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VALUE CHAINS FOR PRODUCTION OF RENEWABLE TRANSPORTATION FUELS USING INTERMEDIATES

- CASE STUDIES FOR BIO-OILS IN REFINERY APPLICATIONS AND BIO-SNG

Report from a project within the collaborative research program Renewable transportation fuels and systems

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PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 39587-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

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

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

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The part of the report concerning the bio-SNG value chains is based on a scientific paper:

Pettersson K, Lundberg V, Anheden M, Ehn C, Fuglesang M (2016). Systems analysis of different value chains based on domestic forest biomass for the production of bio-SNG. *Submitted for publication.*

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Anheden M et al. (2016). *Value chains for production of Renewable Transportation Fuels Using Intermediates.* Report No 2016:05, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

SHORT SUMMARY

An increased share of renewable transportation fuels requires utilisation of new low-cost sources of bio-based raw materials other than what is currently used in the pulp and paper industry and for power and district heat generation in the bioenergy sector. Currently, proposed raw material includes forest residues (branches and tops), stumps, waste round wood and different by-products from pulp and paper industry and sawmills. Of these, forest residues and stumps have, by far, the largest potential for increased utilisation. However, these types of raw materials are often voluminous and heterogeneous and are difficult to handle in existing refineries for production of transportation fuels. The cost of transporting this type of raw material over large distances in order to supply a larger plant is often said to be high. This report includes an analysis of the possible advantages and disadvantages of transforming forest-based biomass to an intermediate product with a higher energy density that is more homogeneous and easier to handle during transport and during final conversion to transportation fuel.

Two value chains are investigated as case studies a) bio-SNG production using forest residues, bark and sawdust as raw material and b) bio-oil production from forest residues, lignin in black liquor and tall oil, which can be upgraded to transportation fuels at a refinery. In the study we have assumed that the conversion of the original biomass to an intermediate product mainly takes place at a pulp mill. The intermediate conversion technologies included for value chain a) are drying and pelletizing and for value chain b) pyrolysis and distillation. The final conversion to end product bio-SNG takes place in connection to a district heating system, and the final deoxygenation and upgrading of bio-oil to hydrodeoxygenated (HDO) oil takes place at an oil refinery. The value chains with intermediates are compared with value chains without intermediates where the entire conversion process to final product is located in connection to a district heating system in value chain a) and at a stand-alone plant near to a refinery in value chain b). The value chains are studied from a well-to-gate perspective, from extraction of the forest biomass to produced bio-SNG/HDO bio-oil. A direct comparison between value chains for bio-SNG and bio-oil production should be avoided. They are based on different reference data that are not synchronized. A direct comparison between the chains should in addition be done in a well-to-wheel perspective.

The results show that the initial hypothesis that local production of a more energy dense intermediate would reduce transportation costs could not be verified. The reason is primarily the introduction of a second transport step to transport the intermediate to the final conversion site in addition to the transport of the raw material. The transport costs are associated with relatively high fixed cost especially for ship and train transport, so the introduction of a second relatively high fixed transport cost of the intermediate has a dominating effect. Further, it can be concluded that the transport cost make up a relatively small share of the total production cost of the final product, in the order of 10%, and in a few cases up to 20%. There is therefore a relatively small difference in total specific production cost for the final product between value chains with and without intermediates considering the level of uncertainty in the input data and the assumptions behind the scenarios studied.

Summarizing, the results indicate that the production costs are highly sensitive to the economies of scale, oxygen content in the bio-crude oil and raw material costs (forest residues price or electricity price in the case where lignin is used as raw material). Transportation costs have, comparatively, a little effect in the total production cost.

EXTENDED SUMMARY

An increased share of renewable transportation fuels requires utilisation of new low-cost sources of bio-based raw materials other than what is currently used in the pulp and paper industry and for power and district heat generation in the bioenergy sector. Currently, proposed raw material includes forest residues (branches and tops), stumps, waste round wood and different by-products from pulp and paper industry and sawmills. Of these, forest residues and stumps have, by far, the largest potential for increased utilisation. However, these types of raw materials are often voluminous and heterogeneous and are difficult to handle in existing refineries for production of transportation fuels. The cost of transporting this type of raw material over large distances in order to supply a larger plant is often said to be high. This report includes an analysis of the possible advantages and disadvantages of transforming forest-based biomass to an intermediate product with a higher energy density that is more homogeneous and easier to handle during transport and during final conversion to transportation fuel.

Two value chains are investigated as case studies: a) bio-SNG production using forest residues, bark and sawdust as raw material and b) bio-oil production from forest residues, lignin in black liquor and tall oil, which can be upgraded to transportation fuels at a refinery. In the study we have assumed that the conversion of the original biomass to an intermediate product mainly takes place at a pulp mill, since the pulp mill is often located in areas with high availability of forest raw material, there is an infrastructure available in form of road access, wood yard and handling facilities, and a lot of know-how with respect to handling and conversion of forest-based biomass and opportunities for process and energy integration. The intermediate conversion technologies included for value chain a) are drying and pelletizing and for value chain b) pyrolysis and distillation. The final conversion to end product bio-SNG takes place in connection to a district heating system, and the final deoxygenation and upgrading of bio-oil to hydrodeoxygenated (HDO) oil takes place at an oil refinery. The value chains with intermediates are compared with value chains without intermediates where the entire conversion process to final product is located in connection to a district heating system in value chain a) and at a stand-alone plant near to a refinery in value chain b). The value chains are studied from a well-to-gate perspective, from extraction of the forest biomass to produced bio-SNG/HDO bio-oil. A direct comparison between value chains for bio-SNG and bio-oil production should be avoided. They are based on different reference data that are not synchronized. A direct comparison between the chains should in addition be done in a well-to-wheel perspective.

The results show that the initial hypothesis that local production of a more energy dense intermediate would reduce transportation costs could not be verified. The reason is primarily the introduction of a second transport step to transport the intermediate to the final conversion site in addition to the transport of the raw material. The transport costs are associated with relatively high fixed costs, especially for ship and train transport, so the introduction of a second relatively high fixed transport cost of the intermediate has a dominating effect.

With the above said, it can also be concluded that the transport cost makes up a relatively small share of the total production cost of the final product, in the order of 10%, and in a few cases up to 20%. There is therefore a relatively small difference in total specific production cost for the final product between value chains with and without intermediates considering the level of uncertainty in the input data and the assumptions behind the scenarios studied.

Decentralised production of intermediates in several smaller plants can lead to increased total production cost. This is the case when the capital cost of the intermediate conversion plant is high. The exception is when the intermediate conversion plant has a low capital cost, for instance just a drier. In cases where e.g. low temperature excess heat is used in the conversion to intermediates, several smaller plants could be preferred since the availability of excess heat is limited at each plant (mill).

An example of results regarding energy efficiency, specific net CO_2 emissions and production costs for the bio-SNG value chain is presented in Table A. The case without intermediate means transportation of forest biomass directly to the bio-SNG plant, whereas the case with intermediate here refers to drying of forest biomass at pulp mills before (further) transport to the SNG plant. There are two factors working in opposite directions, almost cancelling each other out and making the total cost for the case with and without intermediates similar (as can be seen in Table A). The total transportation costs are somewhat increased for the case with intermediates, due to the introduction of an additional transportation step. However, the benefit of drying the biomass using excess heat at pulp mills, is that excess heat is “moved” from a place where it could be hard to find profitable ways to use it, to the SNG plant where the excess heat can be used for district heating. The results within brackets in Table A refer to cases where the biomass feedstock is falling bark instead of forest residues. This option offers the opportunities to lower the cost somewhat. However, there is a high uncertainty regarding how much bark that can be used in the bio-SNG process.

Table A. Example of results for the bio-SNG value chain.

Specific production cost (EUR/MWh)		**Specific net CO_2 emissions (kg_CO_2/MWh)**		**Energy efficiency ($MW_{heleq\ net\ output}/MWh_{eleq\ net\ input}$, %)**	
Bio-SNG without intermediate	Bio-SNG with intermediate	Bio-SNG without intermediate	Bio-SNG with intermediate	Bio-SNG without intermediate	Bio-SNG with intermediate
59 (59)	59 (55)	3 (-2)	0 (-3)	86 (87)	88 (88)

To use pellets is the most expensive and clearly the least energy efficient option (70%) out of the studied alternatives. This shows that further pretreatment than necessary (drying is required by the SNG process) is not energy efficient and not profitable. The total cost is dominated by the raw material and capital cost. The cost is reduced with increased SNG production rate (the results in Table A are for production of 300 MW SNG). The cost for the case with intermediates is reduced somewhat more than the case without intermediates when the SNG production rate is increased. The results here, as well as in general, emphasize the importance of large scale production. Then, the relevance of intermediates could increase for this value chain if larger and larger plants are being built.

For the bio-oil value chain, an example of the results regarding energy efficiency, specific CO_2 emissions and production costs is presented in Table B. The results of the forest-based value chains with and without intermediate product production (pyrolysis oil) are similar, particularly regarding energy efficiency and specific CO_2 emissions. The results within brackets in Table B refer to a value chain with intermediate product production where lignin extracted from black liquor is used as raw material (instead of forest residues).

The specific production cost for the value chain without intermediate product is lower than with intermediate. This is not because there is no intermediate product production, but rather because a single large facility is used instead of three smaller ones. Therefore, benefits related to economies of scale can be reaped. This was confirmed by another value chain studied (PYR1, not shown in Table B) where the intermediate product was produced at a single facility. For this case, the specific production cost was 86 EUR/MWh. The results indicate that economies of scale play a more important role than the choice of where to produce the pyrolysis oil and how it is transported.

Table B. Example of results for the bio-oil value chain.

Specific production cost (EUR/MWh)		**Specific net CO_2 emissions (kg CO_2/MWh)**		**Energy efficiency ($MWh_{eleq\ net\ output}/MWh_{eleq\ net\ input}$, %)**	
HDO-oil without intermediate. Case REF_R	HDO-oil with intermediate. Case PYR3 (LIG3)	HDO-oil without intermediate. Case REF_R.	HDO-oil with intermediate. Case PYR3 (LIG3)	HDO-oil without intermediate (Case REF_R)	HDO-oil with intermediate. Case PYR3 (LIG3)
87	90 (94)	93	92 (85)	74	74 (84)

Besides the economies of scale, other parameters appeared to be important, e.g. the oxygen content in the bio crude pyrolysis oil as it determines the necessary amount of hydrogen for hydrodeoxygenation. The hydrogen consumption has, in turn, a significant effect on energy efficiency, specific CO_2 emissions and production costs. For the value chain with lignin as a raw material, significantly higher energy efficiency and lower specific CO_2 emissions are obtained. This is due to the lower oxygen content of lignin-oil compared to bio-oil from forest residues.

The production costs of lignin-oil are higher than those for the chains with forest residues. This is because the separation of lignin from the black liquor results in a reduced electricity production at the mill. With the current electricity price and the possibility to receive green electricity certificates, the production cost of bio-oil from lignin is higher than for bio-oil from forest residues. However, in this study, no credit has been included for the potential pulp production capacity increase. Lignin separation can enable an increased pulp production, in case the recovery boiler is the main bottleneck for a capacity increase. If the alternative cost for enabling such a capacity increase would have be deducted from the lignin case, this case would probably be more economically attractive despite the loss of electricity production. Moreover, no consideration has been taken to the fact that the produced lignin-oil may have a higher value than pyrolysis crude-oil from forest residues due to valuable molecular structures (e.g. aromatics).

The lower oxygen content in the lignin-oil compared to the crude pyrolysis oil from forest residues makes this value chain particularly attractive if the hydrogen price is higher than in the base case scenario. In a sensitivity analysis the price of hydrogen was increased by 80%. This could represent a case in which hydrogen is produced by methane reformation at a cost similar to the highest in the last 4 years. In this case, the production cost for the lignin value chain is 101 EUR/MWh whereas the cost for the forest residues chain with intermediates (PYR3) is 107 EUR/MWh.

Summarizing, the results indicate that the production costs are highly sensitive to the economies of scale, oxygen content in the bio-crude oil and raw material costs (forest residues price or electricity price in the case where lignin is used as raw material). Transportation costs have, comparatively, a little effect in the total production cost.

Even though this study could not prove a clear economic benefit of intermediate products, there are other important advantages related to transformation to intermediate products that need to be emphasised. These advantages are valid when the intermediate conversion is located at an already existing industrial plant handling biomass such as a pulp mill as in this study. These include opportunities to utilise industrial by-products in the intermediate conversion plant, utilisation of existing infrastructure in the form of access roads and receiving stations for biomass handling, power generation, steam, process water, cooling water and waste water purification at a low marginal cost, use of excess heat from the industrial plant to provide energy for the upgrading to intermediate, opportunities to integrate the intermediate production with the industrial plant to valorise by-products and excess heat from the conversion to intermediate. An important factor is also that the existing know-how related to handling of biomass that takes time to build up, could also be available at the intermediate conversion plant. Safety aspects related to handling of biomass could also have an influence on where it is possible to locate a biomass conversion plant and how it can be integrated with existing industry. The advantages should be investigated in more detail in a follow-up study, with the goal of determining the monetary value of these opportunities.

A case for production of an intermediate that could be advantageous is when the industrial plant connected to the conversion to intermediate is located in an area with high excess of forest residue raw material close by. Low market price of the raw material could then result in a low production cost of the intermediate, as the raw material cost is one of the dominating factors in the total cost. Other important advantages of intermediate conversion processes identified include easier build-up of a new value chain if the produced intermediate can be easier linked to the existing production of the final product. An example of this is the intermediate conversion of forest residues to a bio-oil that can be linked in to the production in an oil refinery compared to having the oil refinery organisation build up a whole new operation for production of bio-oil from forest residues at the vicinity of the refinery. An already existing good biomass market insight might also benefit the intermediate conversion plant, including own assets in forest resources and a mature biomass procurement organisation. The business model and strategy as well as the competitive situation on the market for intermediate and final products for the actors along the chain will also have a great influence on the potential for building up value chain with intermediates, and where in the value chain that it is possible to generate profits. These aspects have not been included in the current study and should be further considered and investigated.

KORT SAMMANFATTNING

En ökad andel förnybara drivmedel kräver att vi utnyttjar nya billigare biobaserade råvaror än vad som för närvarande används i massa- och pappersindustrin och för el- och fjärrvärmeproduktion inom bioenergisektorn. För närvarande föreslås att råvaror som GROT (grenar och toppar), stubbar, gallringsrester och olika biprodukter från massa- och pappersindustrin och sågverk används i en utbyggd bioekonomi. Av dessa har GROT och stubbar den överlägset största potentialen för ökad användning. Emellertid är dessa typer av råvaror ofta voluminösa och heterogena, och är svåra att hantera i befintliga raffinaderier för produktion av drivmedel. Kostnaden för transport av denna typ av råvara över långa sträckor för att leverera till en större produktionsanläggning sägs ofta vara hög. Denna rapport innehåller en analys av möjliga för- och nackdelar med att omvandla skogsbaserad biomassa till en intermediär produkt med högre energitäthet, som är mer homogen och lättare att hantera vid transport och vid slutliga omvandlingen till drivmedel.

Två värdekedjor utreds i form av fallstudier; a) bio-SNG-produktion med GROT, bark och sågspån som råvara och b) produktion av bioolja (som kan slutuppgraderas till drivmedel på ett befintligt raffinaderi) från GROT, lignin från svartlut och tallolja. I studien har vi antagit att omvandlingen av den ursprungliga biomassan till en intermediär sker på ett massabruk. De teknologier som inkluderats för omvandling till en intermediär produkt inkluderar för värdekedja a) torkning och pelletering och för värdekedja b) pyrolys och destillation. Omvandlingen till slutprodukten bio-SNG äger rum i anslutning till ett fjärrvärmesystem i värdekedja a), och den slutliga deoxygeneringen och uppgradering till bioolja äger rum på ett oljeraffinaderi i värdekedja b). Värdekedjorna med intermediärer jämförs med värdekedjor utan intermediärer där hela omvandlingen från råvara till slutprodukt sker i anslutning till fjärrvärmesystem i värdekedja a) och vid en fristående anläggning nära ett raffinaderi i värdekedja b). Värdekedjorna studeras från ett well-to-gate-perspektiv, från uttag av skogsbiomassa till producerad bio-SNG/bioolja. En direkt jämförelse mellan kedjorna för bio-SNG och biooljeproduktion bör undvikas. Detta eftersom de är baserade på olika underlag med olika grundantaganden som inte synkroniserats. En jämförelse bör i tillägg ske från ett well-to-wheel perspektiv för att vara relevant.

Resultaten från studien visar att den ursprungliga hypotesen att lokal produktion av en intermediär med hög energitäthet skulle minska transportkostnaderna inte kan verifieras. Anledningen är främst införandet av ett andra transportsteg för transport av intermediären till platsen för den slutliga omvandlingen, utöver transport av råvaran. Transportkostnaderna är förknippade med relativt höga fasta kostnader, särskilt för fartygs- och tågtransport, så införandet av en andra, relativt hög, fast transportkostnad för intermediären har en dominerande effekt. Det kan också konstateras att transportkostnaden utgör en relativt liten andel av den totala produktionskostnaden för slutprodukten, omkring 10%, i några fall dock upp till 20%. Därför är det en relativt liten skillnad i totala specifika produktionskostnaden för slutprodukten mellan värdekedjor med och utan intermediärer, särskilt med tanke på osäkerheten i indata och antaganden bakom de scenarier som studerats.

Sammanfattningsvis visar resultaten att produktionskostnaderna är mycket känsliga för uppskalningseffekter, syrehalten i bio-råolja och råvarukostnader (pris på skogsrester eller elpriset för fallet med lignin som råvara). Transportkostnader har relativt liten inverkan på den totala produktionskostnaden.

FÖRLÄNGD SAMMANFATTNING

En ökad andel förnybara drivmedel kräver att vi utnyttjar nya billigare biobaserade råvaror än vad som för närvarande används i massa- och pappersindustrin och för el- och fjärrvärmeproduktion inom bioenergisektorn. För närvarande föreslås att råvaror som GROT (grenar och toppar), stubbar, gallringsrester och olika biprodukter från massa- och pappersindustrin och sågverk används i en utbyggd bioekonomi. Av dessa har GROT och stubbar den överlägset största potentialen för ökad användning. Emellertid är dessa typer av råvaror ofta voluminösa och heterogena, och är svåra att hantera i befintliga raffinaderier för produktion av drivmedel. Kostnaden för transport av denna typ av råvara över långa sträckor för att leverera till en större produktionsanläggning sägs ofta vara hög. Denna rapport innehåller en analys av möjliga för- och nackdelar med att omvandla skogsbaserad biomassa till en intermediär produkt med högre energitäthet, som är mer homogen och lättare att hantera vid transport och vid slutliga omvandlingen till drivmedel.

Två värdekedjor utreds i form av fallstudier; a) bio-SNG-produktion med GROT, bark och sågspån som råvara och b) produktion av bioolja (som kan slutuppgraderas till drivmedel på ett befintligt raffinaderi) från GROT, lignin från svartlut och tallolja. I studien har vi antagit att omvandlingen av den ursprungliga biomassan till en intermediär sker på ett massabruk, eftersom massabruk ofta ligger i områden med hög tillgång på skogsråvara, det finns en befintlig infrastruktur i form av tillgång till vägar, vedgård och lageranläggningar och dessutom kunnande när det gäller hantering och omvandling av skogsråvara samt möjligheter till process- och energiintegration. De teknologier som inkluderats för omvandling till en intermediär produkt inkluderar för värdekedja a) torkning och pelletering och för värdekedja b) pyrolys och destillation. Omvandlingen till slutprodukten bio-SNG äger rum i anslutning till ett fjärrvärmesystem i värdekedja a), och den slutliga deoxygeneringen och uppgradering till bioolja äger rum på ett oljeraffinaderi i värdekedja b). Värdekedjorna med intermediärer jämförs med värdekedjor utan intermediärer där hela omvandlingen från råvara till slutprodukt sker i anslutning till fjärrvärmesystem i värdekedja a) och vid en fristående anläggning nära ett raffinaderi i värdekedja b). Värdekedjorna studeras från ett well-to-gate-perspektiv, från uttag av skogsbiomassa till producerad bio-SNG/bioolja. En direkt jämförelse mellan kedjorna för bio-SNG- och biooljeproduktion bör undvikas. Detta eftersom de är baserade på olika underlag med olika grundantaganden som inte synkroniserats. En jämförelse bör i tillägg ske från ett well-to-wheel perspektiv för att vara relevant.

Resultaten från studien visar att den ursprungliga hypotesen att lokal produktion av en intermediär med hög energitäthet skulle minska transportkostnaderna inte kan verifieras. Anledningen är främst införandet av ett andra transportsteg för transport av intermediären till platsen för den slutliga omvandlingen, utöver transport av råvaran. Transportkostnaderna är förknippade med relativt höga fasta kostnader, särskilt för fartygs- och tågtransport, så införandet av en andra, relativt hög, fast transportkostnad för intermediären har en dominerande effekt.

Med ovanstående sagt, kan det också konstateras att transportkostnaden utgör en relativt liten andel av den totala produktionskostnaden för slutprodukten, omkring 10%, i några fall dock upp till 20%. Därför är det en relativt liten skillnad i totala specifika produktionskostnaden för slutprodukten mellan värdekedjor med och utan intermediärer, särskilt med tanke på osäkerheten i indata och antaganden bakom de scenarier som studerats.

Decentraliserad produktion av intermediärer i flera mindre anläggningar kan leda till en ökad total produktionskostnad. Detta är fallet när kapitalkostnaden för anläggningen för omvandling till intermediär är hög. Undantaget är när anläggningen för omvandling till intermediär har en låg kapitalkostnad, t.ex.

en tork. I fall där t.ex. överskottsvärme används vid omvandlingen till intermediär, kan flera mindre anläggningar vara att föredra eftersom mängden överskottsvärme som finns tillgängligt vid varje anläggning (bruk) är begränsat.

Exempel på resultat när det gäller energieffektivitet, specifika nettoutsläpp av CO_2 och produktionskostnad för bio-SNG-värdekedjan presenteras i Tabell A. Fallet utan intermediär inkluderar transport av skogsbiomassa direkt till en bio-SNG-anläggning, medan fallet med intermediär inkluderar torkning av skogsbiomassa vid ett massabruk innan (ytterligare) transport till SNG-anläggningen. Som kan ses i Tabell A uppvisar fallen med och utan intermediärer liknande kostnader. Detta är resultatet av två faktorer som påverkar kostnaden i olika riktningar och som nästan tar ut varandra. De totala transportkostnaderna ökar något för fallet med intermediärer, på grund av införandet av ett ytterligare transportsteg. Fördelen med torkning av biomassa med överskottsvärme vid massabruket är dock att överskottsvärme "flyttas" från en plats där det kan vara svårt att hitta lönsamma sätt att använda det till SNG-anläggningen där överskottsvärmen kan användas som fjärrvärme. Resultaten inom parentes i Tabell A) är relaterade till fall där råmaterialet som används är fallande bark (i stället för GROT). Detta alternativ kan sänka kostnaderna något. Det finns dock en stor osäkerhet avseende hur mycket bark som kan användas i bio-SNG-processen.

Tabell A. Exempel på resultat för värdekedjan för produktion av bio-SNG.

Specifik produktionskostnad (EUR/MWh)		**Specifikt nettoutsläpp av CO_2 (kg_CO_2/MWh)**		**Energieffektivitet ($MW_{heleq\ net\ output}/MWh_{eleq\ net\ input}$, %)**	
Bio-SNG utan intermediär	Bio-SNG med intermediär	Bio-SNG utan intermediär	Bio-SNG med intermediär	Bio-SNG utan intermediär	Bio-SNG med intermediär
59 (59)	59 (55)	3 (-2)	0 (-3)	86 (87)	88 (88)

Att använda pellets är det dyraste och det absolut minst energieffektiva alternativet (70%) av de studerade alternativen för värdekedja a). Detta visar att mer förbehandling än vad som är nödvändigt (torkning krävs i SNG-processen) varken är energieffektivt eller ekonomiskt lönsamt. Den totala kostnaden domineras av råvaru- och kapitalkostnaderna. Kostnaden minskar med ökande storlek på SNG-produktionsanläggningen. Resultaten i Tabell A är för produktion av 300 MW SNG. Kostnaden för fallet *med intermediärer* minskas något mer än för fallet *utan intermediär* när storleken på SNG-anläggningen ökas. Resultaten här, liksom i allmänhet, betonar vikten av storskalig produktion. Relevansen för intermediärer kan öka för denna värdekedja, om större och större anläggningar byggs.

Exempel på resultat med avseende på energieffektivitet, specifika CO_2-utsläpp och produktionskostnad för värdekedjan för produktion av bioolja visas i Tabell B. Resultaten för värdekedjorna *med* respektive *utan* produktion av intermediär produkt (pyrolysolja) är lika, särskilt när det gäller energieffektivitet och specifika CO_2-utsläpp. Resultaten inom parentes i Tabell B avser en värdekedja med produktion av en intermediär produkt där lignin från svartlut används som råmaterial (i stället för GROT).

Den specifika produktionskostnaden för värdekedjan *utan intermediär* produkt är lägre än för värdekedjan *med intermediärer*, även för bioolja. Detta beror inte på att det saknas produktion av intermediär produkt i kedjan utan intermediär, utan det är snarare ett resultat av att en enda stor anläggning används i fallet *utan intermediär*. I fallet *med intermediärer* sker samma totala produktion fördelat på tre anläggningar. Resultatet är därmed ett resultat av stordriftsfördelar och uppskalning. Detta bekräftades av en annan värdekedja som studerats (PYR1, vars resultat inte visas i Tabell B), där intermediären producerades vid en enda anläggning. För detta fall är specifika produktionskostnaden 86

EUR/MWh. Resultaten visar att stordriftsfördelar och uppskalning spelar en viktigare roll än var pyrolysoljan produceras och hur den transporteras.

Tabell B. Exempel på resultat från värdekedjan för produktion av bioolja.

Specifik produktionskostnad (EUR/MWh)		**Specifika nettoutsläpp av CO_2 (kg CO_2/MWh)**		**Energieffektivitet ($MWh_{eleq\ net\ output}$/$MWh_{eleq\ net\ input}$, %)**	
Bioolja utan intermediär. Fall REF_R	Bioolja med intermediär. Fall PYR3 (LIG3)	Bioolja utan intermediär Fall REF_R.	Bioolja med intermediär. Fall PYR3 (LIG3)	Bioolja utan intermediär (Fall REF_R)	Bioolja med intermediär. Fall PYR3 (LIG3)
87	90 (94)	93	92 (85)	74	74 (84)

Förutom stordriftsfördelarna är andra parametrar viktiga, t.ex. syrehalten i bioråoljan, som bestämmer den nödvändiga mängden vätgas för hydrodeoxygenering. Vätekonsumtionen har i sin tur en betydande effekt på energieffektiviteten, specifika CO_2-utsläppen och produktionskostnaden. För värdekedjan med lignin som råvara nås en betydligt högre energieffektivitet och lägre specifika CO_2-utsläpp. Detta beror just på det lägre syreinnehållet i bioolja från lignin jämfört med bioolja från skogsrester.

Produktionskostnaderna för ligninolja är högre än de för kedjor med skogsrester som råmaterial. Detta beror på att separation av lignin från svartluten resulterar i en minskad elproduktion från massabruket. Med nuvarande elpris och möjlighet att erhålla elcertifikat är kostnaden för produktion av bioolja från lignin mycket högre än för bioolja från skogsrester. I denna studie har emellertid ingen ekonomisk fördel av potentiellt högre massaproduktion tagits med. Ligninuttag kan möjliggöra en ökad massaproduktion i de fall sodapannan är den största flaskhalsen för kapacitetsökning. Om alternativkostnaden för att möjliggöra en sådan produktionsökning skulle avräknas ligninfallet, skulle detta fall troligen vara mer ekonomiskt attraktivt trots förlusten av elproduktionskapacitet. Dessutom har ingen hänsyn tagits till att den producerade ligninoljan kan ha ett högre värde än olja från skogsrester pga förekomsten av värdefulla molekylära strukturer i oljan (t.ex. aromater).

Den lägre syrehalten i råoljan från lignin jämfört med råolja från skogsrester gör denna värdekedja särskilt attraktiv om vätgaspriset är högre än i basalternativet. I en känslighetsanalys ökades priset på vätgas med 80%. Detta skulle kunna motsvara ett fall där vätgas framställs genom reformering av naturgas till en kostnad baserat på den högsta kostnaden för naturgas under de senaste 4 åren. I detta fall är produktionskostnaden för ligninvärdekedjan 101 EUR/MWh medan kostnaden för kedjan utgående från skogsrester med intermediärer (PYR3) är 107 EUR/MWh.

Sammanfattningsvis visar resultaten att produktionskostnaderna är mycket känsliga för uppskalningseffekter, syrehalten i bio-råolja och råvarukostnader (pris på skogsrester eller elpriset för fallet med lignin som råvara). Transportkostnader har relativt liten inverkan på den totala produktionskostnaden.

Även om denna studie inte kan visa på en tydlig ekonomisk fördel av intermediära produkter, så finns det andra viktiga fördelar med omvandling till intermediära produkter som behöver betonas. Dessa fördelar gäller när konverteringen till intermediärer är integrerad i en redan befintlig industrianläggning för hantering av biomassa, t.ex. ett massabruk, som i denna studie. Dessa fördelar inkluderar möjligheter att utnyttja industriella biprodukter i anläggningen för intermediärproduktion, utnyttjande av befintlig infrastruktur i form av vägar och mottagningsstationer för hantering av biomassa, utnyttja system för kraftproduktion, produktion av ånga, processvatten, kylvatten och vattenrening till låg marginell kostnad, användning av överskottsvärme från industrianläggningen för att uppgradera till intermediär, samt möjlighet att integrera med industrianläggningen för att ge värde till biprodukter och överskottsvärme från produktion av intermediären. En viktig faktor är också att den existerande kunskapen kring hantering av biomassa som tar tid att bygga upp, direkt kan utnyttjas vid den integrerade anläggningen för produktion av intermediär. Säkerhetsaspekter relaterade till hantering av biomassa kan också inverka på var det är möjligt att lokalisera en anläggning för omvandling av biomassa och hur den kan integreras med befintlig industri. Dessa aspekter bör utredas närmare i en uppföljande studie, med målet att fastställa det monetära värdet av dessa möjligheter.

Ett fall för produktion av intermediär som skulle kunna vara fördelaktigt är när industrianläggningen integrerad med anläggningen för omvandling till intermediär ligger i ett område med stort överskott av restprodukter från skogsbruk. Lågt pris på råvaran kan då ge en låg produktionskostnad av intermediären, då råmaterialkostnaden är en dominerande faktor i den totala kostnaden. Andra viktiga fördelar med omvandling till intermediär som identifierats inkluderar enklare uppbyggnad av en ny värdekedja om intermediären lättare kan kopplas samman med den befintliga processen för produktion av den slutliga produkten. Ett exempel på detta är omvandling till intermediär från GROT i form av en bioolja som kan uppgraderas integrerat med ett oljeraffinaderi, jämfört med om oljeraffinaderiets organisation skulle bygga upp en helt ny organisation för produktion av bioolja från GROT i närheten av raffinaderiet. En redan existerande god insikt i marknaden för biobränslen kan också vara av fördel för produktion av intermediär vid en redan existerande anläggning som använder biomassa, särskilt som man då kanske har egna tillgångar av biomassa eller en väl fungerande organisation för inköp av biomassa. Affärsmodell och strategi, samt konkurrenssituationen kring råvaror, intermediärer och slutprodukt längs värdekedjan, samt var det är möjligt att generera vinster kommer också ha stor inverkan på potentialen för att bygga upp en värdekedja baserad på intermediära produkter. Dessa aspekter har inte undersökts i denna studie men bör inkluderas i en fortsatt studie.

CONTENTS

1 INTRODUCTION

An increased share of renewable transportation fuels requires utilisation of new low-cost sources of bio-based raw materials other than what is currently used in the pulp and paper industry and for power and district heat generation in the bioenergy sector. Currently proposed raw material includes forest residues (branches and tops), stumps, waste roundwood and different by-products from pulp and paper industry and sawmills. Of these, forest residues and stumps have, by far, the largest potential for increased utilisation. However, these types of raw materials are often voluminous and heterogeneous and are difficult to handle in existing refineries for production of transportation fuels. The specific production cost decreases with increasing plant size just as for any other production plants. However the cost for transporting the biomass is relatively high, especially when large volumes of biomass for a large plant is required, since the sourcing area increases leading to an increase in average transport distance.

In this study we looked into the possible advantages and disadvantages of transforming forest-based biomass to an intermediate product with a higher energy density that is more homogeneous and easier to handle during transport and during final conversion to transportation fuel. Examples of intermediates are crude pyrolysis oil, lignin, torrefied biomass, dried wood chips and pellets. In the study we have assumed that the conversion of the original biomass mainly takes place at a pulp mill, since the pulp mill is often located in areas with high availability of forest raw material, there is an infrastructure available in form of road access, wood yard and handling facilities, and a lot of know-how with respect to handling and conversion of forest-based biomass. In addition, an intermediate conversion plant could be integrated with the pulp mill and make use of existing utilities. Pulp mill excess heat could be utilised to increase the energy content of the biomass for instance through drying. There is also an opportunity to increase the overall biomass utilisation efficiency by integrating any by-products produced during conversion of the biomass to intermediate with the pulp mill system. Examples of such by-products are process excess heat in flue gases, excess steam, combustible gases and remaining char products from an intermediate conversion plant. They can be upgraded in the pulp mills power and recovery boiler system and be used for additional power generation.

The goals of this study are to calculate total energy efficiency, net specific emissions of fossil carbon dioxide, and specific total cost for the studied value chains. The sub-goals are to:

- Identify at least two value chains with intermediate products for production of bio-SNG (synthetic natural gas) or renewable diesel or gasoline at an oil refinery and study them in more detail
- Identify relevant value chains without intermediates for comparison
- Compare the total energy efficiency, carbon dioxide reduction potential and cost efficiency for value chains with and without intermediates with relevant sensitivity analysis on important parameters

Geographically specified locations are not studied in the project; instead the total cost and emissions of fossil CO_2 are calculated as a general function of transport distance and mode (truck, train or ship) for the different value chains, focusing on assumptions relevant in Sweden.

The work has been carried out by a project group consisting of representatives from petroleum oil refinery (Preem), bio-SNG producer (Göteborg Energi), pulp and paper industry research institute

(Innventia), technical consultants (ÅF Industry) and academia (Chalmers University of Technology). The project has had as a general purpose to generate a better understanding of the possibilities of collaboration between forest industry and transportation fuel producers. The collaboration in this diverse group has made this possible, as well as lead to exchange of experience and improved comprehensive view of the entire value chain. It is the hope that this will lead to that the results from this study can be used when developing future industrial solutions for renewable transportation fuels in Sweden.

The material presented in the report can be used by industry to evaluate pros and cons with value chains with intermediate products. The results will create an understanding of which types of intermediates that are estimated to be available based on cost and volume. The results can also be used by authorities to see the overall effects on available volumes, economy and emissions from an societal point of view, and in the case the effects are seen as positive, steer the development in that direction through incentives.

2 BACKGROUND AND PREVIOUS WORK

During 2013 Sweden consumed approximately 9.3 million m^3 of diesel and gasoline. In 2020, EU has as a target to reach at least 10% (energy basis) bio-based fuel volumes while greenhouse gas emissions from the transport sector shall decrease by 6%. The requirements on biofuels to be used are very high and mainly focusing on that the raw material should be sustainable and traceable (EU Renewable Energy Directive (RED) and Fuel Quality Directive (FQD)). Sweden also has a target to have a fossil free transportation fleet by 2030. To reach the above targets, biofuels that can be used in existing vehicle fleet play an important role. The reported current situation in Sweden shows that the target of 10% renewable energy in the transport sector was reached already in 2012, based on the calculation method in RED, see Figure 1 (ER2014:10). The biofuels used in Sweden in road transport are mainly biodiesel (HVO and FAME), ethanol and biogas. 9.7% (energy basis, RED) was based on renewable raw materials, see Figure 2.

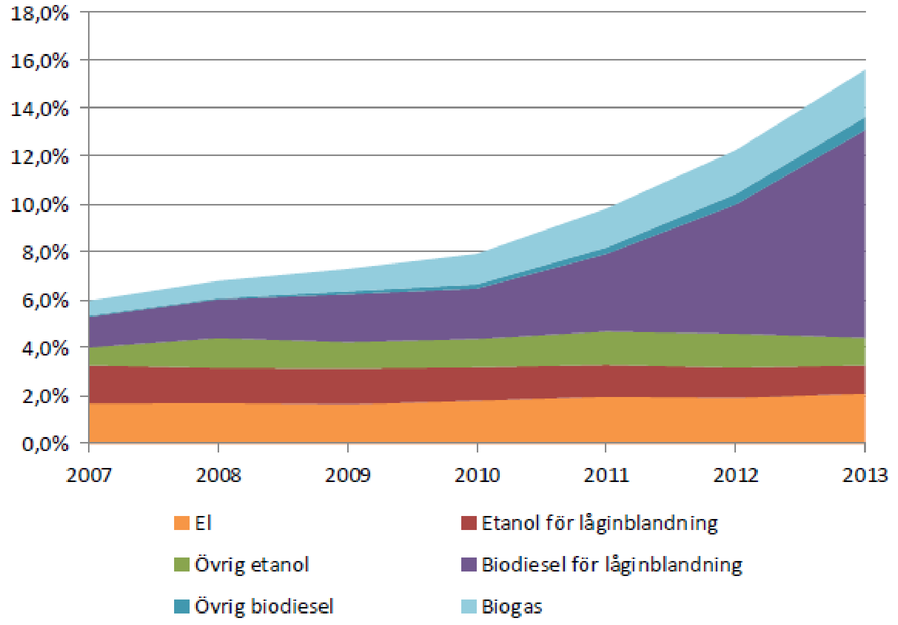

Figure 1. Share of renewable energy in the transport sector in Sweden (energy basis, according to RED) (Energimyndigheten 2014).

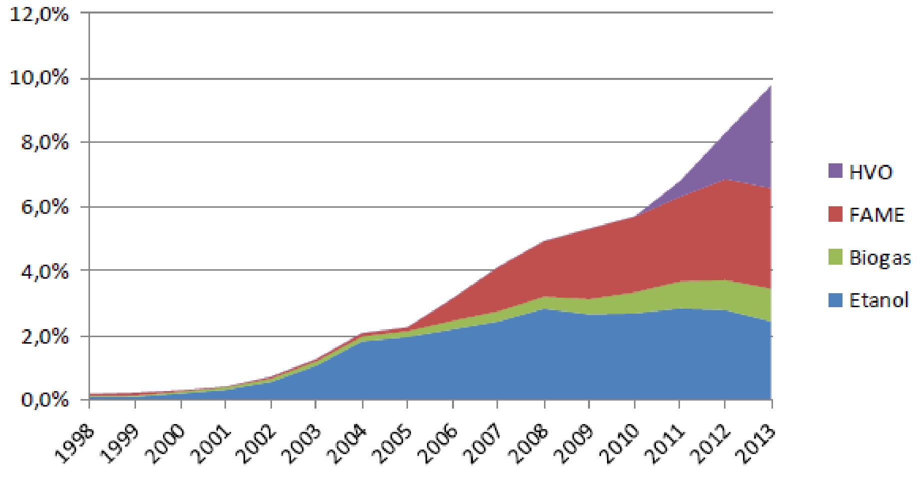

Figure 2. Share of renewable fuels in the road transport sector in Sweden (energy basis, according to RED) (Energimyndigheten 2014).

The use of locally produced waste material and by-products as raw material for production of biofuels is an effective way to create sustainable local value chains for fuel production with a high ability to reduce greenhouse gas emissions. Often, a reduction of above 80% compared to fossil counterpart can be accounted for.

Production of intermediate products from forest-based raw materials has been studied by Benjaminsson et al. (2013), Broström (2012), Neves et al. (2011), Svanberg et al. (2013) and Tapasvi (2012). The effect of transport of densified biomass has been studied among others by Benjaminsson et al. (2013), Svanberg et al. (2013), Stephen (2010), Uslu et al. (2008), and the effect of transport distance by Isaksson et al. (2013), Laskar et al. (2013), Weiland et al. (2014) and Holmgren et al. (2014). Some studies are focusing on the technical development of one component in the value chain, e.g. Broström (2012) and Weiland et al. (2014), while others are evaluating several process steps on a higher system level e.g. Stephen (2010) and Isaksson et al. (2013) or the entire value chain e.g. Uslu et al. (2008).

Regarding production costs and conversion yields, Uslu et al. (2008) show that the production cost decreases due to upscaling for torrefaction and pelletizing plants in Latin America up to 40 MW. Svanberg et al. show that the production cost decreases for torrefaction plants up to 90-120 MW located in Sweden. Benjaminsson et al. conclude that crude pyrolysis oil can be produced to a lower cost when it is integrated with a pulp mill, compared to integration with a district heating plant or stand-alone mode. Uslu et al. (2008) also show that the primary energy usage during transport decreases with 30% respective 60% when the biomass is pyrolysed or torrefied and pelletized compared to transport of pelletized biomass from Latin America to Europe. Isaksson et al. (2013) show that production of FT (Fischer-Tropsch) crude through entrained flow gasification can be made with a higher total conversion yield if the forest-based raw material is first pyrolysed, while intermediate conversion through torrefaction has a similar conversion yield as for pulverized biomass. The intermediate conversion and production of FT crude is assumed to take place integrated with the pulp mill. Uslu et al. (2008) have compared the total production cost for FT fuels delivered to Western Europe from biomass from Latin America. The biomass was assumed to be collected for local or central pelletization, torrefaction or pyrolysis before being transported to Europe. The results showed that transportation fuels produced through a torrefied intermediate have a somewhat lower production cost than if produced through an intermediate that was only pelletized. Pyrolysis oil as intermediate showed the highest production cost. The production of the intermediate and the transportation fuel was here assumed to take place in stand-alone plants.

We have not been able to find any previous study that is systematically evaluating the influence of transport means and distance, process integration opportunities, yields and volumes on the economic and environmental performance of forest-based transportation fuel value chains with intermediate products and compared them with equivalent chain without intermediates.

3 METHODOLOGY

In this study, value chains where the raw material is upgraded to intermediate products are compared against a reference chain in which the raw material is upgraded in a single facility into the final product. Two final products have been studied: forest-based HDO-oil and bio-SNG. The criteria for choosing these two products are defined in Section 5.2 and Appendix 1.

The value chains for production of the two products are completely independent of each other and so are the results to some extent. Therefore, this study can be considered as a two-part study, with independent value chains. Still, the same research question is studied with a common and consistent methodology.

The reference chain for each of the final products is compared against various value chains with intermediate products. In these chains, various parameters are varied in order to understand the effect these have on the overall performance. The varied parameters include for example:

- Type of raw material utilized
- Number of sites where the intermediate product is produced
- Production rate

The complete set of value chains studied for both of the final products is described in Sections 5.2.1 and 5.2.2.

The energy efficiency, (*fossil*) CO_2 emissions and economic performance for the value chains are studied from a *well-to-gate* perspective, that is, from the outtake of raw material to the production of the end-product. Accordingly, the use and end-of-life of the end-product is not evaluated. This part of the life cycle is the same for the value chains that are compared to each other and will therefore not influence the comparisons made here. The phases of the life cycle studied are:

I. Collection of the raw material
II. Raw material transportation
III. Intermediate product production[1]
IV. Intermediate product transportation[2]
V. Final product production

The economic performance is evaluated by estimating the total specific cost for the value chains. It consists of all costs and revenues in the studied value chain. The annuity method is used to incorporate investments costs.

The total CO_2 emissions for the value chains includes emissions related to the collection and transportation of the raw material, the intermediate production and transportation and the intermediate conversion to final product. There are also credits given for the co-production of e.g. district heating and

[1, 2] For the value chains with intermediate product production.

electricity. Impact of soil carbon decrease is not considered. Also for waste biomass, such as forest residues, soil carbon dynamics can have a substantial impact. When logging residues are removed from the forest, the soil carbon stock will in general be lower than if the residues were left in the forest to decompose, particularly if looked at over a short time period. The magnitude of the impact of the soil carbon decrease is, however, uncertain (Holmgren et al. 2007).

In order to take the energy quality of different energy carriers into concern, electrical equivalents are used when calculating the total energy efficiency. All energy carriers are converted to their electricity equivalents according to the electricity generation efficiency (η) of the best-available technologies known (see Section 6.9).

4 DESCRIPTION OF TARGETED END PRODUCTS

4.1 BIO-SNG

Synthetic natural gas (SNG) is a versatile energy carrier that is interchangeable with Natural Gas (>95% methane, high HHV) and can be produced from fossil (e.g. coal) or non-fossil (i.e. biomass) feedstock. The advantages of SNG are the high conversion efficiency (raw material to final product), the already existing gas distribution infrastructure such as pipelines, and the well-established and efficient end use technologies, e.g., CNG cars (Compressed Natural Gas), heating, CHP (combined heat and power) and power stations (Kopyscinski et al. 2010).

Synthetic substitutes for natural gas have been produced from coal on a commercial scale since 1984 when The Great Plains Synfuels Plant by the Dakota Gasification Company began production with a subsequent capacity of 4.8 million m^3 of SNG per day ever since (Ahrenfeldt et al. 2010). Most plants and technologies for SNG production have been developed for coal, lignite or other fossil carbon sources. However, historic research for coal gasification can now be utilized to some extent for production from other feedstock since many of the design considerations and unit operations are somewhat similar (Ahrenfeldt et al. 2010).

Biomass-based SNG (bio-SNG) can be produced from a variety of cellulosic materials e.g. forest residues and energy crops. The production of bio-SNG consists typically of an initial gasification step followed by gas cleaning, shifting of the gas, and methanation. Biomass gasification technology is still under development. A limited number of demonstration plants and commercial plants are in operation.

There is a growing interest for bio methane[2] for grid injection as a way to make the natural gas greener or to be used as vehicle fuel, especially in Sweden. In fact, the steady growth of bio methane as vehicle fuel in Sweden surpassed the use of natural gas in the transport sector in 2006 and the relation in the last years have been approx. 60% upgraded biogas and 40% natural gas (Held 2013).

During the last years, the focus in Sweden has been on relatively large scale bio-SNG production. The GoBiGas project aiming at producing 100-120 MW bio-SNG was inaugurated in 2014 and was fully operational and delivering methane to the natural gas grid in December 2014 (EBTP 2015). The current plant has a maximum production capacity of 20 MW bio-SNG (Göteborg Energi 2016). E.ON’s Bio2G project is planned to produce 200 MW bio-SNG, pending planning approval (EBTP 2015).

4.2 FOREST-BASED BIO-OIL AS PARTIAL FEED TO A PETROLEUM REFINERY

Biomass can be converted to a bio-oil by pyrolysis which, similarly to gasification, is a thermal decomposition of biomass occurring in the absence of oxygen. For some applications such as combustion in boilers, the quality of the product obtained via pyrolysis might be sufficient for direct use (de Miguel Mercader 2010). However, in this study, it is assumed that the bio-oil produced will be blended with a refinery feed and fed directly to a refinery process. For economic reasons the oxygen content should be as low as possible, to optimize the hydrogen needed in the refinery if a hydrodeoxygenation (HDO) process is chosen.

[2] Bio methane can be produced via anaerobic digestion (bio-gas) or by gasification and methanation (bio-SNG).

In the 'HDO process', crude pyrolysis oil is treated with hydrogen at an elevated pressure in the presence of a catalyst. The HDO-oil can be fed directly to the refinery process, and upgraded according to the refinery's traditional upgrading scheme. By using HDO-oil, the refinery can produce fuels with a share of renewable feedstock. Prehydrogenation at the production site of the bio-crude can also be an option, to lower the oxygen content before blending with a traditional refinery feed. In this value chain, the final product is HDO-oil and further upgrading to transportation fuels is considered outside the system boundaries.

5 DESCRIPTION OF IDENTIFIED BIOMASS VALUE CHAIN OPTIONS

5.1 PREREQUISITES FOR IDENTIFIED VALUE CHAINS

The value chains selected for this study are targeting the production of either one of the following end products:

a) Synthetic natural gas from forest-based raw material (bio-SNG)

b) Bio-oil from forest-based raw material that can be blended with fossil refinery feed and then fully upgraded to a transportation fuel in a petroleum refinery (final upgrading is not included in the analysis)

The project is focusing on analysing the effect of using different forest-based raw materials and locally converting the raw material to an intermediate product that has a higher energy density on a volume and weight basis, is more uniform and easier to handle. The objective is to thereby decrease the cost and CO_2 emissions for transporting the biomass compared to handling the entire conversion from raw material to product in one integrated step at one place.

It has been decided to mainly use a pulp mill as the place for the conversion to an intermediate product for the following reasons:

I. Pulp mills are often located in areas with large forest resources and they generally have high availability of various waste and by-products that could be used for production of a biofuel intermediate. High availability of raw material reduces the necessary transport distance and/or make possible to have a high production capacity.

II. Necessary infrastructure such as access roads, harbours and rail way terminals and receiving stations are available and could be extended to also handle raw material for production of the intermediates.

III. A lot of knowhow related to handling of forest-based raw materials exists within the pulp mill organisation that could be used in the handling of biomass raw material and the upgrading to intermediate. The operation is a close extension of the already ongoing daily operation and could benefit from coordinated use of plant operation and maintenance personnel and re-sources, control room, laboratory facilities, engineering, procurement, administrative and management resources.

IV. The production of the intermediate product could be integrated with the operation of the pulp mill so that by-products and residual energy generated during the conversion to intermediate could be utilised for electricity and steam generation in the pulp mills boiler system at the same time as the mills utility system could be used for supply of electricity, steam, cooling water and waste water handling. Residual products and energy from the pulp mill could as well be utilised in the production of the biofuel intermediate. This ensures a high degree of overall resource efficiency.

V. The pulp industry is currently looking for new business opportunities to extend their operation in order to be more competitive and replace products with a decreasing demand on today’s market.

VI. Associating the biofuel intermediate conversion with the pulp mill operation also has the added benefits that existing contacts with suppliers of forest-based raw material can be utilised and in case the pulp mill operator also has own forest resources they can now be put into extended use.

VII. The development of new business models for the pulp mill could also support locating the intermediate conversion process at the pulp mill. The pulp mill could then provide selected services, and different models for investment and ownership could be applied.

Another industry, closely related to the pulp and paper industry, is the sawmill industry. Existing sawmills are potential integration sites with e.g. by-products such as sawdust and bark available on-site. Sawmills are included as potential sites for production of intermediates in the bio-SNG value chains (see Section 5.2.1).

The final conversion to the end product a) bio-SNG will take place in a gasification and methanisation plant connected to a district heating network. The conversion to end product b) HDO-oil that can be fed to a petroleum refinery will take place at the refinery. The intermediate product transported to the refinery should at minimum be in a liquid pumpable state suitable for ship transport according to demands from the refinery operator. The treatment of the oil with hydrogen to achieve the final reduction of the oil's oxygen content to the level specified by the refinery is taking place at the refinery site due to access to hydrogen.

The transport options for raw material and intermediates considered in this report are:

- Transport by truck
- Transport by railway
- Transport by ship

5.2 SCREENING AND SELECTION OF OPTIONS

At the beginning of the project, an initial screening of the options to be included in the value chain analysis was performed. The screening was performed in a series of workshops with all project partners being involved. The project partners have identified different feasible options with respect to:

- Raw material (either directly forest-based raw material or as a by-product from the pulp mill)
- Transportation of raw material
- Intermediate product
- Process to produce intermediate product
- Transportation of intermediate
- Process(es) for conversion of intermediate to final product

The options initially identified and developed by the project group are summarised in Appendix 1.

Based on the identified value chain options included in Appendix 1, different screening criteria for selection of value chain options were identified and summarised by the project group. The screening criteria were put together to assist in the selection of primary value chain options and are also found in Appendix 1.

The project partners have stated that the time perspective for the studied technologies is that they should be possible to implement at full scale at multiple site in the time frame of 5-10 years from today.

The motivation and result from the screening phase is found in Appendix 2. The more detailed description of the finally selected value chains are found in Sections 5.2.1 and 5.2.2.

5.2.1 Selected bio-SNG value chains

Figure 3 presents the studied system the bio-SNG[3] value chains. All phases and flows are not present in all value chains (see below).

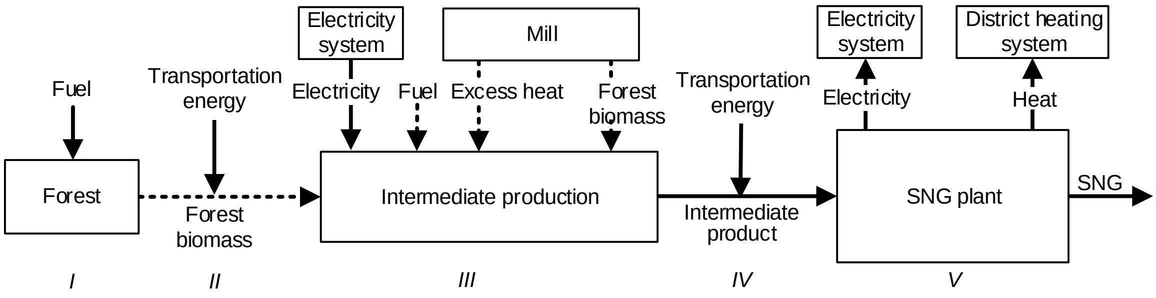

Figure 3. Studied system for the bio-SNG value chains.

For the bio-SNG value chains, the SNG production plant is integrated with a district heating system. This integration option provides the opportunity to use excess heat from the SNG production down to lower temperatures compared with integration with e.g. a pulp mill, where the need for heat are at higher temperatures than for district heating systems. However, the forest industry could still be part of the value chain by upgrading forest biomass prior to further transport to and processing at the SNG production plant. Biomass needs to be dried prior to gasification in order to lower the moisture content. This could be done using low temperature excess heat at pulp mills. One of the main question to be addressed include if it is better to first transport forest residues to a pulp mill for drying (before transporting it further to the SNG production plant) than transport forest residues directly from the forest to the SNG plant. These alternatives have implications on transport; where the first option means truck transportation of wet biomass followed by transportation of dried biomass by e.g. train, whereas the second option means truck transportation of wet biomass. Furthermore, it will influence the SNG production plant, where more excess heat will be available if the drying is performed externally. Another opportunity that the forest industry, including sawmills and pulp mills, provide is availability of by-products such as bark and sawdust. Another question to be addressed is the influence the opportunities to use such by-products would have on the overall performance of the value chain.

Three different value chains for bio-SNG are compared:

1. Sawdust is pelletized at sawmills and transported to an SNG plant for further upgrading to the final product.
2. Forest biomass, either forest residues or bark available on-site, is dried at kraft pulp mill/s and transported to an SNG plant for further upgrading to the final product.

[3] Hereafter, SNG is used to denote renewable SNG.

3. Forest biomass is transported directly to an SNG plant where the raw material is upgraded in a single facility into the final product (reference chain).

The SNG plant is integrated with a district heating system.

Figure 4 shows the studied value chains with bio-SNG as final product.

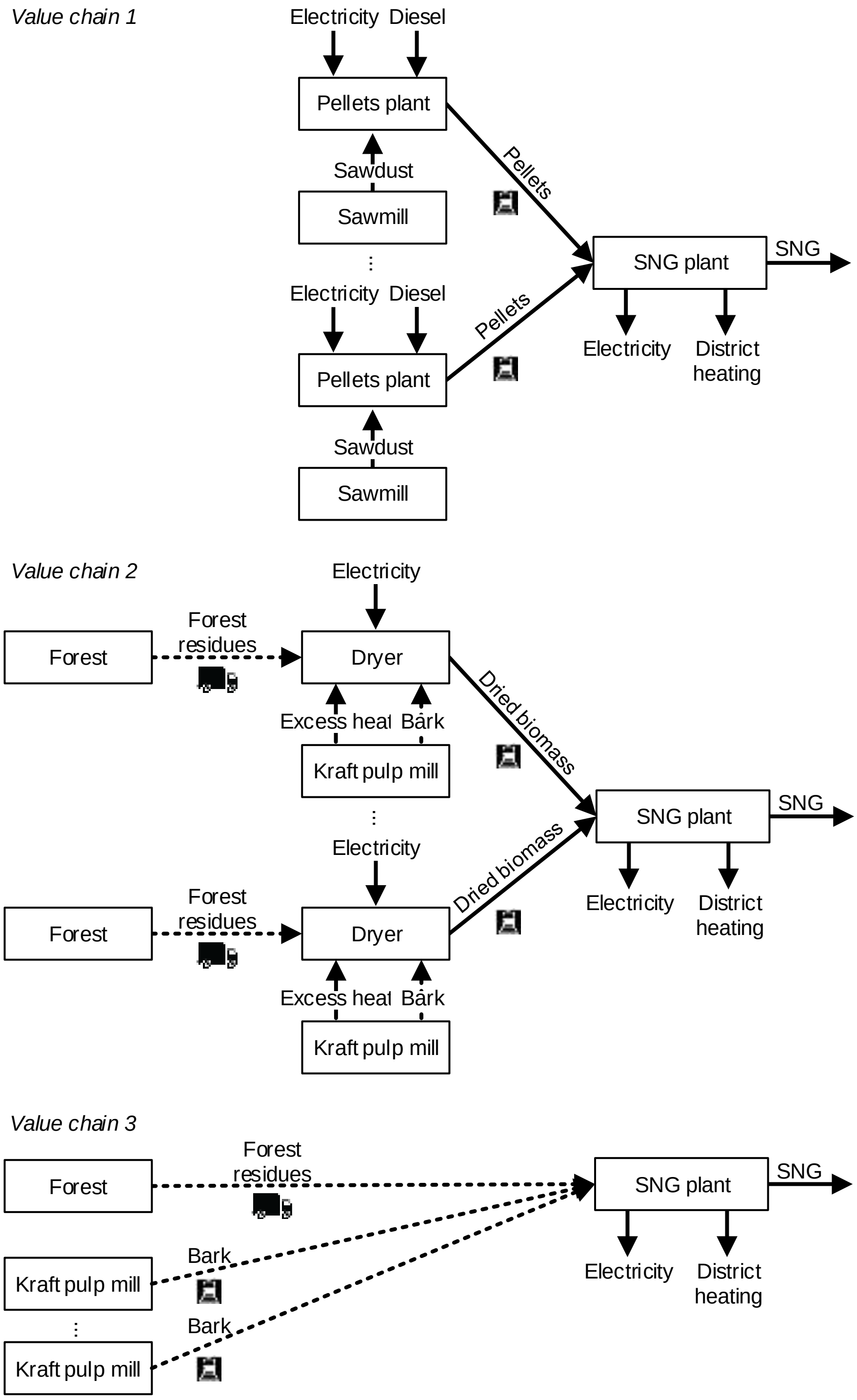

Figure 4. The studied bio-SNG value chains.

In the studied value chains, various parameters are varied. The varied parameters include:

- SNG production rate
- Type of raw material utilized
- Number of mills where the intermediate product is produced
- Drying temperature at the pulp mills

In Value chain 1, sawdust from sawmills are used for pellets production. The pellets are then transported by train for further upgrading at an SNG plant. The number of mills is determined by the availability of sawdust at one mill.

In Value chain 2, raw forest biomass is dried using available excess heat at kraft pulp mills before it is transported by train for further upgrading at an SNG plant that is co-located with a district heating system. Two different production rates for SNG are considered; 100 MW and 300 MW SNG. Also for the raw material, two different alternatives are considered. One alternative considered is to use forest residues. Forest residues is then collected from the forest and transported by truck to kraft pulp mills. Another alternative is to use falling bark from the pulp mills. The number of kraft pulp mills considered is also varied, from one single mill up to six mills for the largest SNG production rate in the cases with forest residues. For the cases with bark, the number of mills is determined by the availability of falling bark at one mill. Two different alternatives are considered for the drying temperature; 85°C and 60°C. In total 16 different cases are considered for Value chain 2 (see Table 1).

In Value chain 3, the reference chain, no intermediates are considered. Raw forest biomass is transported directly to the SNG plant. As for Value chain 2, two different production rates for SNG are considered; 100 MW and 300 MW SNG. Also when it comes to the raw material, the same alternatives as for Value chain 2 are considered. Forest residues is collected from the forest and transported by truck to the SNG plant. Falling bark is collected from kraft pulp mills and transported by train to the SNG plant. In total four different cases are considered for Value chain 3.

Table 1 and Table 2 presents the cases included in this study. For Value chain 1, only the 100 MW production rate is considered. The reason that the 300 MW production rate is not considered in this case is due to the large number of sawmills that would be required in order to satisfy the need for raw material (see Section 6.2.5).

Table 1. Studied cases for Value chain 1 and Value chain 2 (SD = sawdust, FR = forest residues).

Value chain		1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
SNG production	MW	100	100	100	100	100	100	100	100	100	300	300	300	300	300	300	300	300
Raw material		SD	FR	FR	FR	FR	FR	FR	Bark	Bark	FR	FR	FR	FR	FR	FR	Bark	Bark
Number of mills		8	1	1	2	2	4	4	2	2	1	1	3	3	6	6	6	6
Air drying temperature	°C	-	85	60	85	60	85	60	85	60	85	60	85	60	85	60	85	60

Table 2. Studied cases for Value chain 3 (the reference value chain).

Value chain		Ref	Ref	Ref	Ref
SNG production	MW	100	100	300	300
Raw material		FR	Bark	FR	Bark
Number of mills		-	2	-	6
Air drying temperature	°C	-	-	-	-

5.2.2 Selected Refinery Value Chains

Four value chains have been studied for the production of HDO oil:

1) Reference chain with no intermediate production using fast pyrolysis and HDO treatment to produce HDO-oil at the refinery. The forest residues are transported to the refinery using trucks (REF_R).
2) Bio-oil production from forest residues at three pulp mills using fast pyrolysis and HDO treatment of the crude bio-oil at the refinery. The forest residues are transported to the pulp mill by truck and the crude bio-oil is transported to the refinery by ship (PYR3).
3) Bio-oil production from forest residues at a single pulp mill using fast pyrolysis. HDO treatment of the crude bio-oil takes place at the refinery. The forest residues are transported to the pulp mill by truck and the crude bio-oil is transported to the refinery by ship (PYR1).
4) Lignin-oil production at three pulp mills using fast pyrolysis. HDO treatment of the crude lignin-oil takes place at the refinery. The crude lignin-oil is transported to the refinery by ship (LIG3).

For comparison purposes an additional value chain is studied where bio-diesel is produced from crude tall oil (TO6). The value chains are described in detailed in Section 6.6.2. The main features and differences between them are presented in Figure 5 and Table 3.

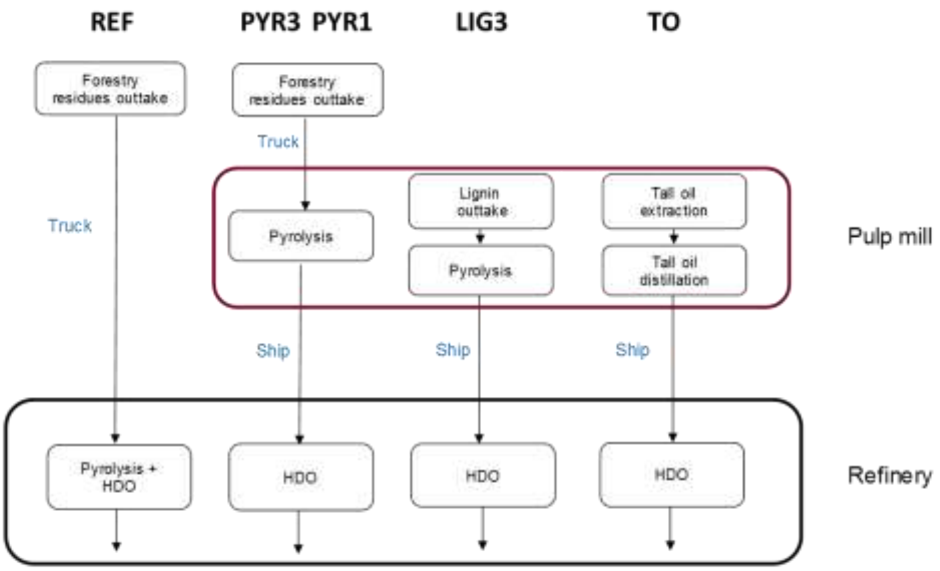

Figure 5. Overview of the cases studied.

Table 3. Cases studied - Refinery value chain.

Case		REF_R	PYR3	PYR1	LIG3	TO6
HDO-oil production	$t_{HDO\text{-}oil}$/y	100 000	100 000	100 000	100 000	100 000
	MW	138	138	138	138	138
Raw material		FR	FR	FR	Lignin	Tall oil

6 INPUT DATA AND ASSUMPTIONS

This section presents the input data and assumptions for the studied value chains. Sensitivity analyses of relevant parameters are introduced here as well.

6.1 GENERAL ASSUMPTIONS

All flows of biomass and other energy have been converted to energy units, based on lower heating value (LHV). The operating time is assumed to be 7840 h/y for all studied value chains.

All investment costs are in year 2014 money value. Adjustments have been made using Chemical Engineering Plant Cost Index (CEPCI). The annuity factor is set to 0.1, which for example corresponds to an interest rate of 8% and a life time of 20 years. Sensitivity analyses are made where the annuity factor is raised from 0.1 to 0.15 to represent an investment with a shorter time perspective.

The data used in this study is generally based on today's situation. However, for relevant parameters a sensitivity analysis is performed to show how the results are influenced.

6.2 RAW MATERIAL

6.2.1 Forest residues

In this study, outtake of forest residues (branches and tops) in Sweden is assumed to be 19 TWh/y, which is in line with the potential presented in Wetterlund et al. (2014). It is assumed that 75% of this potential is available for usage in the applications studied here. The pulp mills are assumed to be located in more forest rich regions than the refinery and the district heating system.

Estimations of future potential for forest biomass indicate a significantly larger potential than what is currently used. According to scenarios presented in (Wetterlund et al. 2014), the potential for forest residues 2030 are estimated to 28-31 TWh/y. In addition, the potential for stumps 2030 is estimated to 23-25 TWh/y. Table 4 summaries the data for the forest residues outtake and usage.

Table 4. Data for forest residues outtake and usage.

		Base	Sensitivity analysis
Forest residues outtake	TWh/y	19	29
Usage of total outtake	%	75	-
Area Sweden	km^2	449964	-
Usage around pulp mill[1]	$MWh/y/km^2$	36	54
Usage around refinery and DH system[2]	$MWh/y/km^2$	18	27

[1] 14% above assumed average outtake

[2] 43% below assumed average outtake

Sensitivity analyses regarding the outtake of forest residues are conducted where the potential is increased by 50% to 29 TWh/y. Also, for the refinery value chains, a sensitivity analysis was made where the cost for extraction of forest residues is increased by 100%. This could represent a scenario with an increased competition for forest residues or more difficult accessibility to the outtake area.

The energy demand (in the form of diesel fuel) associated with the outtake of forest residues is estimated to 3 kWh/MWh (Eliasson 2014).

6.2.2 Black liquor lignin

It is assumed that lignin separation is done according to the “LignoBoost” concept, in which lignin is precipitated from black liquor by injecting CO_2, thereby lowering the pH and causing an agglomeration of lignin molecules. The precipitated lignin is separated and then washed with acidified condensate from the evaporation plant (H_2SO_4 is used as the acidifier). The filtrates from the lignin separation plant are recirculated to the evaporation plant. Details about the LignoBoost process can be found in Tomani (2010).

The depleted black liquor is returned to the mill for combustion in the recovery boiler. It is assumed that each pulp mill has the capacity to extract 75 000 t_{lignin}/y i.e. approximately 110 kg/ton pulp (ADt) without affecting the operability of the recovery boiler. This corresponds to ~20% of the lignin in black liquor. Lignin extraction at three pulp mills is required to obtain sufficient raw material for the production of 100 000 $t_{HDO\text{-}oil}$/y.

Lignin extraction affects the energy balance of the pulp mill. First, less organic material is sent to the recovery boiler and therefore less steam and thereby also power is produced. Second, the lignin extraction process demands electricity.

The effects of lignin extraction on the mill have been simulated in WinGEMS. All the direct (e.g. chemicals) and indirect (e.g. power loss) costs of lignin extraction are taken into account as the “cost” of lignin.

A sensitivity analysis is made where 30% of lignin is extracted. A higher extraction rate would affect the energy balance of the pulp mill more severely. Still, it is considered that it is possible to achieve this extraction rate without affecting the operability of the recovery boiler.

6.2.3 Tall oil

Tall oil has traditionally been used as a low valued combustion fuel within and outside the mill. Recent developments result in an increased interest for other use of tall oil. State-of-the-art use of tall oil is producing diesel fuel and chemical products.

The spent black liquor from the paper making process is concentrated in the mill evaporators and left to settle (Heather Wansbrough 1987). The top layer known as "tall oil soap" is skimmed off. The tall oil soap is reacted with acid to form crude tall oil. The acids formed from this reaction make up the crude tall oil (CTO). The oil is distilled into five components with different boiling points: heads will boil off first, then fatty acids, next is distilled tall oil comprising of a mixture of fatty and resin acids, next is resin acids, and pitch which is the bottom fraction residue. The plant for distillation includes three distillation columns. It is the top fraction of two of the columns that are mixed and make up raw tall diesel (RTD). RTD is mainly fatty acids. RTD is an oxygenated oil although with significantly less oxygen than both forest-based bio-oil and lignin-oil. After RTD separation the remaining fractions is sent to other industries such as chemical industries for processing into chemicals.

It is assumed that each pulp mill has the capacity to extract 40 kg/ton pulp (ADt), which corresponds to common practice. Collection of tall oil from 6 pulp mills is required to obtain sufficient raw material for the production of 100 000 $t_{HDO\text{-}oil}$/y.

6.2.4 Bark

At kraft pulp mills, the bark is removed from the loggings before the digester. The amount of falling bark at a kraft pulp mill producing 2000 ADt of pulp/day is approximately 70 MW (KAM 2003). The process steam demand at kraft pulp mills have been decreased as the energy prices has gone up the last decades (Wiberg and Forslund 2011). Most market kraft pulp mills do not need the bark to satisfy the internal process steam demand. The steam production from the recovery boiler, where black liquor is burnt, is enough to satisfy the mill process steam demand (FRAM 2005). However, the bark could still be used internally to generate steam for power generation, as is the case for the reference mill used in this study (see Section 6.4). However, in the bio-SNG cases where bark is used it is assumed that all falling bark is purchased from the mill to the same cost as for forest residues (see further Section 6.7). Alternatively, it could have been assumed that the cost for bark corresponds to the cost of loss of electricity generation. The energy demand for debarking of the logs is not considered within the studied system.

6.2.5 Sawdust

Sawdust, together with wood chips and bark, are by-products at sawmills. Approximately 20 MW of sawdust is produced at a sawmill with an annual capacity of 350 000 m^3 sawn wood (typical size of a large sawmill) (Danielsson 2003, SFIF 2012), which is the assumed size of sawmills used in this study. A part of the by-products of a sawmill is used to satisfy the internal heat demand. However, since bark is of lower quality it is assumed to be used for this purpose and all of the sawdust is therefore assumed to be available for pellets production. As for bark, the process resulting in sawdust is not considered within the studied system.

6.3 TRANSPORT

Truck is the only reasonable way for the initial transportation of chipped forest residues from the forest. For the studied SNG value chains using forest residues, the area needed for outtake of forest residues is determined by the usage of forest residues (presented in Table 18), the number of sites (in the case of transportation to pulp mills), the SNG production rate and the efficiency of the SNG process (see Section 6.5.2). From the area needed for outtake, the average transportation distance can then be determined (0.71 of the radius of the outtake area). For the refinery value chains the average transportation distance is determined according to the same principal. However, for the case PYR_3, an average transportation distance of 50 km is assumed, and the number of pulp mills required is calculated.

Transportation of bark, lignin and sawdust to the mills, as part of transportation of logs, is not considered within the studied system.

Intermediates (dried forest residues and bark, pellets) are assumed to be transported from the mill/s to the SNG plant by train in average 500 km. The average transportation distance from the mills to the SNG plant is naturally very case specific. It could be reasonable to assume that it is likely the average transportation distance is increased if the number of mills is increased. It is, however, very difficult to make a general assumption regarding how the distance vary with the number of mills and has therefore not been done here. A sensitivity analysis is conducted where the average transportation distance instead is 10 km. Bark (not dried, as considered in Value chain 3) is assumed to be transported from the mills to the SNG plant by train 500 km, i.e. the same assumption as for transport of dried forest residues and bark.

The bio oil produced at the pulp mill(s) is transported 500 km by ship to a refinery. For TO6, transport is assumed to be done by ship for a distance of 2000 km.

6.3.1 Transport costs

Transport costs for transport by truck and train have been derived from Benjaminsson et al. (2013) while costs for ship transport have been calculated based on information from Preem (Håkansson 2015) and costs in Börjesson and Gustavsson (1996). Appendix 4 provides a more detailed explanation of how the costs have been calculated. Table 5 presents all the transport costs used in this study.

Table 5. Transport costs.

Type of transport	Transported feedstock	Energy density (GJ/m^3)	Fixed cost (EUR/GWh)	Variable cost (EUR/GWh km)
Truck	Chipped forest residues, 50% MC	2.96	866	30.4
Train	Dried forest residues, 5% MC	4	2512	4
Train	Pellets, 8% MC	9	2444	2.8
Ship	Bio oil	19.2	2553	0.84
Ship	Lignin oil, 21% MC	23	2129	0.70
Ship	Crude tall oil, 0% MC	35	1399	0.46

The introduction of a ”kilometer tax” has been discussed for a long time in Sweden. However, there are concerns that it would affect the rural areas severely. Therefore, introduction of such tax has been postponed to the next mandate period (Persson 2015). To take into account a possible introduction of kilometer tax and other factors affecting the costs for transportation, sensitivity analyses were made where the transportation costs were increased by 100%.

6.3.2 CO_2 emissions from transport

CO_2 emissions for truck and train were calculated using data from the Network for Transport and Environment (NTM INT Road, 2010; NTM INT Rail, 2008). Ship CO_2 emissions were calculated using data from Gode et al. (2011). The fuel for truck transport is assumed to be diesel MK1 including 5% RME while trains are assumed to have electrical traction and ships are assumed to be fuelled with heavy fuel oil. The emissions presented only include direct emissions during transport but include empty trips (50% of the distance). Appendix 4 provides a more detailed explanation of how the CO_2 emissions have been calculated. Table 6 summarizes the CO_2 emissions for the transport of the different feedstock.

Table 6. CO_2 emissions from transport.

Type of transport	Transported feedstock	Energy density (GJ/m^3)	CO_2 emissions (gCO_2/MWh, km)
Truck	Chipped forest residues, 50% MC	2.96	12.86
Train	Dried forest residues, 5% MC	4	0.018
Train	Pellets, 8% MC	9	0.024
Ship	Bio oil	19.2	3.32
Ship	Lignin oil, 21% MC	23	2.77
Ship	Raw tall oil, 0% MC	35	1.43

6.3.3 Energy for transport

For calculating the energy used for transport of the different feedstocks, the same sources and methodology as above have been used. Instead of looking at the CO_2 emissions associated with the fuel consumption of the transport, the energy content of the consumed fuel was used. As for the CO_2 emissions, the energy use includes empty trips (50% of the distance).

The energy content in the fuel consumed for the transport of the different feedstocks is presented in Table 7.

Table 7. Energy for transport.

Type of transport	Transported feedstock	Energy density (GJ/m^3)	Energy content in consumed fuel (kWh/MWh, km)
Truck	Chipped forest residues, 50% MC	2.96	0.05
Train	Dried forest residues, 5% MC	4	0.005
Train	Pellets, 8% MC	9	0.007
Ship	Bio oil	19.2	0.01
Ship	Lignin oil, 21% MC	23	0.009
Ship	Raw tall oil, 0% MC	35	0.004

6.4 REFERENCE PULP MILL

The kraft pulp mill is a reference mill that represents a new built state of the art pulp mill using softwood as feedstock (Berglin et al. 2011). The production was set to 700 000 ADt kraft pulp per year (2000 ADt/day). This is about the size of the largest pulp mills in operation in Scandinavia today (2015). The tendency in the pulp and paper industry is fewer mills with larger production capacity (CEPI 2008). This means that some mills will be closed down, while the remaining mills will increase their production capacity. Therefore, this size could be representative for future Swedish kraft pulp mills.

The softwood raw material used in the pulp mill consists of 50% pine (Pinus sylvestris) and 50% spruce (Picea abies). The softwood debarking is performed in dry debarking drums which are designed for a barking efficiency of 95%.

The kraft reference pulp mill is self-sufficient in steam by burning the black liquor in the recovery boiler. Therefore, the falling bark from the incoming biomass could be sold or used as fuel in the lime kiln and power boiler. The plant has a large steam surplus which is used for power generation in a condensing turbine. Some key features of the energy system are:

- Recovery boiler and bark boiler with steam data 100 bar(g), 505ºC.
- Feed water preheating to 175ºC to increase HP steam generation.
- Recovery boiler flue gas cooler to reduce LP steam consumed in air preheating.
- Top preheating of all recovery boiler combustion air to 205ºC.
- 7 effect evaporation plant.
- Recovery boiler soot blowing steam is extracted at 25 bar(g) from the turbine instead of using HP steam.
- Medium pressure steam is extracted from the steam turbine at 9 bar(g) and 12 bar(g)
- Low pressure steam is extracted at 3.5 bar(g)
- Pressurized condensate system
- Temperature of the hot water (85ºC) and maximum use of hot water for boiler feed water heating.
- Bark press for bark to power boiler.

The power consumption for the mill is set to 722 kWh/ADt and the resulting power balance is presented in Table 8. As can be seen 878 kWh is sold per ADt produced. This corresponds to 72 MW electricity exported to the grid. The power balance is based on the case where all bark is burnt in the power boiler.

Table 8. Power balance for the reference mill, kWh/ADt.

Power balance	**kWh/ADt**	**MW**
Back-pressure part of the turbine	825	68
Condensing part of the turbine	774	64
Sum	1599	131
Consumption	kWh/ADt	MW
Process	722	59
Sold	878	72

Besides electricity production from surplus steam, the mill has excess water available at relatively high temperature. This water is produced in the hot and warm water system and could be used for e.g. drying of biomass.

6.5 BIO-SNG VALUE CHAINS

In this section assumptions and data related specifically to the bio-SNG value chains, described in Section 5.2.1, are presented.

6.5.1 Intermediate production

6.5.1.1 Drying

Before gasification the biomass has to be dried in order to lower the moisture content. In Value chain 2, forest residues and bark are dried at kraft pulp mills using excess heat. The drier considered is a low temperature air dryer, where excess heat is used for heating up the air.

In the dryer, the biomass is dried from the moisture content of 50% down to 10% moisture content. Key data for the air dryer is presented in Table 9.

Table 9. Required air flow and electricity for drying of biomass from 50% to 10% moisture content. Data based on model developed by Heyne and Harvey (2009).

Air temperature	˚C	85	60
Heat use	MWh/MWh_{Bio}	0.16	0.17
Air flow	km^3 hot air/MWh_{Bio}	10	14
Electricity use	kWh/MWh_{Bio}	5	7

The temperature of excess heat from kraft pulp mills is generally in the temperature interval from approximately 20°C to above 100°C (see e.g. Axelsson et al. 2006). For excess heat at the higher temperatures there could be options for internal usage. An example is usage of excess heat (around 90°C and above) in the evaporation plant design in an unconventional way (see e.g. Axelsson et al. 2006). The most common way for external usage of excess heat from pulp mills in Sweden is export to a district heating system. With typical district heating supply and return temperatures used today, there could be that significantly less than half of the excess heat available could be used for this application. For some mills, the option of exporting excess heat for district heating is not available, due to e.g. too long distances to a district heating system.

Here, it is assumed that there is available excess heat for drying of the biomass. To illustrate the uncertainty of the amount of available excess heat at different temperature levels, two different temperatures are considered for the dryer; 85°C and 60°C (as mentioned in Section 5.2.1). This implies that there must be some excess heat available above 90°C and 65°C respectively, to be able to heat up the air to 85°C and 60°C respectively with reasonable temperature differences. For the higher drying temperature, there could be competition for the excess heat both from external and internal usages. For the lower dryer temperature, there is less competition than for the higher drying temperature, e.g. with district heating which is only partly competing with this application considering the temperature interval used for heating up district heating water and the drying air respectively.

6.5.1.2 Pellets production

In Value chain 1, pellets are produced in connection to sawmills, using sawdust from the mills. A part of the wet sawdust is used as a fuel in the pellets plant. Data for pellets production is presented in Table 10. Data is taken from Mani (2005). The produced pellets have a moisture content of 10%.

Table 10. Data for the pellets production ($MWh/MWh_{pellets}$) (Mani, 2005).

Sawdust, as raw material for pellets	0.90
Sawdust, as fuel i pellets process	0.18
Electricity usage	0.02
Diesel usage	0.004

6.5.2 SNG production

Data for the SNG plant is taken from Holmgren et al. (2015), which in turn base their calculations on data from Heyne et al. (2010) and Heyne et al. (2012). A flow sheet of the considered SNG production process is presented in Figure 6. In Value chain 3, the biomass is dried integrated with the rest of the SNG process using a steam dryer (down to 20% moisture content), whereas for Value chains 1 and 2, the biomass enters the plant as pellets and dried biomass respectively. Dried biomass or pellets are gasified using an indirect gasifier. The produced syngas is then cleaned before methanation takes place.

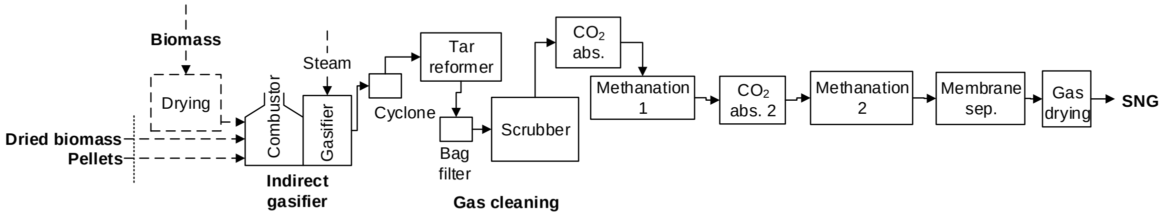

Figure 6. Flow sheet of the biomass-based SNG production via indirect gasification (based on Holmgren et al. 2015).

There is a high uncertainty regarding how much bark that can be used in this process due to the high alkali content in bark (Gunnarsson 2015). To use some bark could have positive effects, but to which extent bark could be used is highly uncertain. The cases in this study using bark as raw material should therefore be seen as an illustration of what the consequences would be if bark could be used. The same data for the SNG process has been used regardless of raw material (this also include the economic data).

Table 11 presents the energy balances for the SNG plant for Value chains 1 and 2 and Value chain 3 respectively. A heat recovery steam cycle is used to recover excess heat from the SNG production. In Value chain 3, where drying of the biomass is integrated with the SNG plant, less excess heat is available on site. This is the reason for the somewhat lower electricity and district heating production in Value chain 3 compared to Value chains 1 and 2. A more detailed description of the methodology and calculations behind the energy balances can be found in Holmgren et al. (2015).

Table 11. Energy balances for the SNG production excluding external drying/ pelletizing. Input and output of energy is presented as MWh/MWh$_{Biomass}$.

	Value chains 1 and 2	Value chain 3 (Reference)
Input		
Biomass[1]	1.00	1.00
Electricity	0.06	0.06
Output		
SNG	0.70	0.69
Electricity	0.09	0.08
District heating	0.17	0.15

[1] Raw biomass.

It has been assumed that it is possible to deliver the district heat all year around (the same amount of hours as the SNG plant is in operation). However, it is not uncommon that the operating time for these technologies is around 5000 h/y (Axelsson and Pettersson 2014). Therefore, a sensitivity analysis has been included where the operation is reduced to 5000 h/y.

6.5.3 Investment costs

There are investment cost associated with the intermediate production and the SNG production. The main part of the investment is the same in all studied cases. The parts that differ between the different cases include all investment costs associated with intermediate production (biomass handling, air dryer, pellets production) and some parts within the SNG plant (biomass handling, steam dryer, gasifier and steam turbine). Table 12 presents the investment cost functions used. The data is primarily based on Heyne and Harvey (2014) and Holmgren (2015) (for specific references, see Table 12). The operation and maintenance costs are set to 6.2% of the investment cost (Heyne and Harvey 2014).

For the biomass handling system (receive, unload and storage) at pulp mills it is assumed that additional investments are made to an already existing, large system. However, for handling of bark no additional investments are assumed since it is done within the normal pulp mill operation. At the SNG plant located within a district heating system, it is assumed that investments are made in a new handling system.

The investment cost for the air dryer is dependent on the flow of air required. Thus, lowering the air temperature will result in a higher investment cost for the air dryer.

The maximum capacity of the considered type of gasifier is uncertain since no large plants exist today. Here, it has been assumed that one gasification unit is used for the 100 MW SNG plant, whereas for the 300 MW SNG plant three units are used. This is in line with the assumptions of maximum gasifier capacity made in Holmgren (2015). A sensitivity analysis is included where instead two and six units are used.

Table 12. Investment cost (IC) functions used (IC = A*C^F). All investment costs are in MEUR$_{2014}$.

	A	F	C	Based on
Intermediate production (III)				
Pellets production	0.75	0.65	Pellets production (t/h)	Mani (2005)
Biomass handling (additional investment to large existing system)	0.07	1.00	Wet biomass (t/h)	Heyne and Harvey (2014), Holmgren (2015)
Air dryer	27	0.80	Inlet air (Mm^3/h)	Johansson et al. (2004)
SNG production (V)				
Investment cost excl. biomass handling, drying, gasification and ST	3.2	0.65	Biomass input (MW)[1]	Holmgren (2015
Biomass handling (new investment)	0.43	0.64	Wet biomass (t/h)	Heyne and Harvey (2014), Holmgren (2015)
Steam dryer	0.91	0.70	Evaporation capacity (kg/s)	Thek and Obernberger (2010)
Gasifier	2.4	0.72	Biomass (dried) (MW)	Heyne and Harvey (2014), Holmgren (2015)
Steam turbine	2.6	0.65	Electricity production (MW)	Pettersson and Harvey (2012)

[1] Raw biomass.

6.6 REFINERY VALUE CHAINS

6.6.1 HDO-oil production

The production of HDO-oil consists of two main processing steps: fast pyrolysis of biomass to produce pyrolysis oil and hydrogenation of the pyrolysis oil to produce HDO-oil. The main energy flows of the processes are presented in Figure 7. Note that the cases studied in this project have different types of biomass input (forest residues, lignin or tall oil).

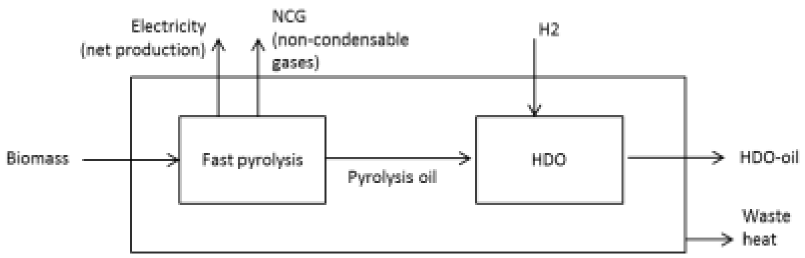

Figure 7. Energy flows for the HDO-oil production.

6.6.1.1 Fast pyrolysis

Fast pyrolysis is chosen as the conversion technology to produce bio-oil. The pyrolysis plant consists of chip handling, dryer, grinder, pyrolysis reactor, steam boiler, gas cleaning, char burning, condenser and storage tank, see Figure 8.

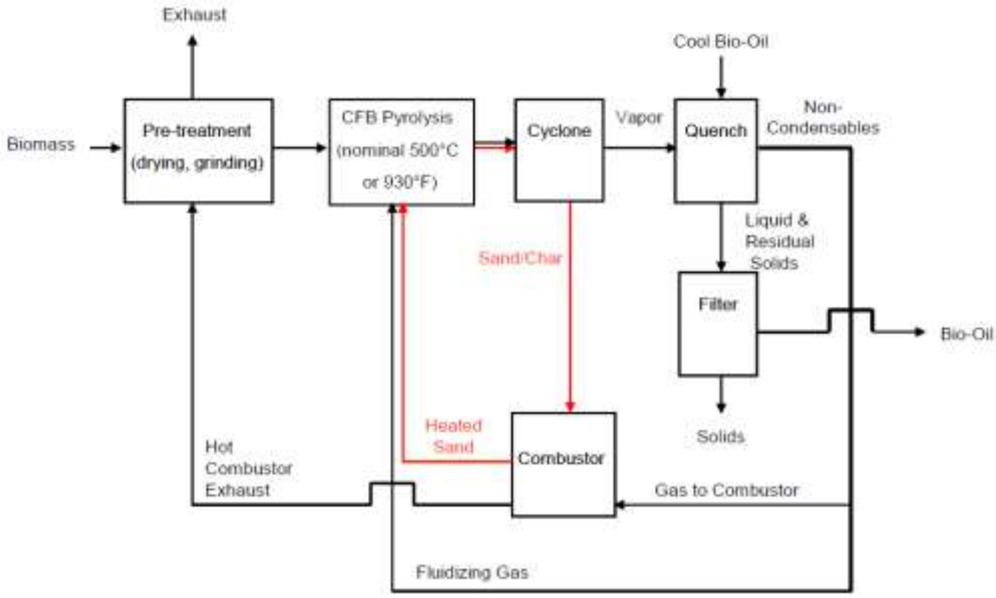

Figure 8. Illustration of the fast pyrolysis process (Jones et al. 2009).

Biomass is first dried and milled to particles of 1-3 mm in a pre-treatment unit. The biomass material comprise of large molecules in the range 10^3 g/mol. The fast pyrolysis process begins by rapidly heating the milled and dried material in a circulating fluidized bed (CFB) reactor to a temperature around 500°C in the absence of oxygen. The heating comes from contacting the biomass with hot circulating sand. Typical heating rate is 1000°C/s. During the temperature ramp-up the material starts to disintegrate and forms smaller molecules. At peak temperature, the biomass is in a vapor and solid state with typical vapor average molecular weight 200-400 g/mol. The solids are in the form of char and sand. The sand and the char are separated from vapor in a cyclone. The subsequent process step is to rapidly cool the vapor in a quench cooler as to freeze further molecular breakdown. Cooled “bio-oil” is used as quenching media. After quenching, the cooled material comprises of gas, liquid and small amounts of solids that were not separated in the cyclone. The solids in the liquid are separated by filtering. The liquid is the pyrolysis oil or “bio-oil” which is the desired product. The gas fraction from the quenching comprise of non-condensable gases. A portion of the non-condensable gases is used as fluidizing gas in the reactor. The remaining portion is combusted in the combustor. The char is combusted in the same combustor. The combustor heat will heat the sand which is transported to the reactor as to close the loop. The total time for the heating and quench cooling should be as short as possible. At the very best to 1-2 seconds total time can be achieved in practical designs.

The objective with the fast pyrolysis process is to produce bio-oil at maximum yield. The process is temperature dependent. An illustration of the yield of gas, liquid and char as a function of temperature is shown in Figure 9.

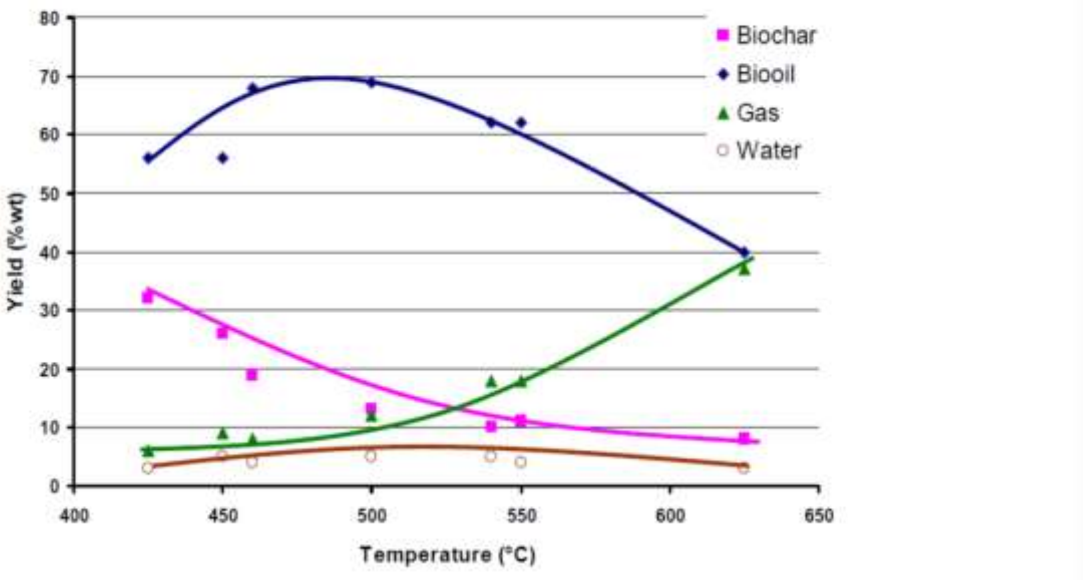

Figure 9. Relative proportions of end products in pyrolysis of biomass (Jahirul et al. 2012).

Figure 9 shows that if the temperature is very low, much of the material will be in form of char. At higher temperatures gas formation increases where at very high temperatures the process will enter a state of gasification. The evolution of char is opposite to gas formation. There is a temperature where oil formation is at its peak, approx. 500°C in Figure 9. Therefore in bio-oil production an important process control parameter is to balance around this optimum temperature.

6.6.1.2 Hydrodeoxygenation

In order to produce transportation fuel from a bio-oil that fulfils standard fuel requirements, hydrodeoxygenation must be done. The process consists on the thermal separation of gases (particularly oxygen) from the bio-oil. An energy yield of 98% was assumed from pyrolysis oil to HDO-oil (not taking into account energy from H_2) (Hjerpe 2015).

Hydrogenation or hydrodeoxygenation (HDO) is a hydrogenolysis process for removing oxygen from oxygen containing compounds. The removal is necessary as refineries produce transportation fuels which are free from oxygen. A simplified flow diagram of the HDO process is shown in Figure 10.

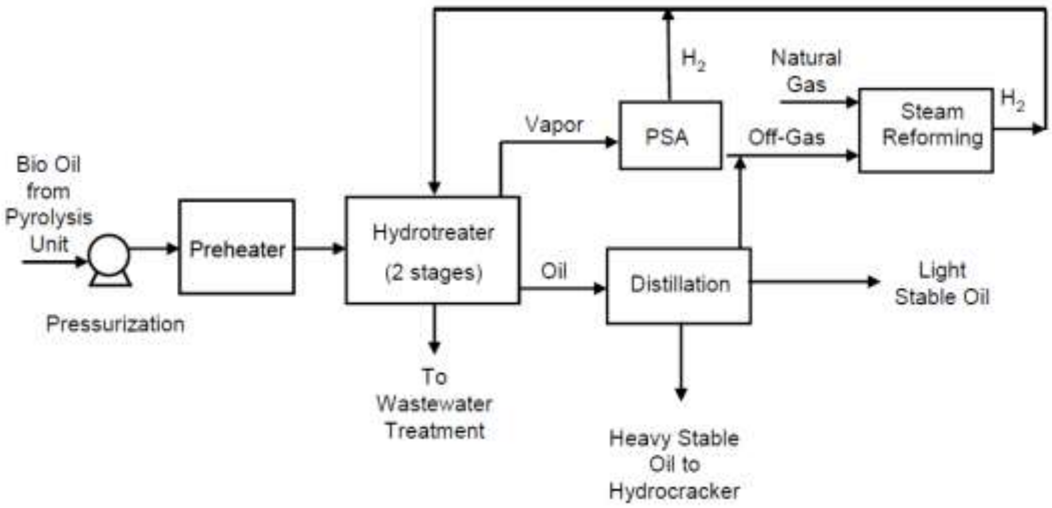

Figure 10. Illustration of the HDO process (Jones et al. 2009).

Removing oxygen from bio-oil can take two forms. In hydrogenation, hydrogen gas is added where the hydrogen reacts with oxygen and forms water. In de-oxyfication carbon monoxide reacts with oxygen and forms carbon dioxide.

Oxygen removal to upgrade pyrolysis oil is in the research stages (IEA Bioenergy: Task 34). The upgrading step involves contacting the bio-oil with hydrogen under pressure and at moderate temperatures (<400°C or 750°F) over fixed bed reactors. Single stage hydrotreating has proved to be difficult, producing a heavy, tar-like product. Dual-stage processing, where mild hydrotreating is followed by more severe hydrotreating has been found to overcome the reactivity of the bio-oil.

Refereeing to Figure 10, two catalytic reaction stages are used (Jones et al., 2009). The first stage catalytic reactor serves to stabilize the bio-oil by mild hydrotreatment over cobalt molybdenum (CoMo) hydrotreating catalyst. The product oil is further processed in the second-stage hydrotreater. The second stage hydrotreater operates at higher temperature and lower space velocity than the first stage. CoMo catalyst is also used in this reactor. The second-stage product is separated into product oil, wastewater, and off-gas streams. The arrangement with a two stage catalytic treatment will also overcome problems with coke formation on catalyst surface.

Both the water and the CO_2 are separated from the oil by flashing. After flashing there are small remains water and gases in the oil. These are de-gassed from the oil by heating in a lights removal column. The top fraction of the column is sent to combustion. The bottom fraction comprise of water free hydrocarbons that can be sent to the refinery for further processing and distillation.

In Figure 10 above, Distillation refers to distillation in several (not shown) columns where a first lights removal column is included in the HDO unit as described above. Other columns required for final gasoline and diesel products are parts of the refinery. The configuration of these columns is refinery specific and the following description may serve as an example. The product oil from HDO is sent to a naphtha splitter column operating at 3.4 bar. The light top fraction of the naphtha splitter is of gasoline quality. The heavier bottom fraction is sent to a diesel splitter column operating at atmospheric pressure. The light top fraction of the diesel splitter is of diesel quality while the heavier bottom fraction is sent to a hydrocracker. Hydrogen for the hydrocracker is supplied by the refinery. Gases from hydrocracking are consumed by the refinery while the liquid fraction from hydrocracking is sent back to distillation.

6.6.1.3 Refinery processing

The refinery process is out of scope of this study and mentioned here only as background. The HDO-oil delivered to the refinery is blended with regular refinery feedstock and processed into diesel and gasoline according to the refinery regular practice, see the above section. For PYR1, PYR3, LIG3 and REF_R the split of gasoline/diesel is around 50/50. However, the HDO-oil also contains heavier components (higher carbon numbers) that result in a fraction that does not fit into diesel or gasoline. This fraction is sent to a cracker in the refinery for cracking into lighter components that are then sent back to distillation. For TO6 the refinery processing results in 100% diesel.

6.6.2 Value Chain Schemes

Key data for process yield as well as for investment and operating costs for both pyrolysis and HDO-process is obtained from Benjaminsson et al. (2013) and Hjerpe (2015).

6.6.2.1 Bio-oil production from forest residues at a single pulp mill (PYR1) or at three pulp mills (PYR3)

The process description of PYR1 also applies to PYR3 as PYR3 is multiple mill units of PYR1. A block flow diagram of PYR1 is shown in Figure 11.

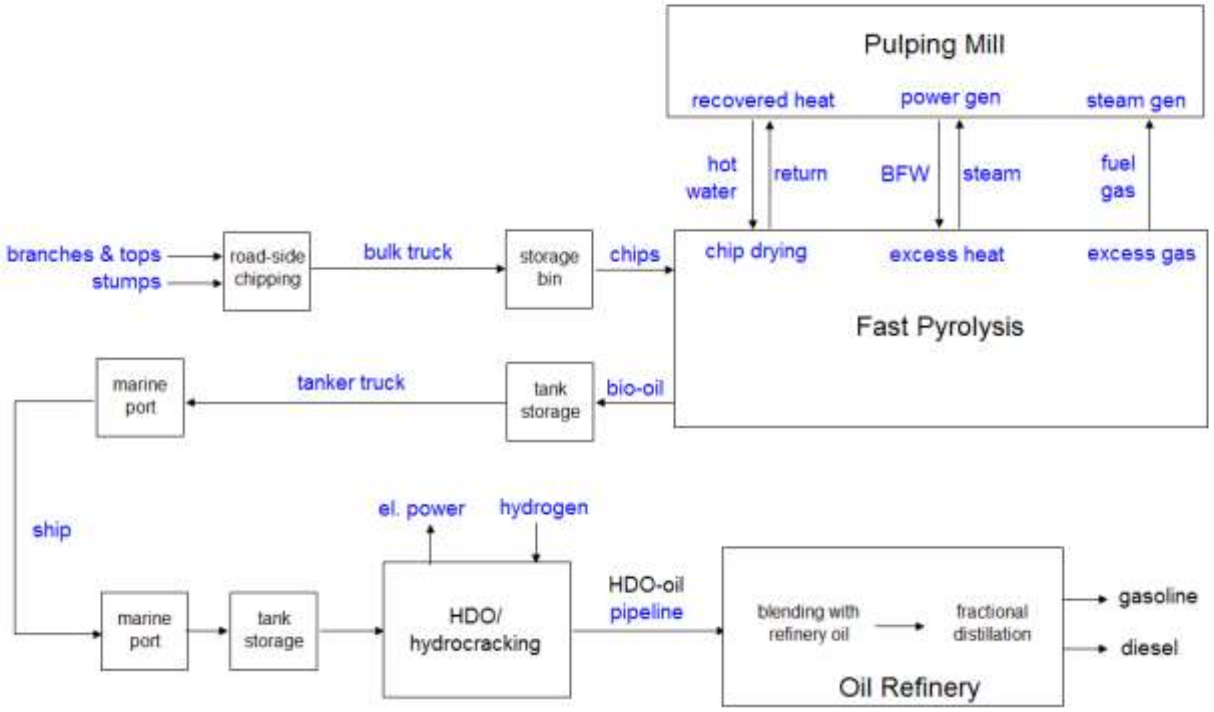

Figure 11. General representation of HDO-oil production. In this study, the bio-oil is assumed to be shipped directly to the HDO plant (i.e. no tanker truck needed).

The raw material for PYR1 is forest residues. Forest residues are collected and chipped by a mobile chipper at the road side. The mobile chipper may be a drum chipper or a disc chipper. Bulk load trucks carry the chipped material to a storage bin located by the Fast Pyrolysis plant (FP). The FP is co-located with a kraft pulp mill.

Chipped biomass from the storage bin is dried in a dryer and milled to size 1-3 mm. The material enters the pyrolysis reactor where it contacts a flow of heated sand. The high contact surface of fine sand and fine biomass enables fast pyrolysis. In a cyclone the sand and char is separated from the vapors. The vapors are quenched cooled in a scrubber by scrubbing cold and filtered pyrolysis oil. At the top of the scrubber non-condensable gases are re-cycled to the reactor as carrier gas for the sand. The portion of excess gas not required for re-cycling is exported to the mill where it is used as fuel gas. The fuel gas may be fired in the lime kiln or recovery boiler or bark boiler. The fuel gas will contribute to the mill energy balance. The char separated in the cyclone is combusted for heating the sand. There is no net production of char. At the bottom of the scrubber the bio-oil is filtered and cooled. Part of the cooled bio-oil is used for quenching while the remaining oil is the product bio-oil pumped to storage tank. Detailed information about the fast pyrolysis process is found in PNNL-18284 (Jones et al. 2009) and NREL/TP-510-37779 (Ringer et al. 2006).

The FP process produces excess heat inherent with the thermo-chemical process. If FP was done stand-alone, the heat could be utilized by installing a steam boiler and a turbine for power generation (as assumed to be done in case REF_R, see section 6.6.2.2). However, if FP is integrated with a kraft pulp mill, the heat can be exported to the pulp mill for steam production. Another contribution to efficient energy management is drying the chips with low grade heat (excess heat) available from the mill. Drying is done in a low temperature dryer. The dryer is assumed to be a belt dryer. Surplus fuel gas from FP is piped to the mill for combustion in a bark boiler or a recovery boiler where it will contribute to the mill energy balance.

The co-location of FP with a pulp mill has advantages as described above. The integration with the pulp mill is assumed to decrease the total investment cost with 15% due to integration benefits (cases PYR3 and PYR1 compared to case REF_R). The wood handling and other infrastructure is also in place at the pulp mill which will decrease the investments.

The produced pyrolysisoil is transported to the refinery by ship. It is assumed that the refinery has marine port access as most refineries do have port access. After discharging the oil from the tanker to a storage tank, the oil is pumped to a hydrogenation plant (HDO) located close to or at the refinery. It is assumed that the HDO is not integrated with the refinery because the refinery is a highly specialized industry surrounded by severe safety regulations. Within the refinery fence, Hazardous Area Classification and Control of Ignition Sources so called "Ex"-areas is practiced, due to the risks associated with flammable gases and vapors. With this follows significant installation costs and controls for assuring the electrical installation and anything else that may cause ignition. For this reason, it was assumed that the HDO shall be outside the refinery fence and the connection between the HDO and the refinery is the pipe for product oil delivery only. The practical and economic benefits of this are likely to be site-specific and should be checked.

The HDO produces excess steam and combustible off-gases which the refinery could take advantage off. However, the advantages were found to be small and may lead to more investments inside the refinery than outside. Hence, it is assumed the HDO will manage its excess steam and off-gases by a boiler and a steam turbine installation included in the HDO plant. Moreover, it may not be enough area at the refinery fence, for the HDO plant.

The HDO consumes significant amounts of hydrogen. The production of hydrogen is excluded in this study as it can be produced through different well known and competitive technologies. Hydrogen is assumed to be bought from the market at market price. In this project it is assumed that hydrogen is produced by steam reformation. However, it is likely that hydrogen could be sourced from the refinery as the refinery already is a large hydrogen producer and consumer. These two hydrogen production alternatives are compared in a sensitivity analysis presented in Section 7.2.3. For efficient energy management, the HDO includes a PSA (Pressure swing adsorption) for recycling non-reacted hydrogen emanating from the hydrogenation reactors. The reject gas after hydrogen separation in the PSA is combusted in a boiler for producing steam where part of the steam is used in the HDO process and the remaining part drives a turbine for generation of electric power.

The HDO-oil from the HDO process in this case is piped to the refinery where it will blend with regular refinery feedstock and further processed into gasoline and diesel. It is assumed that no accountable investments are needed by the refinery.

6.6.2.2 Reference chain with no intermediate production (REF_R)

The raw material for REF_R is forest residues. A block flow diagram of this value chain is shown in Figure 12.

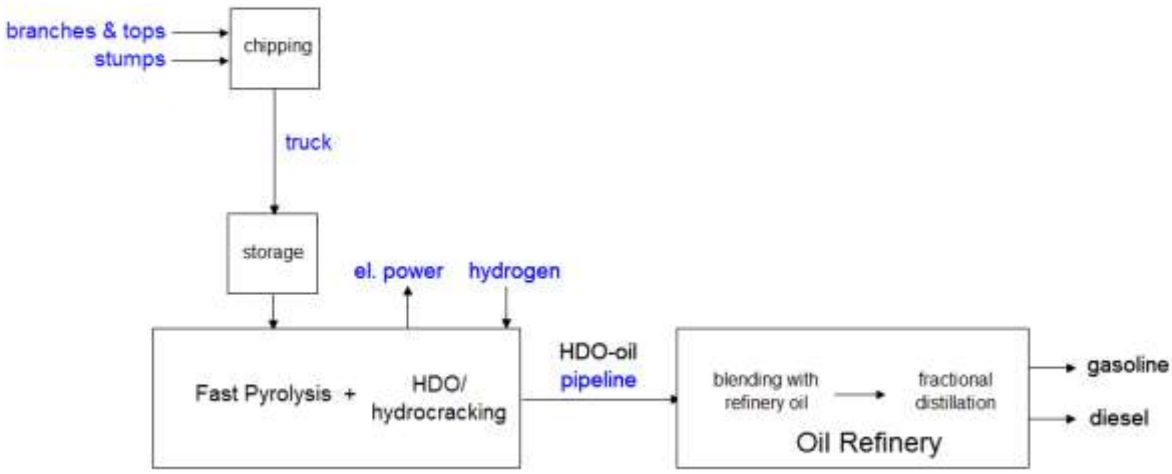

Figure 12 REF_R block flow diagram

Forest residues are collected and chipped by a mobile chipper at the road side similar to the case in PYR1. The chipped material is transported by bulk truck. Both REF_R and PYR1 use forest residues as feedstock and produce identical pyrolysis oil.

In the REF_R chain, the whole processing from forest residues into HDO-oil is done at a single facility, instead of producing an intermediate product (pyrolysis oil) at the pulp mill, as in PYR1. The plant comprise of a FP unit integrated with HDO. The process of FP and HDO are technology wise the same as when separated in PYR1 and PYR3 but do not share the advantages of PYR cases regarding the integration with the energy system of the pulp mill. The excess heat from FP and HDO unit is used for internal drying of chipped material and for power generation in a separate steam turbine. The FP and HDO is accordingly not integrated with the refinery due to assumed severe safety regulations. Within the refinery fence, Hazardous Area Classification and Control of Ignition Sources so called "Ex"-areas is practiced, due to the risks associated with flammable gases and vapors. With this follows significant installation costs and controls for assuring the electrical installation and anything else that may cause ignition. For this reason, it was assumed that the FP and HDO shall be outside the refinery fence and the connection with the refinery is the pipe for product oil delivery only. The practical and economic benefits of this are likely to be site-specific and should be checked.

In the REF_R case, the integrated FP/HDO plants have a common steam system. In the PYR1 case the heat produced by combustion of char was exported as steam to the mill. In REF_R this heat is used for steam generation in a 46 bar steam header. There are two major steam consumers, LP flashing of HDO-oil and re-boiling for de-gassing the flashed HDO-oil. The reboiler consumes about 4 times as much steam as for flashing. The net steam after consumption drives a steam turbine for power generation resulting in power export. The stand-alone plant (case REF_R) must therefore have a boiler and turbine, whereas in PYR1, the pulp mill's boiler and turbine may be used.

The HDO-oil is delivered to the refinery via a pipeline.

6.6.2.3 Lignin-oil production at three pulp mills (LIG3)

The raw material in this value chain is lignin extracted from kraft pulp mills. Three pulp mills are required to extract sufficient amounts of lignin for the production of 100 000 $t_{HDO\text{-}oil}$/y (see Table 21 in Section 7.2.1). A block flow diagram of LIG3 is shown in Figure 13.

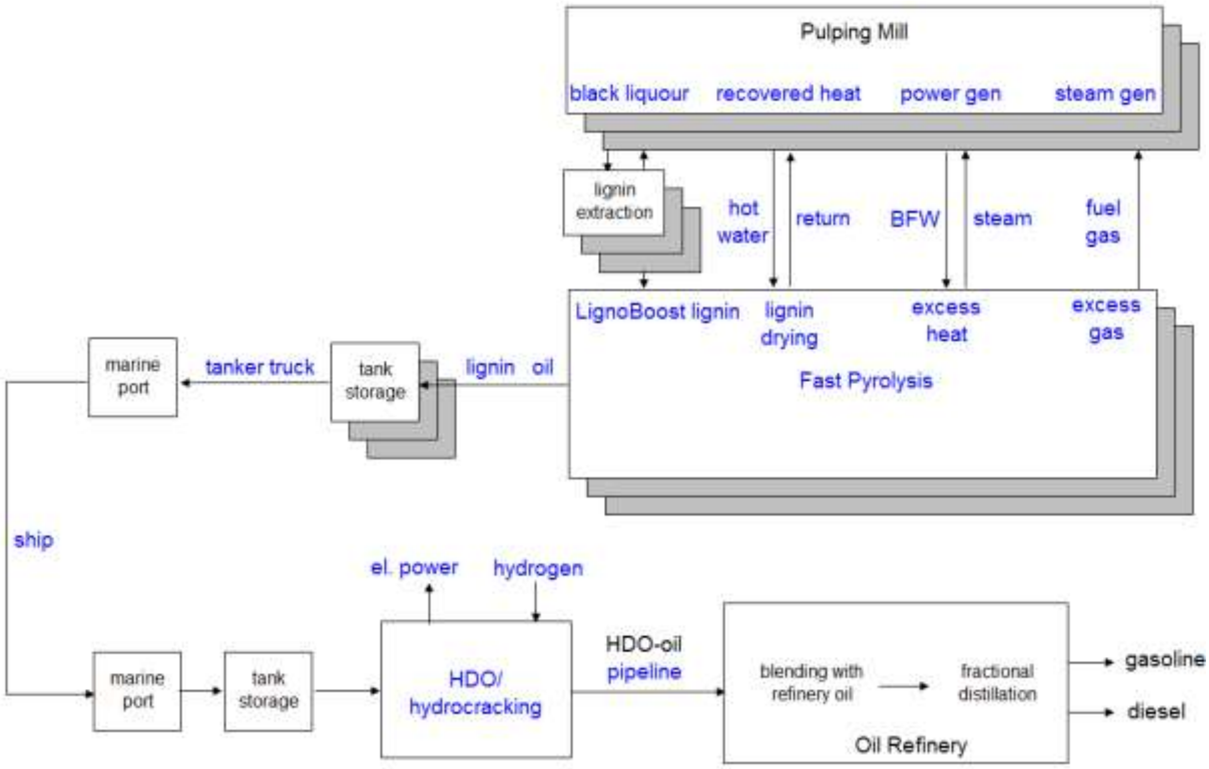

Figure 13. General representation of HDO-oil production. In this study, the lignin-oil is assumed to be shipped directly to the HDO plant (i.e. no tanker truck needed).

The raw material for LIG3 is LignoBoost lignin extracted from black liquor. It is assumed that each pulp mill has the capacity to extract approximately 110 kg/ton pulp (ADt). It is possible to extract more than 110 kg/ADt. The maximum extraction rate is mill specific. Combustion characteristics in the recovery boiler, steam surplus and Na/S-balance may be factors effecting and limiting lignin extraction. 150 kg/ADt, corresponding to 112 500 ton/year has been investigated as the maximum rate. A more ambitious lignin extraction rate is one of the parameters varied in the sensitivity analysis presented in Section 7.2.5.

Downstream of FP, the LIG3 and PYR1 cases are similar. The difference between forest-based bio-oil and lignin-oil is in the oil composition which will vary as a consequence of the difference in elemental composition of the chip feed vs. the lignin feed. As lignin contains less oxygen than forest residues, the lignin-oil is with less oxygen than the bio-oil.

The FP process produces excess heat inherent with the thermo-chemical process. The heat generates steam for export to a mill steam header where it will contribute to the mill energy balance. Boiling feed water (BFW) for the steam generation is taken from the mill and piped to FP. Surplus fuel gas from FP is piped to the mill for combustion in the lime kiln, bark boiler or recovery boiler where it contributes to the mill energy balance. The moisture content of lignin is reduced by drying, where excess heat from the mill is used (hot water).

The lignin-oil has similarities with the forest-based bio-oil with respect to storage, pumping and transportation. The produced lignin-oil is pumped to a storage tank at the mill. It is assumed that the mill is located in connection to a marine port.

One advantage of lignin extraction is that it can serve for load relief of the recovery boiler, albeit this is needed. This gives the mill a welcomed flexibility in operating the mill. Another advantage of producing lignin-oil at the mill is that the LignoBoost lignin is in a dry powder state and requires safety measures to be transported to receivers outside the mill. Yet another advantage is that the lower oxygen content in the lignin-oil result in less hydrogen consumption in the HDO compared to bio-oil produced from forest residues.

6.6.2.4 Bio-diesel production from tall oil (TO6)

An additional value chain is studied for comparison. This value chain is quite different than the previous ones but has in common that biomass-based oil is obtained, and is sent to a HDO unit for further upgrading. In this case the product oil can blend directly to diesel. This chain has already been implemented today, even though the physical location of the different equipment is not exactly as described here. In the Sunpine process, the distillation and fractionation is done externally to the mill. More details about the process can be found in Sunpine (2015).

The raw material for TO6 is tall oil extracted from spent liquor in the evaporation unit of a kraft pulp mill. A block flow diagram of TO6 is shown in Figure 14.

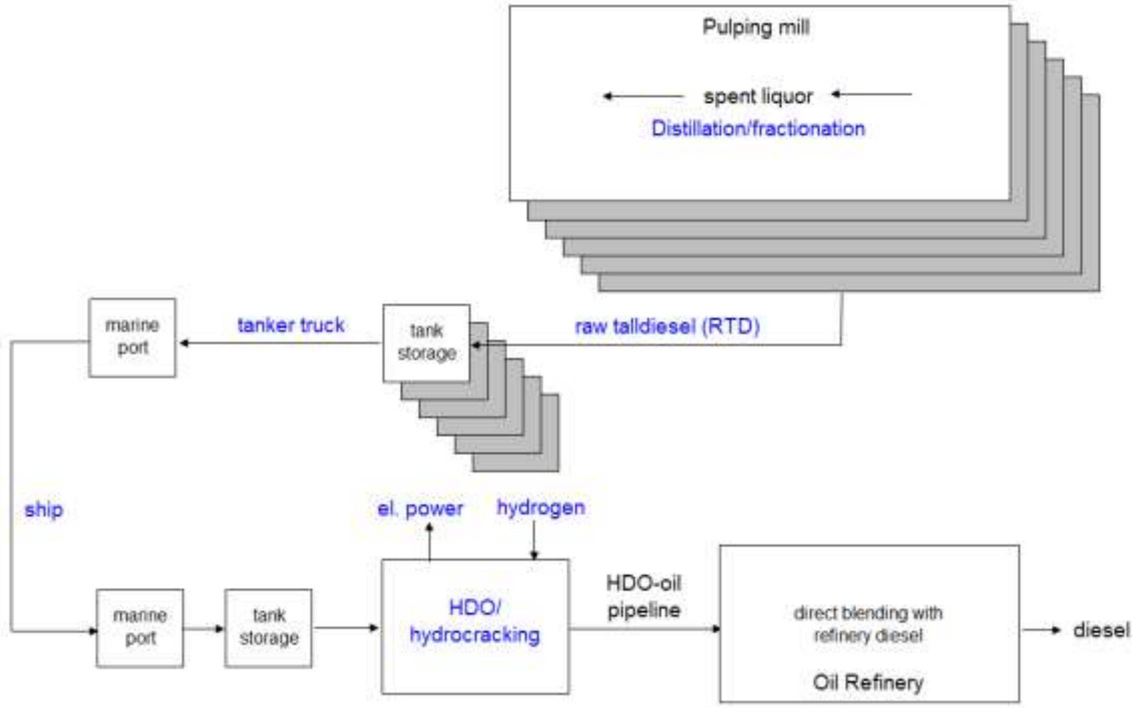

Figure 14. General representation of HDO-oil production. In this study, the tall oil is assumed to be shipped directly to the HDO plant (i.e. no tanker truck needed).

The HDO of tall oil is similar to HDO of forest residues bio-oil and lignin-oil. However, significantly less hydrogen is required as raw tall diesel (RTD) contains much less oxygen. Note that the HDO of RTD result in longer carbon chains than HDO of forest residues bio-oil and lignin-oil so that the HDO-oil is best suited as diesel fuel.

6.6.2.5 Energy balances for the studied cases

The energy balance for the cases studied is presented in Table 13.

Table 13. Energy balances for the HDO-oil production. Input and output of energy is presented as MWh/MWh$_{Biomass}$.

	REF_R, PYR1, PYR3	LIG3	TO6
Input			
Biomass	1.00	1.00	1.00
H_2	0.21	0.09	0.04
Output			
HDO-oil	0.64	0.67	0.66
Electricity	0.02	0.04	0.00
NCG	0.05	0.05	0.00

6.6.3 Investment costs

The investment costs associated with the refinery value chains were estimated based on data available in literature (Benjamisson et.al. 2013) and adjusted to the specific cases studied. For example, a different investment cost function was used for the cases where pyrolysis is conducted at the pulp mill, in order to reflect the possibility to utilize the biomass handling system, the boiler and turbine of the pulp mill, avoiding thus the purchase of these pieces of equipment. The estimations are based on Hjerpe (2015). The investment costs for the HDO-process are based on the input from Hjerpe (2015) and Håkansson (2015).

Table 14. Investment cost (IC) functions used (IC = A*C^F). All investment costs are in $MEUR_{2014}$.

	A	F	C	Based on
Pyrolysis				
Pyrolysis plant, forest residues, stand-alone (REF_R)	3.2	0.7	Forest residues (MW)	Benjaminsson et al. (2013), Hjerpe (2015)
Pyrolysis plant, forest residues, at pulp mill (PYR3, PYR1)	2.8	0.7	Forest residues (MW)	Benjaminsson et al. (2013), Hjerpe (2015)
Pyrolysis plant, lignin, at pulp mill (LIG3)	2.8	0.7	Lignin (MW)	Benjaminsson et al. (2013), Hjerpe (2015)
Distillation tower for tall oil (TO6)	0.03	0.7	Crude tall oil (MW)	Hjerpe (2015), Håkansson (2015)
HDO				
HDO-plant, bio-oil (REF-R, PYR3, PYR1), lignin-oil (LIG6)	3.9	0.65	Forest residues/lignin (MW)	Hjerpe (2015), Håkansson (2015)
HDO-plant, tall oil (TO6)	3.8	0.64	Crude tall oil (MW)	Hjerpe (2015), Håkansson (2015)

6.7 PRICES OF ENERGY CARRIERS

Table 15 shows the prices of different energy carriers used. The prices used as base values are chosen to represent the current situation in Sweden. A sensitivity analysis is conducted where the prices of the raw material are doubled. This is for example in line with future projections for the Swedish market presented by Andersson (2010).

Table 15. Prices of raw material, electricity, electricity certificates, diesel, natural gas, fuel oil and hydrogen [EUR/MWh].

	Based on	Base	Sensitivity analysis
Forest residues	SEA (2015)	16	32
Bark		16	32
Sawdust		16	32
Electricity	Nordpool (2015)	20	35
Electricity certificates	SKM (2013)	20	-
Diesel	Ekonomifakta (2016)	114	-
Hydrogen (estimated as LNG price*3)	Ycharts (2015)	62	115

The revenue for district heating is assumed to correspond to the alternative cost for district heating. It is assumed that the alternative district heating production technology is a heat only boiler fired by bark, with a heat efficiency of 90%. The alternative cost includes the cost for bark (including the transportation, where the transportation distance is assumed to be 200 km). No costs related to investments are included.

Renewable electricity production is assumed to be entitled to support from the electricity certificate system[4]. The used price of electricity certificates is included in Table 15. Consumed electricity is assumed to be purchased for the price of non-renewable electricity. A sensitivity analysis on the electricity price is made where the average market price of electricity the last 4 years (since August 2011) is used instead of the current price.

For the refinery value chains, it is assumed that the market price of hydrogen is approximately three times the price of natural gas. The prices of energy carriers were especially low during 2015. Therefore, a sensitivity analysis was made using the highest price of natural gas during the last 4 years (since August 2011) instead of the current price.

6.8 CO_2 EMISSIONS

Table 16 presents the CO_2 emission factors used. For electricity, the emissions are for the Nordic electricity mix.

Table 16. CO_2 emission factors (kg CO_{2eq}/MWh) used.

	Emission factor	Data from
Diesel	284	Gode et al. (2011)
Electricity	102	Fredén (2010)
Hydrogen	270	Collodi (2010)

Currently, the majority of hydrogen is produced from fossil fuels by steam reforming or partial oxidation of natural gas. The emissions presented in Table 16 represent this method of hydrogen production. In Section 7.2.5 a sensitivity analysis is presented where the carbon dioxide emissions for hydrogen production are varied.

6.9 ENERGY EFFICIENCY

Table 17 presents the electricity generation efficiencies used for calculation of electricity equivalents.

Table 17. Electricity generation efficiencies (%), η, used for calculation of electricity equivalents. Data is mainly taken from Andersson et al. (2013).

Biomass	46.2
Diesel	55.9
SNG	57.6
District heating	10.0
H_2	58.3
HDO oil[1]	57.6
Ship fuel[1]	57.6
Tall oil[2]	46.2

[1] Due to lack of data available, it was assumed to be the same as SNG.

[2] Due to lack of data available, it was assumed to be the same as biomass, although in reality should be higher

[4] Policy instrument incentive scheme promoting the production of renewable electricity, where electricity producers receive one certificate per MWh produced renewable electricity. The certificates are traded between the suppliers and consumers. A quota obligation for consumers creates a demand for the certificates and thus provides them with an economic value.

7 RESULTS AND DISCUSSION

7.1 BIO-SNG VALUE CHAINS

Table 18 presents the resulting energy flows, transportation distances, number of truck/trains used, mill excess heat usage and investment costs for the studied SNG cases.

The radius of the outtake area and the corresponding estimated average transportation distance are shown for the cases using forest residues. For the 300 MW cases where only one mill is considered the radius of the outtake area is approximately 170 km. If transported directly to the SNG plant, the corresponding radius is approximately 250 km (due to the assumption of being located in less forest rich regions). If more mills are considered the radius of the outtake area (per mill) naturally decreases. If for example four mills are considered it is less than 90 km. A large outtake area, means in most cases that agreements have to be made with several different forest owners, which could be a complicating factor. However, it could be easier for large pulp mills, already having agreements for pulp wood, to buy forest residues from the same suppliers. If the availability of forest residues is increased by 50%, the radius of the outtake area for the case with four mills is reduced to less than 70 km, whereas for transport directly to the SNG plant it is less than 170 km.

The number of truck loads required for transportation of forest residues is approximately 110 per day for the 300 MW SNG production rate. If instead dried biomass is transported by train from the pulp mills to the SNG plant, the number of train loads required is four per day. From a local perspective, it could be argued that it is better for a district heating system located in a densely built-up area to receive biomass feedstock by train than by truck. Pulp mills are often located outside densely built-up areas and thereby the local impact of truck transportation is less.

The excess heat used at pulp mills for drying of forest residues and bark varies from 46 GWh/y (6 MW) up to 552 GWh/y (70 MW) per mill for the cases with the higher SNG production rate and where only one mill is considered. The more excess heat that is used, and the higher temperature that is required to heat the air, the likelihood for competition for the excess heat increases. This is important to have in mind, since there are no cost assumed connected to the excess heat in any of the cases here. Even if there is no real competition for the excess heat, there could still be costs associated with collection of the excess heat. There is a small difference in dryer investment cost for the air dryer in Value chain 2 between cases that use air of 85°C and the cases using air of 60°C.

For the cases using bark, the investment cost connected to the intermediate production at pulp mills are lower due to that no investments were considered for biomass handling. The total investment cost is around 200 MEUR for the 100 MW SNG cases and around 500 MEUR for the 300 MW SNG cases.

Table 18. Energy flows, transportation distances, number of truck/trains used and investment costs for the studied cases.

Value chain		1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	Ref	Ref	Ref	Ref
SNG production	MW	100	100	100	100	100	100	100	100	100	300	300	300	300	300	300	300	300	100	100	300	300
Raw material		SD	FR	FR	FR	FR	FR	FR	Bark	Bark	FR	FR	FR	FR	FR	FR	Bark	Bark	FR	Bark	FR	Bark
Number of mills		8	1	1	2	2	4	4	2	2	1	1	4	4	8	8	6	6	-	2	-	6
Air drying temperature	°C	-	85	60	85	60	85	60	85	60	85	60	85	60	85	60	85	60	-	-	-	-
Raw material (I)																						
Raw material usage	GWh/y	1116	1116	1116	1116	1116	1116	1116	1116	1116	3349	3349	3349	3349	3349	3349	3349	3349	1129	1129	3387	3387
Raw material outtake, diesel usage	GWh/y	-	4	4	4	4	4	0	0	11	11	11	11	11	11	0	0	4	0	11	0	0
Raw material transportation (II)																						
Raw material, radius of outtake area	km	-	99	99	70	70	50	50	0	0	172	172	86	86	61	61	0	0	141	0	245	0
Raw material, average transportation distance	km	-	70	70	50	50	35	35	0	0	122	122	61	61	43	43	0	0	100	500	173	500
Raw material transportation, energy usage	GWh/y	-	4	4	3	3	2	2	0	0	21	21	11	11	8	8	0	0	6	5	31	16
Raw material, radius of outtake area	*km*	*-*	*67*	*67*	*47*	*47*	*33*	*33*	*0*	*0*	*116*	*116*	*67*	*67*	*47*	*47*	*0*	*0*	*95*	*0*	*165*	*0*
Raw material, average transportation distance	*km*	*-*	*47*	*47*	*33*	*33*	*24*	*24*	*0*	*0*	*82*	*82*	*47*	*47*	*33*	*33*	*0*	*0*	*67*	*150*	*117*	*350*
Raw material transportation, energy usage	*GWh/y*	*-*	*3*	*3*	*2*	*2*	*1*	*1*	*0*	*0*	*14*	*14*	*8*	*8*	*6*	*6*	*0*	*0*	*4*	*1*	*21*	*6*
Truck/train loads	No/day/plant	-	36	36	18	18	9	9	0	0	108	108	27	27	14	14	0	0	36	2	109	5
Intermediate production (III)																						
Mill excess heat usage	GWh/y/mill	0	184	184	92	92	46	46	92	92	552	552	138	138	69	69	92	92	0	0	0	0
Air dryer, electricity usage	GWh/y	-	5	7	5	7	5	7	5	7	16	22	16	22	16	22	16	22	0	0	0	0
Pellets production, fuel (sawdust) usage	GWh/y	225	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pellets production, electricity usage	GWh/y	29	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pellets production, diesel usage	GWh/y	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Intermediate production, investment cost	MEUR	15	6	7	6	7	7	8	2	3	17	19	19	21	20	22	7	10	0	0	0	0
Intermediate transportation (IV)																						
IP transportation, energy usage	GWh/y	3	3	3	3	3	3	3	3	3	10	10	10	10	10	10	10	10	0	0	0	0
Train loads	No/day/plant	1	1	1	1	1	1	1	1	1	4	4	4	4	4	4	4	4	0	0	0	0
SNG production (V)																						
SNG production	GWh/y	784	784	784	784	784	784	784	784	784	2352	2352	2352	2352	2352	2352	2352	2352	784	784	2352	2352
District heating production	GWh/y	189	189	189	189	189	189	189	189	189	566	566	566	566	566	566	566	566	166	166	497	497
Electricity production	GWh/y	100	100	100	100	100	100	100	100	100	299	299	299	299	299	299	299	299	86	86	258	258
Electricity usage	GWh/y	69	69	69	69	69	69	69	69	69	206	206	206	206	206	206	206	206	69	69	208	208
SNG plant, investment cost	MEUR	196	196	196	196	196	196	196	196	196	489	489	489	489	489	489	489	489	203	203	505	505

7.1.1 Energy efficiency

Figure 15 presents the total energy efficiency (well-to-gate) for the studied cases. The energy efficiency is quite similar for the different cases, except for Value chain 1 where the energy efficiency is significantly lower. This is due to the energy used in the pellets production, above all the fuel in the form of sawdust (but also electricity and diesel).

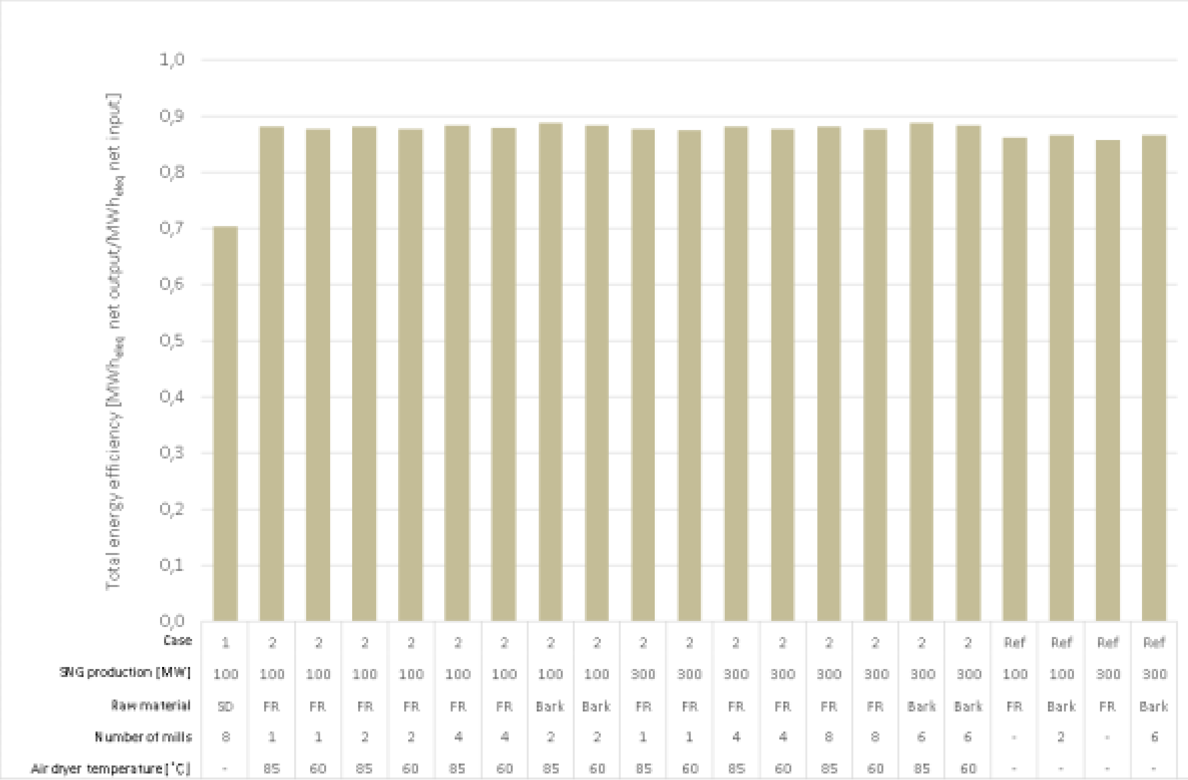

Figure 15. Total energy efficiency (MWh$_{eleq}$ net output/MWh$_{eleq}$ net input).

For Value chain 2, the cases using bark as raw material has somewhat higher energy efficiency (though the difference is very small) since no energy is used for extraction and transportation of the raw material. There is also a small difference between cases with different drying temperature, due to a higher dryer electricity usage for the cases with 60°C drying temperature. For Value chain 3, the energy efficiencies are a bit lower than for Value chain 2. This is due to somewhat less by-products produced and somewhat higher biomass usage.

If comparing the results for the energy system efficiency, presented in Figure 15, with the yield of SNG from the raw material presented in Table 11 (approximately 0.7), one can see that the system energy efficiency is significantly higher (with the exception of Value chain 1), although all energy usage from biomass extraction to final product is considered. This emphasizes the importance of an efficiently designed SNG production where the excess heat is utilized for production of valuable by-products such as electricity and district heating. The main part of the excess heat from the SNG production process is at high temperatures, thereby it can also be utilized also at an industrial site (through a steam cycle) with a heat demand at higher temperatures than the district heating system. It could therefore still possible for these value chain to achieve high energy system efficiency, in case integration of the production with a district heating system wouldn't be possible (e.g. due to limited need for additional production capacity in district heating systems).

7.1.2 CO_2 emissions

Figure 16 presents the specific change in CO_2 emissions from a well-to-gate perspective. Consequently, the usage of SNG is not included. Substitution of fossil natural gas reduces the GHG emissions with approximately 224 kg CO_2/MWh_{SNG} (Gode et al. 2011). Thus, the emissions connected to the other stages of the value chains, presented in Figure 16, constitutes only a few percent of the total change in CO_2 emissions when substituting fossil natural gas with bio-SNG.

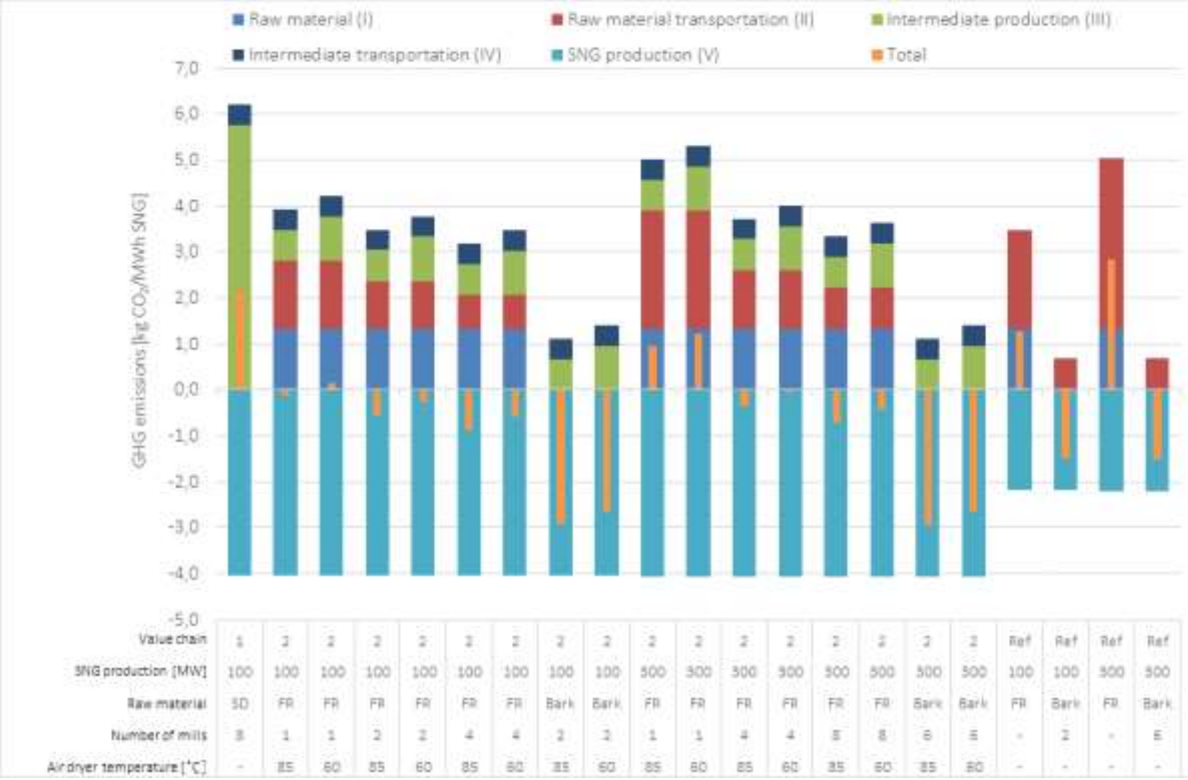

Figure 16. Change in CO_2 emissions (kg CO_2/MWh). Usage of bio-SNG is not included. Negative values indicate a decrease of CO_2 emissions.

For Value chain 1 the emissions are relatively high (compared to the other cases), due to emissions associated with the pellets production (electricity and diesel). However, the difference compared to the other studied cases is not at all as significant as for the total energy efficiency, since no emissions associated with wood fuel usage (the wet saw dust that is used as fuel at the pellets plant) has been included.

For Value chain 2, the lowest emissions are associated with the cases using only train transportation (that is the cases using bark). For the cases using forest residues, the emissions are higher due to the emissions associated with extraction and truck transportation of the forest residues. The emissions decrease somewhat with the number of mills used due to shorter truck transportation distances. For the same reason the emissions are lower for the cases with 100 MW SNG production compared with the corresponding cases for 300 MW SNG production. Also here a small difference can be seen depending on drying temperature due the difference in dryer electricity usage.

For Value chain 3, the reference cases, the effect of using only train transportation (bark cases) and the size of the SNG plant are the same as for Value chain 2. Comparing Value chain 2 and Value chain 3, one can see that Value chain 2 has lower emissions than Value chain 3 (if comparing corresponding cases) due to higher emissions reduction from by-products in the SNG production and lower emissions from transportation for the cases when more than one mill is used.

If instead of using the emissions associated with Nordic electricity mix, the emissions for coal power would be used for the net electricity for the different cases, the decrease of CO_2 emissions from the stages presented in Figure 16 would be up to approximately 25 kg CO_2/MWh_{SNG} (for Value chains 2 and 3 with a net surplus of electricity). Thus, it would then constitute up to about 10% of the total reduction achieved when substituting fossil natural gas with bio-SNG.

7.1.3 Economic performance

Figure 17 presents the total specific cost for SNG for the cases with 100 MW production. The figure shows the cost for the different parts of the SNG value chain (I-V) that together constitutes the total SNG cost (from well-to-gate).

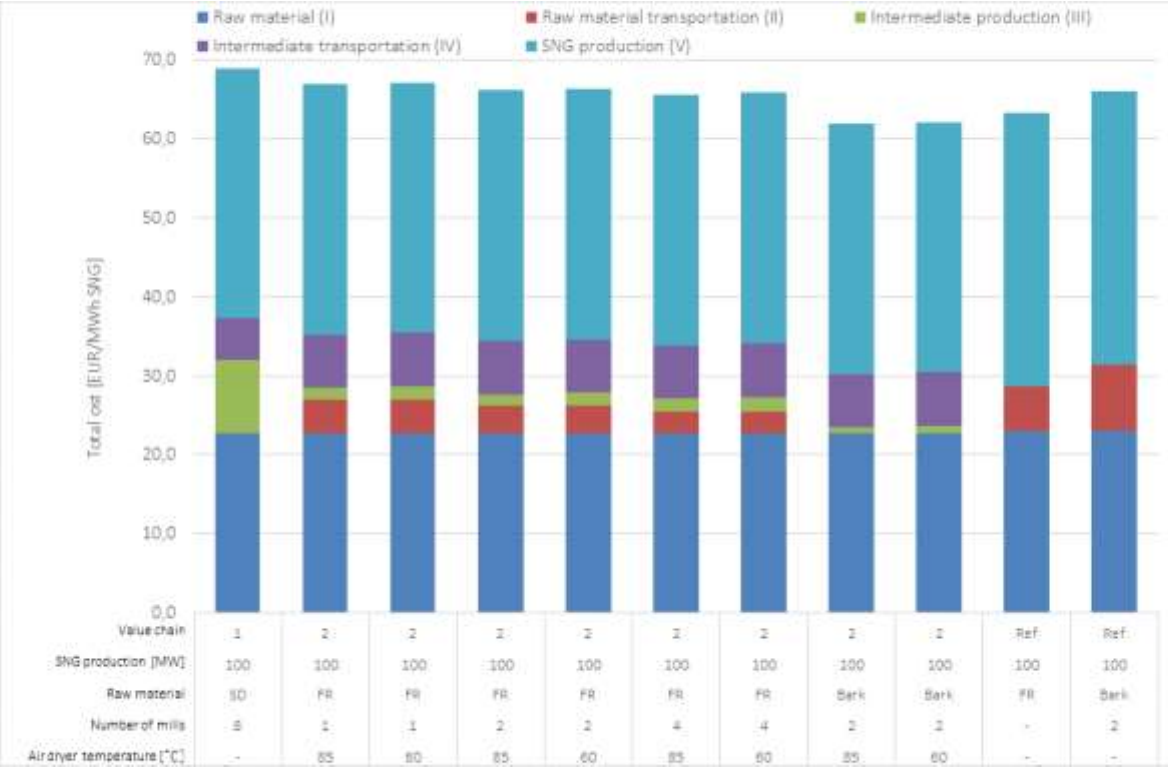

Figure 17. Total cost for SNG (EUR/MWh) for the cases with an SNG production of 100 MW.

Looking at the results in Figure 17, one can see that the differences between the different cases are relatively small. Value chain 1, where pellets are produced at sawmills and transported for further upgrading at the SNG plant, shows the highest cost of the studied cases. The cost for train transportation of pellets is almost equal to the transportation costs for the reference chain with usage of forest residues. The SNG production cost is somewhat lower in Value chain 1, due to more revenue from by-products (electricity and district heating), than for the reference case. But in Value chain 1 there is a significant cost for the pellets production. Thus, in total the SNG cost is higher for Value chain 1 than for the reference case using forest residues.

For Value chain 2 the cost is lower than for Value chain 1, but higher than the reference case, if forest residues are used. The total transportation costs are higher in Value chain 2, and in addition there are costs associated with the intermediate production. This is somewhat compensated by a lower SNG production cost. Thus, the cases with intermediate products are not advantages from a transportation point of view. For Value chain 1 the transportation cost is almost the same as for the reference value chain (with FR) and for Value chain 2 the transportation costs are higher. This is due to the high fixed cost that is associated with transportations, especially by train (see Section 6.3.1). For Value chain 2, the cost for intermediate transportation only is about the same as for transportation of forest residues in the reference case. However, the transportation distance for the intermediates is very uncertain (see further Section 7.1.3.1). The advantage with intermediates for this studied system is that more excess heat is available at the SNG production plant to be used for district heating and electricity generation.

The difference between the cases where different numbers of pulp mills are used for intermediate production is very small. The raw material transportation cost is naturally decreasing with the number of mills since the outtake area per mill decreases. On the other hand, it is likely that the average transportation distance for intermediates increases if more mills are considered. This is however, as discussed in Section 6.3, not considered here.

A reduction of the cost is achieved for Value chain 2 if bark is used instead of forest residues. When bark is used, the transportation costs are reduced (no cost for transportation of raw material) and the costs associated with intermediate production are reduced (no extra cost for biomass handling). The cases where dried falling bark from pulp mills is used have the lowest cost of all studied cases. However, as mentioned in Section 6.5.2, there is a high uncertainty regarding how much bark that can be used in the SNG process. In the reference value chain, the usage of bark increases the cost for the intermediate transportation (for the distance considered as a base value, see further Section 7.1.3.1).

As can be seen in Figure 17, the difference between cases with different air dryer temperature is barely visible. The cases using air of 60°C have a somewhat higher cost. However, as has been discussed, it is less competition for the excess heat needed in these cases.

Figure 18 presents the total specific cost for SNG for the cases with 300 MW SNG production. The costs for the cases with 300 MW SNG production are lower (about 10%) than the corresponding case with 100 MW SNG production. This is due to the significantly lower specific investment costs for the cases with 300 MW. The raw material transportation costs are higher than for the corresponding cases with 100 MW SNG production, but this increase is significantly lower compared to the decrease of SNG production cost due to economy of scale.

For Value chain 2, if four (or more) mills are considered, the total cost is approximately equal to the cost for the reference case (with both forest residues and bark). Thus, if the size of the production is increased, the cost for Value chain 2 is reduced more in relation to the cost for the reference case. This is because the transportation costs for Value chain 2 could be about the same when the SNG production rate is increased (compare e.g. two mills for 100 MW SNG and four mills for 300 MW SNG), whereas for the reference case the transportation cost is increased due to a significantly larger outtake area for forest residues. Here, the cases when bark is used in Value chain 2 have somewhat lower transportation costs than the reference case.

Figure 18. Total cost for SNG (EUR/MWh) for the cases with an SNG production of 300 MW.

Figure 19 shows the total specific cost for SNG (for some selected cases), where the division of cost is not presented according to the value chain, as in Figure 17 and Figure 18, but divided into cost for raw material, transportation, capital, O&M and other fuels as well as the net revenues for electricity and district heating. The total cost is dominated by the capital cost and the raw material cost (constituting more than one third each). Also the operation and maintenance cost is relatively large (more than one fifth). The revenue from electricity is about 5% and the revenue from district heating is about 10%. The transportation cost's contribution to the total cost varies from below 10% up to about 20%. The cases with the lower SNG production rate with no intermediates or the cases with intermediates using raw material available at sawmills or pulp mills have lower transportation costs, whereas the cases with intermediates using forest residues as raw material, especially the ones with few mills considered and high SNG production rate, have higher transportation costs.

Figure 19. Total SNG cost showing the contribution from the cost of raw material, transportation, capital, O&M and other fuels as well as the net revenues for electricity and district heating.

7.1.3.1 Sensitivity analysis

Figure 20 shows the changes of the total specific cost for SNG for the different parameters included in the sensitivity analysis.

If the capital recover factor is increased by 50%, the total SNG cost increases by around 20%. An increase of the capital recovery factor could also represent an increase of the investment cost or a combination of these.

If the gasifier unit capacity is reduced to half, i.e. the number of units is doubled in each case, the total cost increases by 6-8%. Increasing the number of units, increase the plant availability. If, for example, there is a problem with one gasifier unit the effect on the total production capacity is less the more units that constitute the plant. This is not reflected in the economic calculations.

The influence of an increase of the outtake of forest residues by 50% is generally very small. However, for the larger reference case using forest residues, the cost is reduced by more than 2% (due to the significantly decreased transportation distance, see Table 18). If the price of biomass is doubled, the effect is very large. The total cost is then increased by approximately one third. As mentioned in Section 6.7, doubled price of wood fuel is in line with predictions of future price development. An increase of the price of biomass will probably go hand in hand with increased prices and/or emission charges on fossil fuels. Thus, in this scenario the cost for fossil natural gas will also increase.

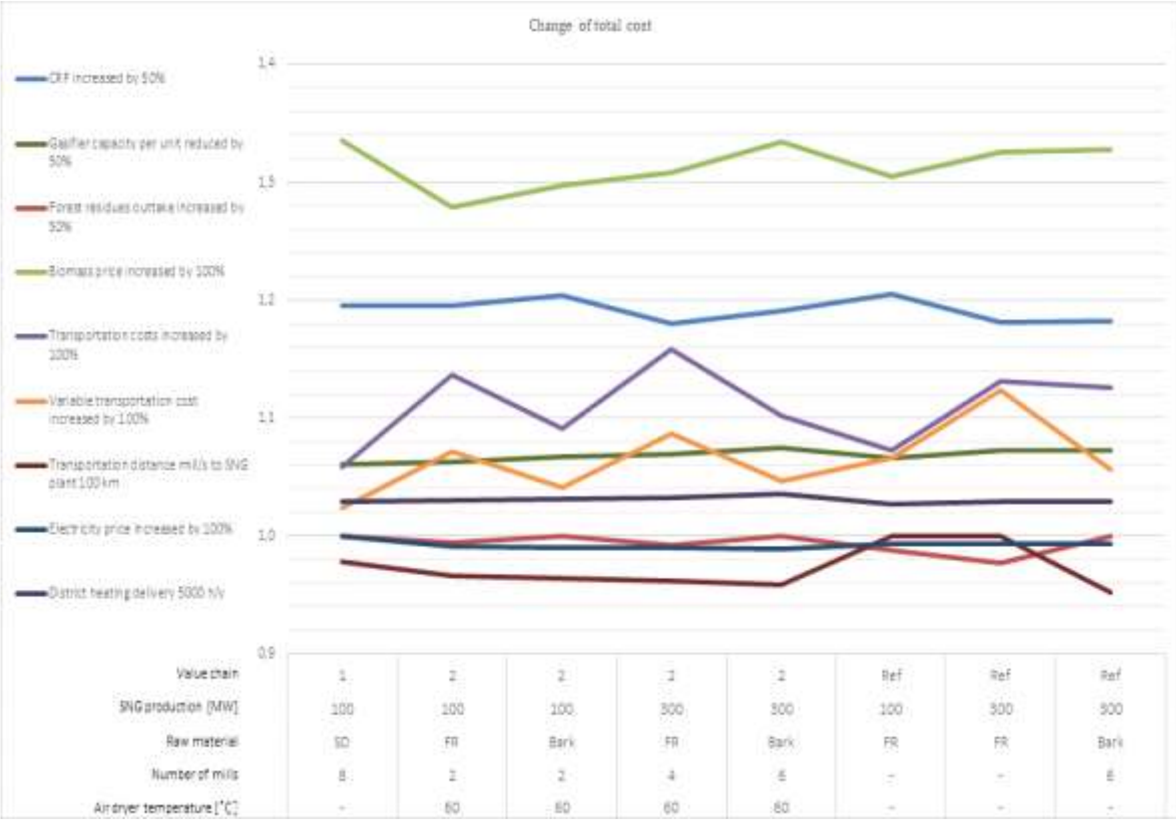

Figure 20. Change of total cost for SNG for changes of some selected parameters.

Doubling the transportation costs (both the fixed and the variable cost) increases the total cost with 6-16%. Cases with the lower SNG production rate that only have one transportation step, that is the cases that use mill by-products (sawdust or bark) or the reference case using forest residues, are less influenced by the change in transportation costs. The cases with two transportation steps and the reference cases with the higher SNG production rate are more influenced if the transportation costs are doubled. If only the variable transportation cost is doubled, the cases that include truck transportation are more influenced. For the reference case with the higher SNG production rate using forest residues, the increase of the total cost is 12%. However, doubling the transportation costs represent a relatively extreme scenario. If e.g. policy measures related to the variable cost for truck transport is discussed that would influence the cost per km with around 10%, the influence of this measure on the total cost for these value chains would be small.

An increased variable transportation cost could also represent longer transportation distances. In this study, the average truck transportation distances have been calculated assuming straight roads. This leads to an underestimation of the average transportation distances. However, the actual underestimation could reasonably vary from case to case and therefor no general correction factor for this has been used. In addition to the transportation distances in the studied value chains, there could also be indirect effects on transportation for other applications outside the studied system. These effects are not included here.

If the average distance between mills and the SNG plant is changed from 500 km to 100 km, the total cost is decreased from 2-5% for the cases having this (train) transportation route. As discussed in Section 6.3, the likelihood of having longer average transportation distances increases with the number of mills. Thus, this shorter transportation distance is generally more relevant for the cases with fewer mills. If considering different average transportation distances for different number of mills, the difference in total cost would be even more equal.

Doubling the electricity price has a very small influence on the total cost. If the yearly time for district heating delivery is limited to 5 000 h, the total cost is increased by around 3%.

7.1.4 Summary of results for the SNG value chains and further discussion

Since the results here generally indicate relatively small differences between the studied value chains, the results and order of cases could differ if specific case studies are conducted. There, the availability of forest biomass around mills and the SNG plant, transportation distances, access to mill excess heat and by-products, etc. could differ from the assumptions used in this study. However, some interesting indications can be found in the results.

To first dry forest residues at pulp mills before further transportation to and upgrading at a SNG plant do not lead to decreased transportation costs, it leads to increased total transportation costs. This is due to the high fixed costs that are associated with transportation, especially by train. However, the benefit of drying the biomass using excess heat at pulp mills, are that excess heat is “moved” from a place where it could be hard to find profitable ways to use the excess heat to the SNG plant where the excess heat could be used as district heating. With the assumptions used in this paper, these two factors working in opposite directions approximately cancel out each other and the total cost is thereby similar for these cases.

The number of mills and the drying temperature used in the case where forest residues are dried at mills, influence the results to a relatively small extent (especially the drying temperate). However, the less excess heat (per mill) and the lower the temperature of the excess heat is, the likelihood for competition for the excess heat decreases. This suggests that not too few mills should be used and that the drying temperature should be as low as possible.

To use falling bark from kraft pulp mills is interesting from an economic point of view according to the results, since the first transportation step is avoided and no additional investment for biomass handling at the mill is needed. However, as has been emphasized, there is a high uncertainty regarding how much bark that can be used in the SNG process. No additional costs related to e.g. operation and maintenance of the SNG plant has been included when using bark, which could be the case in reality.

To use pellets is the most expensive and clearly the least energy efficient option out of the studied alternatives. This shows that further pretreatment than necessary (drying is required by the process) is not energy efficient and not profitable. The transportation costs and energy usage is decreased compared to drying only, but this decrease is significantly less than the extra energy and costs associated with the intermediate production. From an economic point of view, though, the difference is not that great.

The total cost is dominated by the raw material and capital cost. As has been shown, the total cost is then increased by approximately one third if the raw material cost is doubled. Doubled price of wood fuel is in line with predictions of future price development. An increase of the price of biomass will probably go hand in hand with increased prices and/or emission charges on fossil fuels. The effect of larger scale of the SNG production on the specific capital cost as well as the total cost is significant, as shown by the results. However, the decrease of the specific capital cost with scale is damped since scale up of the gasifier unit capacity is limited for the gasification technology considered here. The total cost for Value chain 2 with intermediates is reduced more than the reference value chain when the SNG production rate is increased. Since the results here, as well as in general emphasize the importance of large scale production, the relevance of intermediates could increase if larger and larger plants are being built.

This study investigates the cost for different value chains, not the profitability. The possibility for profitable production of bio-SNG will, besides from the cost estimated here and the distribution costs, be influenced mainly by the development of fossil fuel prices, charges for emitting fossil GHG and policy instruments promoting production of e.g. renewable transportation fuels.

The starting point in this study has been production of SNG integrated with a district heating system and if biomass should be taken in to the plant directly from the forest or if the forest industry should be a part of the value chain by first pretreat the biomass, either taking in the forest residues or by using internal by-products. Another alternative is that the SNG production takes places at a pulp mill or a saw mill (which for example has been considered in Pettersson et al., 2015). As mentioned, the main part of the excess heat from the SNG production process is at high temperature, thereby it can be utilized also at a pulp mill (through a steam cycle). However, as described in Section 6.4, market kraft pulp mills, do not generally have a steam deficit (the steam demand is satisfied by the recovery boiler). Therefore, it is mainly at integrated kraft pulp and paper mills, or mechanical mills, a heat integration possibility for this technology exist. Then, the bark boiler could be replaced and the bark, together with forest residues, could be used in the SNG production. Integration with industry has the advantage of a heat demand that is fairly constant all year around, which is not the case for district heating systems.

This study includes the part of the life cycle (well-to-gate) where there are differences between the studied value chains. Therefore, distribution and usage of SNG is not included. The cost associated with distribution of SNG could be relatively high if the production is not located by a natural gas grid. Then, the SNG needs to be compressed (CNG, compressed natural gas) or liquefied (LNG, liquefied natural gas) before distribution. This aspect is important to consider when different possible localisations for SNG production are compared. If located by a natural gas grid, the gas needs to be further compressed (to 230 bar) at the filling station before it can be used in personal cars. This requires approximately 9 kW_{el}/MW_{SNG} (Holmgren et al. 2015).

7.2 REFINERY VALUE CHAINS

7.2.1 GENERAL RESULTS

As mentioned in the previous chapter, energy densification is an incentive for producing intermediates. Energy densification enables a more cost effective transportation and in most cases also a more practical handling. Energy densification becomes very significant already early in the value chain considering the sparsely grown trees in the forest which are harvested and the chipped material is put in a pile. Already in this early step the increase in energy by volume becomes very significant. Densification continues as the chips are dried and milled at the pyrolysis plant where the densification appears as mass and volume reduction. A very significant densification step is the transformation of the solid woody material into a liquid (pyrolysis oil) in the pyrolysis reactor simply by the cellular structure in the wood transforms into liquid organics. A final densification occurs at hydrogenation in the HDO-plant in form of increase through mass/volume decrease. For the TO6 case where the raw material is already a liquid state (tall oil) the energy densification in the value chain is less relevant as it relates only to the increase at hydrogenation.

Energy densification should be regarded from both the mass and the volume perspective. Table 19 shows the transformation steps from raw material to intermediate to final oil product. Energies are LHV on a wet basis, i.e. the conditions at which they are transported. Densification factor is the ratio out/in. As seen in the table case the volume densification can be as much as 16 times and mass densification is 5 times. This is for the PYR 1 and PYR3 case.

Table 19. Energy densification for the refinery value chains.

Energy densification		LHV (wet) kWh/kg	Density kg/m3	LHV (wet) kWh/m3
PYR1 and PYR 3	chipped forest residues	2.3	290	667
	bio-oil	6.0	1200	7200
	densification factor	2.6		10.8
	bio-oil	6.0	1200	7200
	product oil for refinery	12.3	890	10947
	densification factor	2.1		1.5
	overall value chain densification factor	5.3		16.4
LIG 1 and LIG 3	LignoBoost lignin	4.6	960	4416
	lignin-oil	7.7	1200	9240
	densification factor	1.7		2.1
	lignin-oil	7.7	1200	9240
	product oil for refinery	11.6	890	10324
	densification factor	1.5		1.1
	overall value chain densification factor	2.5		2.3
TO6	CTO	10.4	940	9776
	RTD	10.2	960	9792
	densification factor	1.0		1.0
	RTD	10.2	960	9792
	product oil for refinery	12.0	890	10680
	densification factor	1.2		1.1
	overall value chain densification factor	1.2		1.1
REF_R	forest residues	2.3	290	667
	product oil for refinery	12.3	890	10947
	overall value chain densification factor	5.3		16.4

The advantage with each energy densification of intermediates cannot be seen individually as it has to be put in context with other issues such as transportation means, distances and costs. The advantage of energy densification is reflected in the economic analysis.

The oxygen content of the raw material and intermediates play an important role for the value chain. Table 20 illustrates the evolution of oxygen, mass and energy yields through value chain PYR3, LIG3 and TO6.

Table 20. Oxygen, mass and energy yields through refinery value chains.

	PYR3	LIG3	TO6
Producing Intermediate			
Feed input	wood chips	LignoBoost lignin	crude tall oil (CTO)
Process	fast pyrolys	fast pyrolys	distillation
Intermediate output	bio oil	lignin oil	raw tall diesel (RTD)
Oxygen in feed, wt%	42	26	10
Oxygen in intermediate wt%	40	20	12
Mass yield	0.72	0.71	0.62
Energy yield	0.65	0.68	0.62
Energy densification by mass	2.6	1.7	1.0
Processing of intermediate			
Intermediate input	bio oil	lignin oil	RTD
Process	HDO	HDO	HDO
Final product output	oil product	oil product	oil product
Oxygen in intermediate wt%	40	20	12
Oxygen in final product, wt%	0	0	0
Mass yield	0.44	0.56	0.89
Energy yield	0.98	0.98	1.06
Energy densification by mass	2.1	1.5	1.2
From Feed to Final product			
Mass yield	0.32	0.40	0.55
Energy yield	0.64	0.67	0.66
Energy densification by mass	5.3	2.5	1.2

Increasing mass yield →

← Increasing oxygen and energy densification

The columns are arranged with the highest oxygen content in the feed to the left and the lowest to the right. Each chain includes a first process for producing an intermediate and a second process for the final product. Each process results in conversion of mass and energy. Each process is governed by certain conversion efficiency. The mass yield (kg_{out}/kg_{in}), energy yield (MWh_{out}/MWh_{in}) and energy densification ($LHV(wet)_{out}/LHV(wet)_{in}$) is shown for each chain and process. The bottom of the figure summarizes the overall feed to final product. We then note that the mass yield increases from left to right while the oxygen content and energy densification increases to the left. The total energy efficiency is reported in Section 7.2.2.

A conclusion from this is that it is an advantage if oxygen could be removed already at the intermediate process as this will increase energy densification and reduce mass for the transportation of the intermediate to the HDO process. In the PYR1 and LIG3 cases where the intermediate is a fast pyrolysis oil, process improvement could be done by extracting the non-condensable gas used as carrier gas in the fluidized bed reactor, and shift the gas in a reactor according to the water-gas-shift reaction for a higher content of hydrogen which can result in a state of hydrogenation already in the pyrolysis process. However, this is out of the scope of the present study.

Table 21 presents the resulting raw material usage, transportation distances, and number of truck/ships used for the studied cases. The average transport distance for the cases REF_R and PYR1 is 123 km and 87 km respectively. For PYR3, the average transport distance is set to 50 km (as described in Section 6.3).

Table 21. Raw material usage, number of mills and transportation distance and trucks/ships required.

Case		REF_R	PYR3	PYR1	LIG3	TO6
Number of mills		-	3	1	3	6
Raw material usage	GWh/y	1697	1697	1697	1625	1742
HDO-oil production	t/y	97 299	97 258	97 252	97 461	110 410
Raw material, average transportation distance	km	123	50	87	-	-
Truck loads raw material to pulp mill/refinery	No/day/plant	55	18	55	-	-
Intermediate transportation (ship)	km	-	500	500	500	2000
Ship loads pyrolysis oil to refinery	No/month/plant		2-3	2-3	2-3	2-3

The number of truck loads required for transportation of forest residues is the same for the REF_R case and for the PYR1 case (55 per day). In both cases, pyrolysis is done in a large scale plant. However, from a practical and logistically point of view, it might be more complicated for a refinery to handle these flows of biomass than for a pulp mill.

7.2.2 ENERGY EFFICIENCY

Table 22 presents the total energy efficiency for the refinery value chains. In addition, the energy yield for raw material to final product is also shown (energy content in the produced HDO-oil divided by the energy content of the raw material). The cases REF_R, PYR3 and PYR1 share the same raw material and process yields; therefore the energy efficiency is the same. Although the cases differ regarding process integration possibilities and transportation, these aspects have, comparatively, a very little effect in the total energy efficiency. LIG3 and TO6 chains have a significant higher efficiency. This is because the oxygen content of the pyrolysis oil is lower than for the other chains and requires therefore less hydrogen during HDO-treatment.

The energy yield of LIG3 and TO6 is slightly higher than the other chains. Using lignin as raw material gives a higher yield during pyrolysis, whereas tall oil has a higher yield during HDO-treatment.

From these two process indicators, it is possible to conclude that lignin and tall oil are raw materials that are more suitable for the production of HDO-oil from an energy efficiency perspective.

Table 22. Total energy efficiency and energy yield of the refinery value chains.

Case	Total energy efficiency (electricity equivalents)	Energy yield (raw material to product)
REF_R	74%	64%
PYR3	74%	64%
PYR1	74%	64%
LIG3	84%	67%
TO6	78%	66%

7.2.3 CO_2 EMISSIONS

The carbon dioxide emissions for each of the processing steps are presented in Table 23. Generally, the emissions from transportation are very low compared with other emissions in the chain. The differences in emissions for transportation between the reference chain and the intermediate chains are very small. Lignin-oil has a higher energy density than the bio-oil from forestry residues which is reflected in lower CO_2 emissions from transportation; however, this is a small difference.

Lignin has lower CO_2 emissions than the forestry residues chains due to the lower oxygen content in the bio-oil and consequently lower hydrogen demand in the HDO-step. However, high emissions are associated with lignin extraction due to the loss of electricity production in the pulp mill.

Tall oil has even lower hydrogen consumption than lignin and therefore the lowest emissions among all the cases in the HDO-step (i.e. conversion to product). The results are nevertheless not comparable since for the tall oil chain, the emissions were taken from Preem's in-house data. Most likely, the data does not include any alternative usages of the tall oil such as green chemicals or energy, as is the case of lignin.

Table 23. Carbon dioxide emissions of the refinery chains at each processing step [kg CO_2/MWh].

Case	REF_R	PYR3	PYR1	LIG3	TO6
Raw material	FR	FR	FR	Lignin	Tall oil
Number of mills	-	3	1	3	6
FR outtake / Lignin extraction	2.4	2.4	2.4	55.1	32*
Raw material transportation	5.7	2.3	4.0	0.0	0
Pyrolysis / Distillation	-3.1	-3.1	-3.1	-6.1	0
Intermediate transportation	0.0	1.7	1.7	1.4	0
Conversion to product	88	88	88	35	15
Total CO2 emissions	**93**	**92**	**93**	**85**	**47**

* Total CO2 emissions for all the value chain until delivery to HDO-plant.

In Figure 21a sensitivity analysis on the CO_2 emissions of hydrogen production is presented. The top of the green bars represent methane reformation (same result as in Table 23), whereas the bottom of the bars is a much lower estimate representing e.g. hydrogen obtained as a by-product in a refinery.

The results are very sensitive to the carbon dioxide emissions of hydrogen. For the cases REF_R, PYR3 and PYR1, the total emissions vary almost by an order of magnitude. This is an indication of the importance of having access to environmentally friendly hydrogen for the overall environmental performance of these chains.

The black bars in Figure 21 show also the CO_2 emissions depending on how hydrogen is produced (top of the bars: methane reformation, bottom of the bars: by-product). The difference with respect to the green bars is that a Swedish electricity mix (as opposed to a Nordic electricity mix) is used. The dominant types of electricity production in Sweden are nuclear power and hydropower. Clearly, the lignin chain is particularly sensitive to assumptions on the electricity mix and is favoured by greener electricity production. This is due to the reduced penalty due to electricity loss production at the pulp mill. Still, it is questionable that the Swedish electricity mix should be used for the assessment. According to recommendations from the Swedish Energy Agency, a Nordic electricity mix should be used since electricity in Sweden is traded in a Nordic market (Energimyndigheten 2016).

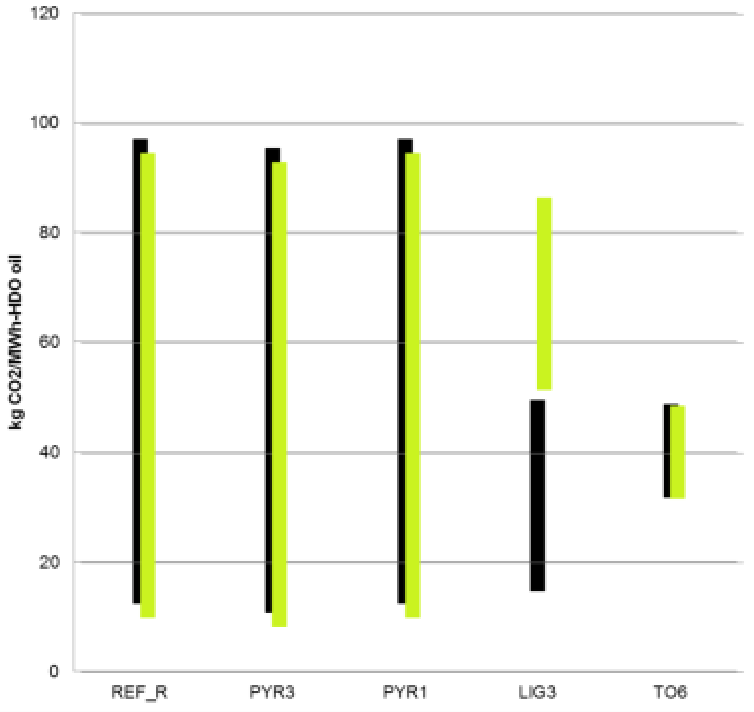

Figure 21. Sensitivity analysis CO_2 emissions. Green bars: Nordic electricity mix (102 kg_{CO2}/MWh), black bars: Swedish electricity mix (25 kg_{CO2}/MWh). Top of the bar: H2 from methane reforming, bottom: H2 as byproduct from refinery.

7.2.4 COST ESTIMATES

The total cost for each chain is presented in Figure 22, as well as the cost for each of the step of the chain. Clearly, the production cost is similar for all the chains. Although the tall oil chain seems more expensive than the others, the results are not directly comparable. This is due to the difficulties obtaining production cost data for the tall oil chain. In this case, the tall oil *selling price* was used instead of the *production cost*. The price is expected to be significantly higher than the production costs since it should include two profit margins i.e. the profits the pulp mill makes when selling raw tall oil to the upgrading facility and the profit the upgrading facility makes when selling the upgraded oil to the refinery. To estimate these profits is very complicated and outside the scope of this study. Therefore, for all the cost estimates (and sensitivity analysis in next section), the reader is reminded that the tall oil chain is not directly comparable with the other chains.

Excluding the tall oil chain, the lignin chain has the highest total cost. This is because of the loss of electricity production at the pulp mill due to the lignin extraction. However, possible benefits of lignin extraction have not been included in this analysis, for example, the possibility to increase the pulp production if the recovery boiler is the bottleneck at the pulp mill. By the time this study was made (2015) the H_2 cost was very low (~2 EUR/kg). An increase in H_2 cost would favour the lignin chain since the H_2 demand for the HDO-treatment of lignin-based bio-oil is lower than the other chains. This is investigated in the sensitivity analysis presented in the following section.

There are significant scale effects that favour the production at a single big facility than at several smaller units. The advantages are even higher than the increased transportation costs to gather enough raw materials for the single facility. This can be seen by comparing the chains REF_R and PYR1 against PYR3 and LIG3 and realising that the total production costs are lower for the single facility chains. This is an interesting result since it is often assumed that the advantages of upgrading biomass (specifically: increasing its density along the production chain) are related to the decreased transportation costs. The results of this study indicate that those possible advantages cannot offset for the increased investment costs of several upgrading units.

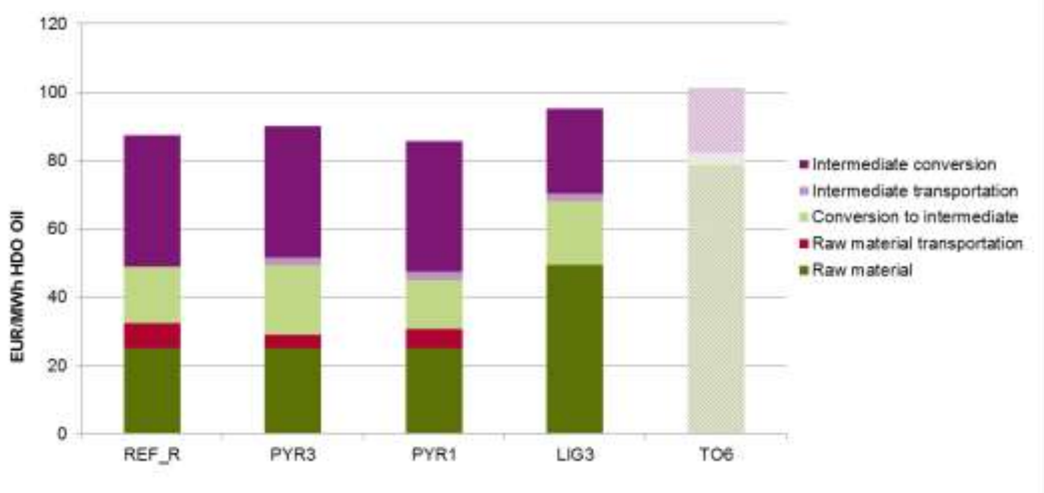

Figure 22. Total cost estimates refinery value chains.

In Figure 23, the importance of different types of costs is presented more explicit. Even in the chain with largest share of transportation costs, PYR1, these are only <10% of the total production cost.

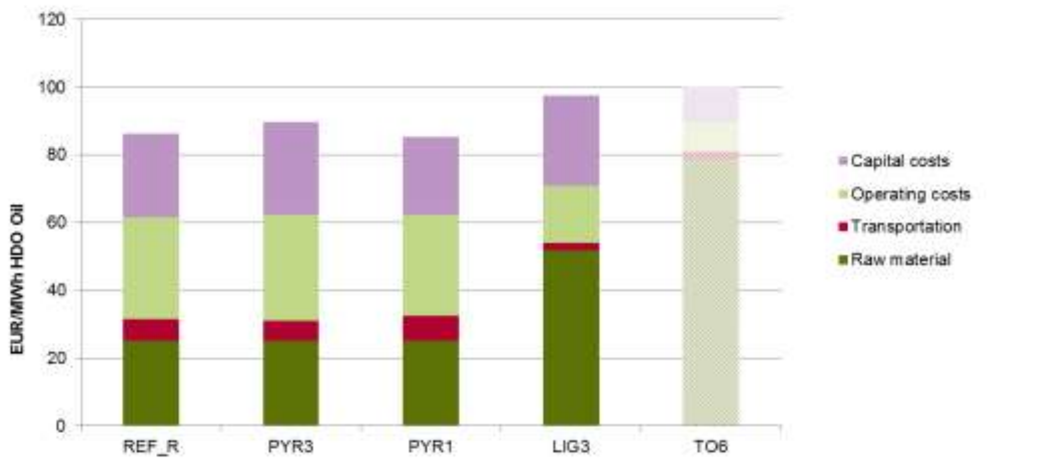

Figure 23. Costs distribution refinery value chains.

The raw material costs are particularly high for the lignin chain since the loss of electricity production at the pulp mill is taken into account as an "extra cost". On the other hand, the operating costs for the lignin chain are significantly lower than the other chains. This is because lignin bio-oil has lower oxygen content than bio-oil produced from forest residues and therefore demands less hydrogen in the HDO-step.

7.2.5 Comments on further refinery processing of HDO-oil

As mentioned in Section 6.6.1.3, the refinery processing of the HDO-oil is outside the scope of this study. The remaining steps include distillation and cracking of the heavy components. To anyway get a feeling for the additional energy consumption and CO_2 emission in this part of the full chain from well-to-tank, some data on this part has been collected based on Jones et al. (2009). The energy losses in the final steps consist of combustion of gaseous components from the cracker, excluding separated H_2. This energy loss is estimated to 0.028% of the energy value of the diesel and gasoline. Additional CO_2 emissions are related to combustion of these gases and the H_2 for the cracker. They are estimated to contribute with 0.8 g CO_2/kg gasoline and diesel (or about 0.07 kg CO_2/MWh) from the combustion of the gases and additional 11% H_2 production equivalent to about 9 kg CO_2/MWh product assuming reforming of natural gas, however the share of the heavy fraction is uncertain. It can thus be concluded that the impact on energy consumption and CO_2 emissions of these final steps are small when compared to Figure 21. With respects to additional costs it is assessed that the costs are negligible as the biofuel flow rate is small in relation to the fossil fuel flow rate through these final common processing steps.

7.2.6 SENSITIVITY ANALYSIS

The importance of various parameters was study by conducting sensitivity analyses. In Table 24, the parameters varied in each analysis are presented.

Table 24. Parameters varied in each sensitivity analysis.

	Varied parameter	Relevance
1. Higher forest residues outtake density, same production	Outtake density *1.5	In a scenario where more forest residues can be collected, shorter transportation distance is needed to collect the raw material for the same production level.
2. Higher forest residues outtake density, more production	Outtake density *1.5	In a scenario where more forest residues can be collected and the same transportation distance is maintained, the production can be increased (gives bigger production units)
3. Higher forest residues outtake and lignin extraction rate	Outtake density and density extraction *1.5	Same as sensitivity analysis 2, but with an increased rate of lignin extraction.
4. Higher transportation costs	Transport costs *2	The transportation costs are doubled. This is relevant to study e.g. the effects of a possible "kilometre tax" (although severely exaggerated).
5. Higher annuity factor	a= 0.15	The annuity factor is raised from 0.1 to 0.15 to represent an investment with a shorter time perspective.
6. Higher H_2 costs	LNG*3= 115 EUR/MWh (i.e. 84% higher than base case)	In this sensitivity analysis the highest price of natural gas during the last 4 years (since august 2011) was used instead of the current price.
7. Higher H_2 and electricity costs	H_2: 115 EUR/kg El: 35 EUR/MWh (elec 74% higher than base case)	Same as sensitivity analysis 6, but the average market price of electricity the last 4 years (since august 2011) was used instead of the current price.
8. Higher forest residues costs	32 EUR/MWh (i.e. 100% higher than base case)	A scenario reflecting increased competition for forest residues or more difficult accessibility.

The results of the sensitivity analyses are presented in Table 25. The total production costs for each chain are presented in EUR/MWh. For each sensitivity analysis the chains are ranked from best (dark green) to worst (red).

From the overall colouring of Table 25, it can be seen that the ranking among the chains is the same in analyses 1-5, where several parameters are varied drastically. The chains PYR1 and REF_R are the best ones. This is because the advantages of economies of scale (i.e. investing in a large unit is better than investing in a few smaller ones). These two chains are still the best ones even when transportation costs are doubled (sensitivity analysis 4) which affects these cases severely (compared with LIG3). This is a clear an indication that the investment costs are a more important parameter than the transportation costs.

The overall colouring of Table 25, changes drastically in analyses 6-8. There are two explanations for this. In analysis 6, the price of hydrogen is increased. The lignin chain changes from being the worst one to being the best one. One conclusion of this is that hydrogen is a very important parameter that affects the economic performance of the chains to a large extent.

As expected, changes in the raw material costs have a very large effect on the overall production costs. This is reflected in sensitivity analysis 7 and 8. In sensitivity analysis 7, a high electricity price is assumed which represents a high price for lignin (due to the electricity loss at the mill). In this case, the lignin chain performs worst. In sensitivity analysis 8, the cost for forest residues is doubled, which logically favours LIG3. Here, again, LIG3 becomes the best alternative. These results are not surprising considering that raw material costs are a large share of the overall production costs (as shown in Figure 23).

To summarise the results of the sensitivity analyses, the most important parameters are the size of the units (economies of scale), the raw material costs and the price of hydrogen, whereas transportation costs seem less important.

Table 25. Sensitivity analysis of refinery value chains. All production costs in EUR/MWh.

	REF_R	PYR3	PYR1	LIG3	TO6
Base Case	**87**	**90**	**86**	**95**	**100**
1. Higher forest residues outtake density, same production	86	87	85	91	100
2. Higher forest residues outtake density, more production	83	85	82	93	98
3. Higher forest residues outtake and lignin extraction	83	85	82	88	98
4. Higher transportation costs	94	96	93	97	102
5. Higher annuity factor	100	104	97	112	106
6. Higher H_2 costs	104	107	102	101	103
7. Higher H_2 and electricity costs	104	106	102	109	103
8. Higher forest residues costs	112	115	111	95	

7.3 OTHER ASPECTS

In this study, the most important direct costs for the production of forest-based bio-oil and bio-SNG have been quantified. These included raw material collection, transportation and processing. However, other indirect costs and general implications have not been considered. In this section, some interesting results outside the original scope of the project are presented.

7.3.1 Forest residues market

It has been assumed that 75% of the total forest residues available can be used and that there is no competition for them i.e. they are free for whatever user that collects them. While this is a realistic assumption today, it might not be in the future, if new actors are interested in upgrading forest residues.

Moreover, collecting as much forest residues as needed in the value chains studied may imply new challenges. For example, in the reference chain of the refinery value chain (REF_R), a collection area of <94 000 km^2 around the refinery is required. This is about 20% of Sweden's total area. For the case where forest residues is transported directly to the large SNG plant (300 MW product), a collection area of approx. 200 000 km^2 corresponding to about 45% of Sweden's area, is required. Considering that the forest residues are very unevenly distributed and that large areas of Sweden are not productive (e.g. fell, "fjällen"), an even larger proportion of the actual available collecting area may be needed.

Collecting forest residues from large areas is associated with new challenges. For example, new actors' constellations may appear, as well as new business models. Selling contracts may need to be issued with many different land owners. Although these issues may not prohibit the collection of forest residues, they may result in additional costs that were not included in this study. Moreover, collecting forest residues from large areas may require new infrastructure (e.g. roads) that is not available today, resulting thus in additional costs.

7.3.2 Potential benefits of intermediate products

The results from this study show that the production costs of the value chains with and without intermediates are very similar. Producing an energy product with higher energy density does not necessarily decrease transportation costs or the total production costs. Instead, other factors affect the overall economic performance to a larger extent e.g. how suitable the raw material is for production of the specific product or economies of scale.

Still, other aspects may favor the production of intermediate products. For example, the use of existing knowledge at the pulp mill about handling and processing the raw material, utilization of existing infrastructure and utilization of the existing supply chain.

Intermediate production at a pulp mill may result in efficient mass and energy integration between the processes. This could also be achieved at the final user. However, for refineries safety reasons can hinder such integration. Therefore, intermediate production at a pulp mill could indeed be a more practical way to produce these products than as a stand-alone plant.

In this study, it was shown that the production of intermediates is not necessarily beneficial from a transportation cost point of view. However, the fact that transportation costs are only a minor share of the total production costs may, in fact, open the possibility for new supply chains and markets on an international scale. For example, the production of an intermediate product could be located where the raw material costs are low and then transported to the final upgrading scale (or final user). This alternative could be more profitable than trying to optimize the value chains locally. However, not all nations can rely on biomass imports if significant CO_2 cuts should be achieved globally. From this perspective it is highly questionable that a biomass-rich country like Sweden in the future could depend on large net imports of biomass. Therefore, it is interesting to limit studies to domestic resources, as has been done here, and how to design efficient supply chains based on these. However, large scale facilities and access to and knowledge about biorefinery technology, could be a reason for biomass import to Sweden. The products could then partly be sold outside Sweden.

7.3.3 Legislation

The results clearly show that the transportation costs are a minor share of the total production costs and are less relevant than other parameters in the overall economic performance of the value chains. This is an indication that the effects of a "kilometer tax" on transportation will most probably not affect the production costs in a considerable way.

8 CONCLUSIONS

8.1 GENERAL CONCLUSIONS

The general conclusions from this study of value chains for production of renewable transportation fuels in the form of bio-SNG and bio-oil with and without intermediate products produced integrated with a mill are listed in this section. Assumed raw materials have been forest residues and by-products from a pulp mill and sawmill such as kraft lignin, bark and sawdust. The conclusions are based on the cases defined in the study and the sensitivity analyses performed.

- The initial assumption that decentralized local production of a more energy dense intermediate would significantly reduce transportation costs could not be verified. Even though assuming a higher potential for outtake of raw material in the case of intermediate production, the introduction of a second transport step of the intermediate to the site for final conversion results in a total transportation cost that is in the same range or somewhat higher than the transportation cost without intermediate. The reason is the introduced second step in the transportation chain and the often relatively high fixed cost for transport, especially ship and train transport.
- The transport cost make up a relatively small share of the overall production cost of the final product. Our estimations in this project show that the transportation cost generally is about 10% of the total cost along the value chain, but can in some cases constitute up to 20%.
- There is a relatively small difference in total production cost for the end product when including all the steps in the value chains between the chains with and without intermediates, considering the level of uncertainty in the input data and the assumptions behind the scenarios studied.
- There are still important advantages related to transformation to intermediates. These include:
  - Opportunities to utilize by-products from the pulp mill such as lignin and bark for partial or full supply of raw material.
  - Opportunities to use existing infrastructure for biomass handling.
  - Opportunities to utilise excess heat from the pulp mill to partially or fully upgrade to intermediate.
  - Opportunities to integrate the intermediate production with the pulp mill, i.e. increase the utilisation of by-products from the intermediate production such as excess heat or gases in the mills energy system.
  - Possibility to utilise the mill's existing utility system for power, steam, process water, cooling water or waste water purification to low marginal cost.
  - There is an opportunity for pulp mills located in areas with high assess to forest residue raw material close to the pulp mill to produce an intermediate to a competitive cost compared to other centrally located plants such as a petroleum refinery or district heating plant. The transport distance for collection of the same amount of raw material can be reduced and the advantage of a lower market price if there is a low competition on this raw material can be utilised.

- Decentralised production at several plants smaller in size is likely to increase the total production cost.
    - This is the case when the capital cost of the intermediate conversion process is high as in the case of pyrolysis for conversion to the intermediate bio crude oil.
    - However, this conclusion is not necessarily true if the capital cost of the intermediate conversion process is low such as in the case the intermediate conversion process is a dryer and the intermediate is dried wood chips.
    - In case a certain amount of raw material needs to be available or if a certain amount of excess heat is necessary for the intermediate conversion it still might be necessary, and possibly beneficial, to divide the intermediate conversion into several separate plants.
- Other factors might be more important for finding intermediate conversion an attractive option.
    - Possibility to easily link in the final conversion of the intermediate to end product with the existing production process without significant modification in today's operation as in the case of using bio crude oil in an oil refinery vs. starting the refinery operation from the bio raw material such as forest residues and lignin.
    - Cost benefits from utilisation of existing infrastructure around the decentralised plant such as access roads, receiving stations and know-how on the handling, processing and conversion of biomass.
    - It is likely that the intermediate producer, if a pulp mill or other industry dealing with biomass conversion, has a good insight in the local market conditions for biomass or even owns forest as well as a procurement organisation that can take on also this part of the business. It is most likely more difficult for e.g. a refinery to build up this knowledge and organisation.
    - Safety aspects related to handling of biomass on the site and possibilities to handle frequent deliveries of biomass raw material at the site for final conversion to product are other aspects that are likely to be important for deciding if production of an intermediate is a favoured option.
    - The business models of the actors along the value chain and the definition of core business for each actor is also an aspect that will influence the willingness to step in as an actor in the value chain with an intermediate product.
    - The size of the required investment, the possibilities to get acceptance for new investments combined with requirements on return on investment are other factors that will affect how attractive it will be for a potential producer of an intermediate product to enter the value chain. Joint ventures or new separate businesses might be required.
    - The competitive situation on the market depending on the number of potential producers of intermediates and customers is of course also important factors.

There are several reasons why the Bio-SNG and Refinery value chains should not be directly compared with each other. First of all, they are based on different reference reports that have slightly different background assumptions, and it is not possible to adjust them to similar conditions based on the limited information in these references. Secondly, the results presented are based on a well-to-gate perspective. A direct comparison should be done in a well-to-wheel perspective.

8.2 BIO-SNG VALUE CHAINS

For bio-SNG, this study has compared value chains where the raw material is upgraded to intermediate products, either dried biomass at pulp mills or pellets at sawmills, before transportation for further upgrading at an SNG plant integrated with a district heating system with a reference chain in which the raw material is upgraded in a single facility into the final product. For each value chain different cases has been considered to study the effect of different parameters including SNG production rate and type of forest raw material (forest residues, bark or sawdust). The main conclusions are:

- From an energy efficiency point of view there are only small differences between the studied value chains (86-89%), with the exception of the chain using pellets where the total energy efficiency is significantly lower (70%).
- The difference in change in CO_2 emissions is small between the studied value chains (varies from +3 to -3 kg/MWh SNG), since the total emission change from well-to-gate is small compared to the reduction achieved when using the bio-SNG (i.e. when e.g. substituting fossil natural gas).
- Under the basic assumptions considered in the economic evaluation, the estimated total cost is in the range of 62-69 EUR/MWh for cases with an SNG production rate of 100 MW. The corresponding results for a production rate of 300 MW SNG is 55-62 EUR/MWh.
    - Thus, higher SNG production rate leads to significantly lower total cost. This is due to that the decreased capital cost is significantly higher than the increased transportation costs.
    - Value chains with intermediate products based on forest residues have higher total transportation costs than the reference chain due to inclusion of a second transportation step. However, if mill by-products such as bark are used, thereby avoiding the first transportation step, the transportation costs are lowered and in line with the reference chain.
    - Using available pulp mill excess heat for biomass drying is a way to “move” excess heat to another site (the SNG plant) where it could be used as district heating which increases the revenues (lower the costs) for the SNG plant.
    - The lowest total cost out of the studied value chains is achieved for value chains where falling bark is dried at pulp mills and transported to the SNG plant.
    - Similar total costs, somewhat higher than when falling bark is used, are shown for value chains where forest residues are transported directly to the SNG plant and for value chains where forest residues are first transported to a pulp mill for drying.
    - Not just drying the biomass, but to make pellets, lower the transportation costs somewhat, but the total costs are highest for this value chain due to the relatively high energy usage in the pellets production. Thus, further pretreatment than required by the SNG process in order to lower transport costs is not profitable.

  - The total cost for SNG is dominated by the capital cost and the cost for raw material and are therefore very sensitive to the assumed annuity factor and investment cost as well as the price of the raw material.
  - The total cost is less sensitive to the assumed level of transportation costs, especially the variable transportation cost (per km).
  - The total cost for value chains with intermediate products are somewhat more reduced than the total cost for the reference chain when the SNG production rate is increased.

8.3 REFINERY VALUE CHAINS

The specific conclusions related to the refinery value chains are the following:

Under given basic assumptions:

- The calculated production cost for HDO-oil based on forest residues is in the range of 86-90 EUR/MWh and for lignin oil 95 EUR/MWh. The costs are most sensitive to the raw material costs (electricity price for the lignin case), cost of hydrogen and capital costs. The estimations contain uncertainties in the estimation of investment costs and conversion efficiencies. The differences identified here should therefore be used carefully when making conclusions about benefits of using different raw materials.
- The calculated energy efficiency is in the range of 74% for the value chain using forest residues as raw material and 85% in the case of lignin. The energy yield from raw material to final product is 64% in the case of forest residues and 67% for lignin.
- The calculated CO_2 emissions is 93-94 kg/MWh HDO oil (or 26 g/MJ) when using forest residues as raw material and 85 kg/MWh (23 g/MJ) for lignin.
- A very important aspect that affects the economic performance and CO_2 emissions of the produced oil is related to the oxygen content in the bio crude oil.
  - The oxygen content in the bio crude oil (pyrolysis oil) determines the necessary amount of hydrogen (H_2) for hydrodeoxygenation (HDO).
  - The amount of oxygen in the bio crude oil (pyrolysis oil) is dependent on the oxygen content of the raw material and the depolymerisation process.
  - Lignin has a lower oxygen content than forest residues, resulting in a significantly lower oxygen content in the crude pyrolysis lignin-oil.
  - The CO_2 emissions and cost of hydrogen is dependent on the raw material for the hydrogen production and the process selected. In this study steam reforming of natural gas has been assumed as the base case.
- In the value chain based on kraft lignin it has been assumed that the separation of lignin from the black liquor results in a reduced electricity production at the mill. Therefore, assumptions regarding electricity price and grid emissions have a large effect on the production cost and the CO_2 emissions of the lignin-oil.

- No credit has been included for the potential pulp production capacity increase that can be realised in case the recovery boiler is the main bottleneck. This is due to the difficulty in estimating how much the capacity can be increased and the costs related to removing other potential bottlenecks.
- In the base case in this study, the replacement electricity has been assumed to have the same cost and CO_2 footprint as the average Swedish electricity on the grid today.

- The produced pyrolysis bio-oils from forest residues and lignin contain different components and molecular structures that can give different value to the final produced oil.
  - This has not been considered in this study.
  - It is known that highly oxygenated components and poorly filtered bio crude oil may show poor stability resulting in storage and pumping problems. In this study. it has been assumed that this is not an issue.

9 SUGGESTIONS FOR CONTINUED WORK

The following ideas have been identified to extend the here presented study:

- The sensitivity study could be extended to take into account more scenarios relevant for the two identified value chains.
- Other raw materials than the materials selected for this study could be included, such as stumps.
- Alternative intermediate transformation technologies and other intermediates could be included as well, to get a more complete picture.
- Other possibilities for integration for conversion to intermediate, e.g. district heat plant, and combined heat and power plants, could be included to get a more complete picture of the costs of different options, and which potential hubs for intermediate production provide good integration opportunities.
- Detailed study of development paths for hydrogen production, with the objective of decreasing cost of hydrogen and reducing the CO_2 emissions.
- Comparative techno-economic assessment of alternative technologies and/or process modifications to decrease the oxygen content in the crude bio-oil, as well as, identification of how the costs and benefits of such modifications are distributed among the actors in the whole value chain.

10 NOMENCLATURE AND ABBREVIATIONS

10.1 ABBREVIATIONS

ADt	Air dried ton
BFW	Boiler Feed Water
Bio-SNG	Synthetic Natural Gas made from biomass raw material
CEPCI	Chemical Engineering Plant Cost Index
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CTO	Crude Tall Oil
DH	District Heating
Ex	Explosion
FAME	Fatty Acid Methyl Ester
FQD	Fuel Quality Directive
FR	Forest Residues
FP	Fast Pyrolysis
GHG	Greenhouse Gas
GROT	GRenar Och Toppar (Branches and tips)
HDO	HydroDeoxyGenation
HHV	Higher Heating Value
HVO	Hydrogenated Vegetable Oil
LHV	Lower Heating Value
O&M	Operation and Maintenance (cost)
PSA	Pressure Swing Adsorption
RED	Renewable Energy Directive
RME	Rapeseed Methyl Ester
RTD	Raw Tall Diesel
SD	Sawdust
SNG	Synthetic Natural Gas

10.2 ABBREVIATIONS USED FOR THE REFINERY CASES

REF_R	Reference chain with no intermediate production using fast pyrolysis and HDO treatment of the crude bio-oil at the refinery. The forest residues are transported to the refinery using trucks.
PYR3	Bio-oil production from forest residues at three pulp mills using fast pyrolysis and HDO treatment of the crude bio-oil at the refinery. The forest residues are transported to the pulp mill by truck and the crude bio-oil is transported to the refinery by ship.
PYR1	Bio-oil production from forest residues at a single pulp mill using fast pyrolysis. HDO treatment of the crude bio-oil takes place at the refinery. The forest residues are transported to the pulp mill by truck and the crude bio-oil is transported to the refinery by ship.
LIG3	Lignin-oil production at three pulp mills using fast pyrolysis. HDO treatment of the crude lignin-oil takes place at the refinery. The crude lignin-oil is transported to the refinery by ship.
TO6	Bio-diesel is produced from crude tall oil, beginning with fractionation and distillation of the tall oil removed in the evaporator plant of the pulp mill. The produced raw tall diesel (RTD) is shipped to a refinery for HDO treatment and cracking. The tall oil diesel can then be directly blended with diesel

11 REFERENCES

Ahrenfeldt J, Jørgensen B, & Thomsen T (2010). *Bio-SNG potential assessment: Denmark 2020*. Retrieved from Roskilde:

Andersson A, Långsiktsprognos 2010 (Longterm forecast 2010); available in Swedish only, 2010: Swedish Energy Agency, Stockholm, p. 99.

Andersson J, Lundgren J, Malek L, Hulteberg C, Pettersson K, and Wetterlund E. *System studies on biofuel production via integrated biomass gasification*. 2013, The Swedish Knowledge Centre for Renewable Transportation Fuels (f3), 51.

Axelsson E, Olsson M R, and Berntsson T. *Heat integration opportunities in average Scandinavian kraft pulp mills: Pinch analyses of model mills*. Nordic Pulp and Paper Researsh Journal 2006;21(4):466-475.

Axelsson E and Pettersson K. *Energy price and Carbon Balances Scenarios tool (ENPAC) – a summary of recent updates*. 2014, Chalmers University of Technology.

Benjaminsson G, Benjaminsson J, and Bengtsson N. *Decentraliserad produktion av pyrolysolja för transport till storskaliga kraftvärmeverk och förgasningsanläggningar*. 2013, Gasefuels AB.

Berglin N, Lovell A, Delin L, Törmäla J (2011). *The 2010 Reference mill for kraft market pulp*. Tappi Peers conference proceedings 2011.

Broström M et al. *Influence of torrefaction on the devolatilization and oxidation kinetics of wood*. Journal of Analytical and Applied Pyrolysis, 2012, 96: p. 100-109.

Börjesson P and Gustavsson L. *Regional production and utilization of biomass in Sweden*. Energy, 1996, 21(9): p. 747-764.

CEPI. Annual Statistics 2007 -European Pulp and Paper Industry, 2008, Confederation of European Paper Industries: Brussels.

Collodi G (2010). *Hydrogen Production via Steam Reforming with CO2 Capture*. http://www.aidic.it/CISAP4/webpapers/7Collodi.pdf. Retrieved 2016-03-30.

Danielsson B-O. *Uppskattning av sågverkens produktion av trädbränslen inom mål 1-området i Dalarna-Gävleborg* (in Swedish), in Bioenergi i WX Mål 1. Ett strukturfondsprojekt inom Mål 1, Södra skogslänsregionen. Projektbilaga 22003, GDE-Net.

de Miguel Mercader F (2010). *Pyrolysis oil upgrading for co-processing in standard refinery units*. (PhD thesis), University of Twente, Enschede.

EBTP (2015). *Bio-SNG (Synthetic Natural Gas) and Gasification Technologies*. Retrieved from http://www.biofuelstp.eu/bio-sng.html.

Ekonomifakta. http://www.ekonomifakta.se/Fakta/Energi/Styrmedel/Konsumtionsskatter-pa-diesel/. 2016 [cited 2016 0128].

Eliasson et al. *Flisning av bränsleved och delkvistad energived med en stor trumhugg*–CBI 6400, Eliasson et al., Skogforsk 2014

Energimyndigheten, 2014. ER2014:10 Energiindikatorer 2014 Uppföljning av Sveriges energipolitiska mål.

Energimyndigheten, 2016 http://www.energimyndigheten.se/fornybart/hallbarhetskriterier/hallbarhetslagen/fragor-och-svar/vaxthusgasberakning/ Accesed: 2016-06-13.

FRAM. *FRAM Final report Application area: Model mills and system analysis*, FRAM Report No 70, 2005, STFI-Packforsk: Stockholm, Sweden.

Fredén J. *Analysis and calculations of emisson factors for green house gases*, in Department of Energy and Technology, 2010, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Gode et al. 2011, *Emissioner från transport av biodrivmedel och flytande biobränslen, Beräkningsexempel enligt STEMFS 2011:2*.

Gode J, Martinsson F, Hagberg L, Öman A, Höglund J, and Palm D. Miljöfaktaboken 2011 *Uppskattade emissionsfaktorer för bränslen, el, värme och transporter*. 2011, Värmeforsk, Stockholm.

Gunnarsson I. Personal communication with Ingemar Gunnarsson, Process Engineer, Göteborg Energi, 2015-11-11.

Göteborg Energi. http://gobigas.goteborgenergi.se/ 2016-04-15.

Wansbrough H, Grant R and Grant C. *Grant and Hockh's Chemical Dictionary* (5th ed.); McGraw-Hill Book Company, 1987.

Held J (2013). *Small and medium scale technologies for bio-SNG production*. Retrieved from http://www.sgc.se/ckfinder/userfiles/files/SGC281.pdf

Heyne S and Harvey S. *Impact of choice of CO2 separation technology on thermo-economic performance of Bio-SNG production processes.* International Journal of Energy Research 2014;38(3):299-318.

Heyne S and Harvey S. *Production of synthetic natural gas from biomass - Process integrated drying*, in 22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems2009, p. 1877-1886.

Heyne S, Seemann M, and Harvey S. *Integration study for alternative methanation technologies for the production of synthetic natural gas from gasified biomass*, in Chemical Engineering Transactions. 13th International Conference on Process Integration, PRES 20102010, p. 409-414.

Heyne S, Thunman H, and Harvey S. *Extending existing combined heat and power plants for synthetic natural gas production*. International Journal of Energy Research 2012;36(5):670-681.

Hjerpe C-L (2015). [ÅF Industry AB, Senior Consultant].

Holmgren K, Eriksson E, Olsson O, Olsson M, Hillring B, and Parikka M. *Biofuels and climate neutrality - system analysis of production and utilization*. 2007, Elforsk, Stockholm, Sweden.

Holmgren K M, Berntsson T S, Andersson E and Rydberg T. *The influence of biomass supply chains and by-products on the greenhouse gas emissions from gasification-based bio-SNG production systems.* Energy 2015;90, Part 1:148-162.

Holmgren K M. *Integration Aspects of Biomass Gasification in Large Industrial or Regional Energy Systems - Consequences for Greenhouse Gas Emissions and Economic Performance*, 2015. Institutionen för energi och miljö Industriella energisystem och –tekniker, Chalmers tekniska högskola.

Holmgren K M et al. *Heat Recovery Aspects of Importance for the Product Mix and GHG Emission Reductions in a Bio-SNG System*, in 17th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction – PRES 2014 in Prague, Czech Republic 2014, Prag.

Håkansson Å (2015). [Preem, Business Developer]

IEA BIOENERGY, Task 34: EXCO: 2007:01 Annual Report 2006.

Isaksson J, Åsblad A and Berntsson T. *Influence of different pretreatment methods on biomass gasification and production of fischer-tropsch crude integrated with a pulp and paper mill*, in Chemical Engineering Transactions 2013. p. 559-564.

Jahirul Mohammad I. et al. *Biofuels Production through Biomass Pyrolysis - A Technological Review.*

Johansson I, Larsson S, and Wennberg O. *Drying of bio fuel utilizing waste heat*. A4-312. ISSN 0282-3772, 2004, Värmeforsk.

Jones S B et al. PNNL-18284. *Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case.*

KAM. KAM-report A100, *Final report from the Ecocyclic pulp mill programme*, 2003, STFI, Stockholm, Sweden.

Kopyscinski J, Schildhauer T J & Biollaz S M A (2010). *Production of synthetic natural gas (SNG) from coal and dry biomass – A technology review from 1950 to 2009*. Fuel, 89(8), 1763-1783. doi:http://dx.doi.org/10.1016/j.fuel.2010.01.027

Laskar D D et al. *Pathways for biomass-derived lignin to hydrocarbon fuels*. Biofuels, Bioproducts and Biorefining, 2013. 7(5): p. 602-626.

Mani S. *A systems analysis of biomass densification process, in Chemical and Biological Engineering* 2005, The University of British Columbia: https://circle.ubc.ca/handle/2429/17106.

Marton S (2013). *Renewable ethylene - A review of options for renewable steam cracker feedstocks*. (MSc thesis), Chalmers University of Technology.

Matar S & Hatch L F (2001). *Chemistry of Petrochemical Processes* (Second Edition). Woburn: Gulf Professional Publishing.

Network for Transport and Environment,NTM, *Road transport*, version 2010-06-17 (100603 NTM INT ROAD) (Source: HBEFA 3.1, processed by NTM.)

Network for Transportation and Environment, NTM, *Rail transport*, version 2008-03-14 (080314 NTM INT RAIL)

Neves D et al. *Characterization and prediction of biomass pyrolysis products*. Progress in Energy and Combustion Science, 2011, 37(5): p. 611-630.

Nordpool 2015. http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/SYS1/Monthly/?view=table Accessed: 2016-03-16.

Olsson M R and Berntsson T. *Comparing evaporation plants using excess heat with conventional plants: A simulation study*. Submitted to BioResources Online Journal 2009.

Persson M. *Löfven tvingas backa om kilometerskatten*. ÖP, 2015. http://www.op.se/opinion/ledare/lofven-tvingas-backa-om-kilometerskatten. Accessed: 2016-03-17.

Pettersson K and Harvey S. *Comparison of black liquor gasification with other pulping biorefinery concepts - Systems analysis of economic performance and CO 2 emissions*. Energy 2012;37(1):136-153.

Ringer M et al. NREL/TP-510-37779, 2006. *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis*.

Swedish Energy Agency (SEA). *Wood fuel- and peat prices (Trädbränsle- och torvpriser)*, 2015. Eskilstuna, Swedish Energy Agency and Örebro, Statistics Sweden.

SFIF. *Database of member companies*, 2012. Swedish Forest Industries Federation (August 2012).

SKM. *El-certificate price history*, 2013. Svensk Kraftmäkling (SKM).

Stephen J D, Mabee W E and Saddler J N. *Biomass logistics as a determinant of second-generation biofuel facility scale, location and technology selection*. Biofuels, Bioproducts and Biorefining, 2010. 4(5): p. 503-518.

Sunpine (2015). Retrieved from http://www.sunpine.se/en/

Svanberg M et al. *Analysing biomass torrefaction supply chain costs*. Bioresource Technology, 2013. 142: p. 287-296.

Tapasvi D et al. *Torrefaction of Norwegian Birch and Spruce: An Experimental Study Using Macro-TGA*. Energy & Fuels, 2012. 26: p. 5232-5240.

Thek G and Obernberger I. *The Pellet Handbook: The Production and Thermal Utilization of Biomass Pellets*. 2010: Routledge.

Uslu A, Faaij A P C and Bergman P C A. *Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation*. Energy, 2008, 33(8): p. 1206-1223.

Weiland F et al. *Entrained flow gasification of torrefied wood residues*. Fuel Processing Technology, 2014. 125: p. 51-58.

Wetterlund E et al. *Optimal localisation of next generation biofuel production in Sweden – Part II*. 2013: the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). 93.

Wiberg R and Forslund M. *Energiförbrukning i massa- och pappersindustrin 2011*. 2011: Skogsindustrierna.

Ycharts 2015. https://ycharts.com/indicators/europe_natural_gas_price. Accessed: 2016-03-16

12 APPENDIX 1: VALUE CHAIN OPTIONS AND SCREENING CRITERIA USED IN THE SCREENING PHASE

Please note that the options listed below are not intended to be a complete list of possible options, but just the options identified by the partners during the screening phase.

12.1 RAW MATERIALS

a) From forest

- Forest residues
- Stumps
- Thinnings
- Pulp wood

b) From byproduct from pulping

- Bark
- Lignin
- Sawdust
- Black liquor
- Biosludge
- Chips/reject
- Tall oil

12.2 TRANSPORT OF RAW MATERIAL

- Truck
- Train
- Ship
- Combinations
- Upgrading on site in mobile plants (out of scope)

Aspects to consider

- Reloading
- Storage

12.3 INTERMEDIATE PRODUCT

a) Bio SNG value chain

- Chips (torrefied, dried or raw) from forest raw material
- Chips/reject (torrefied, dried, or raw) from pulp mill
- Pellets (white, brown or black)
- Bark powder

- Lignin
- Biocoal from biosludge
- Pyrolysis oil
- Black liquor
- Synthesis gas

b) Refinery value chain

- Chips (torrefied, dried or raw) from forest raw material
- Chips/reject (torrefied, dried, or raw) from pulp mill
- Pyrolysis oil
- Bio oil (from other process than pyrolysis)
- Tall oil or crude tall oil diesel
- Lignin
- FT crude
- Ethanol
- Methanol

12.4 PRODUCTION OF INTERMEDIATE

a) Bio SNG value chain

- Intermediate: dried biomass
  - Drying
- Intermediate: biocoal
  - Torrefaction (different methods)
  - HTC (hydrothermal carbonization)
- Intermediate Pyrolysis oil
  - Fast pyrolysis (different methods)
  - Slow pyrolysis
- Intermediate: Lignin
  - LignoBoost
  - Membrane filtration
  - Organosolv
- Intermediate: Synthesis gas
  - Drying + gasification (different methods)

b) Refinery value chain

- Intermediate: dried biomass
  - Different drying technologies
- Intermediate: Biocoal
  - Torrefaction
  - HTC
- Intermediate Lignin
  - LignoBoost
  - Ultrafiltration
  - Organosolv
- Intermediate: pyrolysis oil, bio oil
  - Pyrolysis
  - Fast pyrolysis
  - Fast catalytic pyrolysis
  - Solvolysis (organic acid or alcohol)
  - Hydrolysis
- Intermediate: Crude tall diesel
  - Estrification
- Intermediate: Methanol
  - Gasification + steam reforming
- Intermediate: Ethanol
  - Hydrolysis + enzymatic treatment (or stem explosion) + fermentation

12.5 TRANSPORT OF INTERMEDIATE

- Truck
- Train
- Ship
- Combinations
- Pipeline

Aspects

- Reloading
- Storage

12.6 CONVERSION TO END PRODUCT

a) SNG value chain

- Intermediate: chips, pellets
    - Atmospheric fluid bed gasification
    - Indirect gasification
- Intermediate: torrefied biomass
    - Atmospheric fluid bed gasification
    - Pressurised downstream solid fuel gasification
- Intermediate: lignin
    - Pressurised downstream solid fuel gasification
- Intermediate: Lignin
    - Pressurised downstream solid fuel gasification
- Intermediate: Pyrolysis oil
    - Pressurised downstream liquid fule gasificaton

b) Refinery value chain

- Intermediate: lignin, torrefied biomass, bio coal
    - Slurry hydrocracker
    - HDO
    - Pyrolysis (fast, fast catalytic)
    - Solvolysis
    - Hydrothermal conversion
    - Suspension gasification for production of FT crude
- Intermediate: Crude tall diesel
    - Pretreatment + distillation
    - Hydro slurry cracker
- Intermediate: lignin oil, bio oil, pyrolysis oil
    - HDO
    - Cracking (hydrocracking, iso-cracking, etc)
    - Distillation
    - Direct mixing
    - Suspension gasification
- Intermediate: Bio SNG
    - Production of H2
- Intermediate: Ethanol, methanol
    - Direct mixing

12.7 SCREENING CRITERIA

12.7.1 Feedstock raw material

- Available in large amounts
- Cost
- Possible to feed into biomass converter with high availability
- Impurities
- Density (mass)
- Competition for other use

12.7.2 Raw material transport options

- Low specific fuel consumption, and other emissions
- Possibility to use in many typical locations
- Possible to handle large volumes
- Cost per km
- Cost for reloading (managing and holding time)
- Cost for local storage (storage facility and holding time)

12.7.3 Intermediate product

- Energy density
- Safety issues
- Possible to handle efficiently at refinery site (safety, existing know-how, can utilise existing infrastructure etc)
- Yield on conversion to refinery/SNG feed
- Proven product
- Market for alternative use (competition)

12.7.4 Intermediate conversion process

- Intermediate product suitable for conversion at refinery/SNG
- Technical maturity
- Available in large scale
- Expected availability
- High yield (if to contribute significantly to bulk production)
- Recovery of by-products and residual energy in pulp mill is possible
- Investment cost
- Operating cost
- Safety aspects

- Additional feed available at pulp mill or other site for upgrading (H2, alkohol, steam etc)
- Waste material to handle or deposit
- Emissions (effluent and air)

12.7.5 Transport of Intermediate

- Low specific fuel consumption, and other emissions
- Possibility to use in many typical locations
- Possible to handle large volumes
- Cost per km
- Cost for reloading (managing and holding time)
- Cost for local storage (storage facility and holding time)

12.7.6 Final conversion to end product

- Compatible with refinery operation
- Safety aspects
- Additonal feed products available at site
- By-products and residual energy can be integrated in the refinery/SNG plant operation
- Similar to other refinery/SNG plant operation. Can use existing know-how
- Expected investment cost
- Operating cost
- Yield
- Quality of product
- Waste material to handle or deposit
- Emissions (effluent and air)
- Technical maturity

13 APPENDIX 2: SCREENING OF VALUE CHAIN OPTIONS

13.1 VALUE CHAIN FOR PRODUCTION OF BIO SNG THROUGH GASIFICATION VIA INTERMEDIATE

13.1.1 Selection of raw material

13.1.1.1 Selection of raw material from forest

The forest raw material selected is ***forest residues (branches and tops)***.

Motivation:

- Large potential (>20 TWh/year)
- Is a residue from other works (timber and pulp wood harvesting)
- Easy access through available forest roads after timber and pulp wood harvesting
- Acceptable cost
- Competition for other use exists but will be dependent on ability to pay

On the negative side is the low mass density, impurities such as sand and the inhomogeneity that is likely to affect the downstream process availability and maintenance cost.

Additional use of ***stumps*** is included, with the motivation that it makes possible a high extraction potential to support supply of raw material for a large bioSNG plant (almost double, potential estimated to 19-21 TWh/year and 27 TWh in short and 30-50 year perspective, which is in the same range as for forest residues). However, it should be mentioned that this scenario requires that the demand for biomass (forest residues) will increase to the extent that it will be cost efficient to start utilising stumps in a large scale within the chosen time perspective. The ecological aspects related to outtake of stumps, need of additional machinery and related costs are still under discussion.

Pulp wood was excluded due to the high price as a consequence of competition for use within the pulp and paper industry.

Wasted round wood was included as a minor case even though the relatively low general potential. The motivation is that the availability of wasted round wood is high today and the next couple of years due to storm felling in recent years.

13.1.1.2 Selection of raw material from by-products from the pulp mill

It was selected to include sawdust as a low priority option in this investigation. The reason for not excluding sawdust was that it is used for SNG production by Göteborg Energi today, and the process is known to work, and data is available. On the negative side is the high price due to availability and competition for other use (pellets, board production). However, it could serve as a reference for the other options. Additionally bark was also included as an option after some serious consideration, see reasoning below:

- Bark was initially not selected due to its high alkali content (even though solutions for this problem is being investigated) and problem to use in the low temperature gasifier selected for syngasgas production with high methane content, even though the potential is judged as high. The data availability for use of bark for SNG production is sparse, making it difficult to study this option in any detail without large uncertainties. In an additional evaluation it was anyway decided to include the bark as it is a fuel that exists in excess today at some pulp mills.

The following options were not selected based on the following motivation:

- Lignin was not selected due to its high S-content and the associated costs for S-removal before methane conversion, even though the potential availability is high
- Sludge and reject was not selected due to low potential
- Tall oil was not selected due the completion for other use (use in production of transportation fuels)

13.1.1.3 Transport of raw material from forest

The transportation option selected for transportation of the selected raw material forest residues is ***truck*** transport.

Motivation:

- Flexible solution that can manage a raw material that is spread in a large geographical area
- Can handle large volumes
- Can be used in all locations
- Relatively easy loading and discharging operation

Train transport is possible from a centrally located collection station, but would not be an option for local transport of the raw material. Ship transport is only possible in some geographical locations with access to waterways and would also require transport to a local collection point. Bothe train and ship transport will most likely require supplementary transport by truck which will add transportation, handling and storage costs.

13.1.2 Selection of intermediate

The intermediate selected for the value chain is dried wood chips, based on the selection of forest residues as raw material and bio SNG as final product.

Motivation:

- Low cost
- Possibility of high overall yield to bio syngas and high methane yield in final bio syngas to methanation step

Torrefied biomass would be an alternative option that could be investigated as a variation due to its higher energy density, improved handling properties during final conversion in gasification combined with decreased problems related to tar formation. It can also be efficiently stored during longer time periods.

Pellets are included as option for sawdust as raw material, even though its high price.

Lignin is excluded as it contains too much sulphur and would require high costs for sulphur removal, and ***pyrolysis oil*** is expected to be too expensive.

13.1.3 Process for production of intermediate

Drying is selected for producing the dried alternative intermediate. Selection of drying technology is left to later work.

Torrefaction is selected as process for production of the torrefied biomass. Selection of torrefaction technology is left to later work.

13.1.4 Transport of intermediate

Train transport is selected for transport of the intermediate.

Motivation:

- Transport between centrally located intermediate production sites and SNG production plant with high probability of existing train infrastructure in place
- Low transport cost
- Possible to handle large volumes

On the negative side is the land footprint requirement for train switch yard and local storage and handling.

The conditions that have to be fulfilled for ***Ship t***ransport to be competitive will briefly be investigated. However this option is expected to be more site-specific since it is not obvious that bio SNG production sites will be located at large harbours and natural waterways to connect intermediate production site with the SNG production facility.

Truck transport is not selected due to high transport cost and higher fuel consumption and emissions.

13.1.5 Conversion technology to bio SNG

An ***indirect atmospheric fluid bed gasifier*** combined with methane conversion to syngas is selected for the final conversion of the main intermediate torrefied biomass to bio SNG.

Motivation:

- High yield of methane and high methane concentration in the syngas results in low requirements on the syngas methane converter
- High technical maturity

However, atmospheric operation gives large footprint and need of parallel units.

The same technology will be considered for conversion of the alternative intermediate torrefied biomass. However, less information is available on gasification of torrefied biomass, making, which increases the uncertainties in the results.

Pressurised, oxygen blown low temperature solid fuel gasification is a variation to be investigated which could have the advantage of smaller footprint and avoiding parallel gasification trains in a high capacity plant. However, it is excluded from this study with the motivation that fuel feeding will be more difficult, the increased cost due to oxygen production. In addition, it is not expected that the selection of gasification technology has any major influence the conclusions related to the pros and cons of biofuel intermediates, other than that the conversion rate in the final conversion to a large part governs the relative influence of the transport of raw material and intermediate on the specific transport fuel consumption and associated emissions per unit of final product produced.

High temperature solid fuel gasification is excluded due to the lower yield of methane in the syngas as the last conversion step includes methanation.

Entrained flow solid fuel gasification is excluded due to its technology advantage being pressurized at high temperature where high temperature is not desired for SNG.

13.1.6 Further reduction of options

In order to further reduce the complexity of the evaluation, it was decided to take the following approach:

- Waste round wood is included in the analysis by making a sensitivity analysis on the forest residue analysis with respect to cost for raw material and outtake density
- Torrefaction is at lowest priority since it is questionable if torrefied raw material is suitable for syngas production as volatile components are removed.

13.2 VALUE CHAIN FOR PRODUCTION OF REFINERY RAW MATERIAL

13.2.1 Selection of raw material from forest

The forest raw material selected is ***forest residues (branches and tops)***.

Motivation:

- Large potential (>20 TWh/year)
- Is a residue from other works (timber and pulp wood harvesting)
- Easy access through available forest roads after timber and pulp wood harvesting
- Acceptable cost
- Competition for other use exists but will be dependent on ability to pay

On the negative side is the impurities such as sand and the inhomogeneity that is likely to affect the downstream process availability and maintenance cost.

Additional use of ***stumps*** will be investigated as a variation, with a consequential increased outtake density, since the potential from outtake of stumps is in the same range as outtake of forest residues. However, the ecological aspects related to outtake of stumps, need of additional machinery and related costs are still under discussion, so therefore this case will only be a subcase to the main case with outtake of forest residues.

Raw material from forest	Positive	Negative
Forest residues (branches and tops)	-large potential > 20 TWh/year -acceptable cost -competition for other use exists for low value applications, but depend-ing on ability to pay	-inhomogeneous -impurities -low energy density
Stumps	-large potential > 20 TWh/year -acceptable cost -competition for other use exists for low value applications, but depend-ing on ability to pay	-inhomogeneous -impurities (more than branches and tops) -low energy density -requires new machinery to get out -ecological concerns, nutrients
Pulp wood	-homogeneous -lower impurities -high energy density	-high competition for other use -high cost
Wasted round wood	-homogeneous -lower impurities -high energy density	-low potential

13.2.2 Raw material from by-products from the pulp mill

It was selected to investigate ***black liquor*** and ***tall oil*** as raw material based on by-products from the pulp mill.

Motivation:

Raw material from pulp mill by-products	Positive	Negative
Bark	-high potential	-high alkali – alkali transferred to product -operational problems likely, high OPEX expected
Black liquor	-high potential -homogeneous -high energy density	-only lignin available for external use, requires extra step for lignin separation -high sulphur
Wood chips (spån)	-homogeneous -	-low potential -high cost -competition with other use (pellets, boards)
Sludge	-low or negative cost	-low potential -inhomogeneous -difficult to handle (high water content etc.)
Chips/reject		-low potential
Tall oil	-used already today, high technical maturity -easy conversion to transportation fuel	-potential already used

13.2.3 Transport of raw material from forest

The transportation option selected for transportation of the selected raw material forest residues and stumps is ***truck*** transport. This is mainly due to the high flexibility of this option, and it is suitable when collecting material in the local area surrounding the pulp mill.

Motivation:

Transport of raw material from forest	**Positive**	**Negative**
Truck	-flexible -can handle large volumes -can be used in all locations-does not require reload	-high cost -high emissions -high specific fuel consumption
Train	-low cost -low fuel consumption -low emissions -can handle large volumes	- requires train infrastructure close by central collection station -requires reload from truck and central collection point
Ship	-low cost -low fuel consumption -low emissions -can handle large volumes (perhaps larger than required?)	-requires harbour access at close-by reloading point -only an option in some geographical areas
Combinations	-lower cost than truck transport	-lower flexibility -will be required in the case of train and ship transport

13.2.4 Selection of intermediate

The intermediate selected for the value chain is bio oil in the case of ***forest residues (branches and tops)*** as raw material, ***lignin oil*** in the case of black liquor as raw material and ***raw tall diesel*** in the case of tall oil.

Motivation:

Intermediate from forest residues (branches and tops)	**Positive**	**Negative**
Dried biomass	-low cost	-low energy density -high transport cost -high fuel consumption for transport -high emissions during transport -difficult to process at refinery with today's technology low technical maturity -expected low yield at refinery conversion -safety issues during handling at refinery (dust explosion) -no infrastructure for handling of biomass at refinery -inhomogeneous
Torrefied biomass	*Same as dried biomass*	*Same as dried biomass*
Bio oil (including pyrolysis oil)	-similarities to other raw materials used in refinery (compared to solid biomass) -liquid product -high energy density	-high oxygen content -viscosity? -content of heavy products? -corrosion risk in refinery
Ethanol	-can be mixed directly with gasoline/diesel	-expected low conversion efficiency(<20%)
Methanol	-can be mixed directly with gasoline/diesel	-expected high production cost, re-quires gasification of raw material -acceptance issues -safety issues
Higher alcohols	-can be mixed directly with gasoline/diesel. -very effective for octane and cetane boosting	-competition by ethanol and metha-nol has they have octane and cetane boosting capability -fossil alternative at low cost
Final intermediate from black liquor from kraft cooking	**Positive**	**Negative**
Lignin oil (bio oil from conversion of lignin, depolymerised lignin in liquid form)	-similar to refinery feed, can be mixed into refinery production -only requires processing of side-stream -conventional recovery process in pulp mill remains untouched	-high content of sulphur -high content of oxygen (but lower than oil from forest residues) -high content of alkali metals -corrosion risk in refinery (but lower than forest residues since no sugars)
FT crude	- Similar to refinery feed, can be mixed into refinery	-requires introduction of black liquor gasification as replacement of today's recovery boiler (major tech-nology change with high barrier) -expected high cost

To produce lignin oil from black liquor requires an additional process step where lignin is separated from black liquor.

Primary Intermediate from black liquor	Positive	Negative
LignoBoost lignin	- commercial process - low investment and operating cost -	- larger fluctuations in quality of lignin
Kraft lignin from filtration	- not commercial yet, however demonstrated in industrial setting -	- risk of fouling of membrane in industrial setting - high investment cost
Kraft lignin from liquid-liquid extraction	- the process has just been proposed and is not tested yet.	- no information available for assessment
Intermediate from tall oil	**Positive**	**Negative**
Tall oil (no further processing at pulp mill)	-use current process in pulp mill -low cost, central processing of larger amounts at refinery	-no return of tall oil pith for utilisation in pulp mill
Raw tall oil diesel	-tall oil pith can be utilised in pulp mill	-low volume to be processed at each pulp mill give high cost

13.2.5 Process for production of intermediate

Fast pyrolysis is selected for production of bio oil from forest residues and lignin. Detailed selection of pyrolysis concept is left to later work in the project.

Process for production of bio oil	Positive	Negative
Pyrolysis (slow)		-low conversion yield to oil
Fast pyrolysis	-high conversion yield to oil	-high oxygen content (higher than catalytic pyrolysis) -oil is highly corrosive -requires special handling equipment and storage tank materials -there will be need to handle char when using torrefied biomass feed
Fast catalytic pyrolysis	-high conversion yield to oil -lower oxygen content in oil	-risk of catalyst deactivation -low data availability -low technical maturity
Solvolysis	-high yield expected	-low level of aromatics -low data availability -low technical maturity
Hydrothermal conversion		-low data availability -low technical maturity
Process for production of tall oil diesel	**Positive**	**Negative**
Distillation/fractionation	-low cost for production (CAPEX + OPEX)	-
Distillation/fractionation and esterification		-higher cost

13.2.6 Transport of intermediate

Ship transport is selected for transport of the intermediate. In this case the selected intermediate is a liquid which has its advantage for handling with marine vessels (pumping) and storage in the harbour area (tank storage)

Motivation:

Transport of intermediate	Positive	Negative
Truck	-flexible -can handle large volumes -can be used in all locations-does not require reload	-high cost -high emissions -high specific fuel consumption
Train	-low cost -low fuel consumption -low emissions -can handle large volumes	- requires train infrastructure close by pulp mill and refinery
Ship	-low cost (lower than train) -low fuel consumption -low emissions -can handle large volumes (perhaps larger than required here?) -all refineries in Sweden are located by harbours and use ship transport as the main option for transport of raw material -handling by pumping -tank storage	-requires harbour access at pulp mill or close to pulp mill (is the case for most pulp mills) -only an option in some geographical area

13.2.7 Conversion technology to transform to refinery feed product

Hydrodeoxygenation and hydrocracking is selected for the treatment of the lignin oil and bio oil intermediate.

Conversion technology at refinery, bio oil, lignin oil	Positive	Negative
HDO/hydrocracking	-well known technology -diesel product can be used in all diesel vehicles	-expensive with hydrogen -the use of bio-components requires adoption of materials.
Esterification	-well known technology	-requires fatty acids as base -limitation in diesel specification (7%)
Distillation + HDO		-distillation is not expected to be required; the entire fraction can be treated. - adds investment and operating costs

For the conversion of tall oil diesel hydrodeoxygenation is selected

Conversion technology at refinery, tall oil diesel	**Positive**	**Negative**
HDO/hydrocracking	-well known technology -diesel product can be used in all diesel vehicles	-expensive with hydrogen -the use of bio-components requires adoption of materials.
Esterification	-well known technology	-requires fatty acids as base -limitation in diesel specification (7%)
Direct blending		

13.3 FURTHER REDUCTION OF OPTIONS

In order to further simplify and reduce the complexity of the evaluation it was decided to perform the analysis of using stumps as raw material as a sensitivity study with respect to price and outtake density based on the forest residue value chain.

14 APPENDIX 3: INPUT DATA – REFINERY VALUE CHAINS

Table 26. Prices and assumptions refinery value chains.

Prices & Assumptions		Unit
Forestry residues incl. chipping	16	EUR/MWh
Electricity	40	EUR/MWh
Natural gas	35	EUR/MWh
Fuel oil	40	EUR/MWh
Hydrogen	2,1	EUR/kg
Hydrogen CO2-fee	0,1	EUR/kg
Ash desposal	100	EUR/ton
Labour	60 000	EUR/manyear
CO2	90	EUR/ton
H2SO4	80	EUR/ton
NaOH	400	EUR/ton
O&M cost	4	% of investment
EUR/SEK	9	
EUR/USD	1,15	
Annuity factor - investment cost	0,1	
Operating hours per year	7840	hours
Pulp mill production	700 000	Adt/year

Table 27. Low heating value of raw material.

LHV		Unit
Forestry residues	19.4	MJ/kg DS (dried solids)
Lignin	25	MJ/kg DS (dried solids)
Crude tall oil	37.3	MJ/kg DS (dried solids)

Table 28. Input data and assumptions, pyrolysis step.

Pyrolysis		
YIELD (raw material → pyrolisys oil)		
Raw material: forest residues	0.65	MWh oil / MWh biomass
Raw material: lignin	0.68	MWh oil / MWh lignin
Raw material: tall oil	0.62	MWh oil / MWh tall oil
ELECTRICITY OUTPUT		
Raw material: forest residues	0.03	MWh/MWh PO
Raw material: lignin	0.06	MWh/MWh PO
Raw material: tall oil	0.00	MWh/MWh PO
INVESTMENT COSTS: a*[MW]^b; b=0.7		
a: raw material: forest residues, REF_R	3.2	
a: raw material: forest residues, PYR3, PYR1	2.8	
a: raw material: lignin	2.8	
a: raw material: tall oil	0.03	

Table 29. Input data and assumptions, HDO-treatment.

HDO-treatment		
YIELD (pyrolisys oil → HDO oil)		
Raw material: forest residues	0.98	MWh HDO oil / MWh oil
Raw material: lignin	0.98	MWh HDO oil / MWh oil
Raw material: tall oil	1.06	MWh HDO oil / MWh oil
OXYGEN IN PYROLYSIS OIL		
Raw material: forest residues	40	%
Raw material: lignin	20	%
Raw material: tall oil	12	%
INVESTMENT COSTS: a*[MW]^b; b=0.65		
a: raw material: forest residues	3.9	
a: raw material: lignin	3.9	
a: raw material: tall oil	3.8	

Table 30. Input data transportation.

Transportation cost **EUR/GWh: a + b*d; d (distance, km)**	
TRUCK	
a	866
b	30.4
SHIP	
a	1918
b	0.63

Table 31. Carbon dioxide emissions.

Carbon dioxide emissions		
Transport forest residues (Diesel) 50 km	1,47	kg CO2/MWh_FR
Transport pyrolysis oil (Diesel) 50 km	1,51	kg CO2/MWh_PO
Transport lignin (Diesel) 50 km	1,52	kg CO2/MWh_lig
Electricity	102	kg CO2/MWh
FR transport emissions	29,4	g CO2/MWh, km
Fuel gas / Natural gas	216	kg CO2/MWh
Hydrogen	9	kg CO2/kg
Forest residue outtake	1,5	kg CO2/MWh
Pyrolysolja	3,32	g CO2/MWh, km
Ligninolja	2,77	g CO2/MWh, km

15 APPENDIX 4: TRANSPORT

The table below summarizes the different parts of the different value chains where truck is used for transport:

Table 32. Transport by truck.

Value chain	Feedstock transported	Average distance transported (km)
Bio-SNG reference value chain	Chipped forest residues	100 (100 MW SNG) 173 (300 MW SNG)
Bio-SNG value chain 2	Chipped forest residues	35-70 (100 MW SNG; 1-4 mills) 43-122 (300 MW SNG; 1-8 mills)
REF_R	Chipped forest residues	123
PYR1	Chipped forest residues	87
PYR3	Chipped forest residues	50

The table below summarizes the different parts of the different value chains where train is used for transport:

Table 33. Transport by train.

Value chain	Feedstock transported	Average distance transported (km)
Bio-SNG reference value chain	Bark	500
Bio-SNG value chain 1	Pellets	500
Bio-SNG value chain 2	Dried forest biomass	500

The table below summarizes the different parts of the different value chains where ship is used for transport:

Table 34. Transport by ship.

Value chain	Feedstock transported	Average distance transported (km)
Refinery value chain with bio-oil, one pulp mill	Forest-based bio-oil	500
Refinery value chain with bio oil, three pulp mills	Forest-based bio-oil	500
Refinery value chain with lignin oil	Lignin oil	500
Refinery value chain with crude tall oil	Crude tall oil	2000

15.1 TRANSPORT COSTS

Transport costs for transport by truck and train have been derived from Benjaminsson et al. (2013). Benjaminsson et al have calculated and compared the costs for transporting chipped forest residues, pellets and pyrolysis oil with train and truck. The present study only uses the cost estimates for transport of chipped forest residues with truck and for transport of chipped forest residues and pellets with train.

Benjaminsson's et al. transport costs include costs for loading and unloading (terminal costs) the feedstock. Moreover, their calculations assume a truck with a maximum capacity of 40 tons and 115 m^3 and a train with a maximum capacity of 946 tons and 2760 m^3.

The cost for truck transport of chipped forest residues from the forest have been taken directly from Benjaminsson et al. who use an energy density of 2,96 GJ/m^3 corresponding to about 50% moisture content in the residues. However, for train transport of dried chipped forest residues and pellets, the costs have been recalculated for the energy densities used in this study (up- or downscaling of Benjaminsson's et al. fixed and variable costs). All costs have been converted from SEK to EUR using a conversion rate of 9 SEK/EUR.

As costs for shipping vary largely from shipment to shipment estimating the cost for ship transport was much more difficult than for truck and train transport. An estimated total cost for ship transport of raw tall oil was provided by Preem (Håkansson 2015). This cost assumes transport in a ship carrying 6000 m^3 of crude tall oil. The distribution between fixed and variable costs was derived from Börjesson & Gustavsson (1996). The cost for lignin oil and bio oil were calculated from the cost for raw tall oil by rescaling with the energy densities as a basis.

15.2 CO_2 EMISSIONS FROM TRANSPORT

Truck CO_2 emissions were calculated using data from the Network for Transport and Environment (NTM INT Road, 2010). The truck was assumed to be of EURO class 5 using diesel MK1 including 5% RME. Moreover, it was assumed to drive with no load in one direction and fully loaded in the other (corresponding to carrying 50% of the load the entire distance). The truck used for transporting forest residues from the forest was assumed to weigh 25 tons without load (Henrik von Hofsten, Skogforsk 2015). When fully loaded with chipped forest residues, the truck weighs an additional 33.35 tons (115 m^3 residues with a density of 0,29 ton/m^3 (Benjaminsson et al. 2013). Thus, a total weight of 58.35 tons has been used to scale down the specific fuel consumption listed in the NTM INT Road handbook where the truck weight is 60 tons. However, as the truck will drive in rough terrain in order to collect the forest residues, it is assumed to consume about 10% more fuel when driving in the forest than on rural roads (Henrik von Hofsten, Skogforsk 2015).

Train CO_2 emissions were calculated using data from the Network for Transport and Environment (NTM INT Rail 2008). The gross weight of the train was assumed to be 1520 tons (Benjaminsson et al. 2013).Moreover, the train was assumed to have electrical traction. The terrain was assumed to be flat (NTM Rail 2008) and chipped residues and pellets are bulk goods. The CO_2 emissions per kWh electricity are assumed to be the same as the emissions for the Swedish fuel mix for electricity generation, 3.6 g/kWh.

Ship CO_2 emissions were calculated by using data from Gode et al. (2011) where emissions were calculated for transport of tall oil pitch between a Swedish harbour and Rotterdam, a distance of 1490 km. The ship in the reference case had a maximum carrying capacity of 5900 tons and was assumed to be fully loaded in one direction and empty in the other (corresponding to carrying 50% of the load the entire distance). Moreover, the ship was assumed to consume 0.024 tons of HFO per kilometre. In this study, we have assumed that transporting bio oil, lignin oil and raw tall oil by ship will have the same fuel consumption as transporting tall oil pitch by ship.