxo, Site Stenungsund. The plant will be integrated in existing systems for raw material and product handling, utility, waste and firefighting already existing on Site Stenungsund. Acetaldehyde, the main raw material, will be provided via truck transport from Gothenburg (train from Örnsköldsvik to Stenungsund). Two new storage tanks for acetaldehyde provide raw material for the biobutanol plant. New truck unloading facilities are integrated in existing installation and piping is integrated in existing pipe racks.

NaOH is already stored and used at the site and hence the biobutanol plant can connect to the existing system. Acetic acid will be stored in the new process area. Auxiliary raw materials and utility including hydrogen, steam, condensate, nitrogen, compressed air and others are provided via existing pipe racks in close vicinity to the designated plot. The final product, biobutanol, is transported to an existing storage tank via the pipe rack.

The production scale was set to 20 000 tpa of butanol. This is judged appropriate to demonstrate the technology on an industrial scale and at the same time produce volumes large enough to be evaluated by the chemical and biofuel market. This size also matches well the production capacity for bio-based acetaldehyde of SEKAB. A fully commercial size in a future second step would be about 10 times as big, 200 000 tpa and produce both biobutanol and other biobased chemicals and biofuels.

4.3 BUSINESS MODEL

The business model for the biobutanol project is a Joint Venture with bio based ethanol as raw material and biobutanol as end product. Both increased production of acetaldehyde in Örnsköldsvik and new production of biobutanol in Stenungsund is included in the Joint Venture.

4.4 ECONOMIC EVALUATION

This is a brief summary of the economic evaluation of the butanol value chain. The evaluation is presented in greater detail in the butanol subproject report. The investment in the biobutanol project comprehends:

1. Expansion of the existing acetaldehyde plant in Örnsköldsvik for supply of feedstock to the new biobutanol production. Total investment 100 MSEK.
2. New plant to produce 20 000 tpa biobutanol in from acetaldehyde in Stenungsund. The pre-FEED has calculated the investment based on the model of the new plant. Total investment 143 MSEK.

The total investment cost for the new biobutanol plant has been calculated with an overall accuracy of ±30 %. Most parts have a higher accuracy though since costs have been compared with and taken from a project currently taking place at the Perstorp site in Stenungsund and which has included, for example, a one billion SEK investment in a new production plant.

Table 6. Summary of key data and results for the butanol plant

	Base case	Alt. 1	Alt. 2
Description		Investment support: 100 MSEK	Investment support: 100 MSEK and 20% green premium on chemical
Investment [MSEK]	243	143	143
Production [tpa butanol]	20 000	20 000	20 000
IRR			
- **Butanol sold as transportation fuel**	9%	16%	16%
- **Butanol sold as a chemical**	-1%	3%	32%

The results are calculated based on world market prices of ethanol estimated in the "Current Policy scenario", excluding import duties. Import duties levied at today's levels would have a negative effect on the result. A production support or green premium on the product price could, on the other hand, have a strong positive impact on the results. In general, the price relation between ethanol and butanol is a key factor in the economic evaluation. In the 450 scenario, this relation changes in an unfavorable way. The present incentives for renewable transportation fuel make this market more interesting, and butanol would be an excellent fuel for blending with diesel.

4.5 ENVIRONMENTAL EVALUATION

LCA analysis shows that forest-based biobutanol has significantly lower impact on global warming but higher impact on acidification and eutrophication than the fossil based butanol. Ethanol production is the activity with the largest environmental impact in all impact categories and this is due to the impact from the production of the enzymes used. The LCA data on enzymes carry large uncertainties. Impacts could be lower, if for example a larger share of the energy input to enzyme production would come from renewable sources, or higher, if for example a larger enzyme dose would be required. The impacts are calculated using enzyme data estimated within Skogskemi. The range indicated in the figure shows results when using enzyme data from another study. The acidification impact for the forest butanol originates mainly from production of enzymes and of sulphur dioxide used in the ethanol production. There are, however, large uncertainties in these data and the actual impact could be higher or lower than the indicated range.

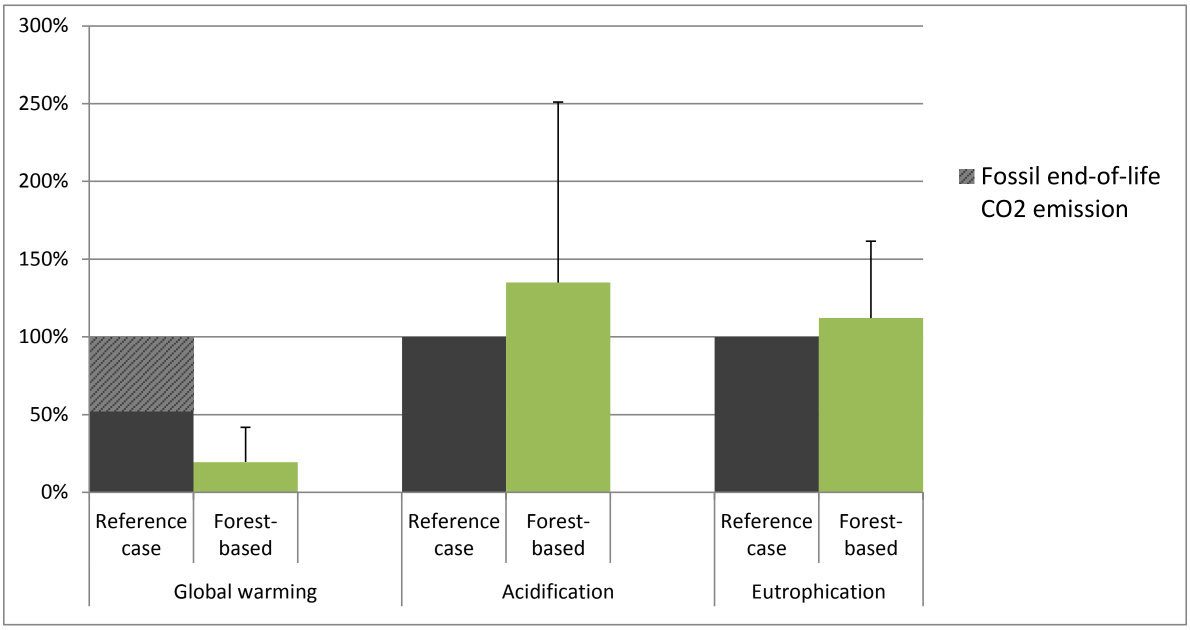

Figure 4. Environmental impact of forest based butanol compared to fossil butanol production.

Note that, in contrast to the olefins case, the comparison is made between 1 t of biobutanol and 1 t of fossil butanol, not for the entire Stenungsund cluster production.

4.6 OPPORTUNITIES AND BARRIERS

Under the course of the project, several potential improvements to the process for producing crotonaldehyde from acetaldehyde have been identified. Further development of the process to produce butyraldehyde instead of butanol could open the door for production of other sustainable chemicals and fuels with higher value than butanol. Perstorp today has several existing plants using fossil butyraldehyde, which could be fed with renewable butyraldehyde to produce green organic acids, heavier alcohols and polyols. This option could improve profitability and reduce the risks of the project.

The base case without any external investment or production support does not give the profitability needed neither for butanol as a biofuel nor as a green chemical. Therefore the most probable scenario for realizing the project is with an external investment support. With the present tax exemption or some kind of mandate-system for biofuels in Sweden, the value of butanol is highest as a fuel, unless similar incentives are given for butanol in other applications. It is therefore most likely that a plant will start producing biobutanol as a fuel. With time, the plant can gradually switch over from biofuel to green chemicals if market conditions change.

To get a profitability which motivates an investment in the project the business model must cover the whole chain from production of acetic aldehyde from ethanol to production of butanol. The business model developed in this project involves a Joint venture that buy ethanol as raw material. However, the integration must be further back to ethanol for the project to be profitable.

The project is subject to several risks, which is likely to make investors demanding a higher IRR in order to invest compared to the corresponding fossil projects. Identified risks include policy uncertainties regarding biofuels and renewable investments, import duties for ethanol, difficulties in getting acceptance for butanol as a new biofuel and difficulties involved in forming a joint venture for this type of project.

4.7 CONCLUSION

The most likely scenario for building this demo plant is with an investment support of 100 MSEK to produce biobutanol as a biofuel. This would give the project an IRR of about 15-20 % which might be considered to be sufficient when taking the project risks into evaluation, see below. A production support would decrease the risk further and could mean that the project can be realized without investment support, although the project considers investment support to be more likely than production support. Further work to develop potential solutions identified in this project could improve the process performance and allow for new chemical products with potentially higher value.

5 VALUE CHAIN 3 - METHANOL FROM PULP MILL STRIPPER GASES

Methanol produced via biomass gasification was described in section 5.1, on the gasification platform. Methanol can also be a byproduct in biomass-based processes, as a decomposition product from hemicelluloses and lignin. Kraft pulping is such a process and a there is a patented method to recover and purify methanol from Kraft pulp mills. This pathway is explored in the Skogskemi methanol value chain. Based on the production of pulp, a theoretical amount of approximately 50 000 t of kraft methanol is available annually in Sweden. In the studied case, methanol is extracted at a pulp mill and shipped to Stenungsund for final purification and utilization. An economic evaluation was also made for a hypothetical case where seven pulp mills supply methanol to a central upgrading unit.

The goal of the methanol project has been to do a Pre-FEED to evaluate and describe a complete process for the upgrading of mill-derived methanol to make it usable as feedstock in existing processes. Perstorp AB is a consumer of more than 100 000 t of methanol including biomethanol annually going into both chemicals and biofuels. The challenge in the project is to be able to produce a sufficiently high purity of the methanol product. The envisioned use of the methanol in the Skogskemi methanol value chain is for RME production at Perstorp facilities in Stenungsund. The project has included the following activities, which are detailed in the methanol subproject report:

- Chemical process evaluation and improvement
- Process design for installation at a pulp mill
- Development of a final upgrading process, presented as in process flow diagram
- Investment cost estimation for pulp mills units and final upgrading unit
- Profitability calculation and analysis
- Investigation of alternative business models

A pre-FEED has been made which comprehends:

- Process design of a pre purification unit for a generic model mill, including an investment model
- A final upgrading unit located at the Perstorp site in Stenungsund, including connection of utilities etc.

The project has verified the chemical process on a larger scale and optimized it further in order to meet quality aspects and reduce operational costs. Also options to reduce investment costs have been elaborated.

5.1 DESCRIPTION

In the Kraft pulping process, cellulosic fiber is separated from lignin and hemicelluloses. Lignin and hemicelluloses are dissolved in water, forming a mixture called black liquor. The black liquor dry matter content needs to be raised in an evaporation plant before it can be combusted for steam generation and recovery of process chemicals. It also contains some methanol which can be recovered from the evaporation process, and is then known as kraft methanol. However, kraft methanol is contaminated with ammonia, turpentine and organic sulfides which cause malodor and it is usually considered as a waste product which is combusted for energy recovery. Purification of the kraft methanol is necessary to make it usable in other processes

The purification of the kraft methanol is proposed to be performed in two separate processes. Valmet has in collaboration with SP Processum developed a patented method (PuriMeth) for pre-purification of kraft methanol, which is applied at the pulp mill. The purpose of the PuriMeth process is to remove ammonia, turpentine and organosulphur components from the methanol to reduce smell and facilitate handling. The pre-purified methanol is further upgraded in a final purification process which is a central unit that collects pre-purified methanol from a number of pulp mills.

5.1.1 FOREST METHANOL AT THE KRAFT PULP MILLS

The Purimeth process at the mill removes contaminants such as ammonia and sulphides by a sequence of distillation and decanting operations. Sulphuric acid is added followed by a separation and decanting of the turpentine. Lipophilic contaminants in the methanol are removed with the turpentine, which also reduces the amount of oxidation agent needed.

5.1.2 FINAL PURIFICATION IN A CENTRAL PLANT

The final purification of methanol which is required after the Purimeth process is proposed to be composed of a two-step distillation unit. In the first distillation column a light fraction is separated and in the second column the methanol leaves the top of the column and a heavy fraction containing water leaves from the bottom.

5.2 IMPLEMENTATION

Pre-purified methanol will be collected from several pulp mills (Munksund and Östrand) to a central plant where the final purification is done in a two-step distillation. The raw material has been pre-purified according to Purimeth process before sending it from the pulp mill. The purpose is to have a central upgrading plant that is designed for a capacity of 20 000tpa, but at startup running at 10 000 tpa and collecting methanol from three pulp mills.

The central plant has to be located at a production site, where utilities and other infra-structure is available to keep investments and production costs low. Placing the unit at a big site like in Perstorp will reduce the total investment cost. Some support utilities (steam, air, nitrogen, water, waste-water treatment etc.) may need expansion but the investment will be much lower than if new ones have to be built.

A challenge of the suggested concept is to achieve sufficiently high degree of methanol purity at a reasonable cost. Based on the results of the project, it is not viewed as feasible to reach the commonly applied IMPCA specification. However, different methanol end uses will have different requirements on the methanol quality, and it is suggested that the pulp-mill based methanol should be evaluated for use in the RME production at Perstorp AB.

5.3 BUSINESS MODEL

Within the framework of the project, there are two business model suggestions which have been explored:

1. A forest company – either SCA or Holmen – invests in one or several PuriMeth units from Valmet. The produced methanol is sold to Perstorp AB that invests in a purification process to obtain a quality level of the product which is suitable to use in the RME process or any other process depending on the obtained quality.

2. A venture, jointly owned by the project partners, invests in both the PuriMeth units and in the further processes to purify to product for production and resale of biomethanol in the open market or to Perstorp AB.

In both cases Perstorp AB is committed to purchase all the methanol which is produced in the PuriMeth units for a certain minimum value, agreed by the parties.

Based on the first model a forest company invests in a Purimeth unit and Perstorp AB undertakes to purchase all methanol produced for an adjusted price. The price for the methanol is determined according to an agreed formula and is a function of the market price for methanol in Europe, the methanol concentration and a quality parameter in relation to a given methanol specification based on the targeted process where it is intended to be used. The project has evaluated several alternatives with respect to pricing and green premiums on the product, which are described in the methanol value chain report.

5.4 ECONOMIC EVALUATION

The economic evaluation of the pulp mill based methanol carries several important uncertainties. Firstly, there are some technical uncertainties remaining within the concept. The purity of the final methanol product is a key challenge, and while the purity may be sufficient for certain applications – such as RME production – it is unlikely the specifications for the standard methanol market could be reached. The market value of the product is therefore not well defined. The economics for a pulp mill will be highly dependent on the alternative costs, i.e. what are the costs for the current methanol system, and the alternative benefits of the present use of methanol. This will vary greatly between mills. Given the uncertainties, we opted to perform a simplified assessment, to give an indication of the economics of the pulp-mill based methanol. The economic evaluation is presented in greater detail in the methanol subproject report.

The investment cost for a PuriMeth installation at a pulp mill with an annual production of 3 000 tpa of methanol was estimated to 40 MSEK, but will vary depending on, for example, the existing equipment and general condition of the methanol system. It was estimated that a final purification unit would have to produce some 20 000 tpa of purified methanol to be economically viable. In the economic evaluation, we have assumed that the central purification unit would collect pre-purified methanol from 7 pulp mills, each producing 3000 tpa of methanol. The investment cost for a 20-25 000 tpa final purification unit was estimated to 65 MSEK. The direct variable costs were estimated to 2.4 SEK/kg methanol for the PuriMeth unit and 1.2 SEK/kg methanol for the final purification unit. This includes costs for wood fuel to replace the methanol energy at the mill, but does not include any benefits in the form of avoided costs as an existing methanol handling system is replaced or reduction of NOx emissions etc., and can therefore be considered an upper estimate.

Table 7. Summary of key data and results for forest methanol purification, including pre-purification at seven mills and one central unit for final purification

	Base case	Alt. 1
Description		Only 25% of pulp mill investment and operation costs* allocated to methanol production
Investment [MSEK]	345	135
Production [tpa methanol]	21 000	21 000
Premium required on fossil methanol price	**108%**	**36%**

* 100% of the biofuel cost to replace the methanol energy in the mill is still included

At a 10% discount rate and 20 years lifetime of investments, the methanol production cost would be about 5.60 SEK/kg, or about double the estimated methanol market price. Taking into account the actual case for an individual mill could give substantially lower production costs. Also without the PuriMeth installation, the mill will need a methanol handling system. The value of the methanol energy content, in the mill – and hence the cost to replace it – may vary from between mills, depending on their overall energy situation. If only 25% of the PuriMeth investments and operating costs are allocated to the methanol product, the required methanol price for the project to break even is approximately 36% above the estimated market price. The market value of the pulp-mill based methanol is however still uncertain.

The value chain includes at least two key actors – the forest industry installing the PuriMeth process and the chemical company Perstorp AB which is the intended user of the methanol and the likely host of the final purification unit. Whether the value chain is realized as a joint venture or other means of cooperation, a model has to be found for distributing costs, revenues and risk between the actors. Several alternative models are explored in the methanol subproject report, with quantitative estimates of the profitability for the forest companies and Perstorp AB, respectively.

5.5 ENVIRONMENTAL EVALUATION

The LCA study shows that the forest based methanol from kraft pulp mill stripper off gasses has a lower global warming potential than fossil based methanol. The methanol process is closely integrated with the pulp mill and a difficulty in the analysis is to decide how environmental impacts from shared processes should be allocated between the methanol and the other products of the mill (mainly pulp). The base case shown assumes that only the additional impacts from the methanol process, compared to a reference case, is allocated to the methanol. The uncertainty range shows the results when impacts are instead allocated based on the economic value of the methanol relative to other products. Acidification potential is higher for the forest methanol case irrespective of the allocation method, but for eutrophication the result will depend on the allocation method. The purification process and the production of the chemicals used in the kraft pulp mill are the processes with the highest environmental impact.

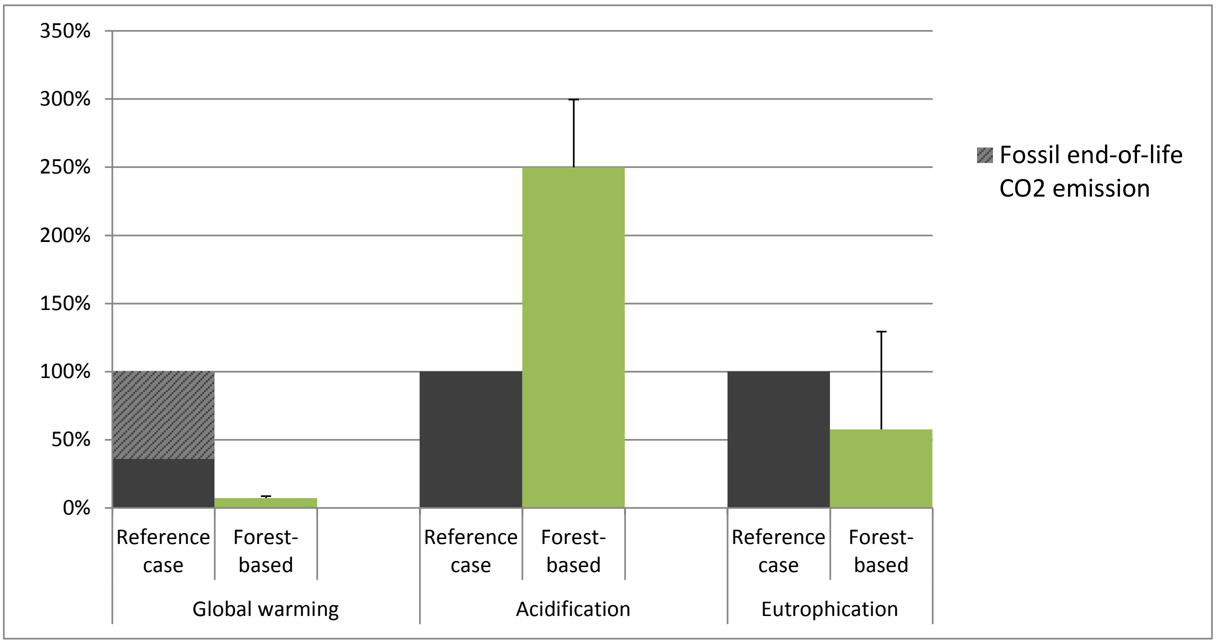

Figure 5. Environmental impact of 1 t of forest based methanol relative to fossil methanol

The largest contributions to the results for the forest methanol come from the methanol purification process and the production of the chemicals used in the pulp production. Use of sulphuric acid in the purification process and in other mill processes contributes to the acidification impact. The uncertainties in the study are largest for the purification process, as this process is under development. The results presented here however shows the environmental performance of the purification technology at its current state and unless there will be large changes in the purification process these results will also be representative for its eventual implementation.

Note that, in contrast to the olefins case, the comparison is made between 1 t of biomethanol and 1 t of fossil methanol, not for the entire Stenungsund cluster production.

5.6 OPPORTUNITIES AND BARRIERS

During the course of the project, it has become evident that there remain certain technical challenges in order to achieve a product of sufficient purity. The project has identified potential improvements to the process, to overcome the technical challenges. Further work would be needed to further improve and verify the solutions. The required product specification will also depend on the intended use of the methanol. With the current specification of the forest methanol, we suggest to focus on optimizing the forest methanol for usage in the RME-process to produce biofuels. It is also our experience that the market with the biggest potential for a green premium is within biofuels with the tax relieves that are implemented based on political decisions and environmental efforts in this field.

There are obvious challenges to setup a profitable supply chain of methanol, however there are indications of a business potential if the PuriMeth technology can deliver a product that fulfils the specification of methanol for the RME-process, and thereby benefit from the present policy incentives placed on renewable transportation fuels. However, the policy uncertainties with respect to support for renewable biofuels would present a risk to such a venture.

The volumes of methanol at one single mill are rather small, and the investment costs for the mills must be kept low to be feasible. The project has suggested design solutions which would reduce the investment costs compared to the initial estimates. A challenge is that a number of mills need to invest in the PuriMeth technology in order to produce sufficient volumes of methanol for a central upgrading unit to be economically feasible.

5.7 CONCLUSION

The project has highlighted critical areas to develop further. With further work within the identified areas we believe that the suggested value chain can become an interesting concept for the production of biobased methanol to be used in certain applications. Key component are to decrease investment cost at the individual mills, and to be able to collect methanol from several mills to reach a reasonable scale of the central upgrading unit.

6 POLICY AND NETWORKING IN THE CONTEXT OF INNOVATION

The existing policy landscape and key issues in the development of new biorefinery innovations were studied within the Skogskemi project. The results from these studies are described in detail in the report of the systems analysis subproject.

In general, policy risks and market risks appear to be important barriers to the advancement of the biomass-based chemicals studied in the project. Pilot and demonstration plants play a key role by reducing uncertainties in the process of innovation. Our report highlights the long development times of new technological fields and the need for different types and scales of pilot and demonstration plants, but also for the interaction between verification and diffusion of technology. This has important policy implications. For instance, innovation requires both R&D and learning-by-doing and for this reason R&D programs should typically not be designed in isolation from practical application.

Based on the innovation system and policy analyses, we draw the conclusion that there is a gap in the current policy landscape of Sweden. There are no policy instruments supporting the upscaling of technologies from the level of technology demonstration and pilot plants to a commercialized level. The development of new value chains requires that not only technical development is supported, but also the deployment phase – i.e. the phase where an innovation is taken from technical demonstration to market, and the organization of the full value chain is formed.

Our results underscore the potential importance of a clear overlap in policy measures for providing conditions that enable small firms (e.g., equipment manufacturers) to grow with the technology, as well as for potential customers, capital goods suppliers and other actors along a possible value chain to invest resources in the field. Without such overlaps and without incentives that also manage the market risk (e.g., fossil fuel price fluctuations), key actors may not be able to succeed in the development of the new value chains envisioned in the Skogskemi project.

6.1 THE IMPORTANCE OF DEMONSTRATION PROJECTS

New technologies and new value chains carry uncertainties of several kinds. To potential stakeholders in the development of innovations, these uncertainties represent risks. Risks may refer to uncertain technological performance, but also to market risks, organizational risks, and policy risks. Pilot and demonstration plants play a key role by reducing uncertainties. In general, PDPs represent a bridge between basic knowledge generation and technological breakthroughs on the one hand, and industrial application and commercial adoption on the other. These plants balance between verifying technological options on the one hand, and creating a first market for technologies on a commercial scale on the other. Thus, the development activities taking place in pilot and demonstration plants not only address technical challenges, but also aim to reduce the organizational, market-related and policy risks and uncertainties that key stakeholders face in progressing the new technologies

6.2 NETWORKS AND DISCUSSION PLATFORMS

An important sub-project of Skogskemi has been devoted to the creation of networks and meeting opportunities between the forest and chemical industries. This has been done in the so-called discussion platform. A number of open seminars have been held during the two-year period. These seminars have treated different themes and innovation areas considered especially interesting to further the development of common innovation projects. The discussion platform or seminars has been held in Stenungsund, Gothenburg, Örnsköldsvik, Södertälje and Stockholm. Both project partners and other relevant parties have participated. The following discussion platforms took place during the project:

- The Skogskemi Conference. Two-day conference with all major parties from the Swedish forest industry and chemical industry present. March 2013. 160 participants.
- The sugar platform - state of the art in creating cheap, clean sugars. April 2013. 30 participants.
- The Biorefinery Demonstration plant – ForestChemistry applications. September 2013. 48 participants.
- The LCA profile of green chemicals and need for new policies. March 2014. 30 participants.
- The Lignin platform for chemicals. May 2014. 40 participants.

In total around 300 participants from the two industry sectors, academia and society took an active part in the seminars. As a consequence of these platforms, new collaboration has been created and a number of projects have and will be started. Some examples of such new collaboration are described in part 7.3 in this report.

7 SUMMARY OF RESULTS

Based on the results of the Skogskemi project, we conclude that the technology is there. Construction could start today, of chemical plants for production of butanol and olefins from biomass-based ethanol and methanol. Butanol and olefins would feed directly into existing product lines of the Stenungsund industries. The step from forest feedstock to methanol and ethanol still carries uncertainties with respect to upscaling of the processes. Large-scale demonstration projects are, however, under way, which is likely to reduce these uncertainties in the near future. Certain measures to increase technological performance and reduce costs along the studied value chains have been identified in the project. Further studies could evaluate these measures and further improve the technical and economic feasibility.

From the studies of the individual value chains, it is apparent that they face economic challenges, under the current market conditions. Without economic incentives the value chains and green bulk chemicals based on Swedish forests will be difficult to realize. The incentives could be in the form of a premium price for renewable productions paid on the market or in the form of policy incentives. The experience of the project partners as well as evidence from literature is that green premium prices exists on certain markets and are paid in value-chains of bio-based chemicals and plastics. Premium levels of 0-30% have been mentioned as reasonable estimates. It is, however, typically not possible to get a guaranteed green premium level before the product actually exists, which presents a hen-and-egg type of problem when new green products are considered. It is also important that the premium finds its way backwards in the value chain from consumer to producer. Closer cooperation and integration along the value chain may be one way to facilitate the propagation of the green premium value.

Under the present market conditions, the use of ethanol, methanol and butanol in the transportation sector seems to have the potential to be economically feasible, as a result of the current policy support for renewable transportation fuels. The policy landscape is, however, very uncertain and subject to rapidly changing conditions. These policy risks add to the already important market risks, which result from, for example, the presently small markets for biomass-based products and large volatility of fossil feedstock and product markets. These risks make investors require higher-than-usual returns on investments making the projects even more challenging to realize. Public investment support could ease this challenge, but does not manage the market and policy risks. In general, long-term stability of policies is required in order to effectively reduce the perceived risks and getting the investments under way.

The present unbalance in the policy support for renewable fuels versus the support for renewable chemicals and materials would at first seem to be a large barrier for forest-based chemicals. However, some participants in the project see synergies between the two markets. The established market for biofuels could act as an early entry market, which could be shifted to production for the chemicals market at a later stage. Also, already available 1st generation bioethanol from sugar and starch crops could act as a feedstock until forest-based ethanol is available at competitive costs and in sufficient amounts. The diversification of feedstock and product markets is thus perceived to reduce risks for the studied projects. This said, it is clear that the transportation fuels market is the most attractive market for the value chains studied in the project. Realization of the value chains with bulk products intended for use as renewable chemicals and materials is unlikely, under current conditions, unless incentives are put in place for these products on a similar level as for renewable transportation fuels.

7.1 ECONOMIC ASSESSMENT

The economic assessment confirms that, while some of the projects appear feasible if the product is sold on the transportation fuel market with the current tax exemption policy, production for the chemicals and materials markets are less promising unless similar incentives can be obtained on these markets. All of the projects require large investments – up to several thousand MSEK, for example in the gasification platform. The investment cost estimates are performed with a relatively good accuracy for the specific value chains. Nevertheless, the uncertainty for parts of the calculations is estimated to be about ±40%. For the gasification and sugar platform, the uncertainties are even larger. The profitability of the projects is dependent on several markets including feedstock and product markets, and on a complex system of policy instruments. Future developments of these are difficult to predict which contribute to large uncertainties in the calculations as well as large perceived risks to the stakeholders. To find ways of minimizing these market and policy risks is the most important factor to realize production of green chemicals from forest feedstock. As a very rough estimate from the Skogskemi project is that a long-term, stable green premium on forest methanol and ethanol as well as the end products in the value chains in the vicinity of 20-50 percent would create sufficient impetus to start realizing investments.

7.2 ENVIRONMENTAL ASSESSMENT

The LCA results give a clear indication that forest-based chemicals have significantly lower life-cycle greenhouse gas emissions than fossil-based chemicals. The LCA studies found lower results also for environmental impact categories other than climate change, but here the picture is more diverse. The risk for eutrophication was, in many cases, higher for the forest-based cases, which should be taken into account when biorefining industries are established. The results of the LCA and the technical system analysis further indicate that environmental impacts and economics are to a large extent dependent on to which extent processes can be integrated to maximize the resource efficiency. The integration options may vary between different localizations and the preferred technical option may therefore depend on case-specific factors. Hence, we also note that the LCA study only included a limited number of a large range of plausible options, and that it carries large uncertainties. More detailed studies would be needed to draw firmer conclusions.

The LCA studies performed in Skogskemi show that the forest-based alternatives in general have lower global warming potential compared to fossil alternatives already in the production phase. Adding the end-of-life emissions to the products with fossil origin increases the benefit of the forest-based chemicals increase substantially. One possible reason for the advantage in the production phase is that the processing of biomass into chemicals and materials in biorefineries tends to be driven with bioenergy supplied from readily available biomass residues. Similarly, in a petroleum refinery, the processes tend to be run with fossil fuels. Since biogenic carbon dioxide emissions are treated as climate neutral, this gives lower climate impact from production in biorefineries.

Today, focus is on the use of biomass for energy as a means to reduce emissions from fossil fuels. The project has not attempted to answer the question of in which sectors and by which technologies biomass should optimally be used. To our knowledge, however, there are no studies showing any apparent climate benefits in replacing fossil transportation fuels with biofuels compared to letting similar biochemicals replace fossil carbon in long-lived materials and products. The system of tax exemption and grants is unbalanced from that perspective.

7.3 PROJECT IMPACT

Apart from the more technical and economical results of the extensive work done in the platforms and value-chains of Skogskemi some very important but more intangible results are worth mentioning.

A number of new collaboration and networks have been set up. Most important is the representation of Chemistry and Forest Industry in the BioInnovation SIO. A lot of the personal trust and networks built in Skogskemi favored the establishment of the SIO and is also mirrored in how different groups and the board of the SIO are staffed.

A number of new concrete development projects between the industry groups have been started, some bilateral, and some larger open ones. The ideas and part of the networks in many of these projects originates from Skogskemi. Examples are the development of new chemicals for the dissolving of cellulose, Value chain for bio-polyethylene, Lignin conversion for fuels etc. In other words, the work started is continuing in an array of projects.

8 RECOMMENDATIONS

Wood is the feedstock for a range of products today, and there are several pathways to new forest-based products. This project has focused on specific value chains for bulk production of drop-in chemicals and on what would be needed to realize the value chains. The project has included the study of technologies at different stages of development. Although some of the processes can be considered as proven technology, it is apparent that the application of the technologies in the context of new value chains is not proven. This entails organizational uncertainties – i.e. uncertainties with the future value chain (who will provide what) and if, and in that case when, functional organizational structures will be created. There are also market risks associated with the large and volatile market for fossil feedstock and products and the comparatively small and underdeveloped markets for renewable feedstock and products. The markets are highly influenced by existing policy measures which are perceived as very unstable, adding policy risks. Finally, some of the studied technologies contain elements of technical uncertainty, with respect to upscaling and product quality.

These risks represent barriers to investments into the realization of the Skogskemi value chains. In the following, we suggest a number of steps that could contribute to reducing risks.

8.1 A POLICY FOR DEPLOYMENT OF NEW TECHNOLOGY IS NEEDED

Demonstration projects in Sweden have hitherto focused on technology verification, including certain upscaling activities. To further develop the Skogskemi value chains, we argue that projects for deployment of the new technologies are needed, as well as policy to support such projects. A deployment project, in contrast to technology verification projects, serves to develop the full value chain. The technologies have to be implemented at a relevant industrial scale and be intended for continuous production, to allow for learning by doing and incremental technical improvements. The production should be large enough to be offered on a market, in order to develop upstream feedstock supply chains as well as downstream distribution chains and markets.

Deployment projects, although with a focus on production, are not likely to be economically feasible without policy support. This is indeed the case for the Skogskemi projects. Investment support for large-scale demonstration plants could be one instrument, but perhaps more important, is instruments that stimulate demand for green products and manage the market risks. Market risks could be addressed by several means. A policy instrument which provide for a predictable premium over fossil alternatives is one example. To establish a demand via renewability requirements in public procurements is another.

The technology for conversion of woody biomass into ethanol and methanol is in an early phase of scale-up and deployment demonstration. In a start-up phase, the Skogskemi value chains could utilize available first-generation bio ethanol. This would be a way of getting started and to diversify the demand for ethanol by introducing a non-energy sector use for bio ethanol. However, import duties for ethanol represent an important barrier, and rapidly changing decisions with respect to exemptions for import duties creates a great policy uncertainty.

8.2 POLICIES SHOULD BE DESIGNED FOR LONG-TERM STABILITY

Long-term stability is essential if a policy should be efficient in reducing risks to the stakeholders developing a value chain. Policies also need to be designed with care, so that they are efficient in achieving their intended purpose. Value chains for renewable chemicals and materials differ from value chains for renewable energy in several ways. The products are, for example, more often long-lived. Hence, the temporal and geographical distance increases between the producer and the final user as well as the eventual waste handling of the product. It is not evident how, for example, climate change benefits should be fed back to the producer of a renewable chemical or material.

The design of criteria for the definition of renewability is essential. Without the option to co-process renewable and fossil feedstock the possibility to utilize existing industry investments would be severely reduced. In practice, the options studied in the Skogskemi project would not be possible to realize without blend-in-solutions. We suggest that a mass-balance approach is taken in the design of renewability criteria. Basically, this means that a producer can claim that a given amount of the production could be defined as renewable, based on the share of renewable inputs into the process, although the streams of renewable and fossil material is mixed in the process.

Although there are important synergies between renewable transportation fuel and renewable chemicals markets, it is apparent that with a strong policy support for bioenergy, applications of biomass for chemical and material purposes will be difficult unless they are given similar conditions.

8.3 NEW VALUE CHAINS MAY REQUIRE NEW BUSINESS MODELS

It is our conclusion from the project that the studied value chains must be built in cooperation with several stakeholders. These agreements may be materialized in the form of joint ventures or other agreements. However, there is a complexity in forming such cooperation that should not be underestimated, which is also an experience from the Skogskemi project.

We suggest that the industry should be proactive and start to develop the required networks, partnerships and new business models that will be required to realize new value chains. A particular matter is the distribution of green premiums and other incentives throughout the value chain. For example, a green premium paid for a renewable product on the market may need to be propagated all the way back to the primary processor of the forest feedstock, in order to motivate the investments into this part of the value chain. In the current business models this premium often stays close to the consumer. The Skogskemi project has increased the awareness among stakeholders to start building new value chains and joint ventures and a couple of such endeavors are already underway.