SKOGSKEMI – SYSTEMS ANALYSIS

Sub-project report to the Skogskemi project

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SKOGSKEMI SYSTEMS ANALYSIS
EXECUTIVE SUMMARY

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Preface
This document is the executive summary report from the Systems Analysis subproject of the Skogskemi project.

More detailed information about the subproject and its results can be found in the individual reports:

Annex I – LCA
Annex II – Policy in the context of innovation
Annex III – Market Scenarios
Annex IV – Process integration aspects

The systems analysis has been executed by SP Technical Research Institute in cooperation with all project partners. The process integration aspects were contributed mainly by Chalmers University of Technology. The LCA studies were performed mainly by SP, Bio4Energy/Umeå University and AkzoNobel Sustainable development.

For the systems analysis sub project, Örnsköldsvik and Gothenburg, September 2014

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**Introduction**

The Skogskemi project has been a cooperation project between forest industries and chemical industries with the aim to bring potential value chains for forest-based chemicals closer to realization. The targeted chemicals have been methanol, butanol and olefins. These chemicals produced from forest-based raw material could act as direct replacement for methanol, butanol and olefins produced from fossil feedstock. Thus, they would be so-called drop-in chemicals, which fit into the current downstream processing, markets and infrastructure. The goal of the project has been to develop pre-FEED studies for demonstration plants for the production of each of the three targeted chemicals from biomass feedstock. In addition, the project has studied two important platform technologies that could deliver forest-based intermediate chemicals into the production: Biomass gasification technology with methanol synthesis and biochemical technology for production of ethanol from wood via the sugar platform.

Industry partners in the project come from the Stenungsund chemical industry cluster and from the Processum biorefinery industry cluster centered around Örnsköldsvik.

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**The systems analysis sub-project**

The role of the systems analysis subproject in Skogskemi has been to put the forest-based value chains into a larger context. The systems analysis has been performed over three dimensions: 1) An environmental dimension where the environmental impacts of forest-based chemicals have been compared to their fossil counterparts by means of life-cycle assessment (LCA), 2) An economic dimension, which has included analyses of the relevant innovation system, the current policy framework with respect to promoting renewable chemicals and the market situation for the studied chemicals products and inputs important to their production, and 3) A technical dimension, where the integration of new processes into their immediate technical environment has been studied using process integration methods.

**Skogskemi value chains**

Figure 1 gives an overview of the platforms and value chains considered in the project. The value chains outlined in blue consist mainly of commercially available or nearly commercially available technology. Detailed pre-FEED studies were made for these value chains within the Skogskemi project. Biomass gasification (gasification platform) and biomass hydrolysis (sugar platform) contains
more elements which are not yet commercially available and were treated in a more general way. 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. Overview of Skogskemi platforms and value chains

In the following sections, the potential value chains from forest feedstock to chemical products are briefly described.

**Methanol value chain**
The methanol value chain is based on the production of methanol from a gaseous side-stream obtained in the KRAFT pulping process (Figure 2). The total potential production of methanol from existing Swedish KRAFT mills is approximately 50 000 tons per year. The methanol would be used as a raw material for Perstorp, where it could replace the 12 000 tons of fossil methanol which are bought today.

Figure 2. Value chain of the methanol production process.

**Butanol value chain**
The second value chain is based on production of n-butanol from forest raw material (Figure 3): Ethano is produced from biomass via the sugar platform, using the CelluAPP technology provided by SEKAB or through the conversion of a KRAFT pulp mill. The ethanol is further processed into acetaldehyde by SEKAB. Acetaldehyde is further processed into croton aldehyde and finally into n-butanol. Perstorp sells 50 000 tons of fossil n-butanol today, which would be exchanged by the bio-based n-butanol.
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**Olefins value chain**

The third value chain is based on production of olefins (ethylene and propylene) through a MTO process (methanol to olefins) and ethanol dehydration (Figure 4). The ethanol for the dehydration comes from the same technique as for the n-butanol. The main methanol supply pathway pursued in this value chain is through gasification of forest raw materials. The olefins will be supplied from the Borealis cracker plant to the rest of the cluster.

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**Figure 3. Value chain of the n-butanol production process.**

**Figure 4. Value chain of the olefin production process.**
Environmental systems analysis
The environmental impacts have been assessed for the production of forest-based chemicals envisioned in the Skogskemi project and compared to the present, fossil-based, production of chemicals. Life Cycle Assessment (LCA) was chosen as the environmental assessment tool as it has positioned itself as one of the most used tools for environmental assessment of product systems, and it offers the possibility to compile and evaluate the potential environmental impacts of a product system through its life cycle.

The results are meant to be used for the Skogskemi project and not for chemical industry clusters in general, as the location, size and type of such clusters will differ, as well as possibilities and constraints.

Life cycle assessment (LCA)
LCA is a method used for compiling and evaluating the potential environmental impacts of a product system through its life cycle. A functional unit is determined to define the basis for comparison. The functional unit can be, for example, one tonne of product and should be identical for compared systems, so that they can be compared on the same basis.

In the Skogskemi LCA, the functional unit was defined separately for the methanol, n-butanol and olefins cases. In the olefins case, a large amount of raw material is replaced, so comparing the current Stenungsund cluster with a future system where about 25% of the olefins are produced from forest feedstock is appropriate. In this case, the functional unit was set to be the total production of the Stenungsund cluster in one year. In the butanol and methanol case, production is not set to be integrated with existing facilities as in the olefin case, and the production volumes are small and will not affect the environmental performance of the Stenungsund cluster as a total noticeably. Therefore, forest based butanol and methanol were compared with fossil butanol and methanol and the functional unit was set to be 1 ton of methanol/n-butanol at gate.

The scope of the performed LCAs is “cradle-to-gate”, meaning that it covers all life cycle activities associated with the extraction, handling and processing of raw materials and energy input as well as production processes required for producing the products. A study that includes impacts also from the use of the product (“use phase”) and from its eventual incineration, decomposing or other terminal fate (“end-of-life”) is said to have a “cradle-to-grave” scope. In the present study, CO2-emissions were assessed also in a cradle-to-grave scope to show the difference in environmental impact between the bio-based and fossil product. Biobased products have a benefit at the end of life since the CO2 formed during incineration or decomposing is, partly or fully, from biotic origin.

The environmental impact categories included were: global warming potential (GWP), abiotic depletion (AD), acidification potential (AP), ozone-depletion potential (ODP), ground level ozone creation potential (POCP) and eutrophication potential (EP).

Allocations
A common issue in LCA is the allocation of emissions and other environmental burdens between products which are co-produced in a process. If, for example, the environmental impacts of a Product X are of interest, and this product is co-produced with a product Y in the Process A, then it is necessary to decided how much of the emissions generated by the Process A that should be allocated to the Product X, and how much should be allocated to the Product Y. Impacts could for example be distributed in proportion to the mass of the products (mass allocation) or in proportion to their economic value (economic allocation).

In the study of the Stenungsund chemical cluster, no allocation was needed in the base case as the functional unit constitute of the total production of the system. The assessment of the techniques in the “green case” however demanded allocation, since both forestry and biorefineries are multi-output processes. We chose economic allocation, since the systems in our case were fixed, meaning that the amount of the different output depend on each other, but that they have quite different...
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values, meaning that some products would not be produced if it was not for the market demand of others.

Since the methanol from Kraft pulp mills is made from waste gas, and not a product or byproduct, we chose to assess three allocation cases: mass allocation, economic allocation and consequential allocation. In the latter case, the methanol does not have the responsibility of any of the environmental impact from the Kraft pulp mill as it is strictly perceived as a waste product from the mill. Only the environmental consequences added are included, which is the environmental impact from the purification process and the environmental impact from replacing the waste gas as fuel in the Kraft pulp mill.

**LCA Results**
LCA results for the studied value chains are presented and discussed in the following sections. The results for global warming potential are shown for all cases, while results for other impact categories are included based on their relevance for the particular case.

**Methanol value chain**
The environmental impact categories that are most interesting for a comparison with fossil methanol are global warming potential (Figure 5), as it is the main focus in environmental debates, fossil resource depletion (Figure 6), since we are comparing a fossil and a bio-based material, and eutrophication potential (Figure 7), as that is one of the impact categories that pulp mills are known to have an impact on. The global warming potential comparison is presented as cradle-to-grave to show the influence of end-of-life emissions.

![Figure 5. Cradle to grave global warming potential of 1 ton of fossil methanol and forest based methanol with three different allocation methods.](image-url)
Applying different kinds of allocation give us different environmental impact factors for forest based methanol, both in terms of total environmental impact and location of environmental hot spots. However, all three allocation scenarios have less GWP than fossil methanol. If we assume that the methanol is combusted after its use phase, each ton of methanol will result in additionally 1.83 ton CO₂, which should be added to the fossil case. No CO₂ is added to the forest-based methanol since the biomass carbon cycle is assumed to give no net contribution to the atmospheric CO₂ concentration. Forest based methanol thus performs significantly better than the fossil methanol.

For the depletion of fossil resources, all the forest based methanol cases perform better than the fossil case. For eutrophication, using consequential allocation gives lower results for the forest methanol but with mass allocation and economic allocation it performs worse than fossil methanol. However, the impact values are below the limits set by the government on emissions contributing to eutrophication from pulp mills.
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The mass allocation has the highest environmental impact as it allocates more of the total pulp mill environmental burden to the methanol product. The consequential case has the lowest emissions of the three cases, as KRAFT pulp mill impacts are not included and the bark added as make-up fuel has little impact.

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. 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.

Butanol value chain

For a comparison between forest-based and fossil n-butanol we chose to show the environmental impact categories global warming potential (Figure 8), eutrophication potential (Figure 9), acidification potential (Figure 10) and photochemical ozone creation potential (Figure 11). The global warming potential comparison is presented as cradle-to-grave to show the influence of end-of-life emissions.

Figure 8. Cradle to grave global warming potential of 1 ton of fossil n-butanol and forest based n-butanol with three different ethanol production methods.
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Figure 9. Cradle to gate eutrophication potential of 1 ton of fossil n-butanol and forest based n-butanol with three different ethanol production methods.

Figure 10. Cradle to gate acidification potential of 1 ton of fossil n-butanol and forest based n-butanol with three different ethanol production methods.
The production of ethanol is the life-cycle stage with the largest environmental impact in the total n-butanol LCA result. In particular, production of enzymes for use in the ethanol process is influential. The uncertainties in the study are largest for the enzyme production, and two different cases were considered: an enzyme base case, and a high enzyme case. All three forest based n-butanol scenarios have less GWP than fossil n-butanol in the enzyme base case. With the high enzyme case, the cradle-to-gate GWP is similar. This changes, however, if we expand the cradle-to-gate to a cradle-to-grave study and the fossil end-of-life CO₂ emissions from combustion (or decomposing) of n-butanol are included. Then, forest based n-butanol has a lower GWP in both the enzyme base case and the high enzyme case.

Enzyme production is the process dominating the environmental impact in all the categories where data was available. Eutrophication potential is the only environmental impact category where other processes (onsite emissions and waste management in the ethanol production) are equally important, but that is only in the enzyme base case. The environmental impact from enzyme production would be reduced if smaller amounts of enzymes could be used in the production. The source of the electricity used in the enzyme production is of importance for the result. In the assessment the production data for enzymes are based on production using electricity produced from natural gas. If the enzymes are produced using electricity produced from renewable sources the impact will be lower than presented here. Another factor which influences the results is the valuation of the co-products of the ethanol production process since this is used as a basis for the allocation of environmental burdens between the co-products.

Of the three ethanol production scenarios, ethanol produced with the SEKAB technique in Örnsköldsvik has the best environmental performance in all environmental impact categories except for eutrophication potential and acidification potential. The reason for this is that the ethanol produced with the SEKAB technique in Örnsköldsvik is more based on biomass than the two others, as it uses steam made from biomass. Ethanol produced with the SEKAB technique in Stenungsund has the worst environmental performance, due to the utilisation of steam from natural gas. Environmental impact from transport is small in relation to other impacts, so the difference in transport distances and modes does not alter the ranking.

**Olefins value chain**
In Figure 12 below, the normalized results are shown for the environmental impact of the entire Stenungsund cluster in the base case and the future case, where 230 kton of olefins are produced.
Since the production of olefins from renewable methanol in an MTO plant in Stenungsund will be integrated in the Borealis cracker plant, the environmental impact of these olefins cannot be analysed separately. The analysis of the change in environmental impact is therefore carried out for the cluster in Stenungsund. The current production in the cluster today (base case) is compared with a future production where part, 230 ktons, of the olefins is produced from forest-based methanol in an MTO plant (200ktons/year) and 30 ktons ethylene is produced from forest-based ethanol in a dehydration plant.

The results show that a future production in Stenungsund, where part of the olefins is produced from wood chips, has lower environmental impact in most categories analysed. The impact on global warming (fossil emissions) from the cradle to grave activities for the products from the cluster decreases with 19% in the future scenario compared to the base case, corresponding to 1.7% of Sweden’s total global warming emissions year 2011. The decrease is due to both reduced emissions in the cradle to gate activities and reduced emissions from fossil CO₂ in the end of life treatment of the products when they are incinerated or decomposed.

The reduced CO₂ 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 is used in the cracker.
- The production of the renewable raw materials, methanol and ethanol, have lower impact than the production of the fossil raw materials (ethane, propane and butane) used in the base case.
The impact on acidification, ozone depletion and creation of ground level smog (POCP) will be lower in the future case and this is mainly due to lower impact from the production of the raw materials. The impact on eutrophication is higher for the future case than for the current case. This is mainly due to higher impact from the production of the incoming raw materials than in the base case, which is expected since forestry activities are known to have an impact on eutrophication.

Different available options for the gasification setup that will be used to supply the methanol to the MTO process will have different impacts on the LCA results. One reason for this is that the amount of co-produced heat and the possibilities to utilise this heat varies between different options.

Conclusions on environmental impact
The forest based methanol from KRAFT pulp mill stripper off gasses has a lower global warming potential than fossil based methanol. For eutrophication, on the other hand, the results will depend on the allocation method applied. The purification process and the production of the chemicals used in the KRAFT pulp mill are the processes with the highest environmental impact.

All three forest based n-butanol scenarios have less global warming potential than fossil n-butanol when the fossil end-of-life CO₂ emissions from combustion of n-butanol are included. For eutrophication and acidification potential, the forest biomass n-butanol production processes have a larger impact than fossil n-butanol. Enzyme production is the environmental hot spot in the life cycle of forest based n-butanol.

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 partly is produced from renewable methanol/ethanol (wood chips) 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.

The technologies assessed in the study should only be compared with associated reference cases and not with each other, as size of the projects, feedstock and energy supply are different. Ethanol, methanol and butanol can be used as transportation fuels. To qualify as sustainable fuels under the RED directive, certain requirements have to be fulfilled regarding life-cycle environmental impacts. The present study was not designed to assess impacts according to the RED directive, and the results should therefore not be applied in such contexts.

Uncertainties
For the studied value chains, there are several possible configurations and there are also several methodological alternatives available when conducting an LCA. The present study has only considered a limited number of the large range of alternative options. Other configurations or assumptions may give other results.

LCA is a tool designed to assess environmental impacts in a holistic manner. There are however, environmental impacts and effects that are challenging to include in LCA and that there have not yet been developed established methods for. There are also disagreements about how the carbon cycle should be assessed and the role of biogenic CO₂ emissions.

Normally biogenic CO₂ emissions are not included in environmental impact assessments as it is assumed that crops and plants will sequester the CO₂. The common assumption is therefore that biogenic CO₂ emissions are climate neutral. If emission of biogenic CO₂ is not balanced by uptake of CO₂ in growing biomass, then the biogenic CO₂ emissions will also contribute to increased amounts of CO₂ in the atmosphere.
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Today Sweden has a net growth of forest. If the market, however, would start to demand a lot more of forest biomass, this could lead to certain consequences, such as i) forests are managed more intensively, ii) new forest areas in Sweden begin to be managed or that iii) forest biomass is bought from abroad, which could lead to that i) and ii) takes place abroad. Such changes could have an effect on biodiversity, as the situation for the involved eco-systems would change, and possibly on other ecosystem services.

In conclusion, it seems that the use of forest feedstock for energy and materials has large CO₂ emission reduction potential, but that care should be taken so that the forest management does not systematically decrease the forest stock and that other values and ecosystem services, which the forest provides, are preserved.
Innovation systems, policy and market analysis

The realization of Skogskemi is about the transition of complex and capital intensive processes in an efficient way, both in the forest industry and the chemical industry. This is not just a technical challenge, but indeed a challenge also for the political and economic systems that will set the frame for this development. In order to study also the non-technical challenges, three main activities have been undertaken:

- **Innovation system analysis**
  Theoretical frameworks for the analysis of innovations systems have been applied to the case of forest-based chemicals. The focus has been on the importance of pilot and demonstration projects in the development of the innovations. Interviews have been performed with key actors in relevant innovation systems.

- **Policy analysis**
  Current policies affecting the feasibility of forest-based chemicals have been surveyed. These have been analyzed with respect to importance in the context of Skogskemi, and Skogskemi partner industries have been interviewed about their views on policies.

- **Market scenario creation**
  Current market prices have been surveyed and consistent scenarios for possible future developments of prices have been created

In the following sections, each of these activities is described and key results are summarized.

**Innovation systems analysis**

Innovation can be described as the motor of organizational and institutional changes that drives the economy forward. An innovation system is a theoretical framework developed with the purpose of understanding the processes around innovation. The development has mainly been driven by policy makers to guide them in their work to detect and apply efficient policy instruments.

**Technological innovation systems (TIS)**

Innovations systems can be viewed from several perspectives. We have chosen to describe the technological innovation system (TIS), mainly motivated by the fact that the three value chains of the Skogskemi project are indeed technological options and thus focused on the conditions for such options.

A TIS can be defined as: “a network of actors and institutions that together collaborate within a specific technology area for the benefit of development, diffusion and utilization of variants of a new technology and/or a new product”. Important elements of TIS have been summarized in Table 1.

<table>
<thead>
<tr>
<th>Structural Elements</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>is made up of artefacts (tools, plants, machinery), coded knowledge (patents, drawings, etc.), and knowledge embodied in, for example, engineers and scientists.</td>
</tr>
<tr>
<td>Actors</td>
<td>are individuals, private and public firms, and organizations that perform a task that contributes to the development of the technological field.</td>
</tr>
<tr>
<td>Networks</td>
<td>are defined by the relationship between the different actors in the system and include both learning and political networks.</td>
</tr>
<tr>
<td>Institutions</td>
<td>are sets of norms, common habits, routines, established practices, rules or laws that regulate the relationships and interactions between individuals and firms.</td>
</tr>
</tbody>
</table>

An innovation system is characterized by its components, but also by how they interact – the functions of the innovation system. In a TIS, the processes between the structural components are described in eight different functions, as listed in Table 2.
Table 2. Functions of a TIS

<table>
<thead>
<tr>
<th>Functions</th>
<th>...is the process of strengthening:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge development and diffusion ...</td>
<td>the breadth and depth of the knowledge base and how that knowledge is developed, diffused and combined in the system.</td>
</tr>
<tr>
<td>Influence on the direction of search ...</td>
<td>the incentives and/or pressures for organizations to enter the technological field. These may come in the form of visions, expectations of growth potential, regulation and policy, articulation of demand from leading customers, technical bottlenecks, crises in current business, etc.</td>
</tr>
<tr>
<td>Legitimation ...</td>
<td>the social acceptance and compliance with relevant institutions. Legitimacy is not given but is formed through conscious actions by organizations and individuals.</td>
</tr>
<tr>
<td>Resource mobilization ...</td>
<td>the extent to which actors within the TIS are able to mobilize human and financial capital, as well as complementary assets such as complementary products, services, network infrastructure, etc.</td>
</tr>
<tr>
<td>Entrepreneurial experimentation ...</td>
<td>the testing of new technologies, applications and markets whereby new opportunities are created and a learning process is unfolded.</td>
</tr>
<tr>
<td>Materialization ...</td>
<td>the development and investment in artefacts such as products, production plants and physical infrastructure.</td>
</tr>
<tr>
<td>Market formation ...</td>
<td>the factors driving market formation. These include the articulation of demand from customers, institutional change, and changes in price/performance.</td>
</tr>
<tr>
<td>Development of positive externalities ...</td>
<td>the collective dimension of the innovation and diffusion process (i.e., how investments by one firm may benefit other firms “free of charge”).</td>
</tr>
</tbody>
</table>

An analysis of the functions in a TIS provides information over what processes are present and which are not. Thus, it is possible to detect barriers and drivers of a specific TIS and where to direct actions.

Risks and uncertainties
In the initial phase of creating a new technological area such as a bio-refinery industry, there are large risks and several uncertainties that investors and policy makers have to manage. Especially four types of uncertainties are present:

Table 3. Risks in the creation of a new technological area.

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological Risk</td>
<td>The uncertainty that the planned systems that not yet has been practically proven, fulfils its intended function.</td>
</tr>
<tr>
<td>Market Risk</td>
<td>Fossil market risk which in this case especially concerns whether the oil price will decrease or that the initial effects of shale gas sustains. Raw material risk that affects biomass, compared with for example wind, since it is placed on a market. Product market risk that concerns the fact that products based on biomass, e.g. biofuel vehicles, yet exist in limited numbers compared with fossil based products, and this create small markets and volatile prices.</td>
</tr>
<tr>
<td>Organizational Risk</td>
<td>Uncertainties with the future value chain (who will provide what) and if, and in that case when, functional organizational structures will be created.</td>
</tr>
<tr>
<td>Institutional (Political) Risk</td>
<td>The uncertainty that political decisions will change the rules of the game and suddenly decrease returns of invested capital</td>
</tr>
</tbody>
</table>
The role of pilot and demonstration activities

In the process of innovation, pilot and demonstration plants (PDPs) play a key role by reducing uncertainties. In general, pilot and demonstration plants 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 PDPs not only address technical challenges, but also aim to reduce the organizational, market-related and institutional risks and uncertainties that key stakeholders face in progressing the new technologies.

### Table 4. A role-based categorization of PDPs with lessons from biorefinery technology development in Sweden

<table>
<thead>
<tr>
<th>Categories</th>
<th>The role of PDPs in the technology development process</th>
<th>Specific experiences and lessons from Swedish biorefinery technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. High-profile PDPs</td>
<td>... creating legitimacy and attention. Strong signal power for companies and/or policy to take further action.</td>
<td>Funded by individual companies (e.g., Volvo). Do not reduce risks in any real sense. Dominant actors can use these to set the future direction of research.</td>
</tr>
<tr>
<td>II. Verification PDPs at either laboratory or industrial scale</td>
<td>... testing, evaluating and characterizing a technology for a particular application, often comparing different models and techniques. Plants on industrial scale play an important role as reference plants, forming alliances and interests from potential users, incipient industrial capacity, and supply smaller volumes for initial niche markets.</td>
<td>In the case of black liquor gasification in the 1990s, the main funding came from the industry. Otherwise these plants were mainly funded through public R&amp;D programmes. The lab-scale plants mainly reduce the technical risk, while the industrial-scale plants also reduce the market risk and the organizational risk. A lack of involvement of potential users and capital goods suppliers. Universities provide neutral but only passive ownership. Strong alignment to commercial interests makes it difficult to convert these to Type IV plants.</td>
</tr>
<tr>
<td>II. Deployment PDPs</td>
<td>... improving performance and reducing costs by stimulating the construction of the first commercial-sized plants, and attracting new actors to the field. The latter involves getting access to the users’ know-how and experiences for further developing the technology.</td>
<td>Funded through public investment support and special market incentives, but virtually absent in the Swedish biorefinery case. Assists in reducing the technical risk, the market risk, and the organizational risk. Complete lack of this type of plant in Sweden, in part due to sole focus on investment support, which was not able to address market risks in the presence of low fossil fuel prices.</td>
</tr>
<tr>
<td>V. Permanent test centres</td>
<td>... facilitating basic and applied research to increase knowledge, i.e., test new applications, materials, fuels, develop and validate theoretical models, etc.</td>
<td>Funded through public R&amp;D, and applied industrial research funding. Mainly reduces the technical risk. Difficult when based on Type II plants that have been aligned with few actors, and there is no market for any of the potential applications experimented with.</td>
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### Analysis results

Within this project, the theoretical framework described above was applied in an empirical case study of two biorefinery TIS developments: Cellulosic ethanol production and black liquor gasification.

The empirical analysis highlights important challenges in creating societal value from PDP activities, such as difficulties in managing the transition from one PDP type to another due to the presence of vested interests, lack of policy support, etc.

We found that Type II (i.e. technology verification) PDPs is the predominant type of plant that has been used in the Swedish cases. Our empirical cases suggest that the scale of a Type II plant is important. The smaller lab-scale PDPs appear to be used primarily for reducing the technical risk,
while the larger industrial-scale Type II PDPs play important roles as reference projects and for creating strategic alliances around the technologies (involving future users and suppliers as well as other key stakeholders). The industrial-scale plants can therefore be used not only to reduce the technical risk but also the product and organizational risks.

Type III (deployment) PDPs have been essentially missing in Sweden for the cases studied, although several attempts have been made to realize such plants. We argue that a lack of appropriate policy support likely played an important role in these failures, in part by relying heavily on investment support that would not address the fossil market risk associated with the technology developments.

After the verification of a technology, the actors have set out to convert Type II plants into permanent research infrastructure, in the form of **Type IV** plants. This has not been without problems, for two main reasons. Firstly, the type II plants were strongly aligned with the commercialization plans of specific actors and it has been a struggle to make the PDPs available to other alliances with other aims and strategies. Secondly, it is costly to maintain the operating capacity of the plants, mainly in terms of competent personnel. The lack of technology deployment, for example through type III PDPs, has limited the demand for development services, which could be carried out in type IV plants. Therefore, the type IV PDPs have become dependent on conventional (publicly funded) R&D solely, instead of industrial, private R&D.

Our report highlights the long development times of new technological fields and the need to be able to go back and forth between various types of PDPs for progressing knowledge. In our empirical cases this has involved challenges when converting later Type II PDPs to Type IV plants (see (c) in Figure 13), the synergies of providing Type III and Type IV plants in parallel (see (b)), and the interaction between verification and diffusion of technology (see (a)). This has important policy implications. For instance, innovation requires both R&D and learning-by-doing (and subsequent cost reductions) and for this reason R&D programmes should typically not be designed in isolation from practical application. The gradual diffusion of a certain technology can also reveal areas where additional R&D would be most productive.

**Figure 13. PDPs and the progression of a technological field: The role of policy.**
Our results underscore the potential importance of a clear overlap in policy measures (see also (d) in Figure 13) 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), small firms, on which much of the technology development depends, risk going bankrupt. This risk is of course especially great in times of general crisis, during which years of development may be needlessly spoiled.

In the studied cases, successful realization of type II PDPs were not complemented with deployment policy schemes that address the fossil market risk. If the R&D support had instead been supplemented with an appropriate deployment policy, the risk for small entrepreneurial firms would decrease, and industrial interests in making investments in biorefinery technology would increase.

**Policy analysis**

The policy analysis part of the systems analysis subproject provides a theoretical background to relevant concepts in economics, an overview over policy instruments with potential impact on the Skogskemi value chains and an analysis of these policy instruments, with a particular focus on technology specific vs technology neutral instruments and on the stability and predictability of policy instruments.

For many of today’s environmental problems there are solutions, both of technical and non-technical nature. These solutions are however not always implemented due to market failures. One important aim of policies is thus to remedy market failures. Policy instruments mirrors economic interests and in some cases there is no single policy instruments that satisfies all groups of society. A policy instrument failure exists when the instruments fails to manage the market failure.

A topic that is discussed often when it comes to policy instruments is the issue of long term predictability and stability. This is often a desire from the actors that are affected by the policy instrument, since it often involves decisions that are affected of future outlooks. The desire is often that before a policy instrument is applied, some guarantee is provided for how long it will exist and if/how the instrument can be reformed under its lifetime. This information is often difficult to provide, partly because of the political structure with 4 years governance periods and partly because of the difficulty to in advance understand what effects the policy instrument will have in practice.

In this project, we have reviewed policies in the field of energy and chemistry related to the realization of the goals in the Skogskemi project. The compiled list of policies has been reviewed by the project members and interviews have been conducted with key stakeholders in the industry.

**Analysis results**

Most of the existing policy instruments relevant to Skogskemi actually targets the use of renewable energy. The close link between the Skogskemi chemicals end the transportation fuel sector still motivates that these instruments are studied. In Figure 14, the policy intent versus actual outcome in terms of technology neutrality is presented for a number of policy instruments. The horizontal axis varies from specific to neutral in terms of how the policy is formulated in law and regulations and its underlying intent. The vertical axis represents its actual outcome; from selective, i.e. if it selects for specific technologies and processes, to variative, i.e. if the policy fosters variation on the market.
Some policies are intended to be selective, such as the targeted subsidy of biogas production from manure in the southern parts of Sweden, whilst others are supposed to create conditions for a variety of technologies and processes to reach the market, such as the carbon tax.

Examples of policies that are neutral in their description but selects only a few, or even single technologies, are the premium for environmental cars, which is so strict that only a few cars qualify for the scheme, and the so called pump law which requires filling stations above a certain size to provide at least one alternative fuel. In reality almost every filling station opted to install an ethanol pump since the investment cost for this was lowest amongst the alternative fuels.

The lower quadrant indicates policy instruments formulated to be technology neutral, but which have an actual outcome of being selective. This indicates policy instruments that are policy failures in the sense that they do not fulfill the intended purpose.

As we can see in figure 14, there seems to be a gap in the middle of the graph. We see this as being a sign of a lack in the Swedish policy system, where the policy instruments for scaling up new technology is the missing piece.

In figure 15 the stability of the policies versus their predictability is presented. The horizontal axis describes the relative stability of the policy as such, from low to high stability. On the vertical axis the predictability of the specific policy’s price signal is presented.
We can see in figure 15 that stable and long-lived policies do not always provide a predictable price signal. An example of a stable policy is the carbon tax, which was first introduced in 1991. The price signal for the carbon tax has also been fairly predictable when compared to other policies. However, there are certain exemptions/reductions for the carbon tax, which are decided on an annual basis, meaning that for many actors the stability of the implications of the carbon tax is much lower.

A policy that in itself is stable but whose price signal is unpredictable is the European Emissions Trading Scheme (EU ETS). This policy was enacted in 2005 and is, in its current form (phase III), in force until December 2020. There are also plans for a fourth phase, stretching to 2030. The price of emissions rights, EUA, has shown large and sometimes rapid variations, for example going from roughly 30 € to 0.10 € per ton carbon dioxide, in the years 2006-2007.

As mentioned before, a general desire of the actors affected by the policy instruments are stability and price predictability, meaning that, from this perspective, all policy instruments should ideally be in the top-right quadrant.

**Market scenarios**

To ensure a certain degree of consistency in the economic evaluation of the Skogskemi value chains, it was decided that a set of input and output products of importance to the project should be identified together with common assumptions on their market prices. To this end, the systems analysis sub-project has created two scenarios for the market price development of the input and output products within the project. The benefits of using scenarios are that alternative, possible, future development paths can be explored while interrelated prices are handled in a consistent way. Prices are however, to a certain degree, case specific and may depend on the type of contract, transportation costs etc. Forest feedstock markets are partly 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 market development of the industries involved in each respective value chain should also be included into the evaluation of the value chains.

All future scenarios for complex systems (such as energy and chemicals markets) are inherently uncertain. None of the created scenarios are predictions of a most likely development, but
represents alternative development paths with different properties, which could be used to gain insights into the viability of the studied value chains under different conditions.

Future price scenarios were developed using the ENPAC tool. The ENPAC tool proposes energy market prices for large-volume customers, based on world market fossil fuel price data and assumed values for energy and climate mitigation policy instruments.

The ENPAC scenarios were not used directly, but rather market scenarios were created by assuming that the prices of the Skogskemi products would be linked to the world market prices developed with the ENPAC tool.

Two of the ENPAC scenarios were used, called the Current Policy scenario and the 450 scenario, which are based on the corresponding IEA scenarios.

- **The Current Policy** scenario reflects the present situation on the international energy and climate arena, taking into account existing CO₂ emission reduction schemes, which on the international level are quite modest.

- **The 450** scenario, as described in the IEA World Energy Outlook, reflects a future scenario where climate policy measures are implemented which would lead to a reduction in CO₂ emissions large enough that the global mean temperature by a 50% probability does not exceed pre-industrial levels by more than 2°C. The cost for emitting CO₂, implemented in the form of a price on CO₂ emission rights in a common EU system, is much higher in the 450 scenario compared to the Current Policy scenario.

Several of the chemicals studied within the project can be used not only for chemical or material purposes, but also as transportation fuel, thereby replacing gasoline or diesel. The product may therefore have two markets with potentially different prices. One on the chemical market, set by the supply and demand situation for that particular chemical, and one on the transportation fuel market, set by the price of the alternative transportation fuel. Presently, the use of biomass-based transportation fuel is incentivized through tax exemptions, while biomass based products for the chemicals markets do not receive the same policy incentives. This situation could, however, change in the future.

Based on this, it was decided to give a number of different prices in the scenarios:

- Price on the motor fuel market, including policy incentives
- Price on the chemicals market, with no policy incentives
- Price on the chemicals market, with incentives similar to the motor fuel market

It is suggested that all three price alternatives are used in the two scenarios to evaluate the Skogskemi value chains.

It should be noted that the prices are based on estimated willingness-to-pay for the considered products, this does not necessarily imply that, for example, biomass based chemicals can be supplied at this price.

**Conclusions on markets, policy and innovation systems**

Considering the present studies, we make the conclusion that there is a gap in the current policy landscape of Sweden. There are no policy instruments supporting the phase of scaling up technologies from the level of demonstration and pilot plants to a commercialized level.

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), small firms, on which much of the technology development depends, risk going bankrupt.

A topic that is often discussed when it comes to policy instruments is the issue of long term predictability and stability. This is often a desire from the actors that are affected by the policy instrument, since it often involves decisions that are affected by future outlooks. The desire is often that before a policy instrument is applied, some guarantee is provided how long it will exist and if/how the instrument can be reformed under its lifetime. This information is often difficult to provide, partly because of the political structure with 4 years governance periods and partly because of the difficulty to in advance understand what effects the policy instrument practically will have on the market failure it attempts to resolve.

Technology neutral policies may not be enough to reduce risks for technologies that are still in the demonstration phase. Also, attention should be given to the fact that policies formulated as technology neutral can in practice be very selective, if, for example, there is only one or a few technologies that are in a development phase where they can benefit from the policy measure, whereas newer, less developed alternatives are effectively excluded.

Therefore, from this point of view, it is important that policy-makers target the entire development chain, which may include certain policy overlaps to avoid failure of the development chain at critical points. Policies should be designed so that they address the relevant risks. These risks vary with different stages of the development process. Here, the long-term predictability of policy incentives is of importance. It should be noted that not only the stability of the policy itself, but also the predictability of the price signal given by the policy needs to be considered. Historically, it appears that policy measures have failed to address the significant market risks that exist for technologies about to enter deployment demonstration, and hence demonstration projects on this level have been lacking.

There are links between the chemicals market and the transportation fuel markets. Indeed, several of the chemicals and intermediate products studied within this project could be used in the transportation fuel sector, to replace gasoline and diesel. With ambitious GHG emission reduction policies targeting the transportation sector, use of biomass for the studied chemicals and materials in non-energy applications, is unlikely to be feasible unless they are given similar incentives as biomass for biofuels market.
Technical systems analysis
The technical options studied within the Skogskemi project will not function in isolation when they are implemented. Rather, they will be more or less integrated with existing industrial facilities, concerning for example infrastructure and energy and material flows. Thus, they represent sub-processes within a larger technical context. The analysis of complex industrial processes in terms of systems made of subsystems (sub-processes) interacting with each other at different levels has become a natural way of thinking with the development of system oriented disciplines.

One approach to the synthesis and the design of an industrial plant is to optimize the exchange of material and energy streams between process parts in such a way that process economic performance is ultimately maximized. The set of methods and tools used for carrying out such tasks are grouped under the name of “process integration”.

Process integration studies have been performed for the technical options studied within the Skogskemi project and the results of these studies are described in the reports of the technical sub-projects. Here, we give a brief overview of some general aspects of the process integration methods and results.

Process integration
Due to their large energy demand, some industrial processes are grouped under the category of “energy intensive industrial processes” which includes for example chemical processes, refineries, pulp and paper mills, cement and steel industries. Since, in these cases, the cost for energy utilities can play an important role on the process economics, a particular attention is paid to energy efficient process design and operation. This in turn requires some engineering tools and methods at various level of the plant life, from grassroots design to retrofitting or revamping.

In case a particular industrial process relies of one or more thermal or thermochemical conversions of raw materials into products or intermediates, a particularly challenging process integration task is to identify the optimal degree of heat recovery within the process and to quantify the relative amount of heat that must be provided by fuel combustion.

Heat integration can be an aspect to consider at various level of aggregation considered for the analysis and the design of an industrial activity:

- Within a process by recovering heat from process heat sources to process heat sinks, by direct heat transfer.
- Between the process heat sources and heat sinks by indirect heat transfer with utility streams, e.g. by heat transfer with a steam network through steam generation and condensation. This is directly related to the analysis and design of combined heat and power systems.
- Between different processes by means import and export of steam or other thermal utilities.

Another process integration aspect, similarly challenging to heat integration, is the degree of “material integration” between parts of an industrial plant. In case of processes with a single product, material integration between sub-processes may be rather straight forward. As soon as multiproduct facilities are considered which can consist of multiple processes, the analysis of possible different conversion routes and therefore the exchange of material flows between processes becomes an interesting aspect of analysis, synthesis and design. This is, for instance, a typical kind of research question in the conceptual design of a biorefinery where biomass can be converted into different intermediates (e.g. cellulose, hemicellulose and lignin) which are themselves converted into other intermediates and final products (e.g. ethanol, butanol, methanol, SNG, olefins, aldehydes, etc.) and in case into heat and electricity.
Evaluation of process integration alternatives

The objectives of the analysis of process integration aspects related to the implementation of the Skogskemi processes are:

- To estimate the opportunities of energy savings by integrating either portions of the same process or different processes together thus contributing to highlight the most promising routes among those suggested.
- To estimate the consequences of locating the suggested processes close to specific existing industrial areas in terms of opportunities of exchanging either thermal energy (e.g. steam or fuel gas) or materials such as by-products that can increase the overall conversion of resources into useful products.

To this end it is necessary to establish for each specific process:

- The size of the process, e.g. in terms of main feedstock intake.
- The need or availability of energy carriers such as steam, fuel, chilled water, power, for a given process size.
- Characteristics of possible additional material flows entering or exiting the process boundaries.
- The location of the process.

Studied alternatives for Skogskemi

The economic and environmental analyses of the different technological platforms and processes were assigned to different work packages within the Skogskemi project. The different technological maturity of suggested processes was mirrored by more or less availability of process data and by the larger or smaller relevance of process integration analysis.

Detailed information of some processes was not disclosed due to proprietary reasons which severely constrained the number of degrees of freedom of process integration analysis thus making new investigation substantially unnecessary. Additionally, some processes are already built. In all these cases the exchange of utility or materials with other industrial processes are defined a priori and can be included directly into economic accountings. These limitations mainly apply to the specific technology pathways for the recovery of methanol from stripper gasses, the production of butanol from ethanol and the production of olefins via MTO.

A larger flexibility in process integration has been considered for the two technology platforms – the biochemical sugar platform and the biomass gasification platform. Still, due to different sources of process data and specific approach adopted in the two separate work packages, different options and degrees of process integration were considered.

Conclusions on process integration

In the process integration analyses of the ethanol production via the sugar platform and of the biomass gasification platforms, integration opportunities with two types of nearby industrial areas were of interest: pulp (and paper) mills, and the petrochemical cluster in Stenungsund. It was found that, in general, the exchange of steam with surrounding industrial plants significantly improves the resource efficiency and the process economics.

The Stenungsund chemical cluster appears to be the most interesting location for the methanol production based on biomass gasification since the gasification excess heat can be exported to the Borealis cracker thus introducing large savings in natural gas in current boilers. While similar fuel savings can be achieved at a pulp and paper mill, the substitution of bark is less interesting than the substitution of natural gas both from an economic and environmental point of view. While the integration of the whole route from biomass to olefins was not studied in detail, it should be noted that placing the methanol production at the Stenungsund site is interesting also for its direct
integration with the subsequent MTO process. This latter process appears in fact to dramatically increase the steam deficit at the cracker.

Less obvious appears the choice of optimal location for the ethanol production via biomass fermentation. While the Stenungsund cluster could offer larger capacity reserve in current natural gas boilers that can be made available to cover the steam needed for ethanol production, the integration of ethanol production with a pulp mill appears more interesting since lignin is a common by-product and can be upgraded and exported using common facilities or used for steam generation in recovery boilers.
Final conclusions and recommendations
The life cycle assessment performed in the project found, in general, lower environmental impacts in the forest-based case than in the fossil reference case for all value chains. Notably, the forest-based chemicals showed a lower global warming potential from the production phase than their fossil counterparts. In most of the considered cases, the global warming potential was lower for the green chemicals also before considering the eventual emission of the carbon in the product itself to the atmosphere, at its end-of-life. Adding the end-of-life emissions to the products with fossil origin increases the benefit of the forest-based chemicals substantially. The risk for eutrophication is 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 indicates 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.

The LCA study carries large uncertainties and certain aspects, such as potential biodiversity impacts should be monitored. We think, however, that the results give a clear indication that forest-based chemicals that replace fossil-based chemicals have the potential to contribute in achieving several environmental goals. Therefore, environmental policy measures should be designed so that the use of biomass for chemical products and materials is not disfavored compared to its use for transportation fuels and other energy applications. Historically, policy measures that have been formulated in a technology neutral way have in practice been very technology selective. This highlights the need for careful consideration when designing policy measures that target renewable chemicals as well as renewable energy carriers. In our LCA results, the production phase accounts for a comparatively large share of the total life cycle global warming potential of the studied chemicals, compared to what is typically reported for transportation fuels. This may be a consequence of methodological choices made, but could also be a factor that should be considered in the design of climate policy measures. Another factor of policy relevance that distinguishes chemicals from motor fuels is the use and end-of-life phases, such as the potentially long time span between the production of a chemical and the eventual emission of its embodied carbon. This may be even more pronounced for recyclable products.

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 phase of scaling up technologies from the level of demonstration and pilot plants to a commercialized level.

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.