REPORT

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OPTIMAL LOCALISATION OF NEXT GENERATION BIOFUEL PRODUCTION IN SWEDEN – PART II

Report from an f3 project

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PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contribute to the development of sustainable fossil free fuels for transportation. The centre is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see www.f3centre.se).

The collaborating partners in this project have been Linköping University, Chalmers University of Technology, Bio4Energy (Swedish University of Agricultural Sciences and Luleå University of Technology), SP Technical Research Institute of Sweden and Innventia, with Luleå University of Technology as project leader.

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This project is a continuation of a previous f3 project (Optimal localisation of next generation biofuel production in Sweden, f3 Report 2013:8). This report has been written as to be comprehensible without reading the report from the earlier f3 project. For this reason, some parts are identical to the previous report.

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SUMMARY

Sweden with its rich forest resources is of significant interest concerning future large scale production of next generation biofuels. Large plant sizes, however, increase the required feedstock supply area and put significant demands on the supply chain. Co-location with other industry provides an opportunity for higher system efficiencies, but also puts additional requirements on the locations, as does competition for the available feedstock. Since production facilities for next generation biofuels are associated with very large investments, careful evaluation of possible plant locations is of utmost importance.

This report describes the continued development of the optimisation model BeWhere Sweden, which is a geographically explicit model for localisation of next generation biofuel production plants in Sweden. The model minimises the cost of the entire studied system, including costs and revenues for biomass harvest and transportation, production plants, transportation and delivery of biofuels, sales of co-products, and economic policy instruments. The model will thus choose the least costly pathways from one set of feedstock supply points to a specific biofuel production plant and further to a set of biofuel demand points, while meeting the demand for biomass in other sectors. Focus is on forest-based biomass and integration with industry, in particular with forest industry.

In this work BeWhere Sweden has been used to model four different roadmap scenarios for 2030 that are based on scenarios presented by the Swedish Environment Protection Agency in their report “Basis for a roadmap for Sweden without GHG emissions in 2050”. The roadmap scenarios used here take into account e.g. demand for transport, transport fuel and next generation biofuels, available forest biomass resources, biomass available for industrial purposes, biomass usage in other energy and industrial sectors, and energy market conditions. The primary objective has been to identify cost-effective types of biofuel production plant locations that are robust to various boundary conditions, in particular regarding energy market prices, policy instruments, investment costs, feedstock competition and integration possibilities with existing energy systems, and to provide a broader analysis of the model results regarding e.g. implications for policy makers and connections between different actors in the biofuel innovation system.

The roadmap scenarios have been focused on the transport sector and how future demand for advanced biofuels can be met by domestic production, using only domestic feedstocks. A detailed bottom-up approach to assess the spatial cost structure of harvesting roundwood, residues and stumps was applied to different scenarios for forest production and availability. Seven different next generation biofuel technologies were considered for integration with existing industry (pulp mills, paper mills, sawmills, refineries, combined heat and power (CHP) plants). Each industrial site was modelled individually, based on current and projected operation. Biomass use in other sectors was also modelled geographically explicitly. The roadmap scenarios encompassed two different next generation biofuel targets: 4 and 9 TWh per year, respectively.

The results show that the biofuel target can be realised in all modelled scenarios using only domestic biomass resources and by investment in new next generation biofuel plants (3-5 plants for the scenarios with low biofuel target, 6-9 plants for the scenarios with high

target). The implementation of next generation biofuel production in addition to the considered increase of the biomass use in other sectors would however require a significant increase in the use of forest residues (branches, tops and stumps), from the 14 TWh currently used annually, to 32-50 TWh/year (depending on biofuel target and biomass use in other sectors). This represents up to 97 percent of the techno-ecological potential.

The total capital requirement to meet the biofuel targets would be substantial – around 600-1,200 MEUR to meet the lower biofuel target, to around 1,300-2,400 MEUR to meet the higher target. The lower numbers represent the incremental investment costs, i.e. it is based on the assumption that the host industries would otherwise have made alternative investments (e.g. investment in black liquor gasification is assumed to be done instead of investment in a new recovery boiler). The difference between these numbers emphasise the significant reduction in capital requirement that results from considering the incremental investment costs, and that plants that are in a situation where they are going to replace existing technology are highly preferred, at least from a capital cost point of view. The specific incremental capital requirement would thus be on the order of 120-150 MEUR per TWh of annual biofuel production capacity. The resulting average biofuel production cost would be on the order of 70-80 EUR/MWh, if incremental capital costs are considered. The specific capital cost was found to make up around 25-40 percent of the total production cost, depending on the assumed annuity factor.

Black liquor gasification with dimethyl ether production (BLG-DME) and solid biomass gasification with production of synthetic natural gas (BMG-SNG) dominate the model results, due to the high biomass-to-biofuel system efficiency. The results also show that low need for transportation of biomass is important in the choice of plant location, with chemical pulp mills and sawmills appearing as the most attractive host industries. For some cases the biomass transported to the mill when biofuels are produced are approximately the same as the by-products transported from the mill when biofuels are not produced. Thus, the net increase in transportation cost could then be close to zero or even negative, depending on the transportation distances for the export and import of biomass.

Large plants could be expected to be more favourable due to economies of scale. However, the selected plants represent the entire scale range from large to small plants, despite the higher specific investment cost for smaller plants. A larger number of smaller plants to cover a given biofuel demand leads to lower total system cost due mainly to shorter net transport distances of both biomass and biofuel, despite the corresponding higher capital requirement. This effect is more pronounced in biomass restricted scenarios, which leads to the conclusion that biomass supply area and net biomass transportation costs are parameters of highest relative importance in the choice of optimal plant locations. High biomass prices and restricted biomass availability also stimulates BLG-DME over BMG-SNG, which further augments the significance of chemical pulp mills as host industries.

The results show that systems with a mix of biofuels in general display a lower system cost compared to more homogenous systems. This shows that future policies need to be carefully designed in order to allow for and promote a variety of technologies and fuels. The results also show that the capital requirement is significant, even though investment costs for commercial “Nth plants” have been considered. Since the analysed technologies still remain to be demonstrated on industrial scale, the estimated investment costs must however be viewed as fairly uncertain. These facts show the importance of initial financial support, increased knowledge and learning to facilitate the construction of first plants and attain an associated reduction of investment costs.

Currently, many process industries in Sweden are experiencing challenging conditions, in particular the mechanical pulp and paper industry. However, the process industry in Sweden represents industrial infrastructure in which billions of euros have already been invested. In addition, especially the forest industry also holds valuable knowledge and structures for biomass logistics and processing. Investment in and integration of next generation biofuel production could provide business opportunities for the industry, which could give both existing process industries and the emerging biorefinery industry added value. The BeWhere Sweden model can be used to analyse how existing industrial infrastructure can be used for efficient production of next generation biofuels as well as other biorefinery products (when further developed). The model can also be used to identify and analyse what transformations of the existing forest industry efficient large scale production of e.g. biofuels or chemicals would actually imply, and in which steps such a transformation could occur.

Based on results from BeWhere Sweden, suitable "first plant" locations and associated stakeholders can be targeted, something which could be of interest for technology development actors, policy makers, as well as industrial financers of technology scale up. Results from BeWhere Sweden could also be used when analysing different actors' possibilities, conditions and roles in a transition towards realising a large scale next generation biofuel and biorefinery industry in Sweden. The model could be used to identify industries and actors of high importance, such as potential "early adopters". Further, model results could help identify actors, types of industry or regions of particular interest for future biofuel production, which can be valuable in the design of future policies.

This project has mainly focused on forest-based biomass and biofuels, and forest industry. In an upcoming project BeWhere Sweden will be soft-linked with the aggregated energy systems model TIMES-Sweden. Within this project the model will also undergo substantial development regarding biofuel production integrated with district heating systems. Other areas of interest for further model development include distribution of SNG in the national gas grid, inclusion of other biofuels and technologies, and addition of agricultural residues and crops. Further, the results in this report show that the biomass supply area has significant impact on the choice of plant locations and types of biofuel production, and that smaller plant sizes relatively often are chosen. Inclusion of intermediate products such as torrefied biomass, pyrolysis oil and lignin extracted from chemical pulp mills would entail lower feedstock transport costs, which could benefit larger biofuel production plants. Intermediate products are thus of particular interest to include in the model. Finally, the inclusion of other types of biorefinery technologies products (e.g. different types of chemicals), could be includeed into the model. By running BeWhere Sweden without fixed goals for various products, competition for biomass for feedstock or energy purposes could be studied explicitly which would also add dynamics to the modelling approach.

SAMMANFATTNING

Sverige har goda tillgångar på skogsbiomassa och är av betydande intresse vad gäller framtida storskalig produktion av nästa generations biodrivmedel. Stora anläggningsstorlekar ökar dock det nödvändiga försörjningsområdet för råvara och ställer avsevärda krav på försörjningskedjan. Samlokalisering med annan industri möjliggör högre totalverkningsgrad men medför också ytterligare krav på lokaliseringen, vilket även konkurrens om den tillgängliga råvaran gör. Eftersom produktionsanläggningar för nästa generations biodrivmedel är förknippade med mycket stora investeringar är det av högsta vikt att noga utvärdera olika lokaliseringsalternativ.

Denna rapport beskriver den fortsatta utvecklingen av optimeringsmodellen BeWhere Sweden – en geografiskt explicit optimeringsmodell för lokalisering av anläggningar för nästa generations biodrivmedelsproduktion i Sverige. Modellen minimerar kostnaden för hela det studerade systemet, inklusive kostnader och intäkter för produktion och transport av biomassa, produktionsanläggningar, transport och leverans av biodrivmedel, försäljning av biprodukter och ekonomiska styrmedel. Modellen kommer således välja de minst kostsamma kombinationerna av råvaror, produktionsanläggningar och leveranser av biodrivmedel, samtidigt som efterfrågan på biomassa i andra sektorer tillgodoses. Fokus är på skogsbaserad biomassa och integration med industri, i synnerhet skogsindustrin.

I detta projekt har BeWhere Sweden använts för att modellera fyra olika färdplansscenarier baserade på scenarier som presenteras av Naturvårdsverket i rapporten ”Underlag till en färdplan för ett Sverige utan klimatutsläpp 2050". De använda färdplansscenarierna beaktar exempelvis efterfrågan på transporter, transportbränsle och nästa generations biodrivmedel, tillgänglig skogsbiomassa, användning av biomassa inom andra energi- och industrisektorer, och energimarknadsvillkor. Det främsta syftet har varit att identifiera kostnadseffektiva typer av lokaliseringar för biodrivmedelsproduktion, som är robusta i förhållande till olika randvillkor, i synnerhet gällande energimarknadsaspekter, styrmedel, investeringskostnader, råvarukonkurrens och integrationsmöjligheter med befintliga energisystem. Dessutom syftar rapporten till att ge en bredare analys av modellresultaten rörande exempelvis konsekvenser för beslutsfattare och kopplingar mellan olika aktörer i innovationssystemet kring framtida biodrivmedel.

Färdplansscenarierna har varit fokuserade på transportsektorn och på hur framtida efterfrågan på avancerade biodrivmedel kan tillgodoses genom inhemsk produktion, med enbart inhemska råvaror. En detaljerad bottom-up-metod för att bedöma den spatiala kostnadsstrukturen för skörd av rundved, avverkningsrester och stubbar har tillämpats på olika scenarier om tillståndet i den framtida svenska skogen. Sju olika produktionstekniker för nästa generations biodrivmedel har beaktats för integration med industri (massabruk, pappersbruk, sågverk, raffinaderier samt kraftvärmeverk). Varje industri har modellerats individuellt baserat på nuvarande och antagen framtida produktion. Även användning av biomassa i andra sektorer har modellerats spatialexplicit. Färdplansscenarierna omfattade två olika användningsmål för nästa generations biodrivmedel – 4 respektive 9 TWh per år.

Resultaten visar att biodrivmedelsmålen kan mötas i alla modellerade scenarier med enbart inhemsk skogsbiomassa som råvara, genom investeringar i nya produktionsanläggningar för

biodrivmedel (3-5 anläggningar för scenarier med det lägre biodrivmedelsmålet, respektive 6-9 anläggningar för scenarierna med högre målet). Införande av produktion av nästa generations biodrivmedel i kombination med den antagna ökningen av biomassaanvändningen i andra sektorer skulle dock kräva en avsevärd ökning av användningen av skogsrester (grenar, toppar och stubbar), från de 14 TWh som används årligen idag, till 32-50 TWh per år (beroende på biodrivmedelsmål och användning av biomassa i andra sektorer). Detta motsvarar upp till 97 procent av den totala potentialen.

Det totala kapitalbehovet för att uppfylla biodrivmedelsmålen skulle vara betydande – ca 600-1200 miljoner euro för att möta det lägre biodrivmedelsmålet, till ca 1300-2400 miljoner euro för att möta det högre målet. De lägre siffrorna i de angivna intervallen representerar inkrementella investeringskostnader, dvs. den ökade kostnad som investering i biodrivmedelsproduktion medför jämfört med alternativa investeringar som annars antas ha varit nödvändiga i respektive industri (exempelvis investering i svartlutsförgasning antas göras istället för investering i ny sodapanna). Den betydande skillnaden mellan den högre och den lägre investeringskostnaden understryker den väsentliga kapitalbehovsminskning som följer av att hänsyn tas till alternativa investeringar, samt att industrier som är i en situation där ersättningsinvesteringar ändå ska genomföras har en betydande fördel, åtminstone ur ett kapitalbehovsperspektiv. Det specifika inkrementella kapitalbehovet skulle följaktligen vara i storleksordningen 120-150 miljoner euro per TWh årlig produktionskapacitet av biodrivmedel, och den resulterande genomsnittliga produktionskostnaden i storleksordningen 70-80 euro per MWh. Den specifika kapitalkostnaden befanns utgöra cirka 25-40 procent av den totala produktionskostnaden, beroende antagen annuitetsfaktor.

Svartlutsförgasning med produktion av dimetyleter (BLG-DME) och fastbiomassaförgasning med produktion av syntetisk naturgas (BMG-SNG) dominerar modellresultaten, på grund av den höga systemverkningsgraden från biomassa till biodrivmedel. Resultaten visar också att lågt transportbehov för biomassa är av stor vikt i valet av anläggningslokalisering, och att sulfatmassabruk och sågverk framstår som mest attraktiva värdindustrier. För vissa industrier är mängden biomassa som transporteras till industrin när biodrivmedelsproduktion implementerats likvärdig med mängden biprodukter (flis, spån mm) som produceras från industrin utan drivmedelstillverkning. Följaktligen kan nettoökningen av biomassatransportkostnaderna för dessa industrier vara nära noll eller till och med negativ, beroende på de faktiska transportavstånden till och från respektive industri.

Stora anläggningar skulle kunna förväntas vara mer gynnsamma på grund av skalfördelar. Resultaten visar dock att de utvalda anläggningarna representerar hela skalintervallet från stora till små anläggningar, trots den högre specifika investeringskostnaden för mindre anläggningar. Ett större antal små anläggningar för att täcka en given efterfrågan på biodrivmedel leder till lägre total systemkostnad, främst på grund av kortare nettotransportavstånd för både biomassa och biodrivmedel och trots det högre kapitalbehovet. Denna effekt är särskilt påtaglig i biomassabegränsade scenarier, vilket leder till slutsatsen att försörjningsområdet och nettotransportkostnaderna för biomassa är parametrar av väsentlig relativ betydelse i valet av anläggningslokalisering. Höga kostnader för biomassa och begränsad råvarutillgång stimulerar vidare BLG-DME över BMG-SNG, vilket ytterligare förstärker sulfatmassabrukens betydelse som optimala värdindustrier.

Resultaten visar att system med flera olika biodrivmedel i allmänhet uppvisar lägre systemkostnad jämfört med mer homogena system. Detta påvisar ett behov att utforma framtida policy omsorgsfullt för att möjliggöra och främja en rad olika tekniker och drivmedel. Resultaten visar också på betydande kapitalbehov, trots att de beaktade investeringskostnaderna rör kommersiella "N:te anläggningar". Eftersom de analyserade teknikerna ännu inte är demonstrerade på industriell skala måste de uppskattade investeringskostnaderna ses som tämligen osäkra. Detta visar på vikten av inledande ekonomiskt stöd för att underlätta byggandet av de första anläggningarna och för att uppnå en följande investeringskostnadsminskning.

För närvarande står många svenska processindustrier inför omfattande utmaningar, i synnerhet den mekanisk massa- och pappersindustrin. Processindustrin i Sverige representerar dock industriell infrastruktur där miljarder euro redan har investerats. Vidare besitter särskilt skogsindustrin värdefull kunskap och redan existerande struktur för logistik och förädling av skogsbiomassa. Investeringar i och integrering av nästa generations biodrivmedel kan innebära framtida affärsmöjligheter för branschen, vilket i sin tur skulle kunna skapa mervärde för både den befintliga processindustrin och för den framväxande bioraffinaderiindustrin. BeWhere Sweden kan användas för att analysera hur befintlig industriell infrastruktur kan användas för effektiv produktion av både nästa generations biodrivmedel och av andra bioraffinaderiprodukter (efter fortsatt modellutveckling). Modellen kan också användas för att identifiera och analysera den omställning av den befintliga skogsindustrin som storskalig integrerad produktion av t.ex. biodrivmedel eller kemikalier skulle medföra. Baserat på resultat från BeWhere Sweden skulle både lämpliga lokaliseringar för första anläggningar och berörda aktörer kunna identifieras, vilket kan vara av intresse såväl för aktörer inom teknikutveckling och finansiering av industriell uppskalning, som för aktörer inom policy- och styrmedelsutveckling. Resultat från BeWhere Sweden skulle också kunna användas vid analys av olika aktörers möjligheter, förutsättningar och roller i en omställning mot storskalig bioraffinaderiindustri. Modellen kan användas för att identifiera branscher och aktörer av stor potentiell betydelse, såsom möjliga “early adopters”.

Detta projekt har främst fokuserat på skogsbiomassa och skogsbaserade biodrivmedel, liksom på integrering med skogsindustrin. I ett kommande projekt kommer BeWhere Sweden mjuklänkas med den aggregerade energisystemmodellen TIMES-Sweden. Inom projektet kommer även betydande modellutveckling genomföras vad gäller produktion av biodrivmedel integrerat med fjärrvärmesystem. Områden av intresse för vidare modellutveckling innefattar också gasnätsbunden distribution av SNG, inkludering av restprodukter från jordbruket och energigrödor för biogasproduktion, samt komplettering med ytterligare biodrivmedel och produktionstekniker. Vidare visar resultaten som presenteras i denna rapport att försörjningsområdet för biomassa har betydande inverkan i valet av anläggningslokalisering, och att mindre anläggningsstorlekar ofta prioriteras. Införandet av intermediärprodukter som torrefierad biomassa, pyrolysolja och lignin från kemiska massabruk skulle medföra lägre råvarutransportkostnader, vilket skulle kunna gynna större produktionsanläggningar. Intermediärprodukter är sålunda av särskilt intresse att inkludera i modellen. Slutligen skulle även andra typer av bioraffinaderitekniker och -produkter, som olika typer av kemikalier, kunna inkluderas i modellen. Genom att köra BeWhere Sweden utan fixa mål för olika produkter skulle konkurrensen om biomassa kunna studeras explicit, vilket skulle tillföra dynamik till modellen.

ABBREVIATIONS

ALK-HF-EtOH	alkaline pre-treatment followed by hydrolysis and fermentation for ethanol production
BB	bark boiler
BLG	black liquor gasification
BLG-DME-BB	black liquor gasification with DME production and bark boiler
BLG-DME-BMG-DME	black liquor and solid biomass gasification with DME production
BMG	solid biomass gasification
BMG-DME	solid biomass gasification with DME production
BMG-FT	solid biomass gasification with FT fuels production
BMG-SNG	solid biomass gasification with SNG production
CEPCI	Chemical Engineering's plant cost index
CHP	combined heat and power
CTL	cut-to-length
DFBG	dual fluidised bed gasification
DH	district heating
DME	dimethyl ether
EFG	entrained flow gasification
ENPAC	Energy Price and Carbon Balance Scenarios tool
EtOH	ethanol
FBG	fluidised bed gasification
FT	Fischer-Tropsch
HRSG	heat recovery steam generator
LHV	lower heating value
MILP	mixed integer linear programming
O&M	operation and maintenance
odt	oven dry tonnes
SE-HF-EtOH	steam explosion pre-treatment followed by hydrolysis and fermentation for ethanol production
SFI	Swedish Forest Inventory
SFIF	Swedish Forest Industries Federation
SNG	synthetic natural gas
SSF	simultaneous sacharation and fermentation
ST	steam turbine

CONTENTS

1 INTRODUCTION

Ambitious targets for renewable energy in the transport sector boost the interest in advanced biofuels, in particular in forest rich regions such as Sweden. In order to obtain competitive biofuel production costs, large biorefinery plants are often assumed to be required to reach favourable economy-of-scale effects (e.g. Soetaert and Vandamme, 2009). Feedstock intake capacities in the range of about 1-2 million tonnes per year, corresponding to a biomass feed of 300-600 MW, can be expected, which may lead to major logistical challenges. To enable expansion of biofuel production in such large plants, as well as provide for associated distribution requirements, it is clear that substantial infrastructure planning will be needed. The geographical location of the production plant facilities is therefore of crucial importance and must be strategic to minimise the transports of raw material as well as of final product. Competition for the available feedstock, from for example industry and the stationary energy sector, further complicates the localisation problem. Since the potential for an increased biomass utilisation is limited, high overall resource efficiency is of great importance. Integration of biofuel production processes in existing industries or in district heating systems is beneficial from several aspects, such as opportunities for efficient heat integration, feedstock and equipment integration, utilisation of already well-developed supply chains, as well as access to existing experience and know-how. A development towards new value chains could also give new vitality and added-value to existing industries.

Appropriate biofuel production plant locations can be identified by advanced systems analysis and models that explicitly take into account geographical aspects (Leduc et al., 2010a; Leduc et al., 2010b; Natarajan et al., 2014; Wetterlund et al., 2013a; Wetterlund et al., 2013b). BeWhere Sweden is a techno-economic, geographically explicit optimisation model for the analysis of location and properties for production of advanced biofuels in Sweden. In Wetterlund et.al (2013b), the development of the model is described in detail. BeWhere Sweden can be used to assess production plant locations that are robust to varying boundary conditions, in particular regarding energy market prices, policy instruments, investment costs, feedstock competition and integration possibilities with existing energy systems. The model results can be useful as decision support for stakeholders as well as for political decision makers. Since Sweden is of considerable interest for future production of advanced biofuels, BeWhere Sweden can also be useful for analysis of various policy measures and strategies at the European level. Unlike models such as TIMES-Sweden and EMEC, BeWhere Sweden take geographical challenges associated with long distances between raw material, appropriate production premises and end users in concern. BeWhere can therefore provide valuable results that can complement and validate results of market and energy systems models used today, and thus for example test and validate the implementation ability of these model results.

The development of BeWhere Sweden is currently focused on forest-based biomass. In the previous project (Wetterlund et al., 2013b) the main focus was put on biofuel production integrated in existing forest industries, even if a few district heating networks also were considered as potential integration sites. Five biofuel production technologies were included: three gasification-based concepts producing DME (dimethyl ether), and two hydrolysis- and fermentation-based concepts producing ethanol. In Wetterlund et.al (2013b), different roadmap scenarios that describe potential future development concerning population, transport and motor fuel demands, biomass resources, biomass demand in other industry sectors, energy and biomass market prices etc. are also presented.

In the previous project, a number of important areas to improve the BeWhere Sweden model were identified that would further increase the value of the modelling results. Examples are inclusion of additional biofuels and other types of industries as potential sites for integrated biofuel production. Moreover, an increased level of detail on the potential amounts, geographical distribution and costs of the feedstock is considered of great importance. Following the review of the existing literature of biomass resources it is clear that there is a strong need for further development of such data, on the supply as well as the demand side, and also regarding foreign trade. Additionally, the quality of some important input data and statistics was found to be highly uncertain and to contain errors.

1.1 OBJECTIVES

The overall aim of the BeWhere Sweden project is to identify and analyse cost-effective types of biofuel production locations that are robust to boundary condition variations, in particular regarding energy market prices, policy instruments, investment costs, feedstock competition and integration possibilities with existing energy systems. As mentioned, in the previously carried out f3 project, the focus was on model development and scenario construction, with the main output being the model and the developed biomass and biofuel scenarios for 2030. The primary objectives of this project have been to:

- Use the model for scenario analysis, in order to visualise how future targets for advanced forest-based biofuels can be accomplished by domestic production and using domestic feedstocks.
- Identify cost-effective types of biofuel production plant locations that are robust to various boundary conditions.

From the results, a broader analysis has been made of the model results regarding for example implications for policy makers and connections between different actors in the biofuel innovation system.

This project has also addressed a number of the areas previously identified as being of interest for future work, regarding further model development and improvement and supplement of input data. Therefore, additional objectives have been to:

- Include other industries and plant sites (e.g. oil refineries), production technologies and biofuel types (e.g. synthetic natural gas (SNG) and synthetic diesel).
- Improve the description of the potential amount, economics and the geographical distribution of the forest biomass feedstock.
- Improve specific pulp mill data by establishing contact with the mills to access more comprehensive data than what is publically available.

1.2 REPORT OUTLINE

Chapter 2 describes the BeWhere Sweden model and the general model input data. A more comprehensive description can be found in Appendix A. In Chapter 3 the modelling of the forest biomass supply is described, and Chapter 4 covers the model input data regarding biofuel production technologies and integration potential in different host industries. Chapter 5 presents the modelled roadmap scenarios and describes how they have been implemented into the model. Model runs and results are presented in Chapter 6 with the concluding discussion following in Chapter 7. Finally, Chapter 8 contains suggestions for future work.

This report has been written as to be comprehensible without reading the report from the earlier f3 project (Wetterlund et al., 2013b). For this reason, some parts are identical to the previous report. Chapters 3-8 mainly consist of new or updated material.

2 BEWHERE SWEDEN

With the BeWhere model total energy system optimisation calculations can be performed, that take into account locations, quantities and costs of feedstocks, use of different energy carriers, transportation of feedstock and products, and CO_2 emissions from transportation, energy use and energy carrier substitution.

The model explicitly takes into account a large number of locations of importance for supply and use of biomass. In this report, sawmills, pulp and paper mills, refineries and CHP plants are included in the model. Sawmills and pulp and paper mills are included as potential biofuel plant sites, as biomass demand points regarding wood and bioenergy use that must be met, and as biomass supply points regarding surplus by-products. District heating systems are considered regarding bioenergy use and CHP plants as potential plant sites. Refineries are included as potential plant sites.

2.1 GENERAL ASSUMPTIONS

All flows of biomass and other energy have been converted to energy units (Wh), based on lower heating value (LHV). This includes supply and use of pulp wood and sawlogs. For conversion between units, conversion factors of 0.42 odt/m^3 (oven dry tonnes wood) and 4.9 MWh/odt (energy content of woody biomass) have been applied.

2010 has been used as base year when developing the model. All economic calculations have been performed using 2010 monetary value and Euro (EUR). Industrial production, population, transport fuel use etc. all apply 2010 as base year.

Investment costs for new plants have been annualised using a capital recovery factor (annuity factor) of 0.11, which for example is equivalent to an economic lifetime of 20 years and an interest rate of 10%.

2.2 MODEL DESCRIPTION

BeWhere is based on mixed integer linear programming (MILP) and is written in the commercial software GAMS, using CPLEX as a solver. The model minimises the system cost of the entire studied system. The system cost includes biomass costs, transportation and distribution costs (biomass and biofuel), setup and operation and maintenance costs for new next generation biofuel plants, costs of imported biomass and biofuel[1], revenues for co-produced energy carriers, costs of fossil energy used in the system, and costs and revenues related to various policy instruments. In addition to this, the impact of fossil CO_2 emissions can be internalised in the model, by adding a cost on the supply chain CO_2 emissions (including offset emissions from displaced fossil energy carriers). Demand side costs related to e.g. fuel use in vehicles are not considered.

The system cost is minimised subject to a number of constraints regarding, for example, biomass supply, biomass use, import/export of biomass and biofuels, production plant opera-

[1] Only biomass import is considered in this report.

tion and biofuel use. The model will choose the least costly pathways from one set of feed-stock supply points to the selected biofuel production plants and further to a set of biofuel use points, while meeting the demand for biomass in other sectors, over the time period chosen (in this study, 1 year).

The model can be run in different modes by changing various constraints. In this report a fixed next generation biofuel demand is defined for each model run, which must be fulfilled by investments in new production facilities. The model chooses the least costly pathways to meet the target. From the resulting system cost the cost to fulfil the specific biofuel target can be derived.

The resulting output from the model consists of the locations and characteristics of a set of plants, types and amounts of biomass used, types and amounts of biofuel produced and the cost and CO_2 emissions of the entire supply chain, as well as for different separate parts of the supply chain and for each biofuel production plant. For a more detailed description of BeWhere Sweden, see Wetterlund et al. (2013b) and Appendix A.

2.3 GEOGRAPHICAL EXTENT

Sweden has been divided into a base grid consisting of 334 grid cells with a half-degree spatial resolution (approximately 20 x 50 km in northern Sweden and 30 x 50 km in southern Sweden), as shown in Figure 1. The base grid is used to express population, biofuel use, biomass supply and biomass use. In addition to the base grid, points representing potential host industries for biofuel production are expressed with explicit coordinates.

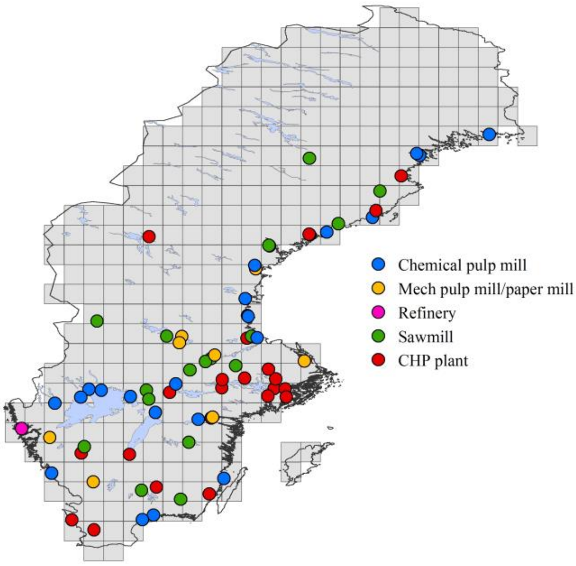

Figure 1. The BeWhere Sweden grid division and the host industries considered as potential biofuel production plant sites.

2.4 BIOMASS SUPPLY AND USE

BeWhere Sweden can incorporate any number of feedstock, such as agricultural crops, forest biomass or various waste flows. At this stage of model development only biomass originnating from the forest has been considered, divided into nine different assortments: sawlogs from final felling and thinning, pulp wood from final felling and thinning, harvesting residues (*grot*) from final felling and thinning, stumps from final felling, sawmill wood chips, and low-grade industrial by-products (bark, saw dust etc.).

Available quantities and costs are given for each assortment, for each grid cell. Chapter 3 describes the modelling of forest biomass supply (roundwood, harvesting residues and stumps) in detail. The available quantities of industrial by-products are based on the modelled production and internal use for each sawmill and pulp mill (see further Chapter 4).

Biomass use in other industry sectors is considered explicitly in the model. The usage is described statically, based on current and projected production levels. In the previous report, only forest and energy industry were considered as significant users of biomass for energy or feedstock purposes. In this project, iron and steel industry and chemical industry have been added as potential biomass users in the scenarios for 2030.

Pulp wood, sawlogs and industrial wood chips can be used in the model to meet the wood demand in pulp mills, while only sawlogs can be used as raw material for sawmills. All biomass types except sawlogs can be used for energy purposes, as feedstock in the chemical industry, and for new biofuel production plants.

The modelling of biomass utilisation in industry is further described in Section 5.3.

2.5 INTEGRATED BIOFUEL PRODUCTION

Seven different next generation biofuel technologies have been considered in this report. Each technology can be integrated into different existing host industries (pulp mills, paper mills, sawmills, refineries or CHP plants). Each industrial site (see Figure 1) has been modelled individually, based on current and projected operation. This is described in detail in Section 4.2**Fel! Hittar inte referenskälla.**.

Energy carriers other than biomass that are affected by the biofuel production plants are also included in the model. Produced and used electricity are treated as separate energy carriers. Surplus co-produced electricity is assumed possible to sell to the grid, without restrictions. New renewable electricity production (i.e. that originates from new investments or changes in electricity production capacity) is assumed entitled to green electricity certificates. Co-produced heat is to different extents assumed possible to use internally in the industrial process (see Section 4.2). Fossil energy carriers (coal, oil and natural gas), that could also be affected by a new biofuel production facility, are also considered.

2.6 POPULATION AND TRANSPORT DEMAND

In this project, the model representation of Sweden's population distribution has been refined compared to Wetterlund et al. (2013b). The GEOSTAT European 1 km^2 population grid (2006) has been used as basis (Eurostat, 2012). The GEOSTAT data was aggregated on the BeWhere grid and calibrated against the total population for each county.

In 2010 the total population in Sweden amounted to 9,415,570 individuals (Statistics Sweden, 2013b). In this report the population for 2030 is assumed to have grown to

10,660,344 (Statistics Sweden, 2013a). The regional population distributions by 2030 are based on the assumptions described by Nilsson (2011) for different regions, that have been adapted to the county level to fit BeWhere Sweden. The demographic patterns observed in 2006-2010 form the basis for the county projections. Thus, the urbanisation is assumed to continue and the counties comprising the three metropolitan areas (Stockholm, Göteborg and Malmö) increase their population the most, whereas the forest counties in northern Sweden are expected to experience only a marginal increase in population.

The modelled population for each county is shown in Table 1.

Table 1. County specific population in 2010 and 2030 and average annual change.

County	Population 2010[a]	Population 2030[b]	Average annual change 2010-2030
Blekinge	153,227	165,593	+900
Dalarna	277,047	283,231	+800
Gävleborg	276,508	282,680	+800
Gotland	57,269	61,890	+300
Halland	299,484	340,894	+2,900
Jämtland	126,691	127,859	+400
Jönköping	336,866	364,052	+2,000
Kalmar	233,536	252,383	+1,400
Kronoberg	183,940	198,784	+1,100
Norrbotten	248,609	254,157	+700
Örebro	280,230	314,681	+2,200
Östergötland	429,642	464,315	+2,500
Skåne	1,243,329	1,482,935	+15,000
Södermanland	270,738	304,021	+2,200
Stockholm	2,054,343	2,570,547	+32,000
Uppsala	335,882	377,175	+2,700
Värmland	273,265	279,364	+800
Västerbotten	259,286	265,073	+700
Västernorrland	242,625	248,040	+700
Västmanland	252,756	283,829	+2,000
Västra Götaland	1,580,297	1,738,844	+12,000
Sweden total:	*9,415,570*	*10,660,344*	

[a] (Statistics Sweden, 2013b)
[b] (Nilsson, 2011; Statistics Sweden, 2013a)

The total energy use in road transport in 2010 amounted to 88 TWh (Statistics Sweden, 2013c; Swedish Energy Agency, 2011), which was used as basis for the modelled transport fuel use in the previous project. The geographical distribution of the transport fuel use has been assumed to be proportional to the population, and thus the total fuel use per county has been downscaled based on grid cell population. For the scenario model runs in this report different fuel use levels are applied. This is further described in Section 5.1.

2.7 TRANSPORT AND DISTRIBUTION

Network maps of roads, rails and shipping routes have been used to calculate transportation routes and distances between all grid points included in the model. Biomass feedstocks and produced biofuels can be transported by truck, train or ship, or any combination of the three transportation means. Transport cost functions of different biomass feedstocks using truck and train have been derived from (Athanassiadis et al., 2009a) and Johansson and Mortazavi (2011). The transport cost of biomass using ship was adapted from Börjesson and Gustavsson (1996). Transport cost functions for biofuels were adapted from (Natarajan et al., 2014) and from Börjesson and Gustavsson (1996).

Fuel dispensing at gas stations was assumed to be more costly for biofuels than for conventional fossil fuels. Leduc (2009) estimated the incremental cost for dispensing methanol compared to fossil fuels to 0.87 EUR/MWh, which was here assumed equivalent for dispensing ethanol. For DME the cost was assumed to be 20 percent higher. SNG has been assumed to only be distributed locally around the biofuel production plant to local gas grids, to an estimated total cost for distribution and dispensing of 12 EUR/MWh (SOU, 2013). SNG could also be distributed to the gas grid in the south-western parts of Sweden, but this has not yet been implemented in the model.

Figure 2 shows the road and rail transport network and Table 2 presents the transport costs applied for feedstocks and biofuels. The costs shown in the table are for 2010, and are calibrated against the transport fuel price in each given scenario (see Section 5.4).

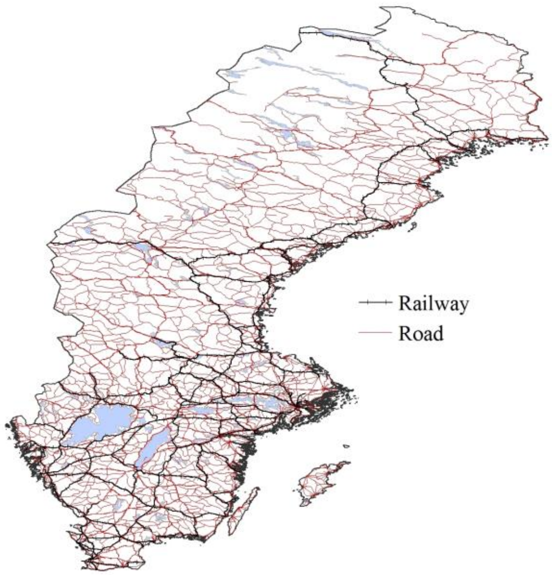

Figure 2. Road and rail network.

Table 2. Transport costs (EUR/GWh) for feedstocks and biofuels. *d* is the transport distance in km. The costs are calibrated against the transport fuel price. Costs shown are for 2010.

Energy carrier	Truck	Train	Ship
Roundwood	428 + 32.4*d*	1730 + 9.36*d*	6470 + 3.42*d*
Harvesting residues, stumps	1100 + 38.3*d*	1920 + 10.4*d*	6470 + 3.42*d*
Industrial by-products	583 + 37.1*d*	1920 + 10.4*d*	6470 + 3.42*d*
DME	333 + 7.06*d*	782 + 16.2*d*	4470 + 1.19*d*
Ethanol	277 + 7.06*d*	652 + 16.2*d*	3720 + 1.19*d*
FT products	277 + 7.06*d*	652 + 16.2*d*	3720 + 1.19*d*

3 SUPPLY OF FOREST BIOMASS

The first objective of this chapter is to estimate and present the potential spatial availability of forest products. Forecasts on the availability are provided in 10-year intervals up until year 2069. The second objective is to calculate geographically explicit forest product harvesting costs, i.e., in each spatial grid cell, an average harvesting and extraction cost per forest product (roundwood, harvesting residues and stumps) is estimated based on e.g., the specific geographical properties of the grid cell. The availability and cost data generated are estimated and designed as input data for the BeWhere model.

3.1 AVAILABILITY OF DIFFERENT FOREST PRODUCT ASSORTMENTS

In the present work potentially available quantities of roundwood, harvesting residues and stumps for the period 2010-2069 were estimated for the whole of Sweden. The estimations were based on data collected from the Swedish Forest Inventory (SFI) from 2002 to 2006 for the "Skogliga konsekvensanalyser 2008" study (Swedish Forest Agency, 2008b). The latter is a hundred year timber production forecast comparing a reference with alternative scenarios, based on different forest management options. The calculations take into account all the productive forest in Sweden, including that within formally protected areas (national parks, nature reserves, etc.).

In this work two of the scenarios presented by the Swedish Forest Agency (2008b) were examined; the *production* and the *environmental* scenarios. Both scenarios originate from the *reference* scenario which assumes that Swedish silvicultural practices will not change and annual fellings will still be at a level that is regarded as sustainable, that environmental legislation will not change and that climate change will be light. The environmental scenario assumes that the protected forested areas in Sweden will increase, more buffer zones along forest streams and lakes will be created (compared to the reference scenario), and that better environmental consideration will be taken in connection with final felling operations (Swedish Forest Agency, 2008b). The production scenario is also based on the reference scenario but in conjunction with traditional silvicultural practices other measures are taken to increase the productivity of the forest areas e.g. more contorta pine is planted (an increase from 500,000 ha today to 900,000 ha by 2030) (Swedish Forest Agency, 2008b).

Forest development in both scenarios was simulated by means of HUGIN, a calculation system that enables the calculation of potential outcomes of roundwood, harvesting residues and stumps from future harvesting operations (final fellings and thinnings) (Lundström and Söderberg, 1996). In the simulation a growth prognosis for the trees of each individual SFI sample plot was produced. Some 31,000 sample plots evenly spread over the complete forest area of Sweden were considered. In both scenarios the B2 emission scenario developed by the Intergovernmental Panel on Climate Change (IPCC) was assumed (IPCC, 2000). In that scenario a world is described in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population (10.4 billion people in 2100) intermediate levels of economic development, and less rapid and more diverse technological change than in other scenarios. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

3.1.1 Production and environmental scenarios: description of the data set

The HUGIN output for the production scenario comprises of a list of approximately 52,000 plots (49,000 for the environmental scenario) that were selected to be thinned or final harvested during the period 2010-2069. Each plot has information on the county within which the plot is located, the harvesting operation (thinning or final felling) that will take place, soil moisture content, peat content, slope, soil texture and ground structure. The volume of roundwood, bark, branches, needles, tops, stumps with attached root system that is forecasted to result after each harvesting operation, that is in fact a theoretical potential, is reported in oven dry tonnes per ha (odt/ha) for every tree species that is found in the plot i.e. spruce, pine and broadleaves (mostly birch). The biomass functions for estimating volumes of all the tree parts except stumps with attached root system are described in Peterson (1999). The biomass functions are based on e.g. the tree species, the breast height diameter of the trees, tree height and the production capacity of the site. Biomass functions for estimating the volume of stumps with attached root system were based on tree species and the breast height diameter of the trees and described in Petersson and Ståhl (2006). Roundwood is the main product of the harvesting operations while branches, needles and tops (hereafter referred to as harvesting residues) and stumps with attached root system (hereafter referred to as stumps) are regarded as by-products.

The theoretical potential expresses an upper limit on the availability of roundwood, harvesting residues and stumps. In order to assess the ecological potential of harvesting residues and stumps a number of restrictions were applied on the theoretical potential (Athanassiadis et al., 2009a; Athanassiadis et al., 2009b). The restriction set was the same for both scenarios and was developed in cooperation with the Swedish Forest Agency (2008b). The output of harvesting residues and stumps from the harvesting operations was reduced by excluding plots in productive forest areas that were situated in:

- Sites of nature protection.
- Wet sites and peat soils with low bearing capacity. In this way soil compaction, rutting and rise of the water layer is avoided both in main as well as secondary strip roads.
- Sites that are located within 25 meters from a lake, sea, waterline or any other ownership category than forest. In this way damage to the water courses is minimised and consideration is taken on social aspects (e.g. risk of damaging sites of cultural heritage, of recreation interest etc.).
- Sites that have a slope of more than 35 percent according to the Swedish terrain classification scheme. In this way erosion is avoided.
- In addition, 20 percent of the harvesting residues, 20 percent of the conifer stumps as well as all hardwood stumps were not considered. Not lifting and extracting stumps located on and close to strip roads retains the bearing capacity of the soil. Some harvesting residues are used as a reinforcement of strip roads and sensitive soils. Due to high biodiversity values all hardwood stumps are retained.

More information on guidelines and recommendations for harvesting of stumps and harvesting residues is provided by the Swedish Forest Agency (2008a; 2009).

Roundwood harvesting was not subjected to any ecological restrictions i.e., the volume that is reported is the theoretical potential for the studied period. It was assumed that in a first thinning operation all roundwood came out as pulpwood while at later thinnings, 70 percent came out as pulpwood and 30 percent as sawlogs. In final felling operations it was assumed that 70 percent came out as sawlogs and 30 percent as pulpwood (Tables 3 and 4). It is assumed that the energy content of the woody biomass is 4.9 TWh/Modt. Figures 3 and 4 show an overview of the resulting potentials for the two scenarios. Figure 5 shows the geographical distribution of the available forest products for two time periods (2010-2019 and 2060-2069, respectively) under the production and environmental scenario (see also Section 5.2 for quantities as used in this report).

Table 3. Number of SFI plots and resulting volume of pulpwood and sawlogs (theoretical potential) as well as logging residues and stumps (ecological potential) for the production scenario. Volumes are millions of m^3 solid excl. bark.

	Number of SFI plots	Pulpwood (Mm^3/year)	Sawlogs (Mm^3/year)	Harvesting residues (Mm^3/year)	Stumps (Mm^3/year)
2010-2019	8213	33.6	45.7	18.8	23.3
2020-2029	8923	34.3	43.6	17.6	22.1
2030-2039	8259	35.7	48.1	16.9	19.8
2040-2049	8550	38.3	52.1	19.0	22.1
2050-2059	9100	42.4	56.7	21.4	24.8
2060-2069	9399	45.2	61.2	22.9	27.1

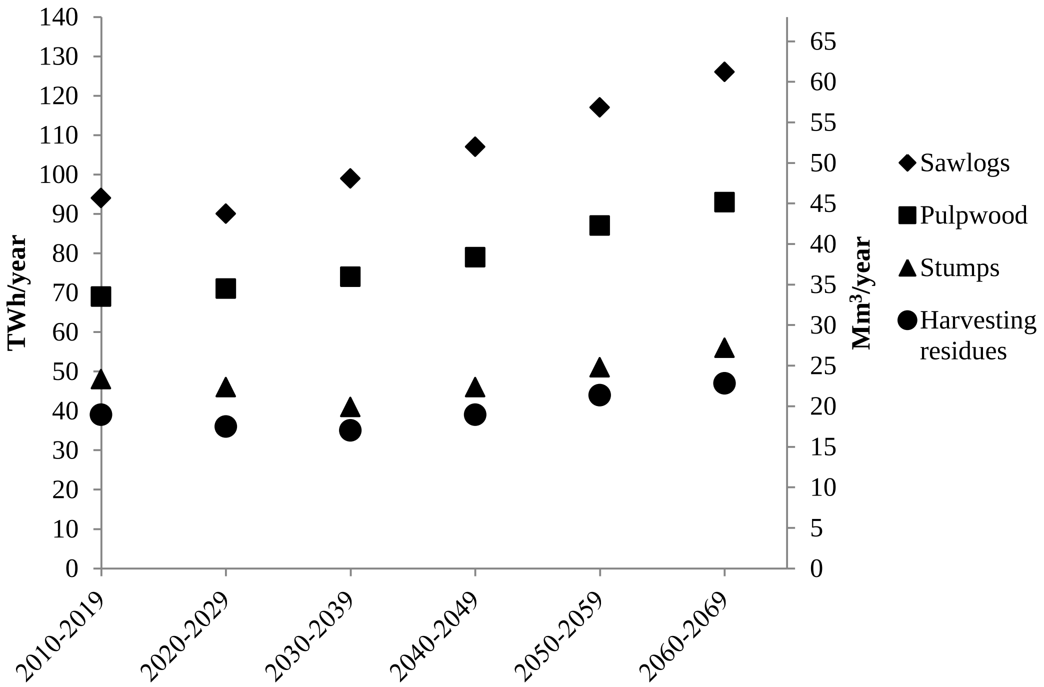

Figure 3. Resulting volumes of pulpwood and sawlogs (theoretical potential) as well as harvesting residues and stumps (ecological potential) for the production scenario. Volumes are millions of m^3 solid excl. bark.

Table 4. Number of SFI plots and resulting volume of pulpwood and sawlogs (theoretical potential) as well as logging residues and stumps (ecological potential) for the environmental scenario. Volumes are millions of m^3 solid excl. bark.

	Number of SFI plots	Pulpwood (Mm^3/year)	Sawlogs (Mm^3/year)	Harvesting residues (Mm^3/year)	Stumps (Mm^3/year)
2010-2019	7978	32.4	43.1	18.3	22.6
2020-2029	8642	32.9	40.7	16.9	21.2
2030-2039	7862	32.9	43.6	15.5	18.1
2040-2049	7970	34.5	46.4	16.7	19.3
2050-2059	8355	37.1	50.0	18.6	21.9
2060-2069	8364	38.6	52.1	19.5	22.9

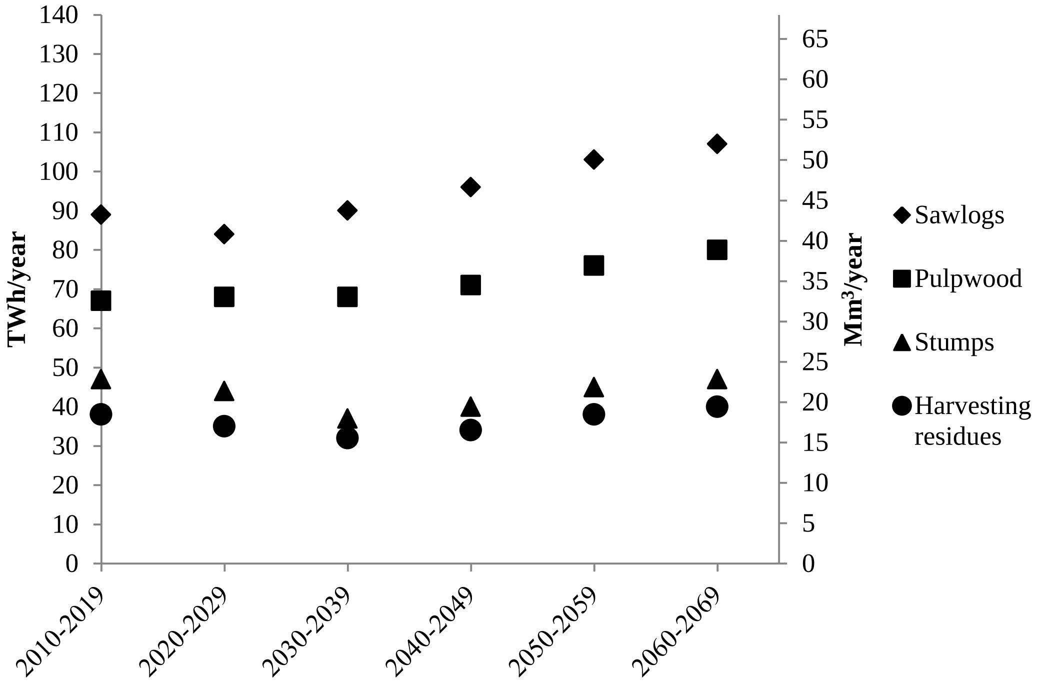

Figure 4. Resulting volumes of pulpwood and sawlogs (theoretical potential) as well as harvesting residues and stumps (ecological potential) for the environmental scenario. Volumes are millions of m^3 solid excl. bark.

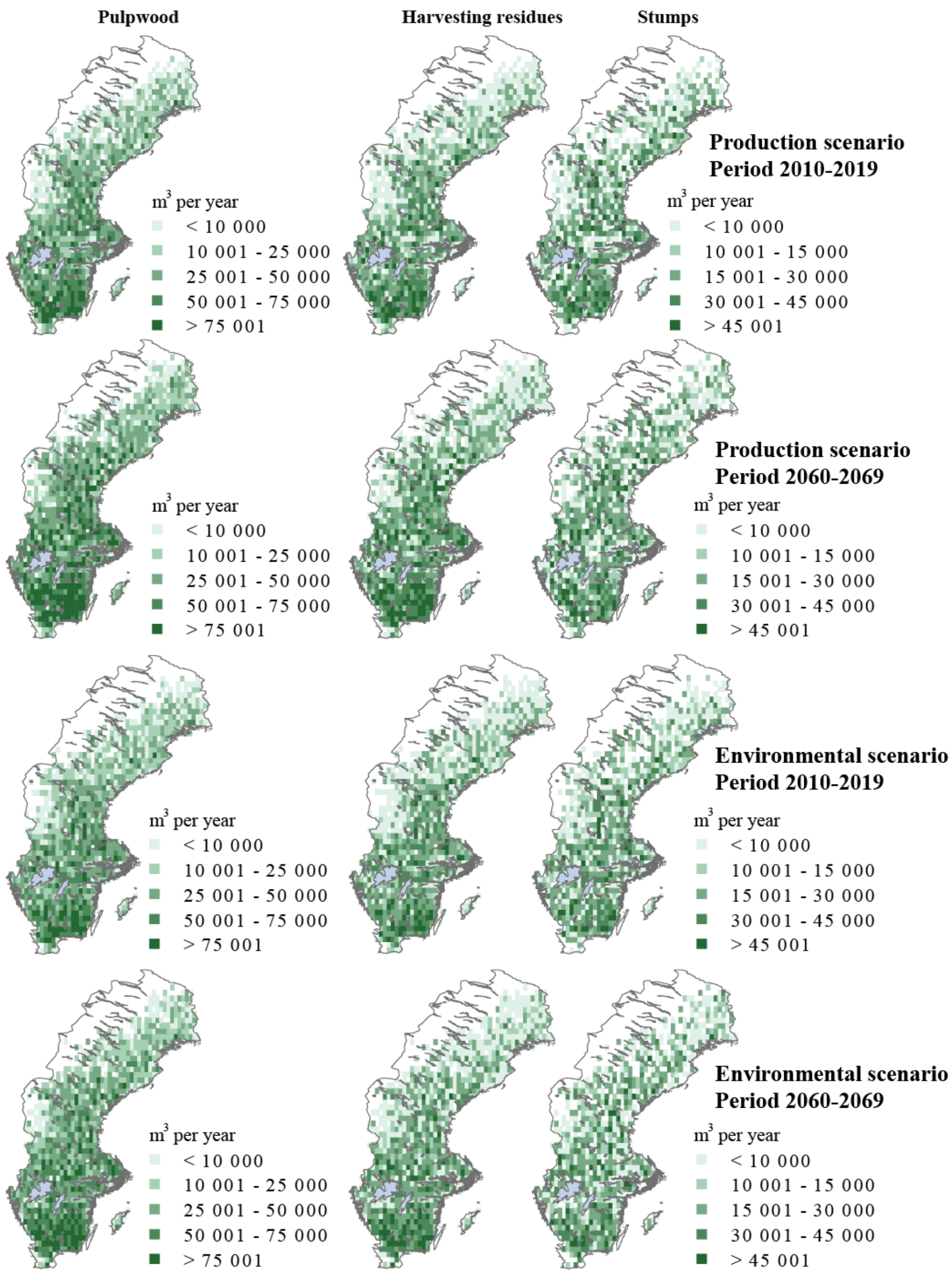

Figure 5. Geographically explicit availability of forest products for period 2010-2019 and 2060-2069 under the production and environmental scenario using a 0.25 longitude and latitude degree resolution.

3.2 A BOTTOM-UP COST APPROACH

This section describes the methodology used to assess the spatial cost structure of harvesting roundwood, residues and stumps in Sweden. To estimate the spatial variation in harvesting and extraction costs, time functions for harvesters and forwarders are used. The time functions are then converted to productivity functions which together with current data are used to estimate the average extraction cost per area. A bottom-up approach is chosen since we wanted to construct a flexible and an easy-to-update model because of the many uncertainties surrounding forest-based biomass and the desire to study technological and market development and the effect of energy and forest policy changes.

3.2.1 Harvesting technologies

While fossil fuel occurs in large deposits and can be produced at a fairly constant cost, forest resources are scattered and must be collected from a large number of stands. Ground conditions and environmental restrictions in these stands vary widely and the variations are reflected in the productivity and the harvesting cost. The harvesting process is technically feasible in a wide range of configurations, including manual chain-saw fellings to mechanised fellings. The commonly used harvesting technique in Sweden is generally referred to as the cut-to-length technique (CTL). This means that stems are cut and processed into shorter logs at the harvesting site (Nurminen et al., 2006). The CTL-technique typically involves harvesters and forwarders as the standard machinery. In the consequent analyses it will be assumed that the CTL-technique is used at all harvested sites. That is, the productivity and cost structure is based in the use of single-grip harvesters together with forwarders. Four stages are defined in the harvesting process: (1) setting up the harvester for harvesting; (2) harvesting and separation of residues; (3) transportation of the forest resources from the harvesting site; and (4) piling and chipping the wood and forest residues in preparation for transport of the final product.

Chipping may take place in the stand, at the road-side, at a terminal, or at the plant where the chips are to be used. The system predominately used today is road-side chipping. Chippers operating at roadside do not operate off-road and can therefore be heavier, more powerful and more efficient than terrain chippers. Henceforth, it is assumed that forest residues are chipped at road-side. No subsequent transportation beyond road-side delivery by the forwarders is included.

The use of single-grip harvesters has a significant effect on the output of forest fuels (i.e., harvesting residues). Nurmi (2007) suggests that the whole harvesting operation is more effective when the residues are accumulated in heaps along the strip road. Nurmi (2007) identifies a number of studies that analyses the efficiency of integrating roundwood harvesting with forest fuel extraction. To increase the efficiency, modifications are required to be made on the utilisations of forwarders. These modifications include increased load space and adjustments to the grapple.

3.2.2 Productivity

A number of studies have analysed the productivity of single-grip harvesters[2]. The general results from these studies suggest that the productivity increases with increasing stem size. However, this relationship is not linear. Kärhä et al. (2004) report that when the optimal stem size for a particular harvester is reached, the productivity instead starts to decline with increasing stem size. In addition, the productivity has also been reported to increase with the

[2] Nurminen et al. (2006) provide a review of productivity studies. Productivity studies for the Nordic countries include: (Brunberg, 1995; Brunberg, 1997; Lageson, 1997; Eliasson, 1998; Glöde, 1999; Hånell et al., 2000; Lundmark, 2003; Lundmark, 2006; Kärhä et al., 2004; Ovaskainen et al., 2004). North American studies include: (Tufts and Brinker, 1993; Kellogg and Bettinger, 1994; McNeel and Rutherford, 1994; Lanford and Stokes, 1995; Lanford and Stokes, 1996; Tufts, 1997).

number of trees removed from a stand (Eliasson, 1998). Finally, terrain conditions, such as slope, surface structure and bearing capacity, will significantly affect the productivity (Nurminen et al., 2006). Nevertheless, the operator's skills and operating experience can be a significant source of variability in the productivity reaching from 40 to 55 percent in the same stand depending on stem size (Ovaskainen et al., 2004).

There have also been a number of studies on forwarders productivity. Nurminen et al. (2006) argue that this literature can be divided into a European and an American approach. In the European approach, harvesters and forwarders are scientifically treated as separate processes, while the American approach treats them as an integrated process[3]. The studies suggest that the productivity of forwarders is correlated with the type of harvesting operation (final felling or thinning), terrain transportation distance, timber density on the strip-road and load volume (Nurminen et al., 2006).

For the purpose of this study, the productivity for single-grip harvesters and forwarders in final felling and thinning operations is based on Brunberg (1995; 1997; 2004). Five time-functions are used to estimate the productivity of single-grip harvesters in final fellings and in thinning and for forwarders in final felling, thinning and in stump harvesting.

3.2.3 Single-grip harvesters

The productivity for single-grip harvesters in final felling is based on a time function expressing the time it takes (1) to move between set-ups; (2) for felling and processing; and (3) miscellaneous time. The time function is expressed in equation [1], where the first term is the time it takes to move between set-ups, the second term is for felling and processing and the last term is miscellaneous time (Brunberg, 1995).

[1] $$T_f^h = \frac{1\,000\,000}{S_f \cdot U_f \cdot K_f\left(1+\frac{50}{U_f}-0.1Y-0.1L\right)} + \left(56V_f + 27{,}3 + \frac{28A_1}{100} + \frac{15A_2}{100} + \frac{37A_3}{100}\right) + 1.6$$

The subscript *f* indicates that the variables are in regard to final felling operations, the superscript *h* indicate that the time function is for harvesters; *S* is swath width measured in meters; *U* is roundwood extraction measured in stems per hectare; *K* is an expression for harvester speed measured in meter per minute; *Y* is surface structure class (1-5); *L* is gradient class (1-3); *V* is average stem volume measured in cubic meter solid excl. bark; and finally A_1, A_2 and A_3 is the share of stems needing secondary saw-cut, having harvester-head positioning difficulty and share of problem trees, respectively. The time function (T_f^h) expresses the overall time needed per tree measured in centiminute per tree.

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[3] Studies using the American approach include: (Tufts and Brinker, 1993; Kellogg and Bettinger, 1994; McNeel and Rutherford, 1994; Aedo-Ortiz et al., 1997; Tufts, 1997). Studies using the European approach include:
(Gullberg, 1997; Brunberg, 2004; Sirén and Aaltio, 2003; Talbot et al., 2003; Wester and Eliasson, 2003).

Equation [2] calculates the productivity (ρ_f^h) for harvesters in final felling, based on the time function and average stem volume (final felling). The constant term transform the expression from m^3 (solid excl. bark) per second to m^3 (solid excl. bark) per G_{15}-hour[4].

[2] $$\rho_f^h = 3312\left(\frac{0.6T_f^h}{V_f}\right)^{-1}$$

The productivity functions for single-grip harvesters in thinning operations are based on the same approach as equation [1] and [2]. The same time function for moving between set-ups is used in thinning operations. However, the time functions for felling and processing and for miscellaneous time are different from final felling operations.

[3] $$T_t^h = \frac{1\,000\,000}{S_t \cdot U_t \cdot K_t\left(1+\frac{50}{U_t}-0.1Y-0.1L\right)} + \left(20{,}3 + V_t(0.089 + 0.00078G) + E(1.9 + 0.025G)\right) + 4.3$$

The subscript *t* indicates that the variables are in regard to thinning operations, *G* is the share of spruce and *E* is the number of trees left standing per hectare. The time function (T_t^h) expresses the overall time needed per tree measured in centiminute per tree.

The productivity (ρ_t^h) for harvesters in thinning operations is based on the time function and average stem volume (thinning). The constant term in equation [4] transform the expression from dm^3 (solid excl. bark) per second to m^3 (solid excl. bark) per G_{15}-hour.

[4] $$\rho_t^h = 3.3\left(\frac{0.6T_t^h}{V_t}\right)^{-1}$$

3.2.4 Forwarders

The time functions for forwarders are based on five components: (1) time spent at terminal/roadside; (2) driving; (3) assortment time; (4) sorting time; and (5) miscellaneous time. For forwarders, the time function (T_i^f) can be expressed as (Brunberg, 2004):

[5] $$T_i^f = B_{i,1}\frac{\alpha_{i,1}+B_{i,2}V_iU_i+\alpha_{i,2}\sqrt{V_iU_i}}{V_iU_i} + \frac{2F}{(75-8.2Y-1.4L^2)W} + M_i^f \ \ (i = f,t,s)$$

The superscript *f* indicate that the variable is for forwarders and the subscript *i* indicate if the time function is for final felling (*f*), thinning (*t*) or stump harvesting (*s*). $B_{i,1}$, $B_{i,2}$ $\alpha_{i,1}$ and $\alpha_{i,2}$ are specific constants for a mid-sized forwarder in the different types of operations, *W* is the forwarders load capacity. The time function is expressed in G_{15}-minutes per m^3 (solid excl. bark). The assortment, sorting and miscellaneous time (M_i^f) have been treated as constants. The corresponding productivity function for forwarders (ρ_i^f) can then be expressed as:

[6] $$\rho_i^f = \frac{60}{T_i^f} \qquad (i = f,t,s)$$

[4] It is assumed that one hour equals 1.08 G_{15}-hours.

3.2.5 Capital, operational and fixed costs

The capital cost for harvesters, forwarders, chippers and crushers are based on a write-off period of seven years, a five percent interest rate and 2 730 G_{15}-hours of operation per year (Athanassiadis et al., 2009a; Athanassiadis et al., 2009b).

Table 5 summaries the calcula-tions for the capital, operational and fixed costs (R). The investment cost is based on annuity calculation. As indicated by the table, harvesters, forwarders, chippers and crushers have a total capital, operational and fixed cost of 121, 55, 117 and 151 EUR per G_{15}-hour, respectively[5].

Table 5. Capital, operational and fixed costs

Capital costs		Harvester	Forwarder	Chipper	Crusher
Investment cost	*million EUR*	*0.55*	*0.27*	*0.60*	*0.98*
Annuity[1]	EUR / G_{15}-hour	34.7	17.3	38.1	62.4
Sum capital costs	EUR / G_{15}-hour	34.7	17.3	38.1	62.4
Operational costs					
Diesel consumption[2]	*litres / G_{15}-hour*	*15*	*15*	*45*	*60*
Diesel cost	EUR / G_{15}-hour	18.4	18.4	55.1	72.2
Oil consumption[3]	*litres / G_{15}-hour*	*0.5*	*0.5*	*0.5*	*0.5*
Oil cost	EUR / G_{15}-hour	1.6	1.6	1.6	1.6
Maintenance	EUR / G_{15}-hour	54.7	10.9	16.4	10.9
Miscellaneous	EUR / G_{15}-hour	10.9	5.5	4.4	2.7
Sum operational costs	EUR / G_{15}-hour	85.6	36.4	77.5	87.4
Fixed costs					
Insurance	EUR / G_{15}-hour	1	1	1	1
Sum fixed costs	EUR / G_{15}-hour	1	1	1	1
Sum (R^i)	EUR / G_{15}-hour	121	55	117	151

[1] Based on 7 year depreciation, 5 percent interest and 2,730 G15-hour per year.
[2] Based on a diesel price of 1.2 EUR per litre.
[3] Based on an oil price of 3.3 EUR per litre.

3.2.6 Total average cost assessment

The total average cost is derived for five categories of forest resources. These are: (1) round-wood from final felling; (2) roundwood from thinning; (3) harvesting residues from final felling; (4) harvesting residues from thinning and; (5) stumps from final felling.

Equations [7] and [8] express the average harvesting costs for roundwood in final felling and thinning operations, respectively. The costs are determined by labour and capital costs for harvesters and forwarders in addition to overhead (OH), silviculture (C_{sil}) and forest road costs $\left(C_{fr}\right)$. Moreover, a moving cost for the forest machines is added corresponding to totally 328 EUR per machine, which is then divided by the available harvesting volume(q). The moving cost is also adjusted by the ratio between the size of the forest area $\left(S_{f\_area}\right)$ and the size of the harvested area $\left(S_{h\_area}\right)$.

[7] $$AC_f^{stem} = \left(\frac{w}{\rho_f^h} + \frac{R^h}{\rho_f^h}\right) + \left(\frac{w}{\rho_f^f} + \frac{R^f}{\rho_f^f}\right) + OH_f + C_{sil} + C_{fr} + \frac{3\,000}{q}\frac{S_{f\_area}}{S_{h\_area}}$$

[5] The exchange rate for 2010 is used implying that 1 EUR = 9.14 SEK.

[8] $$AC_t^{stem} = \left(\frac{w}{\rho_t^h} + \frac{R^h}{\rho_t^h}\right) + \left(\frac{w}{\rho_t^f} + \frac{R^f}{\rho_t^f}\right) + OH_t + C_{fr} + \frac{3\,000}{q}\frac{S_{f\_area}}{S_{h\_area}}$$

Equations [9] and [10] express the average extraction costs of forest residues from final felling and thinning operations. The labour and capital costs are included for forwarders. It is assumed that forwarders are 35 percent less efficient in handling forest residues compared to roundwood (Forestry Research Institute of Sweden, 2012). In addition, the capital cost for chippers (R^{chip}) and compensation to the land-owners (C_{comp}) are also included.

[9] $$AC_f^{residues} = 1.35\left(\frac{w}{\rho_f^f} + \frac{R^f}{\rho_f^f}\right) + \frac{R^{chip}}{\rho^{chip}} + C_{comp} + \frac{3\,000}{q}\frac{S_{f\_area}}{S_{h\_area}}$$

[10] $$AC_t^{residues} = 1.35\left(\frac{w}{\rho_t^f} + \frac{R^f}{\rho_t^f}\right) + \frac{R^{chip}}{\rho^{chip}} + C_{comp} + \frac{3\,000}{q}\frac{S_{f\_area}}{S_{h\_area}}$$

Lastly, equation [11] expresses the average extraction cost for stumps in connection to final felling. The labour and capital costs for forwarders are included, and it is assumed that forwarders are 35 percent less efficient in handling stumps compared to stems. In addition, overhead (OH), stump lifting (C_{sl}) and crushing costs (C_{cs}) are included.

[11] $$AC_f^{stumps} = 1.35\left(\frac{w}{\rho_s^f} + \frac{R^f}{\rho_s^f}\right) + OH_s + C_{sl} + C_{cs} + \frac{3\,000}{q}\frac{S_{f\_area}}{S_{h\_area}}$$

3.2.7 Data for cost calculations

The variables for surface structure class (Y), gradient class (L), share of spruce (G), average terrain transport distance for forwarders (F), size of the forest area(S_{f_area}), the size of the harvested area (S_{h_area}) and the available harvesting volume (q) are geographically specific and vary across areas. In addition, the estimations are based on the input values reported in Table B- 1 in Appendix B. All observations with a gradient class (L) greater than or equal to seven have been removed from the data set. If the sum of the harvested roundwood assortments for an area is equal to zero, it is replaced by one to avoid division by zero in the cost calculations.

According the Forestry Research Institute of Sweden (2012) the average compensation to land-owners for extracting harvesting residues and stumps are 13 EUR per m^3. The Swedish Forest Agency (2012) reports different overhead cost for final fellings (1 EUR per m^3) and thinning operations (1.4 EUR per m^3). It is assumed that the overhead cost for stumps harvest is the same as in final fellings. In the instances where the volume is expressed as tonnes of dry substance, a conversion factor of 2.38 is used to convert the unit to cubic meters (Swedish Forest Agency, 2012).

3.2.8 Results from cost calculations

Based on the time functions and input values, Table 6 presents the descriptive statistics for the calculated unit cost and the productivity for the different forest product assortments.

Table 6. Descriptive results of cost calculations

Total unit cost (EUR per m^3) [a]	Average	Min	Max	St.D.	Median
Roundwood, final felling	21.2	17.6	666	8.9	19.7
Roundwood, thinning	23.9	19.4	669	8.9	22.6
Residues, final felling	22.6	20.1	346	4.6	21.9
Residues, thinning	24.4	22.1	347	4.5	23.5
Stumps, final felling	35.0	31.2	681	8.9	33.6
Productivity (m^3 per G15-hour) [b]	**Average**	**Min**	**Max**	**St.D.**	**Median**
Roundwood, final felling	25.9	21.1	26.5	0.8	26.3
Roundwood, thinning	11.5	9.8	12.8	1.0	11.7
Residues, final felling	22.9	1.8	29.5	5.1	23.4
Residues, thinning	16.1	2.1	18.7	2.3	16.5
Stumps, final felling	23.9	1.8	31.2	5.5	24.4

[a] Including all cost components for road-side delivery of forest resource.
[b] Cubic meters are measured as solid volume excl. bark. G15-hour is productive time including downtime not exceeding 15 minutes per occasion.

For instance, the average unit cost for roundwood in final felling operations is calculated to 21.2 EUR per m^3. The highest cost (666 EUR) is relatively high, but the standard deviation indicates that most areas have a rather similar cost structure, leaving just a few outliers. The same pattern can also be observed for the other assortments. The productivity functions indicate that final felling has, on average, a higher productivity than thinning operations. Among the assortments that can only be used for energy purposes (i.e., residues and stumps), the productivity is highest for stumps. However, stumps also has the highest harvesting cost. This can partly be explained by studying the separate cost components that comprise the average costs.

A few observations can be made based on the information in Figure 6. For instance, there seems to be little difference in the harvesting costs in the two scenarios. Moreover, the harvesting cost for pulpwood is generally higher in southern Sweden than in the northern parts. For harvesting residues and stumps it is the opposite, northern Sweden has the higher harvesting costs. Extracting stumps seems to be most lucrative in the southern region of Skåne. By combining this insight with the information on the potential harvesting volumes from Figure 6, some interesting conclusions can be made. Firstly, the potential harvesting volumes of pulpwood are significantly higher in southern Sweden. In combination with the observation that the harvesting costs for pulpwood are also higher in southern Sweden, this makes a further exploitation of the forest in northern Sweden initially more likely. As a consequence, the harvesting cost – and thus the market price – for woody biomass (e.g., harvesting residues and stumps) might remain relatively high since they are more costly in northern Sweden to extract. That is, in order to enjoy lower harvesting costs for woody biomass, higher harvesting costs need to be accepted for pulpwood.

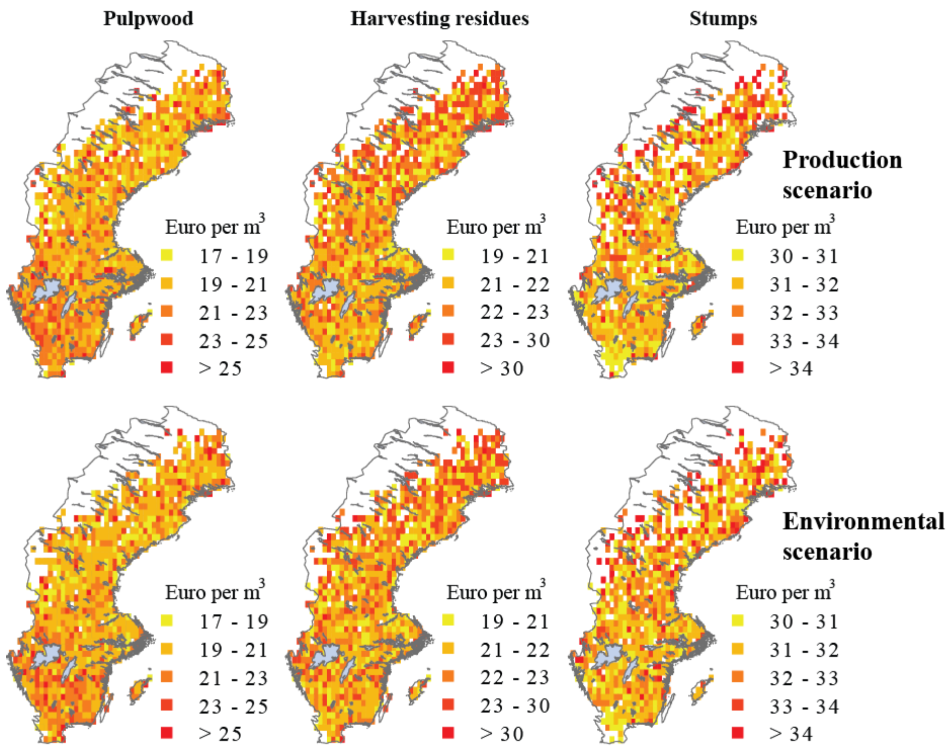

Figure 6. Geographically explicit harvesting costs for pulpwood, harvesting residues and stumps for the production and environmental scenarios

Figure 7 depicts the average magnitude of the individual cost components for roundwood and harvesting residues from final fellings and thinning operations, as well as for stumps from final felling. The average is calculated on all forest areas included in the data set and for the time period 2010-2019. As the figure shows, stumps have the highest average harvesting cost. The other categories have a relatively similar average harvesting cost. As for the individual cost components, compensation to the land-owner for extracting harvesting residues and stumps is the largest cost component for these categories. For roundwood, the capital cost for the forest machines is the largest cost component.

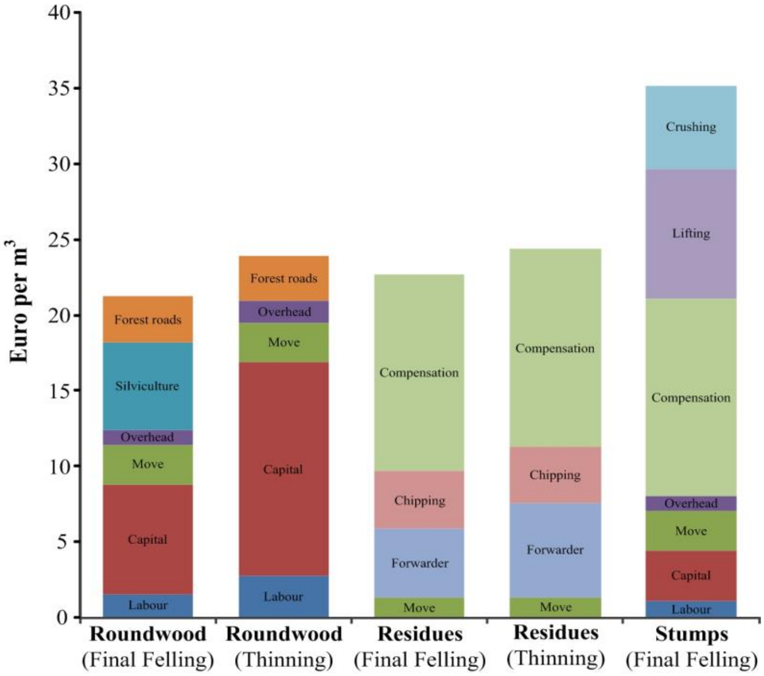

Figure 7. Average size of cost components for the different product assortments

A few observations can be made when examining the estimated cost shares: (1) final felling operations are, on average, less costly than thinning operations; (2) harvesting pulpwood from thinning operations are more costly than if extracted during final fellings; (3) harvesting residues are, in general, less costly to remove if extracted during final fellings than during commercial thinning operations and; (4) harvesting stumps has a significantly higher cost compared to harvesting residues (relevant since both are mainly used for energy purposes).

The cost analysis shown here only considers the harvesting costs of forest biomass for roadside delivery. When used in BeWhere Sweden distance dependent transportation costs are added (see Section 2.7), since transportation costs can have a significant impact on the delivered price of the resources. For instance, the transportation cost of stumps for 100 kilometres amounts to approximately 16.6 EUR per m^3 (Athanassiadis et al., 2009a)[6].

It is also possible to compare the cost estimates with current price level. For instance, in 2012 the national average price for pulpwood was approximately 32.8 EUR per m^3 and for wood chips 32.8 EUR per m^3.[7] At these price levels, some 30.5 million m^3 pulpwood and 9.7 million m^3 wood chips were harvested (Swedish Forest Agency, 2012). Given these harvested volumes, the results indicate that the harvesting cost is 28.4 and 22.5 EUR per m^3 for pulpwood and forest residues, respectively. The discrepancy can partly be explained by the

[6] Athanassiadis et al. (2009a) report the transportation cost for 100 kilometres to 39.8 EUR per odt (oven dry tonne). A factor of 2.4 is used to convert the odt to m^3.

[7] The average reported price for forest chips during 2012 was 21.9 EUR per MWh, which includes transportation cost to user. The price is converted to EUR per m^3 by the using the following conversion factors: 1 metric ton = 2.4 MWh and 0.8 metric ton = 1 m^3 (50 percent moist content). After conversion, a transportation cost on 8.8 EUR per m^3 is deducted (Athanassiadis et al., 2009a).

fact that we observe market prices whilst calculating harvesting costs. This suggest that there might by other factors affecting the price level not measured by the harvesting cost (e.g., market structure, unobserved cost components, regional differences making comparesons of averages difficult, forest-owners profit, etc.). Table 7 extends the cost-quantity discussion by presenting the availability of pulpwood, harvesting residues and stumps at different allowable costs levels. For instance, given a harvest cost corresponding to 35 EUR per m^3, the market, if functioning properly, will make 31.4, 17.5 and 15.8 million m^3 pulpwood, harvesting residues and stumps available, respectively.

Table 7. Availability of forest resources at different cost levels

Allowed cost (EUR per m^3)	Pulpwood (million m^3)	Residues (million m^3)	Stumps (million m^3)
25	28.3	17.3	0
30	30.9	17.5	14.0
35	31.4	17.5	15.8
40	31.6	17.6	16.0
45	31.7	17.6	16.0

Wetterlund et al. (2013a) summarise the results of previous studies assessing the potential for woody biomass in Sweden. The assumptions and applied methods vary between the studies, making a direct comparison difficult. However, a tentative conclusion seems to be that there is no consensus in the assessments. For instance, with a 2020 time frame, there are 14 studies that have estimated the potential for primary harvesting residues. The highest estimate is 81 TWh per year (42.6 million m^3) and the lowest is 16 TWh per year (8.4 million m^3). The potential for stumps is assessed in four studies, for year 2010. The corresponding estimates range between 10 and 57.5 TWh per year (5.3 to 30.3 million m^3). Finally, seven studies assess the potential for additional roundwood extraction dedicated for energy use for the year 2020. The maximum potential is estimated to 80.6 TWh per year (42.4 million m^3) whilst the lowest is zero. In contrast, the results obtained in this study indicate that 33.3 TWh (17.5 million m^3) harvesting residues, 26.6 TWh (14.0 million m^3) stumps and 58.7 TWh (30.9 million m^3) pulpwood are available per year (at a cost level corresponding to 30 EUR per m^3). The result for harvesting residues and stumps are in the lower range of previous assessments. Interestingly, the highest estimate for additional roundwood for energy use is above the totally supplied volume of pulpwood estimated in this study, which is today dominantly used by the forest industry. The highest estimate is also significantly higher than the current total gross fellings of pulpwood reported in statistics (Swedish Forest Agency, 2012). Obtaining an additional 80 TWh of roundwood is, according to our results, not feasible.

3.3 ADAPTATION TO BEWHERE SWEDEN

The forest biomass data was aggregated in order to fit the half-degree spatial grid used in BeWhere Sweden. The quantities of each assortment were aggregated separately, meaning that the quantities for all harvest plots located within a given grid cell were added. For the costs, weighted averages were calculated for each separate biomass in each grid cell. When running the model (Chapter 6) the costs were also calibrated against average biomass market prices for each given scenario.

4 BIOFUEL PRODUCTION TECHNOLOGIES AND EXISTING PLANT SITES

Seven different biofuel technology cases have been included. These cases constitute examples of next generation biofuels and biofuel production technologies that use lignocellulosic biomass. Five cases are based on gasification technology and produces DME (dimethyl ether), SNG (synthetic natural gas) and FT (Fischer-Tropsch) fuels and two cases are based on hydrolysis and fermentation technology and produces ethanol. The biofuel technology cases studied are:

- Solid biomass gasification with DME production (BMG-DME)
- Solid biomass gasification with SNG production (BMG-SNG)
- Solid biomass gasification with FT fuels production (BMG-FT)
- Black liquor gasification with DME production and bark boiler (BLG-DME-BB)
- Black liquor and solid biomass gasification with DME production
- (BLG-DME-BMG-DME)
- Alkaline pre-treatment followed by hydrolysis and fermentation for ethanol production (ALK-HF-EtOH)
- Steam explosion pre-treatment followed by hydrolysis and fermentation for ethanol production (SE-HF-EtOH)

BMG-SNG and BMG-FT were not included in the previous project (Wetterlund et al., 2013b). As described in the introduction, there are several driving forces for locating biofuel production at existing industrial plants or district heating (DH) systems. Important examples include opportunities to deliver excess heat, opportunities for re-use or co-use of existing process units, opportunities to use existing infrastructures such as raw material handling systems and ability to capitalise on know-how concerning the raw material and its supply, operation of production processes and the products and their markets. Five different types of plants have been included as potential biofuel plant host sites. The host sites considered are:

- Chemical pulp mills
- Mechanical pulp mills and paper mills
- Sawmills
- Refineries
- Biomass-fueled combined heat and power (CHP) plants in district heating systems

Refineries and CHP plants in district heating systems were not included in the previous project. Data for most of the chemical pulp mills has been improved in comparison to the previous project (see Section 4.2.1). Most technologies are flexible in localisation and can be located at all types of hosts listed (and of course at other host types, as well as stand-alone). However, black liquor gasification is a part of the chemical pulp process and thus must be located at the mill. Similarly, the ethanol process with alkaline pretreatment is designed to operate at a chemical pulp mill using several process units available there. Table 8 indicates which combinations of biofuel technology cases and types of host sites that have been considered.

Table 8. Combinations of biofuel technology cases and types of host sites that have been considered.

	Chemical pulp mills	Mech. pulp mills and paper mills	Sawmills	Refineries	CHP plants in DH systems
BMG-DME	x	x	x		
BMG-SNG	x	x	x		x
BMG-FT				x	
BLG-DME-BB	x				
BLG-DME-BMG-DME	x				
ALK-HF-EtOH	x				
SE-HF-EtOH	x	x	x		

There are naturally other biofuel technology cases, host types and integration possibilities that have not been considered here. However, the two main production routes for next generation biofuels (gasification and fermentation) are represented and production of four different biofuels is considered (DME, SNG, FT fuels and ethanol). As potential hosts for biofuel production, the existing plants that have experience when it comes to raw material handling (pulp mills, sawmills and district heating systems) and transportation fuels (refineries) have been included. Examples of other biofuel technology cases that could be included are methanol or hydrogen produced via gasification. Other existing industries that could be considered as potential host sites include the chemical process industry and the iron and steel industry. However, in these two industries perhaps integration of production of biomass-based feedstocks to the production processes is more likely. In addition, biofuel technology cases already available today using agricultural crops and waste streams, such as ethanol from starch crops and biodiesel from esterified vegetable oil and biogas could also be includeed if these types of raw material were to be included in the model. DH systems have here only been considered indirectly through biomass-fueled CHP plants where BMG-SNG could be integrated (see Sections 4.1.2 and 4.2.5). Replacement of existing production technologies in district heating systems with heat from biofuel plants has not been considered in this report, but was covered briefly in Wetterlund et al. (2013b).

In order to be able to include a biofuel technology case thorough data for the case has to be available “in-house”. Data published in different studies are often not enough to be able to estimate the mass and energy balances for integration of that technology to different types of host sites. To implement a biofuel technology case and/or biofuel plant site in the model is time consuming and require considerations of criteria for dimensioning the biofuel plant and what possibilities for integration that should be considered, how the integration to different types of sites should be performed and what data is required for the technology and for each existing plant in order to do so, etc. Thus, as many cases with available data as possible within the time frame of the project time have been included.

4.1 BIOFUEL PRODUCTION TECHNOLOGIES

The two main production routes for production of next generation biofuels from lignocellulosic feedstock are gasification of solid biomass or black liquor followed by synthesis into, for example, methanol, DME, SNG, FT fuels or hydrogen, and ethanol produced from lignocellulosic biomass via fermentation.

Three main routes for production of syngas via gasification are being considered in Sweden today: direct Fluidised Bed Gasification (FBG); Entrained Flow Gasification (EFG); indirect Dual Fluidised Bed Gasification (DFBG) (Heyne et al., 2013). Many different combinations of gasification technology and biofuel synthesises are possible. In this study all three mentioned gasification routes are represented and the gasification-based biofuels are assumed to be produced via the gasification technology that perhaps has been most discussed/studied for the biofuel in question.

There are different methods developed for pre-treatment of lignocellulosic biomass prior to the hydrolysis and fermentation steps in the production of ethanol including steam explosion and alkaline pre-treatment, which are considered here.

Table 9 presents the energy balances for the biofuel technology cases based on one unit of fuel input. For references which the numbers in Table 9 have been based on, see Sections 4.1.1 to4.1.6. The different technology cases have been dimensioned in different ways in relation to the different existing plant hosts considered (see Section 4.2). The technologies with significant amounts of excess heat at lower temperatures would naturally be suitable for integration with district heating production, which has not been considered here. However, this excess heat can to different extents also be used when considering integration with pulp mills and sawmills (see Section 4.2).

Table 9. Energy balances for the different biofuel technology cases based on one unit of biomass input.

	BMG-DME	BMG-SNG	BMG-FT	BLG-DME (-BB)[a]	BLG-DME (-BMG-DME)[a]	ALK-HF-EtOH	SE-HF-EtOH
Biomass input	1	1	1	1	1	1	1
Biofuel	0.34	0.70	0.45[b]	0.55	0.55	0.27	0.28
Excess heat – steam	0.15	0.09	0.20	0.26	0.30	0.16	0.15
Excess heat – <120°C	0.04	–	–	0.02	0.02	0.06	0.07
Purge gas	–	–	–	0.11	–	–	–
Electricity production							
Gas turbine	0.12	–	–	–	0.03	–	–
Back-pressure ST	0.05	0.06	0.04	–	0.01	0.08	0.10
Cond. ST[c]	0.04	0.05	–	–	–	0.04	0.04
Electricity use	0.06	0.04	0.10	0.07	0.07	0.04	0.04

[a] This is the balance of only the BLG-DME plant based on a certain amount of black liquor. The BB or BMG-DME plant have different sizes in relation to the BLG-DME plant depending on the specific mill.
[b] 0.33 is FT-diesel and 0.12 is FT-gasoline.
[c] This is in case the excess steam is not used for heating purposes.

As can be seen in Table 9, the BMG-SNG process has the highest biomass-to-biofuel conversion efficiency, significantly higher than e.g. BLG-DME which is also based on gasification and optimised for maximised biofuel production. As has been mentioned, a biofuel production route that has been frequently studied or discussed has been chosen for each gasification technology. SNG production is based on DFBG technology, which has high methane content in the product gas from the gasifier. The used BLG technology, EFG, is less suitable for SNG production due to low methane content in the product gas.

Table 10 presents the investment cost functions used for the biofuel technology cases and components constituting part of the biofuel plants (and/or alternative investments, see Section 4.2). Operation and maintenance (O&M) costs are set to 4% of the investment cost. The investment cost functions have been estimated based on the same references as the energy balances have been based on (see Sections 4.1.1 to 4.1.6). Investment cost estimations are difficult and most of the investment cost functions have been taken from different studies. Therefore, both the absolute level of the investment costs and the relation between the different investment costs could be different if different sources of information had been used or if a deeper analysis had been conducted.

Table 10. Investment cost functions for the different biofuel plants and components constituting part of the biofuel plants and/or alternative investments.

	Investment cost function *a* * capacity(MW)^*b* [$MEUR_{2010}$][a]	
	a	*b*
BMG-DME	5.0	0.7
BMG-SNG	5.0	0.7
BMG-FT	6.7	0.7
BLG-DME(-BB)	4.0	0.7
BLG-DME-(BMG-DME)	4.7	0.7
ALK-HF-EtOH	3.3	0.7
SE-HF-EtOH	4.6	0.7
Bark boiler (steam)	2.9	0.7
Heat water boiler (wood fuel)	2.9	0.7
Recovery boiler	2.5	0.7
Back-pressure steam turbine	1.8	0.6
Condensing steam turbine	2.9	0.6

[a] All investment costs have been recalculated to 2010 money value using Chemical Engineering's Plant Cost Index (CEPCI).

Only production of energy products, including biofuels, from biomass are considered in this study. This means for example that the lignin, which is a by-product in the ethanol production processes, is assumed to be used as a fuel for steam and electricity production and not as a feedstock for production of materials or chemicals (see further Sections 4.1.5, 4.1.6 and 4.2.1).

The following sections include short descriptions of the biofuel technologies considered. References to other sources where more information can be found are provided. The sections also include factors that are important when selecting possible integration sites for each technology.

4.1.1 DME production via gasification of solid biomass (BMG-DME)

Data for the BMG-DME process has been calculated based on Pettersson and Harvey (2012), where the reader is referred to for background references. The gasification technology considered is direct pressurised circulating fluidised bed gasification. Wood fuel is gasified at 25 bar, 850°C using oxygen and steam. The product gas is sent to a tar cracker, cooled and further cleaned from tars and from particles and separated from CO_2 and hydrogen sulphide before it is sent to the DME synthesis (DME is produced via synthesis of methanol). No adjustment of the H_2/CO ratio is necessary. The gas contains considerable amounts of methane, which will go through the DME synthesis unreacted. In order to maximise the yield of produced DME, reforming of the methane would be necessary. This is however not considered here. Instead the unreacted gas, together with purge gas, is fired in a gas turbine. The exhaust gas is cooled in a heat recovery steam generator (HRSG). After the HRSG, the exhaust gas is used for drying the wood fuel (the wood fuel is assumed to have a moisture content of 50% and it is dried to a moisture content of 15%).

Table 9 presents the energy balance for the BMG-DME case. In total, there is a significant heat surplus from the BMG-DME process. This heat surplus is used to generate high pressure steam that is expanded in a back-pressure steam turbine (ST) to generate electricity. The excess heat in the form of steam that is presented in Table 9 is the outlet steam of lower pressure from the turbine. In case the excess steam is not used for heating purposes (depends on the considered type of integration), expansion through a condensing steam turbine is considered (see Table 9). There is also some heat available at lower temperatures (<120°C) that is not used for steam generation.

The most interesting integration possibilities for the BMG-DME process would reasonably offer the opportunity for the process to deliver excess heat. The BMG-DME process has accordingly been considered for integration with pulp and/or paper mills having a deficit of steam and sawmills (see further Section 4.2).

4.1.2 SNG production via gasification of solid biomass (BMG-SNG)

Data for the BMG-SNG process has been calculated based on Heyne (2013) where the reader is referred to for background references. The SNG production process is based on an indirect dual fluidised bed gasification unit using steam and recycled syngas and operating at 850°C followed by tar reforming, two stages of amine-based CO_2 separation and isothermal methanation, and finally compression, H_2-purification by membrane separation and gas drying. Char from the gasification is used in a boiler to provide heat for the gasification process. Prior to gasification, the inlet biomass is dried (the wood fuel is assumed to have a moisture content of 50% and it is dried to a moisture content of 15%) using low-temperature air drying. The investment cost function used for BMG-SNG has been approximated to be the same as for BMG-DME.

Table 9 presents the energy balance for the BMG-SNG case. In total, there is a significant heat surplus from the BMG-SNG process. This heat surplus is used to generate high pressure steam that is expanded in a back-pressure steam turbine to generate electricity. The excess heat in the form of steam that is presented in Table 9 is the outlet steam of lower pressure from the turbine. In case some of the excess steam is not used for heating purposes (depends on the considered type of integration), expansion through a condensing steam turbine is considered.

As for the BMG-DME case, opportunity for the process to deliver excess heat is important and integration with pulp and/or paper mills having a deficit of steam and sawmills has been considered (see further Section 4.2). In addition, integration with existing CHP plants is interesting due to the opportunity to use the boiler as part of the gasification system. The possibility to integrate to existing CHP plants in district heating systems has therefore been considered (see further Section 4.2). Naturally, other CHP plants such as the CHP plants in the pulp mills could also be considered for this type of integration. This has however not been considered here.

4.1.3 FT fuels production via gasification of solid biomass (BMG-FT)

The input data for the Fischer-Tropsch process is taken from Johansson (2013) where the reader is referred to for background references. The process consists of a steam dryer; an oxygen blown pressurised circulating fluidised bed gasifier, operating at 25 bar. The gas cleaning consists of a tar cracker, a cyclone, a bag filer and a wet cleaning step. An autothermal reformer is placed prior to FT-synthesis to decrease the methane content, and the final step before the synthesis is a shift reaction that adjusts the H_2/CO ratio. The gas stream is cleaned prior to the FT reactor to avoid poisoning the FT reactor catalysts. The produced FT syncrude is distilled to produce fractions of naphtha, diesel and wax. These fractions are processed through a series of refining steps before the final products, FT-diesel and FT-gasoline, are obtained.

Table 9 presents the energy balance for the BMG-FT case. In total, there is a significant heat surplus from the BMG-FT process. This heat surplus is used to generate high pressure steam that is expanded in a back-pressure steam turbine to generate electricity. The excess heat in the form of steam that is presented in Table 9 is the outlet steam of lower pressure from the turbine.

Integration of production of FT fuels with refineries has been considered. At refineries there are opportunities to deliver excess steam. In addition, the final upgrading of the FT crude to FT-diesel and FT-gasoline (and some other products), can be performed in existing process units. Production of FT fuels could also be considered for the same integration opportunities as the other gasification cases presented (pulp mills, sawmills), although that has not been considered yet in this model. Production all the way to the final products could then be regarded, or to FT crude with the final upgrading at a refinery, as for example has been considered in Isaksson et al. (2012a) and Ljungstedt et al. (2013). The latter is an example where each industry uses their respective competences in a beneficial way.

4.1.4 DME production via gasification of black liquor (BLG-DME-BB, BLG-DME-BMG-DME)

Data for the for DME production via gasification of black liquor has been calculated based on Pettersson and Harvey (2012), where the reader is referred to for background references. Black liquor gasification is currently being developed as an alternative technology to the recovery boiler for energy and chemical recovery at chemical pulp mills.

The black liquor gasification technology considered in this project is the Chemrec process, based on pressurised, oxygen-blown, high-temperature entrained-flow gasification (Landälv et al., 2010). The black liquor is gasified at 32 bar, 950°C. After gas cooling and cleaning, including separation of hydrogen sulphide and CO_2, and adjustment of the H_2/CO ratio (with a water gas shift reactor), the gas is sent to DME synthesis (DME is produced via synthesis of methanol as for the BMG-DME case). Figure 8 shows the main energy and material flows in the BLG-DME plant.

Table 9 gives the energy balance for the BLG-DME cases. In total, there is a significant amount of excess steam from the BLG-DME plant that can be used in the mill processes. However, replacing the recovery boiler with a black liquor gasification plant producing DME results in a significant decrease of the steam production compared to operation with a recovery boiler. Consequently, all kraft pulp mills will have a significant deficit of steam if black liquor gasification with DME production is implemented. This steam deficit is in one of the cases, BLG-DME-BB, covered by firing wood fuel in a bark boiler connected to a back-pressure steam turbine. In the other case considered in this project, BLG-DME-BMG-DME, a solid biomass gasification plant with DME production, as the one described in Section 4.1.1, is used to cover the steam deficit. Also from the BLG-DME process, there is some heat available at lower temperatures (<120°C) that is not used for steam generation. The BLG-DME cases have been considered for integration with all kraft pulp mills (see Section 4.2.1).

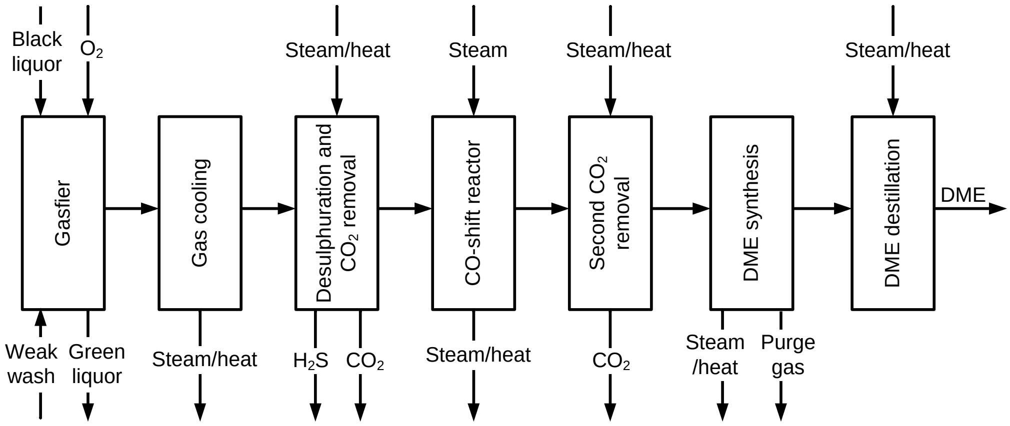

Figure 8. Main energy and material flows in the BLG-DME plant (electricity usage not included).

4.1.5 Ethanol production using alkaline pre-treatment (ALK-HF-EtOH)

Ethanol production with alkaline pre-treatment has been envisioned to be built next to a kraft pulp mill to enable integration between the two production sites. A process scheme of the integrated process is outlined in Figure 9. Data for the process has been calculated based on (Berglin et al., 2009; Jansson et al., 2010; von Schenck et al., 2007; von Schenck et al., 2013).

The first unit operation is the alkaline fractionation where the aim is to defibrate the raw material by degrading the lignin with hydroxide using NaOH (the make-up NaOH needed in the pulp mill) and oxidised white liquor from the mill, giving a rather pure carbohydrate stream and black liquor containing the lignin. The black liquor is sent to the pulp mill's evaporation plant and later combusted in the recovery boiler. This will increase the load on all units in the recovery cycle and a capacity increase is necessary, which has been taken into account in the investment cost.

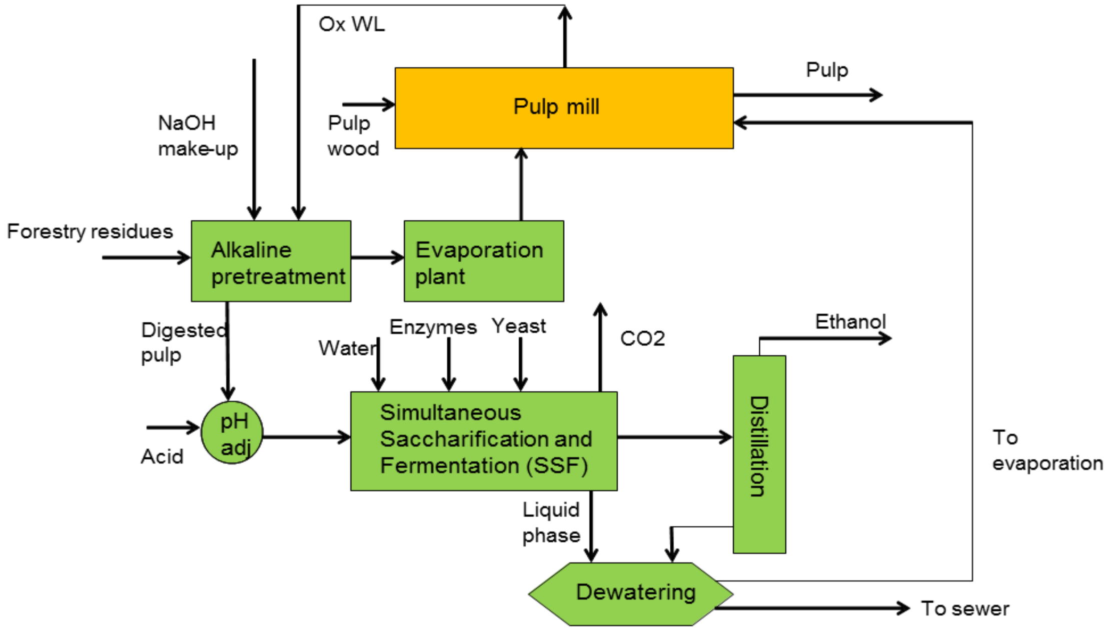

Figure 9. Process scheme of the alkaline pre-treatment concept for producing ethanol.

Next, the rather pure carbohydrate stream is simultaneously hydrolysed and fermented via the SSF (simultaneous sacharation and fermentation) process. In the distillation, the produced ethanol is concentrated and separated from the water and other solids. The thin stillage from the dewatering step consists of about 3-4% dissolved solids and is sent to the evaporation plant and combusted in the pulp mills recovery boiler.

Lignin can be extracted from the black liquor and be used as a feedstock for production of green materials or chemicals. However, since this project is focused on biofuel production (and energy products) the black liquor containing the lignin has been assumed to be combusted in the mills recovery boiler to generate steam for the back-pressure steam turbine in the mill. This may not be the most beneficial way of producing ethanol, as more products than ethanol from the process are required to make the concept of cellulosic ethanol economically feasible. The steam from the turbine that originates from by-products at the ethanol plant is partly used internally at the ethanol plant, but there is a significant amount of excess steam that can be used in the mill processes. If all this steam is not needed, additional electricity can be produced in a condensing steam turbine. There is also some heat available at lower temperatures (<120°C). Table 9 presents the energy balance for the ALK-HF-EtOH case. The ALK-HF-EtOH case has been considered for integration with all kraft pulp mills (see Section 4.2.1).

4.1.6 *Ethanol production using steam explosion pre-treatment (SE-HF-EtOH)*

The other ethanol production process considered in this study starts with a steam pre-treatment step which is efficient on woody biomass. Degraded materials from the pre-treatment are pre-hydrolysed and then simultaneously hydrolysed and fermented via the SSF process. The broth from the SSF-step with a low concentration of ethanol is then sent to distillation. The distillation concentrates and purifies the ethanol in the broth. The by-products in the formed stillage are separated between a solid phase containing mainly lignin and a thin stillage containing dissolved components. The pre-treatment method is in line with what has been presented in previous studies (Wingren, 2005; Sassner, 2007), upon which data has been calculated. Figure 10 shows a simplified process layout of the wood-to-ethanol production process.

Also for this ethanol concept, by-products such as lignin could be upgraded to give extra revenue and improve the economics of the process. For the same reasons as given in the previous section, all lignin and solid residues have been assumed to be combusted in a boiler to generate steam for a back-pressure steam turbine. There is also a possibility to produce biogas from this residual stream from the SSF (Börjesson et al., 2013a). However, this has not been further evaluated in this study. Some steam is used internally at the ethanol plant, but there is a significant steam surplus from the process. In case the excess steam is not used for heating purposes (depends on the considered type of integration), expansion through a condensing steam turbine is considered. There is also some heat available at lower temperatures (<120°C). Table 9 presents the energy balance for the SE-HF-EtOH case.

As for the solid biomass gasification cases, the most interesting integration possibilities for the SE-HF-EtOH process (given the assumptions about usage of by-products for steam generation) would reasonably offer the opportunity for the process to deliver excess heat. The SE-HF-EtOH process has therefor been considered for integration with pulp and/or paper mills having a deficit of steam and sawmills (see further Section 4.2).

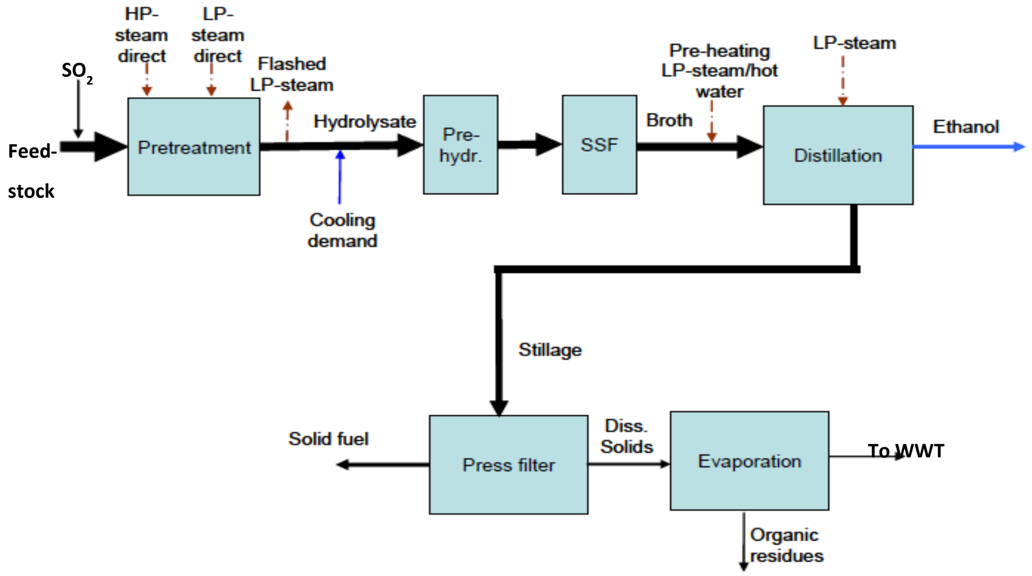

Figure 10. Process scheme of the steam explosion pre-treatment concept for producing ethanol.

4.2 INTEGRATION WITH EXISTING PLANT SITES

In total 69 potential biofuel plant sites have been considered (see also Figure 1). 33 pulp/paper mills have been included, of which 21 have chemical pulp production (kraft process) while 12 produce only mechanical pulp and/or paper. Of all pulp mills, seven are also integrated with a sawmill. 18 stand-alone sawmills have also been included, as have 18 CHP plants in district heating systems.

Chemical pulp mills have existing infrastructures for raw material handling, as well as long-time experience of handling large volumes of biomass. In addition, there are generally good opportunities for heat integration. For the ALK-HF-EtOH case, it is possible to use several of the existing process units. Mechanical pulp mills, as well as sawmills, offer the same opportunities as chemical pulp mills. Paper mills offer good opportunities for heat integration and may, in certain cases, also have existing infrastructures and experience of biomass handling. The CHP plants in district heating systems considered here are biomass-fueled and hence infrastructure and experience concerning biomass handling exist in those systems. Excess heat can be used when integration with the CHP plants are considered (see Section 4.2.5). Refineries have knowledge about motor fuels and their markets and for some fuels experience from part of the production chain and existing infrastructure that could be used for this. It also exist good opportunities for heat integration.

The general approach in this report is that the different plant sites integrated with different biofuel technologies are compared to a case where new investments in conventional technologies (boilers and turbines) are made at the industrial plants instead of a biofuel plant. This is further explained in the following sections. Investment cost functions for these alternative investments are presented in Table 10 above.

4.2.1 Chemical pulp mills

The absolute majority of the chemical pulp production in Sweden is kraft pulp. 21 out of 25 chemical mills in Sweden are kraft pulp mills, and the others are sulphite pulp mills. So far only the kraft pulp mills have been included as potential sites for biofuel production.

For a process description of a kraft pulp mill, see e.g. Wetterlund et al. (2013b). In this report the amount of steam produced by other fuels than black liquor, is denoted steam deficit. The boilers used for this purpose are denoted bark boilers, even though other fuels than bark can also used.

In order to estimate the plant sizes for the different biofuel technology cases and to estimate the consequences when different biofuel technologies are integrated into the kraft pulp mills a number of different data is needed. This includes for example pulp production, generation of black liquor, usage of other fuels, process steam demand and generation of electricity (see Appendix C). Different data is necessary for the different technology cases since they are not dimensioned using the same criteria.

In the previous project the main data needed for kraft pulp mills in order to estimate the integration potential for different biofuel technologies has been calculated mainly based on data from the environmental database of the Swedish Forest Industries Federation (SFIF) (SFIF, 2012b). With our knowledge about pulp and paper mills in general and some specific knowledge about certain mills, it was concluded that some of the data was not of sufficiently good quality. We thought that publically available data from the SFIF’s environmental database together with some general correlations would generate a fairly good estimate of for example a mill’s steam balance. However, this was shown to not be the case for several of the mills. We believe that the main reasons for this are errors in the data reported to the SFIF’s environmental database, that different heating values have been used for the same fuel by different mills when reporting to the SFIF’s environmental database and that too many general assumptions (e.g. how much black liquor that is generated for a certain amount of pulp produced and total boiler efficiencies), which could vary significantly from mill to mill, have to be made in order to estimate the required data.

In this project, more comprehensive data has been used for the majority of the kraft pulp mills. This data comes from a mapping of the pulp and paper industries energy usage 2011 performed by ÅF on behalf of SFIF's Environmental and Energy Committee (Wiberg and Forslund, 2012). The data reported to the study is confidential and each mill had to be contacted in order to ask if we could get access to the data. Due to the relatively short project time, asking for data from an already existing survey was deemed more appropriate than sending out an own survey. For 13 of the mills, data from this mapping has been used in this project. Reasons why the other 8 mills have not been included include denied access to data (4 mills), did not answer the question (2 mills), replied too late (1 mill) and the survey could not be found (1 mill). For these mills, the data estimated based on the data from SFIF's environmental database have been used.

Appendix C describes how the required data has been estimated based on data from the survey and based on the data from SFIF's environmental database. The main difference is that due to the limited amount of data in the SFIF's environmental database, more general assumptions have to be made in order to estimate the data required for the integration calculations in this project.

Table 11 presents an example of energy balances (GWh/y) for a kraft pulp mill without biofuel production and the same kraft pulp mill integrated with the different biofuel technology cases considered for integration with chemical pulp mills. Investment costs and O&M costs for the alternative investment (existing plant cost for new boiler/s and turbine/s) and the biofuel cases are also included.

The flows presented in Table 11 are the flows entering or leaving the mill that are affected by the implementation of a biofuel plant (except pulp wood), thus internal flows like the black liquor are not included in Table 11. For this fictive mill that is presented in Table 11, one can see that there is a net demand for wood fuel. Thus, this indicates that the mill has a steam deficit and is thereby considered for integration with BMG-DME, BMG-SNG and SE-HF-EtOH (which are considered for integration with mills with a steam deficit), as well as the technology cases that are considered for integration with all kraft pulp mills (BLG-DME-BB/BMG-DME and ALK-HF-EtOH).

The investment cost for existing plants includes a new recovery boiler and a new back-pressure steam turbine, and for most mills also a new bark boiler (for a few mills also a new condensing steam turbine). The investment cost for existing plants integrated with biofuel production includes the biofuel plant, a new recovery boiler (not BLG cases), a new bark boiler (only BLG-DME-BB and ALK-HF-EtOH cases), a new back-pressure steam turbine and a condensing steam turbine (ALK-HF-EtOH case connected to a few mills). Thus, pulp mill integrated biofuel production is compared to a case where new investments in conventional technologies (with modern efficiencies, see Appendix C) are made. Biofuel production is not compared to other possible development pathways for the mill such as extraction of lignin or hemicelluloses for production of chemicals or materials. Implementation of these technologies increase the steam deficit at mills and thus the potential for heat integrated biofuel production (BMG-DME, BMG-SNG and SE-HF-EtOH). However, extraction of lignin and hemicelluloses decreases the flow of black liquor, thereby decreasing the potential for black liquor gasification. Since integration of all biofuel production technology cases lead to increased usage of wood fuel, they naturally compete with other usages of biomass such as production of different kinds of chemicals and materials.

Table 11. Example of energy balances (GWh/y) and investment and O&M costs (for the alternative investment and the biofuel plants) for a kraft pulp mill without biofuel production and the same kraft pulp mill integrated with the different biofuel technology cases considered for integration with chemical pulp mills.

	Biomass			Fossil fuels	Electricity			Bio-fuel	Inv. cost	O&M cost
	Demand		Supply		Production		Use			
	Pulp wood	Wood fuel	Wood fuel	Use	Tot.	Green		Prod.		
Existing plant w/o biofuel production	3741	640	0	104	422	422	569	-	219	9
BMG-DME	3741	4622	0	104	1125	1125	849	1683	543	22
BMG-SNG	3741	8502	0	104	813	813	893	6173	746	30
BLG-DME-BB	3741	1615	0	104	323	323	702	992	344	14
BLG-DME-BMG-DME	3741	10228	0	104	1886	1886	1294	4555	884	35
ALK-HF-EtOH	3741	2083	0	104	500	500	634	505	343	14
SE-HF-EtOH	3741	4656	0	104	748	748	760	1408	561	22

As has been described, BMG-DME, BMG-SNG and SE-HF-EtOH plants have been considered for integration with chemical mills having a deficit of steam and have been sized so the excess steam from the plant covers the mill's steam deficit. It has been assumed that all mills are in a situation where they are going to replace their bark boiler and thus have the choice between investing in a new bark boiler or a BMG-DME plant in order to cover their steam deficit. Therefore, the incremental investment cost, as well as operating and maintenance cost, for the biofuel plants compared to investing in a new bark boiler has been used in the model. In Table 11, the investment cost for the alternative investment, as well as the investment cost for the biofuel cases, includes an investment in a new recovery boiler. The incremental investment cost for these cases is however naturally not affected by this. It has been assumed that both for the biofuel cases and the mill base case, a new back-pressure steam turbine would be invested in. In case of integration with pulp and/or paper mills (a part of) the excess heat at lower temperature level is used for make-up feed water preheating, thereby reducing the need for steam to the feed water tank. As can be seen in Table 11, for the BMG-DME, BMG-SNG and SE-HF-EtOH cases, biofuel and additional electricity are produced at the expense of a higher demand for wood fuel, higher electricity use and higher investment as well as operation and maintenance costs.

The BLG-DME cases are naturally sized after the flow of black liquor. It has been assumed that all mills are in a situation where they are going to replace their recovery boiler (and bark boiler) and they have the choice between investing in a new recovery boiler (and bark boiler) or a BLG-DME plant (and bark boiler or BMG-DME plant). Therefore, it is the incremental investment cost, as well as operating and maintenance cost, for the BLG-DME plant compared to investing in a new recovery boiler that has been used in the model. For the BLG-DME-BB case, the size of the bark boiler has then been calculated to cover the mill steam use not covered by the excess steam from the BLG-DME plant. Some of the excess heat at lower temperature level is used for make-up feed water preheating, thereby reducing the need for steam to the feed water tank. Purge gas is used as fuel in the bark boiler together with bark and other wood fuels. For the BLG-DME-BMG-DME case, the BMG-DME plant has been sized to cover the mill steam use not covered by the excess steam from the BLG-DME plant. The load of the lime kiln in the pulp mill increases if black liquor gasification is used instead of a recovery boiler (it is assumed that the increase is 25%). In the cases where the BLG-DME plant is supplemented by a bark boiler, some of the purge gas from the motor fuel synthesis is used to cover this increased fuel demand. In the cases where the BLG-DME plant is supplemented by a BMG-DME plant, the purge gas is used in a gas turbine together with gas from the BMG-DME plant. In this case, it is assumed that gasified bark is used to cover the extra lime kiln load. As can be seen in Table 11, for the BLG-DME-BB case biofuel is produced at the expense of a higher demand for wood fuel, lower electricity production, higher electricity use and higher investment as well as operation and maintenance costs. For the BLG-DME-BMG-DME case biofuels and additional electricity are produced at the expense of a higher demand for wood fuel, higher electricity use and higher investment as well as operation and maintenance costs.

Ethanol production via alkaline pre-treatment, ALK-HF-EtOH, has been considered for integration with all kraft pulp mills. The ethanol production was sized as a fraction, 50%, of the pulp wood used on each site, so the production is larger on larger pulp mills and smaller on smaller pulp mills. This way, the increased capacity needed in each pulp mill process unit that the ethanol plant is using is reasonable. As described in Section 4.1.5, there is a steam surplus from the ethanol plant from burning of solid residues that can be used in the mill processes. Some of the excess heat at lower temperature level is used for make-up feed water preheating, thereby reducing the need for steam to the feed water tank. If there is still a need for steam at the mill, additional fuel (to the solid residues from the ethanol plant) is used. In case the surplus of steam from the ethanol plant is larger than the steam deficit at the mill, a condensing steam turbine is used to generate additional electricity. As can be seen in Table 11, for the ALK-HF-EtOH case, biofuel and additional electricity are produced at the expense of a higher demand for wood fuel, higher electricity use and higher investment as well as operation and maintenance costs.

BLG-DME-BB and BMG-SNG have the lowest net usage of energy carriers per produced unit of biofuel and the lowest specific investment cost. BLG-DME-BB has a lower net usage of fuels (biomass and fossil fuels) but a higher net usage of electricity, while BMG-SNG has a somewhat higher net usage of fuels together with a neutral or net surplus of electricity. The sum of used energy carriers per produced unit of biofuel are however quite similar for these two technology cases integrated with chemical pulp mills.

4.2.2 Mechanical pulp mills and paper mills

All mechanical pulp mills have been included as potential biofuel plant sites. Two paper mills are also included based on the criteria that the steam use should be more than 25 MW.

This was done in order to get reasonable sizes of the biofuel plants when sized according to steam demand.

Data needed for each mill in order to estimate the plant sizes for the different technology cases as well as the consequences of integration with mechanical pulp mills and paper mills include for example usage of different fuels, process steam demand and generation of electricity. Data from SFIF's environmental database has been used. Partly the same conclusions regarding this data, as for the data concerning the kraft mills can be drawn. However, not as many assumptions have to be made and this data could therefore be considered to generally have higher quality. Appendix C describes how the required data has been estimated based on data from SFIF's environmental database.

Table 12 presents an example of energy balances (GWh/y) for a mechanical pulp mill without biofuel production and the same mechanical pulp mill integrated with the different biofuel technology cases considered for integration with mechanical pulp mills and paper mills. Investment costs and O&M costs for the alternative investment (existing plant) and the biofuel cases are also included.

Table 12. Example of energy balances (GWh/y) and investment and O&M costs (for the alternative investment and the biofuel plants) for a mechanical pulp mill without biofuel production and the same mechanical pulp mill integrated with the different biofuel technology cases considered for integration with mechanical pulp mills and paper mills.

	Biomass			Fossil fuels	Electricity			Bio-fuel	Inv. cost	O&M cost
	Demand		Supply		Production		Use			
	Pulp wood	Wood fuel	Wood fuel	Use	Tot.	Green		Prod.		
Existing plant w/o biofuel production	2021	411	0	97	106	91	1156	-	75	3
BMG-DME	2021	3052	0	0	553	553	1337	1090	315	13
BMG-SNG	2021	5828	0	0	367	367	1375	4180	482	19
SE-HF-EtOH	2021	3074	0	0	309	309	1279	912	327	13

The investment cost for existing plants includes a new bark boiler and a new back-pressure steam turbine. The investment cost for existing plants integrated with biofuel production includes the biofuel plant, a new back-pressure steam turbine and a new bark boiler (only SE-HF-EtOH case).

The BMG-DME, BMG-SNG and SE-HF-EtOH cases are, as for the chemical pulp mills, sized after the steam deficit (which for these types of mills corresponds to the steam demand) at the mills. As for chemical mills, it has been assumed that the mills are in a situation where they are going to replace their bark boiler and thus have the choice between investing in a new bark boiler or a biofuel plant in order to cover their steam deficit. Therefore, the incremental investment cost, as well as O&M cost, for the biofuel plants compared to investing in a new bark boiler has been used in the model. In case of integration with pulp and/or paper mills (a part of) the excess heat at lower temperature level is used for make-up feed water preheating, thereby reducing the need for steam to the feed water tank. As can be seen in Table 12, for the BMG-DME, BMG-SNG and SE-HF-EtOH cases, biofuel and additional electricity are produced at the expense of a higher demand for wood fuel, higher electricity use and higher investment as well as operation and maintenance costs.

For mechanical pulp mills and paper mills, BMG-SNG has the lowest net usage of energy carriers per produced unit of biofuel and the lowest specific investment cost of the technologies considered for integration with these types of plants (the numbers are similar to the ones for integration with chemical pulp mills).

4.2.3 Sawmills

Sawmills with an annual production of more than 200,000 m^3 sawn wood have been considered as potential biofuel plant sites. 18 stand-alone sawmills have been included directly as plant sites and another seven mills have been considered indirectly, as they are co-located with pulp/paper mills that have been included as potential plant sites.

Data needed for each mill in order to estimate the consequences of integration of the different technology cases with sawmills include production of by-products and heat demand. Appendix C describes how the required data has been estimated. All biofuel plants that have been considered for integration with sawmills have a size of 300 MW, corresponding to 2,352 GWh/year. This is because sizing the plant according to heat use was found to give very small sizes of the biofuel plants. Also sizing according to the available biomass at the sawmill was found to give relatively small sizes.

Table 13 presents an example of energy balances (GWh/y) for a sawmill without biofuel production and the same sawmill integrated with the different biofuel technology cases considered for integration with sawmills. Investment costs and O&M costs for the alternative investment (existing plant) and the biofuel cases are also included.

The investment cost for existing plants includes a new bark boiler (producing heat water, no steam turbine is assumed at the sawmills). The investment cost for existing plants integrated with biofuel production includes the biofuel plant, a back-pressure steam turbine, a condensing steam turbine and a new bark boiler (only SE-HF-EtOH case).

Table 13. Example of energy balances (GWh/y) and investment and O&M costs (for the alternative investment and the biofuel plants) for a sawmill without biofuel production and the same sawmill integrated with the different biofuel technology cases considered for integration with sawmills.

	Biomass			Fossil fuels	Electricity			Bio-fuel	Inv. cost	O&M cost
	Demand		Supply		Production		Use			
	Saw logs	Wood fuel	Wood fuel	Use	Tot.	Green		Prod.		
Existing plant w/o biofuel production	941	0	506	0	0	0	0[a]	-	12	0.5
BMG-DME	941	1785	0	0	489	489	132	792	265	11
BMG-SNG	941	1785	0	0	229	229	86	1635	265	11
SE-HF-EtOH	941	1785	0	0	310	310	89	658	273	11

[a] The electricity use for the sawmill is not included.

For the BMG-DME and SE-HF-EtOH cases, excess heat at lower temperature levels has been assumed to be used to cover the heat demand at the sawmill, thereby replacing a heat water boiler (there is always a sufficient amount of excess heat from these plants to cover the heat use at all sawmills). The excess steam has been assumed to be used in a condensing steam turbine. The BMG-SNG case uses steam from the back-pressure steam turbine to satisfy the heat demand. The steam that is not needed for this purpose is used in a condensing steam turbine. As for integration with pulp/paper mills, it is the incremental investment and O&M costs that have been considered compare to investing in a new heat water boiler.

As can be seen in Table 13, for the BMG-DME, BMG-SNG and SE-HF-EtOH cases, biofuel and electricity are produced at the expense of a higher demand for wood fuel, higher electricity use and higher investment as well as operation and maintenance costs. Also for sawmills, BMG-SNG has the lowest net usage of energy carriers per produced unit of biofuel and the lowest specific investment cost of the technologies considered for integration with these type of plants (the numbers are similar to the ones for integration with pulp mills).

4.2.4 Refineries

Only the largest refinery in Sweden is at this stage considered for integration with FT fuels production. The other technologies, except BLG and ALK-HF-EtOH, could naturally also be integrated to a refinery. However, since the FT case produce similar products in existing process units, or very similar process units, as is produced at the refinery today, perhaps this is the most likely technology case to be integrated to a refinery. Another option, which has not been considered yet, is to create partly renewable fuels at a refinery by producing hydrogen via gasification of biomass to replace fossil hydrogen used in the process, see e.g. Brau (2013).

Table 14 presents the energy balances (GWh/y) for the considered refinery without biofuel production and the refinery integrated with production of FT fuels. Data is taken from a case study by Johansson (2013). A certain size is assumed for the biofuel plant (500 MW of wood fuel input). The fossil fuel use that is indicated in Table 14 for the existing plant is the amount of natural gas that is saved by using excess steam from the BMG-FT plant when this plant is integrated to the refinery. Thus, the table only indicates net changes between the plant without and the plant with biofuel production. The investment cost for existing plants integrated with biofuel production includes the biofuel plant and a back-pressure steam turbine, and are also shown in Table 14. No alternative investment has been included. As can be seen in the Table 14, production of biofuels requires an input of biomass and electricity, but leads to savings of fossil fuels (natural gas) and generates renewable electricity. Naturally, it also leads to additional investment as well as operation and maintenance costs.

Table 14. The energy balances (GWh/y) for the considered refinery without biofuel production and the refinery integrated with production of FT fuels. The flows in the table are only net flows that are influenced by the integration of BMG-FT to the refinery. The investment cost for existing plants integrated with biofuel production includes the biofuel plant and a back-pressure steam turbine.

	Biomass		Fossil fuels	Electricity			Bio-fuel	Inv. cost	O&M cost
	Demand	Supply		Production		Use			
	Wood fuel		Use	Tot.	Green		Prod.		
Existing plant w/o biofuel production	0	0	886	0	0	0	-	-	-
BMG-FT	3919	0	0	150	150	388	1748	528	21

4.2.5 Biomass-fuelled CHP plants in district heating systems

CHP plants in district heating systems with a fuel effect of approximately 75 MW and higher, with fairly accessible data have been included as potential plant sites for SNG production. In total 18 CHP plants have been included, constituting about 80% of the plants larger than 75 MW. In order to estimate the consequences of integrating a BMG-SNG plant to a CHP plant, data regarding both the fuel input and district heating and electricity output is required. Data has been taken from various webpages, personal communication etc. and has been complemented with general assumptions.

The consequences of integrating a BMG-SNG plant to the CHP plant have been estimated based on data from (Heyne, 2013). As was described in Section 4.1.2, integration with existing CHP plants enables usage of the boiler as part of the gasification system. This is illustrated in Figure 11.

The BMG-SNG plants are dimensioned so that the char from gasifier is equal to the fuel effect of the boiler before integration of a BMG-SNG plant, i.e. resulting in no direct usage of primary biomass fuel in the boiler. Table 15 presents an example of energy balances (GWh/y) for a CHP plant without biofuel production and the same CHP plant integrated with BMG-SNG. The investment costs and O&M costs for the BMG-SNG plant are also included (it has been assumed that the boiler constitutes 20% of the BMG-SNG investment cost presented in Table 15 and that 25% of the boiler cost is included as a retrofit cost).

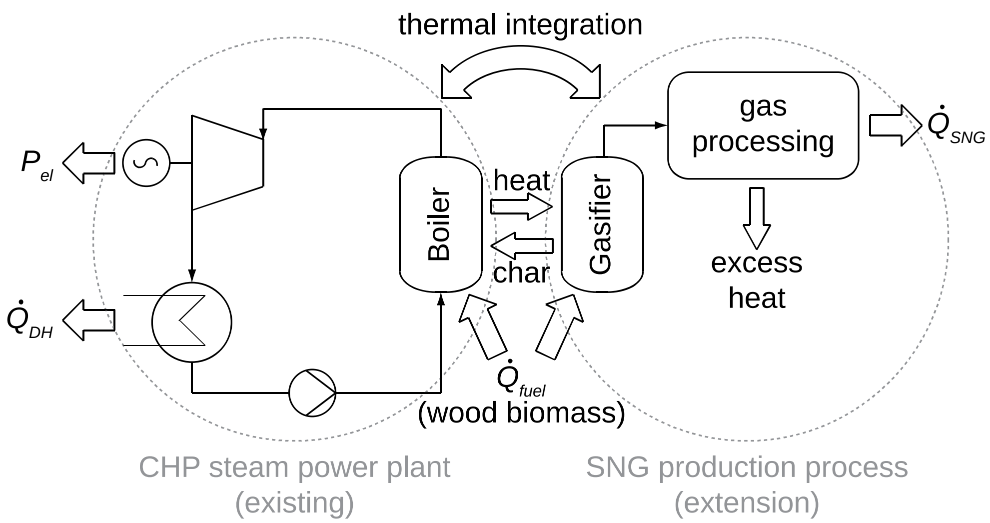

Figure 11. Schematic representation of the integration of BMG-SNG with an existing CHP plant.

Table 15. Energy balances (GWh/y) for a CHP plant without biofuel production and the same CHP plant integrated with BMG-SNG. The investment costs and O&M costs for the BMG-SNG plant are also included.

	Biomass		DH	Electricity			Bio-fuel	Inv. cost	O&M cost
	Demand	Supply		Production		Use			
	Wood fuel		Prod.	Tot.	Green		Prod.		
Existing plant w/o biofuel production	739	-	450	200	200	-	-	-	-
BMG-SNG	2917	-	450	145	145	-	1630	281	11

5 ROAD MAP SCENARIOS

Four different roadmap scenarios for the future development of forest biomass in Sweden in 2030 have been developed and modelled using BeWhere Sweden. Focus is on the transport sector and how future demand for advanced biofuels can be met by domestic production, using domestic feedstocks. The scenarios are, as far as possible, based on the scenario data presented by the Swedish EPA in their report "Basis for a roadmap for Sweden without greenhouse gas emissions in 2050" (including annexes and background reports) (Swedish EPA, 2012c). In the construction of the roadmap scenarios, scenario modules consisting of sector specific scenarios were defined regarding different parts of the studied system, e.g. development of transport and transport fuel demand, demand for next generation biofuels, available forest biomass resources, biomass available for industrial purposes, biomass usage in other industrial sectors, etc. This approach resembles the approach used in the Swedish EPA report, where sector specific scenarios are combined into two target scenarios.

The following sections describe the scenario modules and the model implementation of them. At the end of the chapter the constructed roadmap scenarios are presented. For a more comprehensive discussion around the construction of the separate modules, see (Wetterlund et al., 2013b).

5.1 TRANSPORT AND TRANSPORT FUEL USE

For the development of transport demand and transport fuel use, two different scenario modules are used.

The first module, *Fossil independent transport sector,* is based on the Swedish EPA's Roadmap scenario 1 (Swedish EPA, 2012c) and the related background report concerning the transport sector (Swedish Transport Administration, 2012). This scenario module represents a transport lean future where societal, behavioural and technical changes and improvements coincide and drastically reduce the transport fuel demand, compared to a future demand of transport fuels based on extrapolations of today's fuel use. The total travel demand is similar to the current demand, but with a larger share of travels being constituted by public transport, bicycles and walking. This is facilitated by the continued urbanisation together with more travel-free options. Consequently, the availability has increased, despite the reduced car traffic, since also non-motoring communities have better access to social functions and destinations. The total biofuel use in road transport in the Swedish EPA's Roadmap scenario 1 amounts to 14 TWh. In the background report, the Swedish Transport Administration (2012) comments that biofuel is also exported and used for other types of traffic. This has however not been considered here.

The second scenario module, *Best available technology,* is based on (Profu, 2011).This module assumes a very fast replacement rate of vehicles in order to reach the technical efficiency levels deemed possible. The scenario foresees a very large proportion of biofuels and electricity in the transport energy mix. No behavioural or societal changes towards a transport lean society are assumed, and the transport demand is larger than in the Fossil independent transport sector module, with a relatively high amount of fossil fuels remaining.

Data for the two scenario modules is summarised in Table 16. The table also shows assumed levels of electricity use in road transport and first generation biofuels. This is not explicitly included in BeWhere Sweden, but is presented here in order to give a more complete picture of how the scenario modules are constructed.

Table 16. Energy use in road transport in 2030 for the two scenario modules (TWh/year). Values used in BeWhere for 2010 shown for comparison.

	Fossil independent transport sector	Best available technology	BeWhere 2010
Total road transport energy use	33	50	88
Electricity for transport (road)	4	4.5	0
Total biofuel use	14	31	5.0
of which next generation biofuels	4.0[a]	9.0	–[b]

[a] The share of next generation biofuels in the Swedish EPA Roadmap scenario 1 was not clearly defined by Trafikverket (2012). Instead the same next generation biofuel share of the total biofuel amount has been assumed in the Fossil independent transport sector scenario module, as in the Best available technology scenario module.

[b] In BeWhere 2010 different next generation biofuel targets can be defined.

As can be seen from the table, the total biofuel use and the next generation biofuel use are in both scenario modules relatively moderate, compared to e.g. the 25-30 TWh biofuel potential presented by Börjesson et al. (2013b). The scenario modules used here have been selected as to reflect potential developments for 2030. The restricted biofuel potential reflects the inertia which is inherent in the transition towards in particular next generation biofuels.

When looking at the energy use in transport in kWh/capita, there is today a significant difference between regions, with people in the larger metropolitan areas showing a lower specific transport demand than people living in rural areas, due to e.g. better access to public transport systems. These patterns are assumed to be further consolidated by the year 2030. Further, some Swedish municipalities, regions and counties have stated regional goals or visions regarding e.g. to have a fossil free or independent transport system by 2030. In order to be able to analyse various regional aspects, the BeWhere Sweden model contains the possibility to define biofuel targets on the county level.

When implementing the aggregated energy demand for road transport in the two scenario modules into the model, the transport demand is assumed to change more in metropolitan than in rural areas. In the report by Trafikverket (2012) the assumed reductions for car travels for people living in metropolitan areas, regions and rural dwellings are 25%, 21% and 13% of passenger kilometres per person respectively. For the two transport fuel use scenario modules presented in this report, the county specific transport demand per capita has been adjusted to fit the total transport demand presented in Table 16. About half of the reduction in transport fuel use, representing the reduction in passenger transports, has been distributed based on type of county (rural, region or metropolitan area), with the remaining reduction having been distributed evenly. Table 17 shows the county specific fuel use in each of the two scenario modules.

Table 17. County specific road transport fuel use per capita for the two transport fuel use scenario modules. Values for 2010 shown for comparison.

		Fossil independent transport sector		Best available technology		2010
	County type[a]	Transport fuel use/capita (kWh/capita)	Reduction compared to 2010	Transport fuel use/capita (kWh/capita)	Reduction compared to 2010	Transport fuel use/capita (kWh/capita)
Blekinge	Rural	4.1	57%	5.6	41%	9.5
Dalarna	Rural	5.0	57%	7.0	41%	12
Gävleborg	Rural	5.8	57%	8.1	41%	14
Gotland	Rural	3.7	57%	5.2	41%	8.7
Halland	Region	3.4	68%	5.2	51%	11
Jämtland	Rural	5.7	57%	7.9	41%	13
Jönköping	Region	3.6	68%	5.5	51%	11
Kalmar	Region	3.7	68%	5.7	51%	12
Kronoberg	Region	3.6	68%	5.5	51%	11
Norrbotten	Rural	5.3	57%	7.3	41%	12
Örebro	Region	3.2	68%	4.8	51%	9.9
Östergötland	Region	3.0	68%	4.6	51%	9.4
Skåne	metropolitan	2.2	73%	3.6	56%	8.2
Södermanland	Region	3.0	68%	4.6	51%	9.3
Stockholm	metropolitan	1.8	73%	2.9	56%	6.7
Uppsala	Region	2.9	68%	4.4	51%	8.9
Värmland	Rural	5.2	57%	7.2	41%	12
Västerbotten	Rural	4.3	57%	6.0	41%	10
Västernorrland	Rural	5.7	57%	8.0	41%	13
Västmanland	Region	3.0	68%	4.5	51%	9.3
Västra Götaland	metropolitan	2.6	73%	4.2	56%	9.4
Sweden average:		*3.0*	*68%*	*4.5*	*51%*	*9.3*

[a] Classification based on the level of assumed population growth (a high growth is likely to facilitate densification and a more rapid expansion of public transport both reducing the transport fuel use per capita).

5.2 FOREST BIOMASS RESOURCES

As described in Section 3.1, two different scenarios from SFA (2008a) are used as scenario modules for 2030 (period 3 in the dataset described in Section 3.1.1).

The *Production* scenario module represents a future where forestry is significantly developed and high productivity is prioritised over recreation and other values. Increased forest fertilisation, increased shares of contorta pine and afforestation of agricultural land are measures implemented to increase the forest potential.

The *Environmental* scenario module represents a future where the forests are viewed both as resources for raw material and as an important resource for other types of value creation such as conservation of biodiversity, recreation and tourism. In this scenario it is assumed that the protected forested areas in Sweden will increase, more buffer zones along forest streams and lakes will be created, and that better environmental consideration will be taken in connection with final felling operations.

From the total theoretical potential, all observations with a gradient class greater than or equal to seven have been removed from the data set (see Section 3.2.7). Table 18 summarises the resulting biomass potentials used in the two scenario modules, together with the biomass availability for 2010, as used in (Wetterlund et al., 2013b). It should be noted that in the previous project the estimation of available forest was based on statistics regarding annual growth and felling, applying considerably cruder assumptions and with a lower spatial resolution than for this report. Figure 12 shows the geographical distribution of forest biomass in the two scenario modules, when implemented into BeWhere Sweden.

Table 18. Biomass potentials for 2030 for the two scenario modules (TWh/year). Values used in BeWhere for 2010 are shown for comparison.

	Production	Environmental	BeWhere 2010
Pulpwood	67	61	58
Sawlogs	90	80	71
Harvesting residues	31	28	19
Stumps	25	23	10

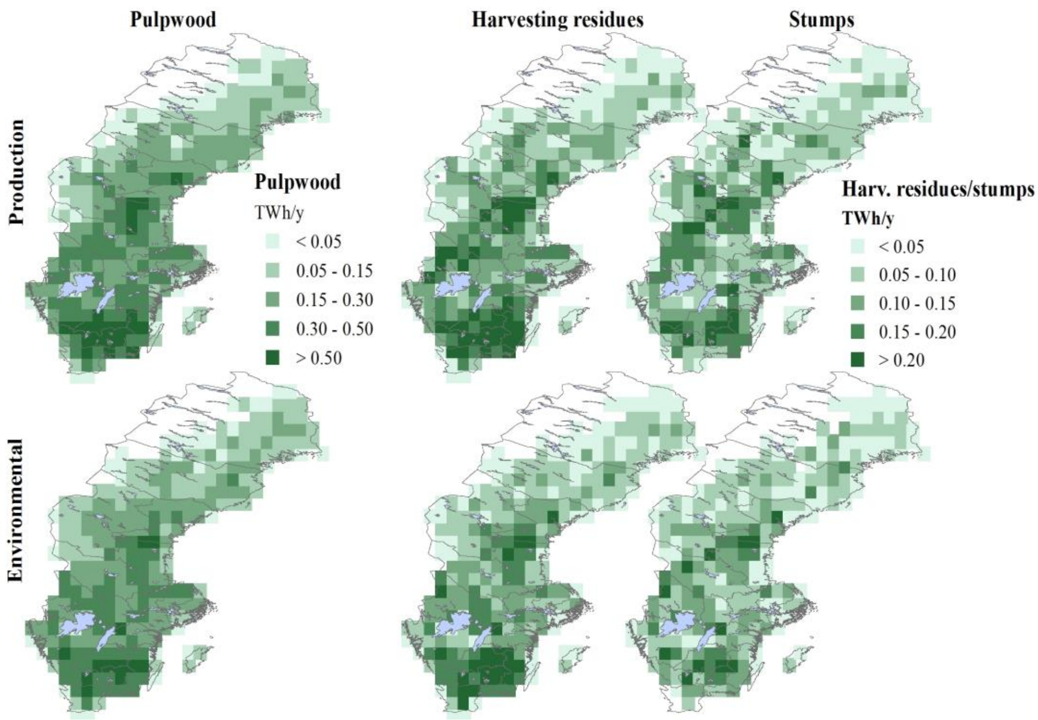

Figure 12. Distribution of forest biomass in the two modelled scenario modules.

5.3 BIOMASS UTILISATION IN OTHER INDUSTRY SECTORS

Four different scenario modules have been constructed regarding industrial usage of forest biomass, as feedstock as well as for energy purposes. The modules are based on the scenarios presented by the Swedish EPA (Swedish EPA, 2012a; Swedish EPA, 2012b), with adaptions and supplements as necessary.

The *Green process industry* module builds on the Swedish EPA's Goal scenario 1. The economic development of the industry is in line with development in the Swedish EPA's business as usual scenario, but with a stronger willingness to invest in energy efficiency measures and correspondingly lower industrial energy use.

The *Expansive forest industry* module is similar to the Swedish EPA's Goal scenario 2, regarding assumptions about substitution of fossil fuels and fossil feedstock for biomass in different industry sectors. The electricity use is assumed to be significantly increased in all industry sectors, giving also a higher share of mechanical pulp in this scenario compared to the other two industry scenarios.

The *Conservative technology development* module builds on the Swedish EPA's Reference scenario. The development of the industry in this scenario is based on current policy instruments and the assumption of no major technology breakthrough, with the biomass usage increasing rapidly. This increase is mainly due to growth in the forest industry and substitution of fossil fuels for bioenergy. The fossil energy substitution occurs in several industry sectors but is greatest in the forest industry.

Since all the Swedish EPA scenarios are based on assumptions of continued economic growth, the *Constant industry* module has been added. This module represents a scenario where the industrial production volumes remain on today's level, with no significant increases of biomass feedstocks and only moderate substitution of fossil fuels for biomass.

The industry branches considered in this report are: pulp and paper industry, sawmill industry, iron and steel industry, chemical industry, and energy industry (heat and power). For the pulp and paper industry, the global demand of paper products is assumed to continue to increase until 2030. However, the market demand varies significantly between different assortments. The demand for packaging and hygiene paper products increase significantly whereas the demand for newsprint and supercalendered paper decrease. Contrary to the global market, the European market demand for paper and paper products is assumed to decline. In Europe only the demand for packaging and hygiene paper products will continue to increase, all other assortments will show a decrease in demand. In three of the four scenario modules here, the pulp and paper industry is assumed to show economic growth until 2030 and increase its production volumes. However, the growth is assumed to be less than the increase in demand globally and thus the Swedish pulp and paper industry will decrease its market share. The economic growth of the sawmill industry is here assumed to correspond to the growth in the pulp and paper industry. When implemented into BeWhere Sweden, all forest industry sites are considered geographically explicitly.

The iron and steel industry today uses significant amounts of fossil energy, in particular in the form of coke in the steel mill blast furnaces, that could to some extent be substituted for biomass. In two of the scenario modules here, the three largest fossil fuel users in the Swedish iron and steel industry sector are assumed to substitute a share of their current fossil energy use for forest biomass (considered geographically explicitly).

In the chemical industry, fossil-based raw materials could be replaced by biomass and other bio-based raw materials, both in refineries and in other chemical process industries. The distinction between bio-chemicals and biofuels for transportation is not easy to make, as the overlap of technologies and products between the two fields of application is substantial (e.g. SNG, methanol, ethanol). Some of the technologies and industries considered in this report could also be suitable for production of bio-based chemicals. At this stage of model development, however, bio-based chemicals have not been considered explicitly. Instead, three of the four scenario modules contain more generic assumptions regarding the development of biomass use in the chemical industry. When implemented into the model, only the chemical cluster in Stenungsund is considered explicitly, while the rest of the biomass use in the chemical industry sector is distributed over the grid (downscaled based on grid population). Forest biomass is assumed to constitute 80% of the increased biomass usage.

The stationary energy sector (heat and power industry) faces different possible development routes. On the one hand, the demand for biomass can increase due to phase out of fossil fuels and increased demand for renewable electricity. On the other hand, the demand for district heating can decrease due to increased end-use efficiency, warmer climate, and competition from e.g. heat pumps. Half of the increase in biomass usage is assumed to be met by forest biomass, while the rest is assumed to be met by e.g. waste and peat.

When implementing the scenario modules in BeWhere Sweden, the assumed stage of development regarding e.g. economic growth, energy efficiency, energy conversion, and technology level is applied to all separate instances of a certain industry type.

Table 19 summarises the key features of the four scenario modules, as modelled in BeWhere Sweden.

Table 19. Key features of the modelled biomass utilisation scenario modules. Values within parentheses indicate increase in biomass usage between 2010 and 2030. Bioenergy demand is solid biomass. For conversion factors and heating values, see Section 2.1.

	Green process industry	Expansive forest industry
Forest industry		
General assumptions	Good economic growth Increased prod. of chemical pulp and decreased prod. of mechanical pulp Decrease in energy use due to structural changes in the industry All fossil fuels replaced by biomass (75%) and electricity (25%) 10-15% increased steam and electricity use efficiency (pulp/paper industry), 5% increased heat use efficiency (sawmills)	Good economic growth Increased prod. of both chemical and mechanical pulp Decrease in energy use due to structural changes in the industry All fossil fuels replaced by biomass (75%) and electricity (25%) 10-15% increased steam and electricity use efficiency (pulp/paper industry), 5% increased heat use efficiency (sawmills)
Chemical pulp mills and paper mills		
Prod. change from 2010	+15%	+25%
Feedstock dem. (TWh/y)	85 (+11)	93 (+19)
Bioenergy dem. (TWh/y)	2.4 (-4.4)	2.6 (-4.1)
Mechanical pulp mills		
Prod. change from 2010	-10%	+25%
Feedstock dem. (TWh/y)	16 (-1.7)	22 (+4.4)
Bioenergy dem. (TWh/y)	3.3 (+0.3)	4.6 (+1.7)
Sawmills		
Prod. change from 2010	+15%	+25%
Feedstock dem. (TWh/y)	79 (+10)	86 (+17)
Bioenergy dem. (TWh/y)	4.9 (+0.4)	5.3 (+0.8)
Iron and steel industry		
General assumptions	Marginal increase in energy use Substitution of some coke, coal and oil by biomass in the three largest fossil energy users	Significant electrification brings radical increase in electricity and hydrogen use No significant substitution of fossil fuels for biomass
Bioenergy dem. (TWh/y)	3.0 (+3.0)	0 (+0)
Chemical industry		
General assumptions	Good economic growth Decrease of specific energy use, increase of total energy use Considerable increase in the use of biomass and electricity Substitution of fossil-based feedstocks for biomass, both in refineries and in other chemical process industries Two thirds of the increase assumed to be as feedstock, the rest replaces fossil fuels for energy purposes, 90% of feedstock in Stenungsund replaced by biomass	Good economic growth, increased production and increased energy use No significant substitution of fossil feedstock for biomass Substitution of significant amounts of fossil fuels by biomass
Feedstock dem. (TWh/y)	15 (+15)	0 (+0)
Bioenergy dem. (TWh/y)	5.0 (+5.0)	6.4 (+6.5)
Energy industry		
General assumptions	Decrease of district heating demand, low electricity use Subst. of fossil fuels for biomass Constant levels of biomass usage for heat and power production No increase in biomass demand assumed except for plants planned to be taken into operation before 2015	Constant district heating demand, high electricity use Subst. of fossil fuels for biomass Modest increase in the use of biomass for heat and power prod. Significant increase in electricity prod. based on biogenic feedstock
Bioenergy dem. (TWh/y)	35 (+3.2)	39 (+7.7)
Total demand industry		
Feedstock (TWh/y)	196 (+35)	201 (+40)
Bioenergy (TWh/y)	50 (+4.5)	58 (+12)

Table 19 (continued).

	Conservative technology development	Constant industry
Forest industry		
General assumptions	Limited economic growth Increased prod. of chemical pulp and decreased prod. of mechanical pulp Moderate increase in energy use Black liquor gasification assumed not to be implemented 75% of fossil fuels subst. by biomass 5% increased steam and electricity use efficiency (pulp/paper industry), 5% increased heat use efficiency (sawmills)	Limited or no economic growth (no change in production volumes) Limited decrease in energy use Limited fossil fuel replacement (50% replaced by biomass) 5% increased steam and electricity use efficiency (pulp/paper industry), 5% increased heat use efficiency (sawmills)
Chemical pulp mills and paper mills		
Prod. change from 2010	+10%	+0%
Feedstock dem. (TWh/y)	82 (+7)	74 (+0)
Bioenergy dem. (TWh/y)	6.8 (+0.1)	5.6 (-1.1)
Mechanical pulp mills		
Prod. change from 2010	-10%	+0%
Feedstock dem. (TWh/y)	16 (-1.7)	18 (+0)
Bioenergy dem. (TWh/y)	3.2 (+0.2)	3.2 (+0.3)
Sawmills		
Prod. change from 2010	+10%	+0%
Feedstock dem. (TWh/y)	76 (+7)	69 (+0)
Bioenergy dem. (TWh/y)	4.7 (+0.2)	4.3 (-0.2)
Iron and steel industry		
General assumptions	Increased production as well as increased energy use Substitution of some coke, coal and oil by biomass in the three largest fossil energy users	No significant substitution of fossil fuels for biomass
Bioenergy dem. (TWh/y)	2.0 (+2.0)	0 (+0)
Chemical industry		
General assumptions	Slower economic growth gives modest increase in energy demand No significant substitution of fossil feedstock for biomass Substitution of some fossil fuels by biomass	No significant substitution of fossil feedstocks or fuels for biomass
Feedstock dem. (TWh/y)	0 (+0)	0 (+0)
Bioenergy dem. (TWh/y)	1.6 (+1.6)	0 (+0)
Energy industry		
General assumptions	Decrease of district heating demand due to competition with heat pumps Change of fuel mix, significant subst. of fossil fuels for biomass Large net export of electricity Significant increase in the use of biomass for heat and power production	No increase in biomass demand assumed except for plants planned to be taken into operation before 2015
Bioenergy dem. (TWh/y)	41 (+9.2)	35 (+3.2)
Total demand industry		
Feedstock (TWh/y)	173 (+13)	161 (+0)
Bioenergy (TWh/y)	57 (+11)	48 (+2.1)

5.4 ENERGY MARKET

Two different energy market scenario modules are used, based on the Swedish EPA report (2012c) including background reports and annexes (e.g. (Swedish EPA, 2012a; Profu, 2011; Swedish Transport Administration, 2012; Swedish EPA, 2012b)). The *Fragmented action* *scenario* represents a future where only the countries within EU maintain and set policies for ambitious climate goals. In contrast the *Global action scenario* assumes a future where all nations jointly act towards achieving a future with less than two degree increase of the global temperature.

To achieve reliable results from an evaluation using prices based on energy market scenarios, the energy market parameters within a given scenario should be consistent, i.e. the energy prices must be related to each other (accounting for energy conversion technology characteristics and applying suitable substitution principles). For this report the ENPAC (Energy Price and Carbon Balance Scenarios) tool (Axelsson et al., 2009; Axelsson and Harvey, 2010) has been used to construct consistent scenarios. The ENPAC tool proposes energy market prices for large-volume customers, based on world market fossil fuel price data and assumed values for energy and climate mitigation policy instruments. The required inputs to the tool are fossil fuel prices and charges for emitting fossil CO_2. Based on these inputs, the probable marginal energy conversions technologies in key energy markets are determined, which in turn yields values for energy prices and CO_2 emissions associated with marginal use of e.g. fossil fuels and electricity.

Table 20 presents the energy market scenario modules used in this report, together with the energy market parameters for 2010 used in the previous project (Wetterlund et al., 2013b).

Table 20. Energy market parameters for the year 2030 for the two scenario modules. Values used in BeWhere for 2010 shown for comparison.

		Fragmented action	Global action	BeWhere 2010
Crude oil	EUR/barrel	97	60	
Gas	EUR/MWh	34	26	
Coal	EUR/MWh	13	11	
Electricity	EUR/MWh	86	84	53
Biomass (wood chips)[a]	EUR/MWh	35	37	14
Heavy fuel oil[b]	EUR/MWh	66	52	39
Transport fuel (pump price)[c]	EUR/MWh	98	76	85
CO_2 charge	EUR/tonne	51	60	114
Green electricity certificates	EUR/MWh	20	20	25

[a] Average value for harvesting residues.
[b] Including CO_2 charge.
[c] Average value for petrol and diesel. Including CO_2 charge, excluding energy tax.

The biomass prices given in the table are used for calibration of the biomass prices estimated from the biomass production costs described in Sections 3.2 and 3.3. The CO_2 charge is assumed to be applied to all fossil energy carriers. Truck transport costs are assumed to vary with the oil price. The transport fuel prices given in the table are used to calibrate the truck transport costs given in Section 2.7.

5.5 MODELLED ROADMAP SCENARIOS

The separate scenario modules have been used to construct four different roadmap scenarios, as shown in Table 21.

Table 21. Modelled roadmap scenarios.

	Green development (GD)	Expansive industry (EI)	Conservative development (CD)	Constant industry (CI)
Transport and transport fuel use	Fossil independent transport sector	Best available technology	Best available technology	Fossil independent transport sector
Forest biomass resources	Environmental	Production	Environmental	Production
Biomass utilisation in industry	Green process industry	Expansive forest industry	Conservative technology development	Constant industry
Energy market	Global action	Fragmented action	Fragmented action	Global action

6 MODEL RUNS

Two sets of model runs are performed for this report. The first set (Section 6.1) consists of initial model runs, the purpose of which are to identify parameters with high impact on the results and to better understand the choices of plant locations and biofuel production technologies. In the second set of model runs (Section 6.2) the roadmap scenarios described in the previous chapter are implemented.

6.1 INITIAL MODEL RUNS

In the initial runs the model was run for one biofuel production technology and one host industry type at a time. The model was run using prices for 2010 (Table 20), biomass supply according to the Production scenario module, and two different biofuel targets – 1-3 TWh/y and 5-9 TWh/y, respectively[8]. For each technology/host industry/biofuel target combination a number of parameters were varied, in order to identify external parameters with high impact on the choice of plant location. The parameters varied are:

- Electricity price (-50%, +50%, +200%)
- Oil price (-50%, +50%, +200%)
- Biomass price[9] (-50%, +50%, +200%)
- Biomass transportation costs (-50%, +50%, +200%)
- Biomass availability9 (-10%, -25%, +25%)
- Residues availability (-25% harvesting residues and -50% stumps)
- SNG variations: no distance limit on SNG distribution (for all runs where BMG-SNG is included), all year operation of CHP plants (for runs including all technologies), SNG transportation and distribution cost -50% (for runs including all technologies)

6.1.1 Biofuel production plant locations

Figures 13-15 show the plant location results for the initial model runs. The results have been aggregated to show in how many model runs a certain plant appears in the model solution. Figure 13 shows how frequently each plant location appears for all the model runs, grouped by host industry type. In Figure 14 the results have been broken down further and are displayed for each biofuel production technology. Figure 15 illustrates how often each technology appears at each plant location, specified by host industry type.

[8] The possible biofuel production plants are all expressed with fixed sizes in the model. By setting the target as a relatively relaxed interval the model becomes less constrained in the selection of optimal plant locations.

[9] Regards all biomass assortments that are included in the model.

From a glance at Figure 13, CHP plants seem underrepresented in the results. It should, however, be noted that CHP plants are only considered for BMG-SNG and are thus included in fewer model runs, for which reason they naturally appear less frequently. Conversely, chemical pulp mills have been considered as potential plant locations for all biofuel technologies and are thus included in a large number of model runs.

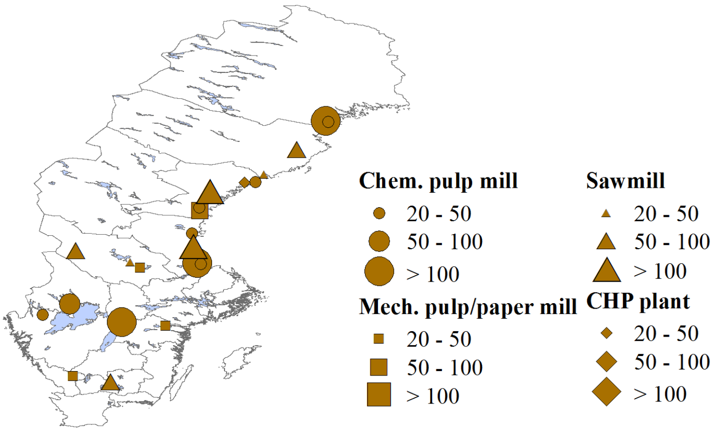

Figure 13. Number of occurrences for all initial model runs. Plant positions with fewer than 20 occurrences are not shown here. Model runs for both considered biofuel targets are represented here.

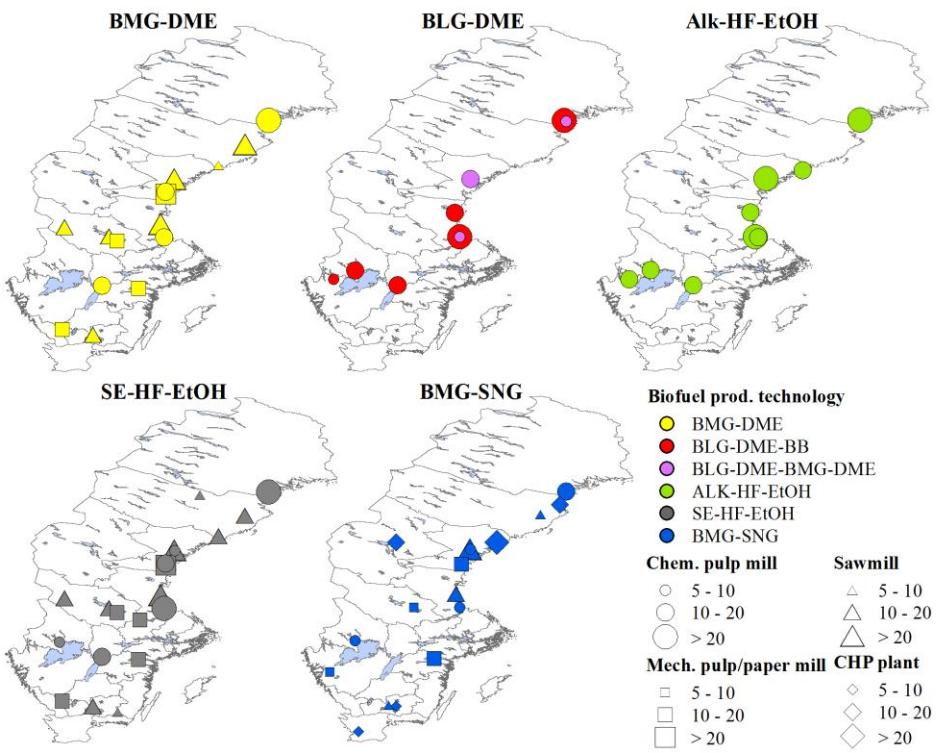

Figure 14. Number of occurrences for each biofuel technology/host industry combination. Plant positions with fewer than five occurrences are not shown here. Model runs for both considered biofuel targets are represented here.

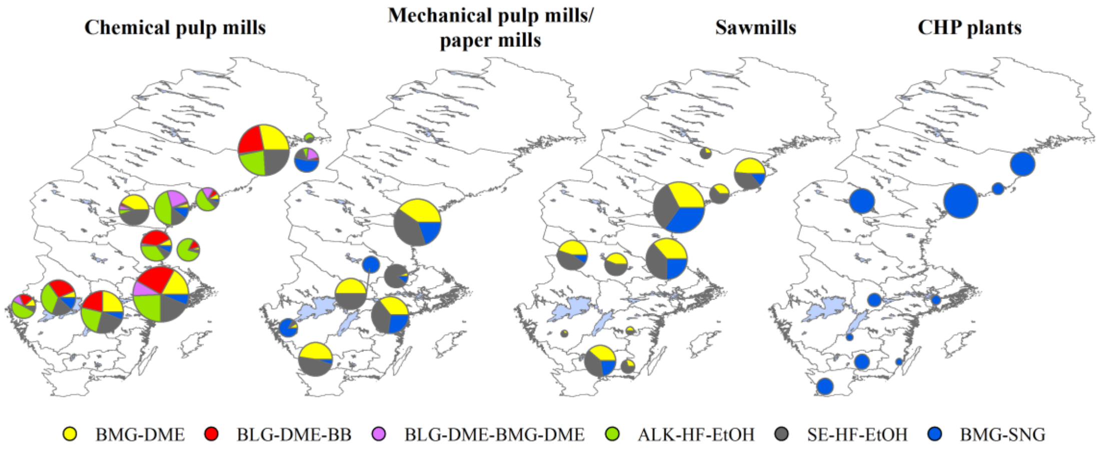

Figure 15. Choice of biofuel production technology for each plant position. The sizes of the markers and pie chart fields reflect the relative total number of occurrences for each plant site and technology, respectively. The colours show which biofuel production technologies appear at each industry site. Model runs for both considered biofuel targets are represented here.

It should be pointed out that the number of occurrences differs between the different technology cases due to different efficiencies. Take the number of BMG-SNG plant occurrences (blue) compared to SE-HF-EtOH plant occurrences (yellow) (Figure 14) as an example. The number of BMG-SNG plant occurrences is significantly lower, due to a higher biomass-to-biofuel conversion efficiency of the BMG-SNG process, compared to the SE-HF-EtOH process. This results in higher biofuel production for each plant occurrence and fewer BMG-SNG plants to cover a specific biofuel demand.

Five host industries are found to occur in significantly more model runs than all other potential plant sites – two sawmills and three chemical pulp mills. The most frequently occurring sawmills are characterised by large production volumes and correspondingly large productions of by-products and large heat demand. The by-products produced at sawmills can be used for biofuel production, which entails a reduced need for external biomass. For the largest sawmills, approximately half of the total biomass demand can be met by internally produced by-products. This means that for the largest sawmills the biomass transported to the sawmill when biofuels are produced are approximately the same as the by-products transported from the sawmill when biofuels are not produced. Thus, the net increase in transportation cost could be close to zero or even negative, depending on the transportation distances for the export and import of biomass. A large heat demand means a large biomass usage and investment cost for alternative heat supply, thereby reducing the net biomass usage and the net investment cost per unit biofuel produced (the plants located at sawmills are of a certain size, as described in Section 4.2.3).

The most frequently occurring chemical pulp mills generally have quite different characteristics. Taking the three most occurring mills, and a few mills more which also occur relatively often, they often possess one or two of the following characteristics:

- Low specific steam deficit (steam deficit/pulp production). This mean that a larger part of the low temperature excess heat from the heat integrated plants (BMG-DME, BMG-SNG, SE-HF-EtOH) can be used at the mill, thereby lowering the specific fuel usage per unit produced biofuel. More important than the possibility to use low temperature excess heat, is the effect that the specific steam deficit can have on the net need for transportation of biomass. If the specific steam deficit is low enough, the mill without biofuel production will have a surplus of biomass that they can export. This means lower net increase of biomass transportation when biofuel production are integrated, compared to if the mill without biofuel production don't export biomass.

- Large steam deficit. This enables larger sizes of the heat integrated plants (BMG-DME, BMG-SNG, SE-HF-EtOH), with corresponding low specific investment costs.
- Low specific flow of black liquor (black liquor/pulp production). If the specific flow of black liquor is low, a larger part of the low temperature excess heat from the BLG-DME plant can be used at the mill, thereby lowering the specific fuel usage per unit produced biofuel.
- Large flow of black liquor. This mean large BLG-DME plants with a low specific investment costs.
- Large production capacity. This mean large production plants with low specific investment costs for ALK-HF-EtOH (since it is dimensioned according to the pulp production).

6.1.2 Parameter sensitivity

The most popular plant locations are found to be relatively insensitive to the tested variations, and appear in most runs where they are included as an alternative. This section briefly describes the most significant patterns that have been identified regarding the effects of the varied parameters.

In general, the model runs with low biofuel target show a higher sensitivity to the tested parameters regarding optimal plant location. In those runs, the number of biofuel plants typically amounts to no more than 1-2 plants. Changes in e.g. the electricity price of +/-50% are then sufficient to shift the optimal plant location to one which enables higher co-production of electricity (technologies with a net surplus of electricity) or which uses less electricity (technologies with electricity deficit). It should also be pointed out that the model runs with low biofuel target excludes a number of plants that are too large. For some technologies this results in that plants with characteristics that differs significantly from the plants preferred for the higher biofuel target are chosen. With high biofuel target the optimal number of plants ranges from 1-11 (3-6 plants in most cases) with the popular plant sites figuring in most scenarios. Price changes etc. then have less effect on the optimal plant locations, within the tested ranges.

Electricity price

BMG-DME, SE-HF-EtOH and BMG-SNG all are net producers of electricity when integrated with sawmills, pulp mills or paper mills. When running those technologies with all types of host industries considered simultaneously, high electricity prices stimulate a shift from chemical pulp mills to sawmills. The reason is that production in sawmills has a higher net production of electricity (due to the inclusion of a condensing turbine and no electricity production in the alternative investment case, see Section 4.2.3). High electricity prices also results in additional biofuel plants (i.e. closer to the maximum production in each given range), which shows that high electricity prices can help stimulate increased biofuel production for biofuel production with a net surplus of electricity. Conversely, BLG-DME (-BB/-BMG-DME) has a net deficit of electricity, for which reason a decreased electricity price leads to more plants and more biofuel production. The sensitivity is however low and no significant shift in optimal plant location was observed (this is due to the assumptions regarding electrical efficiency for the mills, see Appendix C). It should also be noted that the demand for biomass in the stationary energy sector has been described statically in the model, with no correlation to the assumed electricity price. If the possibility to invest in biomass-based CHP would be included explicitly in the model increased regional biomass competition could potentially affect the optimal plant positions.

Oil price

Oil price changes affect the optimal plant location to a higher degree than electricity price changes. A high oil price stimulates a shift from sawmills to chemical pulp mills for the two technologies with highest oil savings per produced unit of biofuel (BMG-DME and SE-HF-EtOH), when running the model with all types of host industries.

Similarly, the optimal chemical mills for biofuel production shift for all technologies when changing the oil price, since the amount of saved oil when integrating biofuel production differs between different mills. When running the model with all biofuel technologies, low oil prices stimulate BMG-SNG and high oil prices stimulate BLG-DME-BB and to some extent also BMG-DME.

Price, transportation cost and availability of biomass

High biomass prices stimulate a shift from BMG-SNG to BLG-DME-BB when running the model with all technologies. This is due to a higher biomass-to-biofuel system efficiency for BLG.

Increased biomass transportation costs result in a larger number of biofuel production plants, in order to minimise the biomass transportation costs. It also stimulates a shift from chemical pulp mills to sawmills as optimal plant positions for BMG-DME and SE-HF-EtOH, and in general causes relatively significant shifts in which plant is the optimal plant location. Increased biomass availability induces a shift towards larger plants with higher biofuel production.

SNG variations

The allowed maximum SNG transportation distance and SNG transportation cost both turned out to have very small effect on the optimal plant positions, which shows that other parameters (site specific) are of greater importance for the choice of plant location. An increase of the annual operation time for SNG integrated with CHP from 5,000 to 7,838 hours (as for other industries) did not induce a shift of optimal host industry for BMG-SNG from sawmills to CHP plants.

6.2 SCENARIO MODEL RUNS

The roadmap scenarios described in Section 5.5 have been implemented into BeWhere Sweden. In each scenario a specific biofuel target (defined as a share of the total energy use in road transport) must be fulfilled and the biomass use in competing sectors must be met. In two of the roadmap scenarios the next generation biofuel target amounts to 4 TWh, and in two scenarios to 9 TWh (see Section 5.1). The objective of the scenario model runs is to analyse and visualise how future targets for advanced forest-based biofuels can be accomplished by domestic production, using only domestic feedstocks[10].

Each roadmap scenario is also run with no next generation biofuel use (reference scenario). In addition to this each roadmap scenario is modelled with a limited number of possible biofuels, in order to represent a development with less infrastructural changes. Thus, successive model runs are executed for each scenario with only technologies producing (i) DME, (ii) SNG and (iii) liquid biofuels (FT and ethanol).

Reduced climate impact, as well as other environmental objectives, is targeted at regional as well as national levels. Many Swedish municipalities, regions and provinces have stated goals regarding e.g. the share of biofuels in their transport system. For this reason, the model is also run with a regional perspective (biofuel share must be met in each county) on the fulfilment of the biofuel target, in addition to the national perspective (biofuel share must be met in Sweden overall).

Finally, as discussed in Section 4.1, assumptions about investment costs of next generation biofuel plants are still uncertain, in particular for the plants sizes assumed here. Model runs are for this reason also run with a higher annuity factor (0.2 instead of 0.11), to represent a less strategic view on the investment. It could, however, also be interpreted as a higher investment costs at the lower annuity factor.

6.2.1 Biofuel production plants

Figure 16 shows the location of new biofuel production plants and where the produced biofuel is used for the four base roadmap scenarios.

The Expansive industry (EI) and the Conservative development (CD) scenarios both have high biofuel usage (9 TWh/year), but where nine new biofuel plants are needed in the EI scenario, only seven plants are needed in the CD scenario. Similarly, the Green development (GD) and the Constant industry (CI) scenario both have lower biofuel usage (4 TWh/year), which is covered by five plants in the GD scenario and three plants in the CI scenario. The main reason for this is the reduction in steam use assumed to take place in the considered industries due to measures to increase the energy efficiency (Table **19**). In the CD and CI scenarios, a more modest efficiency increase is assumed. The scenarios with more ambitious energy efficiency measures assumed (GD, EI) both contain BMG-SNG in chemical pulp mills. The reason is that the net transportation costs for biomass are negative, i.e. more bio-

[10] Import of biomass (sawlogs, pulp wood and wood chips) is allowed in the model, but to a significantly higher cost than for domestic biomass.

mass is transported from the mill when no biofuels are produced than what is transported to the mill when biofuels are produced. This, however, means that these plants are very small[11], due to small steam deficits, and it could be questioned if for example the investment cost functions used are valid for such small plants. Furthermore, with higher investment costs and/or a higher annuity factor, these plants become less competitive. The results are still of interest as they highlight the importance of assumptions regarding biomass transporttation costs and investment and capital costs.

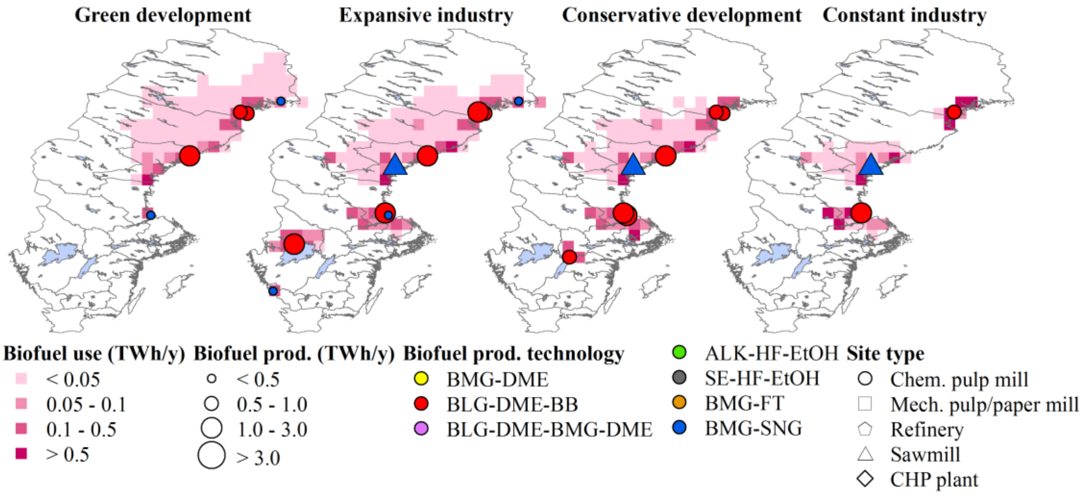

Figure 16. New biofuel plants and biofuel use for the four base roadmap scenarios.

It could be expected that large plants should be more favourable due to economies of scale and specific investment costs (i.e. investment cost per produced unit of biomass). In that case the same BMG-SNG plants should occur in the CD and CI scenarios, but with higher biofuel production due to a higher steam deficit. However, BMG-SNG in chemical pulp mills only occur when steam savings are applied, which leads to smaller biofuel plant sizes. This correlation was verified by running the EI scenario without assumed energy efficiency measures, which led to similar results regarding positions and types of biofuel plants as in the CD scenario. The CD scenario was correspondingly tested with increased energy efficiency, which in turn gave very similar results as the EI base scenario.

When looking at the biomass availability it was found to have a similar effect. Lower biomass availability (Environmental biomass resource scenario instead of Production, or higher use of biomass in other sectors) results in a larger number of small plants, rather than fewer large plants. Also this was verified by cross-testing the EI and CD scenarios, as described above. A larger number of smaller plants to cover a given biofuel demand leads to lower total system cost due mainly to shorter transport distances of both biomass and biofuel, despite the corresponding higher capital requirement (see further Section 6.2.3).

These results show that the biomass supply area for a particular biofuel plant is of signifycant importance, and that this becomes even more important in biomass restricted scenarios.

[11] No biofuel plant size limit has been defined in the model.

BLG-DME and BMG-SNG are the technologies with highest biomass-to-biofuel system efficiencies, and thus dominate the solutions. The optimal plant locations to some extent coincide with the most frequently selected plant positions in the initial model runs. However, as can be seen from Figure 16 compared to Figure 13, sawmills play a significantly less pronounced role in the roadmap scenario runs than in the initial runs, where in particular the large sawmills appeared frequently as host industries. The main reason is the significantly higher biomass price applied in the roadmap scenarios than in the initial runs. As mentioned in Section 6.1.2, high biomass prices stimulate a shift from BMG-SNG to BLG-DME.

The plant positions where BLG-DME-BB are localised in the roadmap scenarios have average or low specific steam deficit and/or average or low specific flow of black liquor, leading to relatively low net biomass transportation and net biomass (fuel) usage. The sizes, i.e. the flow of black liquor, represent the entire scale from large plants to small plants and in between. BMG-SNG are located either at the largest sawmill or, as discussed, at chemical pulp mills with small steam deficits (also specific steam deficits) and with negative net biomass transportation costs with BMG-SNG introduced.

Figure 17 and Table 22 show the results when a regional perspective on the biofuel targets is applied instead of a national. The results show that regional goals would not lead to more biofuel plants or cause any significant shift in optimal plant positions. The most noticeable difference is the total system cost (relative to the system cost of the reference scenario with no biofuel production), which is significantly higher for the regional perspective scenarios. The main reason is the substantially longer transport distances for produced biofuel when biofuel is required in all counties.

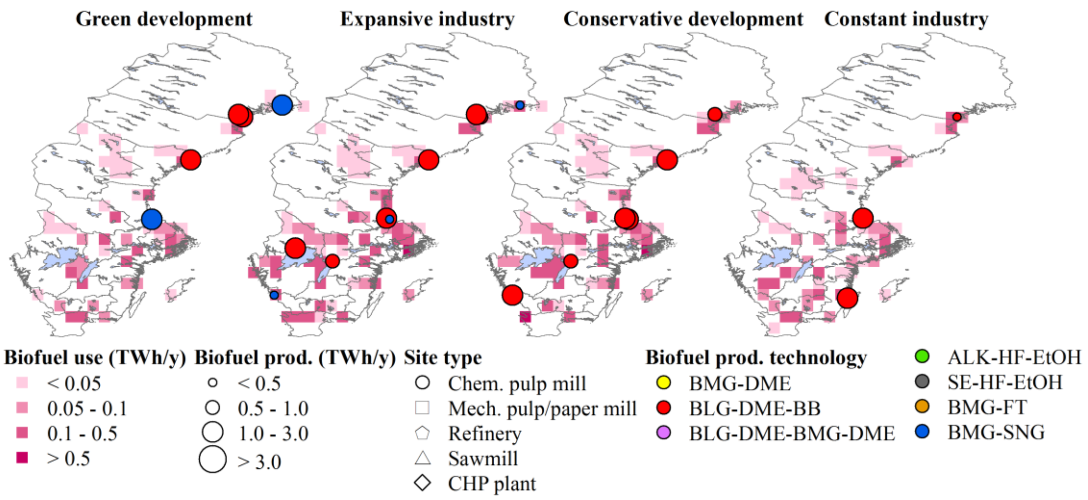

Figure 17. New biofuel plants and biofuel use for the four roadmap scenarios when the biofuel share must be met in each county (regional perspective on biofuel target).

Table 22. Summary of results for the roadmap scenarios when applying a regional perspective on the biofuel target, compared to the national perspective. For further explanation of the various costs, see Section 6.2.3.

	Green development		Expansive industry		Conservative development		Constant industry	
	National	Regional	National	Regional	National	Regional	National	Regional
No. of biofuel plants	5	5	9	9	7	6	3	3
Total capital requirement (MEUR)	1,100	1,100	2,400	2,400	2,300	2,300	980	1,200
Biofuel production cost [a] (EUR/MWh)	72	72	67	71	78	81	70	73
Biofuel supply cost [a] (EUR/MWh)	81	87	77	82	87	90	81	81
Biomass use per prod. biofuel (TWh/TWh)	0.6	0.6	0.8	0.8	1.2	1.5	1.3	1.8
Relative system cost [b] (MEUR/y)	8.4	34	-220	-180	-78	-36	-22	34
Transport of biomass for biofuel:								
Average distance (km)	86	85	126	128	155	152	162	142
Cost (EUR/MWh biofuel)	5.8	5.8	6.1	7.4	10	12	8.7	13
Transport of biofuel:								
Average distance (km)	100	655	78	346	81	253	70	178
Cost (EUR/MWh biofuel)	8,4	15	9,8	11	9,1	8,9	11	8,2

[a] Biofuel production and supply costs are net costs, that also take into account costs and revenues for operation of the industries without biofuel production, as well as capital and O&M costs for alternative investments.

[b] Total system cost relative to the total system cost of the corresponding reference roadmap scenario (no biofuel production). A negative relative cost indicates that a scenario with biofuel production has lower system cost than the same scenario without biofuel.

6.2.2 Biomass use

As has been mentioned the objective of the scenario model runs is to analyse if and how future targets for advanced biofuels from forest biomass can be accomplished by domestic production, using only domestic feedstocks. The results show that the biofuel target can be realised in all four roadmap scenarios using only domestic biomass resources for biofuel production, with national as well as regional perspective on the biofuel target (Figure 18).

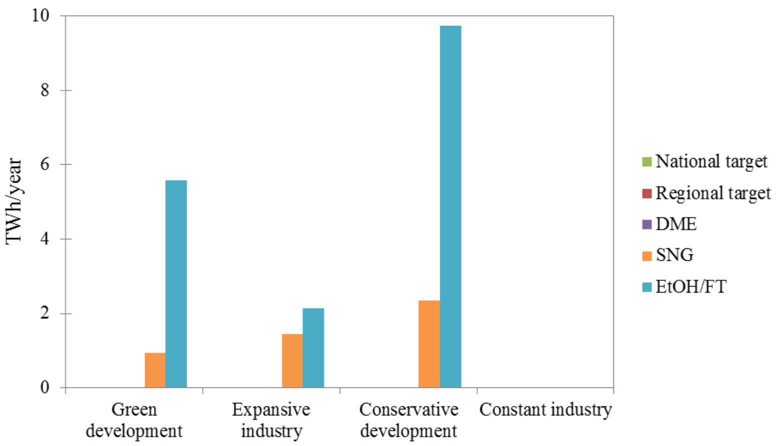

Figure 18. Biomass import for biofuel production for roadmap scenario variations. *National/regional target* refers to whether a national or regional perspective is applied for the fulfilment of the biofuel target, *DME*, *SNG* and *EtOH/FT* refers to model runs with a limited number of allowed biofuels (see the introduction to Section 6.2).

In a future with fewer infrastructural changes and less variation in the transport energy system, the domestic forest resources may however not be adequate to satisfy the feedstock need. As can be seen, in particular the liquid biofuels considered here (EtOH, FT) would put greater requirements on the feedstock supply than what can be met by domestic resources, especially in the two scenarios applying the Environmental biomass scenario (GD and CD). However, methanol has not yet been implemented into the BeWhere model. Since methanol and DME have similar production characteristics, the inclusion of methanol would likely bring down the biomass needs for liquid biofuels to a level comparable to that of DME. Similarly, by-products from ethanol production could be used to produce biogas, which could also be used as transport fuel, which would reduce the biomass needed to satisfy a particular biofuel target. Only one plant for FT fuel production is considered in the model. There is a possibility to make this production larger and include more plants, which would also result in a lower need for biomass when considering liquid biofuels compared to the results presented here.

For roundwood, the increased industry production levels entail a need for imported feedstock in all scenarios except the CI scenario (Figure 19).

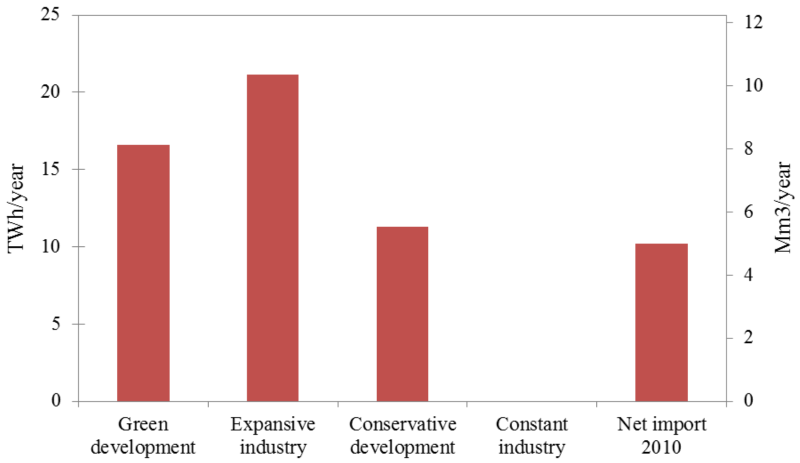

Figure 19. Annual import of roundwood in the four modeled roadmap scenarios. Net import for 2010 shown as comparison (Swedish Forest Agency, 2011).

This means that all domestically available roundwood (with the exception for the roundwood located in hilly areas with slopes that would pose technical difficulties in extraction) would need to be utilised in order to meet the demand from the forest industry's increased production. As commented in Section 3.2.8, no additional roundwood is thus available for use in other sectors than the forest industry.

The figure also shows the actual net import of roundwood in 2010. As can be seen, the necessary import is significantly higher than the current actual import in two of the scenarios. It should also be noted that with current forest industry production, all domestic roundwood in the forest is not utilised, even though approximately 6% of the annual roundwood demand is currently imported. Instead the total standing volume of trees in the Swedish forest increases from year to year (Swedish Forest Agency, 2012). As shown in the figure, the CI scenario (which roughly corresponds to the forest industry situation today) does not contain any import. Instead a larger share of the available domestic roundwood is used, than what is actually the case today. This is due to that trade mechanisms have not yet been fully explored and developed in the model, for which reason import is in the model more costly than use of domestic resources. The development of forest industry and forestry has historically been closely linked, and it could be argued that this has not been sufficiently considered in the design of the roadmap scenarios. In the model runs performed here, roundwood has however little impact on the biofuel production and this is not further discussed in this report.

Figure 20 shows where the biomass used for biofuel production originates (base scenarios). The reason for the seemingly unnecessarily long transport distances in some scenarios can be explained by the heavy strain on biomass resources due to high demand from other sectors, also without biofuel production. This is further illuminated in Figure 21 which shows the share of the total volume of harvesting residues and stumps (hilly areas again excepted) that is exploited in each scenario, including in the reference scenarios where no biofuel is produced. As can be seen, harvesting residues and stumps – the primary feedstocks for biofuel production – are to a large part fully exploited already without biofuel production, in particular in the scenarios where the Environmental forest resource scenario module is applied.

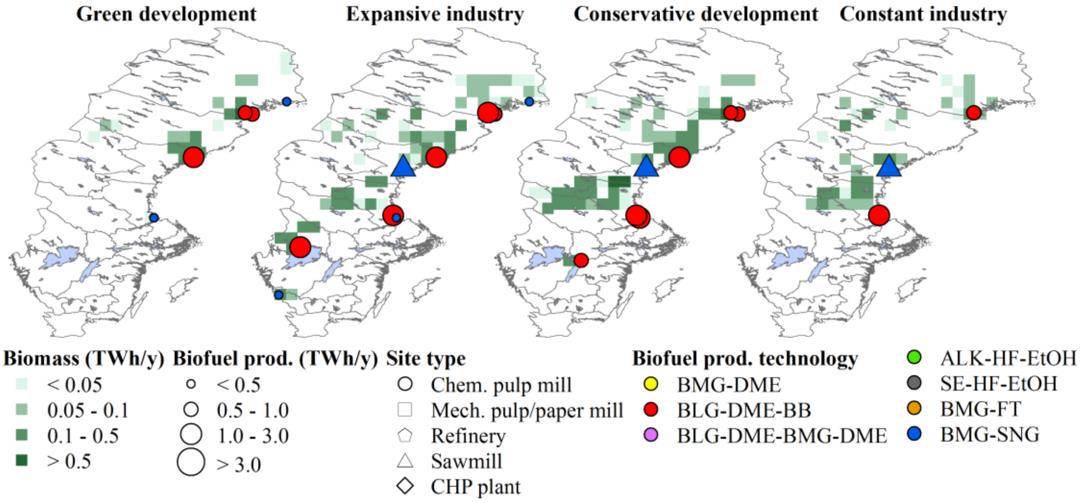

Figure 20. New biofuel plants and biomass origin for the four roadmap scenarios.

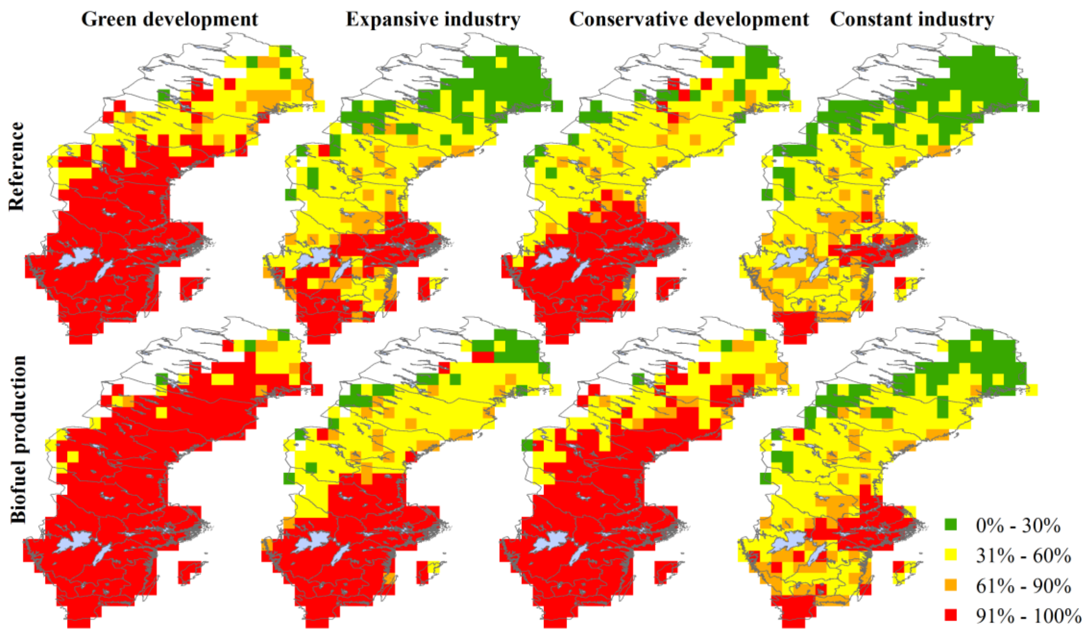

Figure 21. Share of total techno-economic potential volume of harvesting residues and stumps that is exploited in the scenarios. The top maps represent reference model runs with no biofuel plants, the bottom the roadmap scenario runs with targets for biofuel use. The GD and CD scenarios apply the Environmental forest biomass scenario module, the EI and CI scenarios apply the Production scenario module.

6.2.3 Economic results

BeWhere Sweden minimises the cost of the entire studied system, including biomass supply (feedstock and energy) to industry, biomass supply to biofuel plants, investment and O&M costs, costs and revenues for other energy carriers including fossil transport fuels, and costs and revenues related to included policy instruments. As described in Section 4.2, we have assumed in this report that for each potential plant site investment in biofuel production is done instead of investment in alternative technology. Figure 22 shows the resulting total system cost for each studied scenario, relative to the system cost of the reference scenario (with no biofuel production). As can be seen, biofuel production would be profitable in most of the base roadmap scenarios, in particular in the EI scenario, which has high fossil transport fuel price and high biomass availability. The scenarios with lower fossil transport fuel price (GD and CI) have a considerably smaller marginal, and for some of the scenarios (especially the "single biofuel" scenarios), additional support (e.g. investment support, green certificates, tax exemption) would be needed to make biofuel production economic.

If the objective would be to meet the entire next generation biofuel demand by the liquid biofuel production currently considered in the model (see Section 6.2.2 for a discussion regarding what is not considered), significant support would be needed. The exact figures should however not be too heavily focused on. For EtOH/FT significant volumes of imported biomass are required in all scenarios. The imported biomass is probably currently overpriced in the model. In order to accurately describe costs and potential volumes of imported biomass, a more careful study of international biomass trade and potential future international markets would be needed.

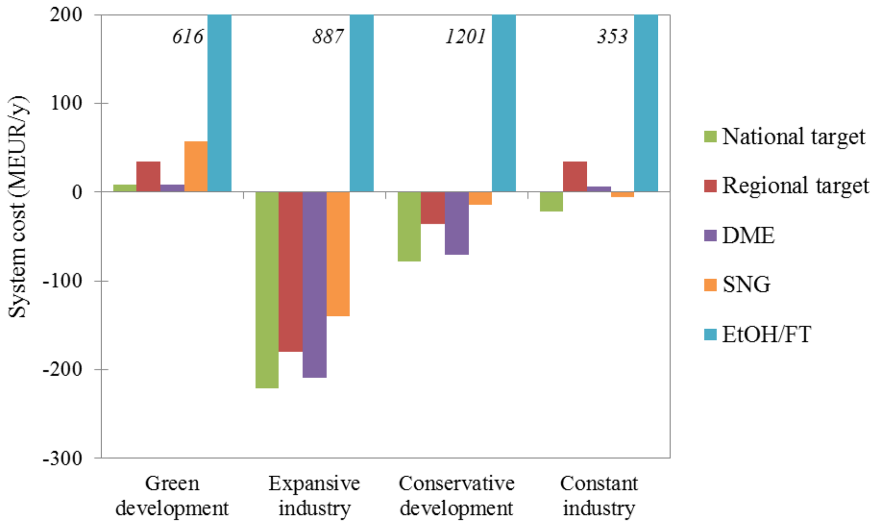

Figure 22. Total system cost for the studied four roadmap scenario variations, compared to the system cost of the corresponding reference scenario. *National/regional target* refers to whether a national or regional perspective is applied for the fulfilment of the biofuel target, *DME*, *SNG* and *EtOH/FT* refers to model runs with a limited number of allowed biofuels (see the introduction to Section 6.2).

With an increased capital cost the picture changes drastically, as shown in Figure 23. Only the EI scenario now shows profitability for biofuel production without any external support. This can be seen to represent either higher investment costs and/or a less strategic view on the investment. Since the capital requirement for this type of investments is substantial, and the projects must still be viewed as high risk projects, it can be argued that the higher annuity factor would be more appropriate. The costs used in this project are all for the N^{th} plant and must be considered uncertain, and the varied annuity factor can be seen as a way to cover some of this uncertainty. The results indicate that next generation biofuel production may not be launched on large scale without investment support for at least the first plants, unless long-term, stable policy conditions are firmly in place. However, looking at the CO_2 charges presented in Table 20, one can see that the roadmap scenarios have CO_2 charges that are significantly lower than the current CO_2 charges in the Swedish transport sector, also presented in Table 20 (used in BeWhere 2010). In the scenarios, all emissions are subject to the same CO_2 charge, i.e. a very different situation compared to the current one.

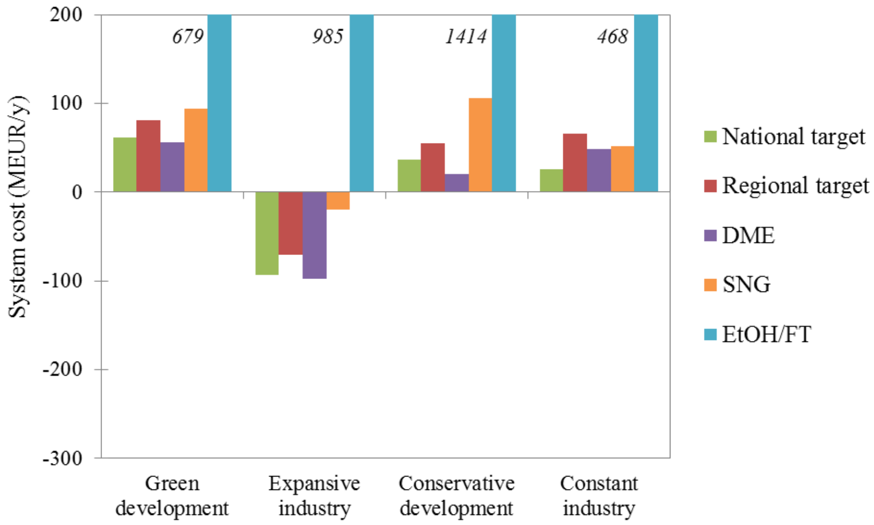

Figure 23. Total system cost for the studied for roadmap scenario variations with an annuity factor of 0.2 instead of 0.11, compared to the system cost of the corresponding reference scenario. *National/regional target* refers to whether a national or regional perspective is applied for the fulfilment of the biofuel target, *DME*, *SNG* and *EtOH/FT* refers to model runs with a limited number of allowed biofuels (see the introduction to Section 6.2).

In Figure 24 the resulting capital requirement to meet the biofuel targets in the roadmap scenarios is shown for the different studied scenario variations. Since the scenarios have different biofuel targets, the figures also show the specific capital requirement (investment cost per unit produced biofuel). As discussed above, higher grade of increased industrial energy efficiency results in a larger number of plants and consequently a higher capital requirement (GD and EI scenarios). Similarly, more strain on the available biomass resources also promotes more plants (GD compared to EI).

As described in Chapter 4 it is assumed that investment in a biofuel plant is done instead of investment in alternative technology in each host industry (e.g. investment in black liquor gasification is done instead of investment in a new recovery boiler). Figure 25 thus shows the incremental investment cost required for biofuel production for the different scenario variations, total as well as specific. As can be seen the total capital requirement is significantly lower if the incremental investment costs are considered. The model chooses between investment in biofuel production and investment in alternative technology for each plant site. Thus the system cost for a scenario with biofuel production is compared to the corresponding scenario without biofuel production, and the incremental capital cost rather than the total capital cost constitutes a part of the total system cost for biofuel production. The argument for this is that the biofuel plants fulfil heating services (steam production) and in the case of BLG also chemical recovery, which would otherwise have to be fulfilled by another plant. However, that all existing plant sites considered for biofuel production would be in a situation where they need to replace existing steam production plants at approximately the same time is naturally unrealistic. Figures 24 and 25 however emphasise the significant reduction in capital requirement that results from considering the incremental investment costs and that plants that are in a situation where they are going to replace existing technology are highly preferred, at least from a capital cost point of view.

Regarding the single biofuel scenario variations, in particular SNG has investment costs lower than in the base scenario, in several scenarios. The total system cost, however, is in all scenarios higher when the number of biofuels is limited, and all studied base roadmap scenarios contain biofuel plants of different types. This indicates that to have a future transport system as homogeneous as the current system will be more costly than to have a more diversified system. To only have liquid biofuels (EtOH/FT) would be substantially more capital intensive. As mentioned above, methanol is however not yet included, and the inclusion of methanol would likely bring down the costs for liquid biofuels to a level closer to that of DME. It should here also again be emphasised that there are uncertainties regarding the absolute as well as the relative level of the investment costs.

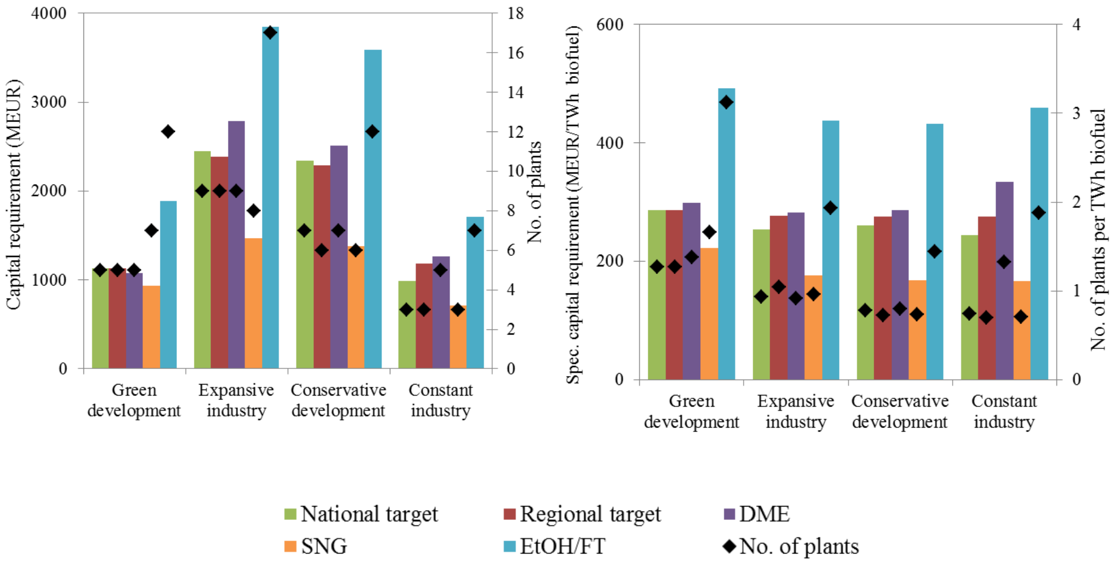

Figure 24. Total capital requirement and number of biofuel production plants (left), specific capital requirement and specific number of plants (right), for roadmap scenario variations.

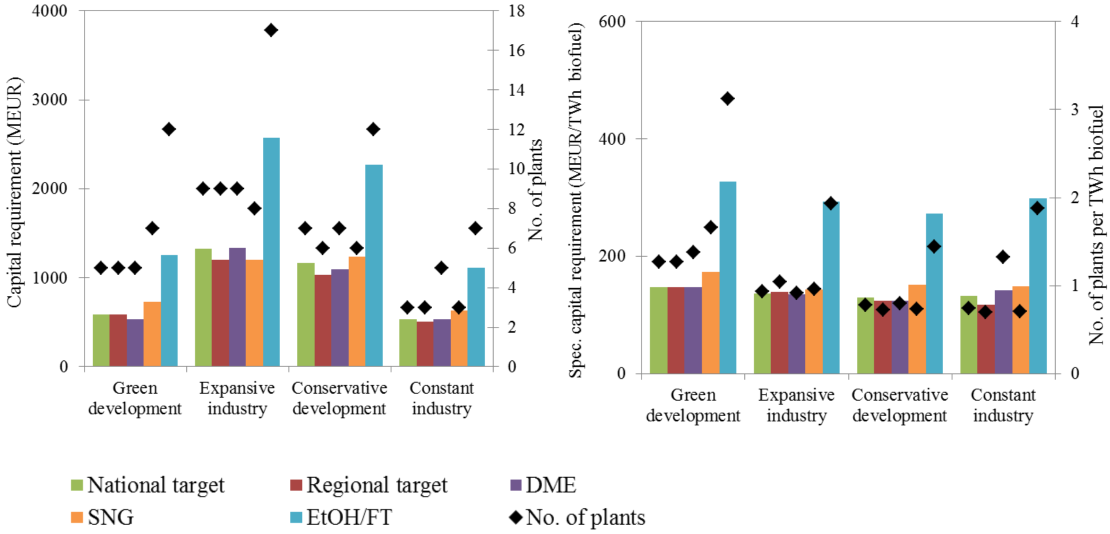

Figure 25. Incremental total capital requirement and number of biofuel production plants (left), specific incremental capital requirement and specific number of plants (right), for roadmap scenario variations.

Figure 26 shows the biofuel production and supply costs[12] for the four base roadmap scenarios, for both used annuity factors. The costs are net costs that also take into account costs and revenues for operation of the industries without biofuel production, as well as capital and O&M costs for the alternative investments. As can be seen, the costs for capital and O&M make up over one third of the total production cost when the higher annuity factor is used and about one fourth when the lower annuity factor is considered. The cost for biomass and biomass transportation constitutes the largest part of the biofuel production cost in all scenarios, also when the higher annuity factor is considered. The production costs in Figure 26 have to be compared to the revenue for transportation fuels (Table 20), where e.g. the EI scenario have the high level of transportation fuel price in combination with the lowest production cost, resulting in the lowest (negative) system cost (Figures 22 and 23).

Electricity production can give a biofuel plant with net electricity production extra revenue, for sold electricity as well as for electricity certificates. However, since BLG-DME dominates the solutions, all scenarios give a net increase in the electricity usage.

[12] Costs for delivering and dispensing biofuel added to the biofuel production cost.

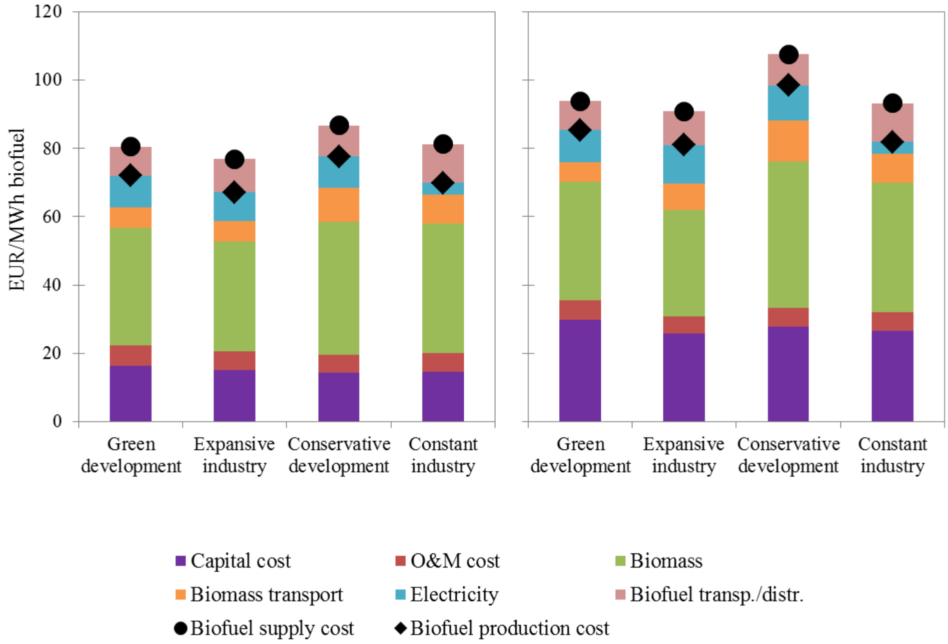

Figure 26. Biofuel production and supply costs for the base roadmap scenarios, for annuity factor 0.11 (left) and 0.2 (right), respectively. All costs are net costs, that also take into account costs and revenues for operation of the industries without biofuel production, as well as capital and O&M costs for alternative investments. Net electricity includes revenues for electricity certificates.

6.3 OPTIMAL TYPES OF PLANT LOCATIONS – SUMMARY

In the previous report (Wetterlund et al., 2013b) preliminary model results showed that black liquor gasification (BLG) was heavily favoured due to the high system efficiency from biomass to biofuel, and that low need for external biomass input was important in the choice of plant location. The results presented in this report partly confirm those results. However, with the addition of solid biomass gasification with SNG production (BMG-SNG), BLG with DME production (BLG-DME-BB) becomes less singularly represented in the results. The biomass-to-biofuel system efficiency of BMG-SNG is also relatively high, both for integration with chemical pulp mills and sawmills, and with a more favourable electricity balance it can compete with BLG-DME-BB.

In the preliminary model runs in the previous project sawmills only occurred as optimal plant locations when BLG was not assumed available. With the introduction of BMG-SNG sawmills appear as attractive options under certain conditions. The most frequently occurring sawmills are characterised by large production volumes and correspondingly large productions of by-products and large heat demand, which means that SNG produced at these sawmills is produced with low (or negative) net biomass transportation costs and with a high biomass-to-biofuel system efficiency.

High biomass prices stimulate a shift from BMG-SNG to BLG-DME-BB, which reduces the significance of sawmills as optimal plant locations. Further, if the steam demand in chemical pulp mills is reduced the net biomass transportation cost for both BLG-DME and BMG-

SNG integrated with pulp mills decrease significantly and the optimal location for these technologies shift from sawmills to chemical pulp mills. However, the plants integrated with the chemical pulp mills are in these cases very small and it could be questioned if the estimated investment cost functions are valid for these small scale plants.

Large plants could be expected to be more favourable due to economies of scale. However, the results from the model runs show that smaller plants surprisingly often appear in the solutions. A larger number of smaller plants to meet a given biofuel target leads to shorter transport distances of both biomass and biofuel, and a lower total system cost. This effect is more pronounced in biomass restricted scenarios, which leads to the conclusion that biomass supply area and net biomass transportation cost (per biofuel unit produced) are parameters of highest relative importance in the choice of optimal plant locations.

7 CONCLUDING DISCUSSION

In this report the continued development of the techno-economic, geographically explicit biofuel production plant localisation model BeWhere Sweden has been presented, together with results from the analysis of the roadmap scenarios for 2030 that were developed within the previous BeWhere Sweden project (Wetterlund et al., 2013b). Where the previous project aimed principally at developing the model structure and drawing up the outlines for the 2030 scenarios, the primary objective of this project has been to implement, execute and analyse the roadmap scenarios using BeWhere Sweden. This project has also addressed a number of areas previously identified as being of interest for future work regarding refinement and improvement of the model and of the model input data.

7.1 MODEL DEVELOPMENT AND INPUT DATA IMPROVEMENT

The description of the potential amounts, procurement costs and the geographical distribution of the biomass feedstock is now represented at a higher level of detail. The dataset on biomass distribution and quantity builds upon forest production forecasts and scenarios presented by the Swedish Forest Agency (2008b), that have been further processed in order to obtain the geographically explicit descriptions of different forest biomass assortments required for BeWhere Sweden. Long term forecasts of available forest biomass from forests that are sustainably managed and the geographical distribution of this biomass, is information of importance for wood processing industry and the energy sector. The geographically explicit biomass procurement cost model has been developed specifically for this project.

On the industry and technology side two new biofuel production technologies have been added – solid biomass gasification to synthetic natural gas (SNG) or to Fischer-Tropsch (FT) fuels. Two new host industry types have also been added – CHP plants (for SNG production) and a refinery (for FT production). In addition to this, a comprehensive review and update of the chemical pulp mill input data has been performed.

This project has also comprised substantial model development with the aim to improve model operation. In particular, possibilities to easily perform various types of sensitivity analysis and parameter variations have been implemented. For example, it is now possible to perform sensitivity analysis regarding the host industries internal energy balances and production levels, which is in turn connected to e.g. potential biofuel plant sizes, by-product production and roundwood demand.

7.2 COST-EFFECTIVE TYPES OF BIOFUEL PRODUCTION PLANT LOCATIONS

From the previous project, where preliminary tests were presented, the model has undergone rigorous testing and considerably more model runs have been performed. The results in this report show that SNG from solid biomass gasification (BMG-SNG) integrated into chemical pulp mills or sawmills can be of considerable significance for future next generation biofuel production from forest biomass, in addition to DME from black liquor gasification (BLG-DME-BB). Both technologies have high biomass-to-biofuel system efficiency, which is of particular importance if the biomass available for biofuel production is limited.

From the results some conclusions regarding the characteristics of cost-effective types of plant locations have been drawn:

- Chemical pulp mills dominate as host industries, with the addition of a few sawmills for BMG-SNG.
- The most frequently occurring sawmills are characterised by large production volumes and correspondingly large productions of by-products (sawmill chips, bark, sawdust etc.) and large heat demand. For the largest sawmills, approximately half of the total biomass demand could be met by internally produced by-products.
- The most frequently occurring chemical pulp mills are characterised by average or low specific steam deficit and/or average or low specific flow of black liquor, leading to relatively low net biomass transportation and net biomass (fuel) usage. The sizes represent the entire scale from large plants to small plants.
- The chemical pulp mills and sawmills that are preferred are all characterised by a low net biomass transportation costs per biofuel produced.
- Biofuel production plants with low net biomass transportation costs are in general selected over large plants with more favourable economies-of-scale. This shows that biomass supply area and biomass-to-biofuel system efficiency are parameters of high importance in the choice of optimal plant locations.
- High biomass prices and restricted biomass availability stimulates BLG-DME over BMG-SNG, which further augments the significance of chemical pulp mills as host industries.

7.3 ROADMAP SCENARIO ANALYSIS

The modelled roadmap scenarios for 2030 encompass two different next generation biofuel targets – 4 and 9 TWh per year, respectively. The results show that the biofuel target can be realised in all modelled scenarios, using only domestic biomass resources and by investment in new next generation biofuel plants. The implementation of next generation biofuel production in addition to the considered increase of the bioenergy use in other sectors would however require a significant increase in the use of forest residues (branches, tops and stumps), from the 14 TWh currently used annually, to 32-50 TWh/year (depending on biofuel target). This represents up to 97% of the techno-ecological potential.

With the high biofuel use the results indicate that 6-9 biofuel plants integrated with existing industries would be needed, with the production per plant ranging from 0.2 to 2.2 TWh biofuel per year. To produce these biofuels, 11-12 TWh of additional biomass per year would be needed (including the biomass that would otherwise be exported from the industries). The total capital requirement would be on the order of 1,300 MEUR, assuming incremental investment costs, i.e. based on the assumption that the host industries would otherwise have made alternative investments (e.g. investment in black liquor gasification was done instead of investment in a new recovery boiler). Without the assumption of alternative investment, the capital requirement would be around 2,400 MEUR.

With the low biofuel use 3-5 plants would be needed, with the production per plant ranging from 0.2 to 1.9 TWh biofuel per year and the amount of additional biomass from 5 to 7 TWh per year. The total capital requirement would be around 550 MEUR, or 1,100 MEUR if not considering the incremental cost.

The specific incremental capital requirement would thus be on the order of 120-150 MEUR per TWh of annual biofuel production capacity. The resulting average biofuel production cost would be on the order of 70-80 EUR per MWh, also here considering the alternative investment and net costs and revenues for biomass, electricity etc. The specific capital cost was found to make up around 25-40 percent of the total production cost, depending on the assumed annuity factor.

The significantly lower capital requirement when considering alternative industrial investments emphasise that plants that are in a situation where they are going to replace existing technology will be highly preferred as hosts for next generation biofuel production, at least from a capital cost point of view.

7.4 IMPLICATIONS FORPOLICY MAKERS AND BIOFUEL INNOVATION SYSTEM ACTORS

The biofuel production technologies analysed in this project are not yet commercial and still need to be demonstrated on industrial scale. By applying the BeWhere Sweden model for the individual production technologies knowledge has been gained regarding which types of locations and host industries that are of particular interest for each specific technology. Based on these results suitable “first plant” locations and associated stakeholders can be targeted, something which could be of interest for the actors involved in the development of these technologies, policymakers as well as industrial financers of technology scale up. Further, the results show that a limited number of locations are heavily favoured as “suitable locations” for integrated biofuel production plants. This can be of interest for actors in the biofuel innovation system by making it possible to target locations with specific characteristics that have here been identified to be of particular interest, as well as associated stakeholders, and thereby indicating to policy makers where efforts should be focused.In this report BeWhere Sweden has been used to compare effects and costs associated with a regional as well as a national perspective on implementation of biofuels targets. As many Swedish municipalities, regions and provinces have stated goals regarding e.g. the share of biofuels in their transport system this kind of analysis can be of value in order to investigate for example whether regional targets on biofuel production and use would create a less efficient system compared to national targets only. Here the national target (as a share of the total transport fuel demand) has been assumed identical in all counties, but the model could also be used to analyse e.g. how regions with individual targets could realise their goals. The results from this project show that a regional perspective on the national goals would not lead to a larger number of plants or significantly higher total capital requirement. It would however entail substantially longer transport distances for in particular produced biofuel, and corresponding higher total system costs.

As could be seen in the results section, systems with a mix of biofuels show a lower system cost compared to more homogenous systems. This shows the value of allowing for different solutions and technologies at different sites, which in turn shows that policy makers need to acknowledge this and carefully design future policy to allow for and promote a variety of technologies and fuels. The results also show that the capital requirement is significant, even though investment costs for commercial "Nth plants" are considered. Further, since the analysed technologies still remain to be demonstrated in industrial scale the estimated investment costs must be viewed as fairly uncertain. These facts show the importance of initial financial support, increased knowledge and learning to facilitate the construction of first plants and attain an associated reduction of investment costs.

7.5 PROSPECTS FOR BEWHERE SWEDEN

For policy makers as well as other actors in the biofuel innovation system, BeWhere Sweden can be used as tool for both aid and support regarding national, regional or local analysis and discussion. As exemplified in this report, the model can be used to analyse and discuss potential development scenarios for implementation of large scale production and use of next generation biofuels. Other areas of use include analysis of specific issues regarding regional policy, diversification of the forest industry and forest economy. When further developed, the model can also be used for corresponding analyses applied to biofuels in general (also agricultural based biofuels) as well as other biorefinery products (e.g. biobased chemicals and materials).

BeWhere Sweden can also be used to generate solutions which can be used as a basis for discussion when analysing different actors' possibilities, conditions and roles in a transition towards realising a large scale biorefinery industry in Sweden. The model can be used to identify industries and actors of high importance, i.e. actors who frequently occur in the model results. Host industries or actors that can be robustly identified by the model as potential "early adopters" are of special interest. Further, the targeting can show actors, types of industry or regions of particular interest for future biofuel production, which can be valuable in the design of future policies. The targeting can e.g. be done for individual industries, industrial clusters or regions, and thus aid innovation system researchers, corporate decision makers and regional as well as national decision and policy makers. Currently, many process industries in Sweden are experiencing challenging conditions, in particular the mechanical pulp and paper industry. However, the process industry in Sweden represents industrial infrastructure in which billions of euros have already been invested. In addition, especially the forest industry also holds valuable knowledge and structures for biomass logistics and processing. Investment in and integration of next generation biofuel production could provide business opportunities for the industry, which could give both existing process industries and the emerging biorefinery industry added value. The BeWhere Sweden model can be used to analyse how existing industrial infrastructure can be used for efficient production of next generation biofuels as well as other biorefinery products (when further developed). The model can also be used to identify and analyse what transformations of the existing forest industry efficient large scale production of e.g. biofuels or chemicals would actually imply, and in which steps such a transformation could occur.

8 FUTURE WORK

In this project BeWhere Sweden has been further developed compared to in the previous project (Wetterlund et al., 2013b). The model is still focused on forest biomass and forest industry, but new biofuel production technologies and new host industries have been added.

In an upcoming project within Fjärrsyn (Swedish District Heating Association) BeWhere Sweden will be soft-linked with the aggregated energy systems model TIMES-Sweden, which is one area of application identified in the previous BeWhere project. Within this project the model will also undergo substantial development regarding biofuel production integrated with district heating system, which has also been identified as of importance.

SNG was shown in this project to be of significant interest, for which reason further model development regarding e.g. distribution is also of interest. Further, liquid biofuels were shown here to be more costly than gaseous fuels, which may be due to that methanol is not currently included, and that by-products from ethanol that could e.g. be used to produce biogas, were here only considered to be used to produce electricity and heat. Agricultural residues and energy crops for biogas production are also considered to be a very important and interesting completion to the model.

The results showed that the biomass supply area had significant impact on the choice of plant locations and types of biofuel production, and that smaller plant with high specific investment costs were included in the solutions. Inclusion of intermediate products such as torrefied biomass, pyrolysis oil and lignin extracted from chemical pulp mills would entail lower feedstock transport costs, which could benefit larger biofuel production plants. Intermediate products are thus of particular interest to include in the model.

While the description in the model of biofuel production integrated into pulp and paper mills, CHP plants and refineries builds on a large number of previous integration case studies (e.g. Pettersson, 2011; Wetterlund, 2012; Heyne, 2013; Johansson, 2013; Isaksson et al., 2012a; Ljungstedt et al., 2013), the modelling of biofuel production integrated into sawmills is to a large part based on more general assumptions. As pointed out by Andersson et al. (2013) few or no system studies of e.g. biomass gasification-based biofuel production integrated into sawmills exist. Since the model results show that sawmills can have a potentially significant role to play in future biofuel production, the modelling assumptions regarding sawmills should be reviewed and possibly revised.

The input data regarding total motor fuel demand could also potentially be improved. The future development of the automotive fuel demand is strongly depending on demographic changes, changes in car travel habits, infrastructure as well as the technological development of the vehicles. One approach could be to link the BeWhere model to the overall energy demand model MAED-2 (Model for Analysis of Energy Demand), which has been developed by the International Atomic Energy Agency (IAEA) (International Atomic Energy Agency, 2006). The MAED model evaluates future energy demands based on medium- to long-term scenarios of socio-economic, technological and demographic developments. The energy demand is disaggregated into a large number of end-use categories. Each category corresponds to a given service or to the production of certain goods. The nature and level of the demand for goods and services are a function of several determining factors, including population growth, peoples' mobility and preferences for transportation modes, national priorities for the development of certain industries or economic sectors, the evolution of the efficiency of certain types of equipment, market penetration of new technologies or energy forms etc. The expected future trends for these determining factors, which constitute the scenarios, are exogenously introduced.

Further, BeWhere Sweden is at the moment focused on the national biofuel demand. However, Sweden is also of considerable interest for future next generation biofuel production from a European perspective. By introducing a link to existing models that operate on a European level, such as BeWhere Europe and the related IIASA model GLOBIOM, BeWhere Sweden could also be used to provide results of value for EU policies and strategies. This report included import of forest biomass, but with a very crude description of the import possibilities. A better description in the model of the international market for biomass would thus be of value.

In its current form, BeWhere Sweden is run for one year, with a static time perspective. It is assumed that the studied technologies are technically mature and commercially available for the studied time frame. By supplementing the model with technology readiness aspects and a more dynamic time perspective, other qualities can be analysed. This also enables consideration of which plants that are about to substitute existing technologies, thereby providing an opportunity for investment in biofuel production. Finally, biomass demand from other sectors is now described statically, and advanced biofuels are the only new biomass-based products considered. Also other types of biorefinery technologies products (e.g. different types of chemicals) could be included into the model. By running BeWhere Sweden without fixed goals for various products, competition for biomass for feedstock or energy purposes could be studied explicitly which would also add dynamics to the modelling approach. This could be of value to be able to further broaden the analysis, in particular regarding policy aspects.

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APPENDIX A. BEWHERE SWEDEN – DESCRIPTION

BeWhere is a techno-economic, geographically explicit optimisation model for localisation of bioenergy production facilities. The model has been developed by the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and Luleå University of Technology[13] and has been used for regional, national and European studies.

BeWhere Sweden[14] is the newest addition to the BeWhere family, with focus on investigation and determination of locations and characteristics of next generation biofuel production facilities. The model is used to identify locations robust to changes in boundary conditions such as energy market prices, policy instruments, investment costs, feedstock competition, and integration possibilities with existing energy systems. The model can be useful for decision support for different biofuel production stakeholders as well as for government and policy makers.

MODEL OVERVIEW

BeWhere Sweden minimises the system cost of the complete supply chain. Biomass of various types (stemwood, different types of waste flows etc.) is transported from supply regions to possible plant sites for biofuel production in different types of plants, producing different types of biofuel. The plants can use or co-produce other energy carriers. Biomass is also used by competing users of different categories, such as industry and district heating systems, that have a demand that must be fulfilled. In defined demand regions there is a demand for transport fuel, which can be met by fossil fuels or biofuel. Biomass and biofuel are transported between supply regions, plants and demand regions using different means of transportation (truck, train, ship). Prices, demands, policies and other external parameters are described on national or county level. Biomass and biofuel can be imported/exported at defined harbours. Figure A- 1 gives a schematic overview of the main flows.

Sweden has been divided into a base grid consisting of 334 grid cells with a half-degree spatial resolution (approximately 20 x 50 km in northern Sweden and 30 x 50 km in southern Sweden). The base grid is used to express supply regions and demand regions. In addition to the base grid, points representing potential biofuel plant sites as well as harbours for import and export are expressed with explicit coordinates. The grid and plant locations are shown in Figure A- 2.

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[13] BeWhere webpage at IIASA: www.iiasa.ac.at/bewhere

[14] BeWhere Sweden webpage: www.ltu.se/bewhere

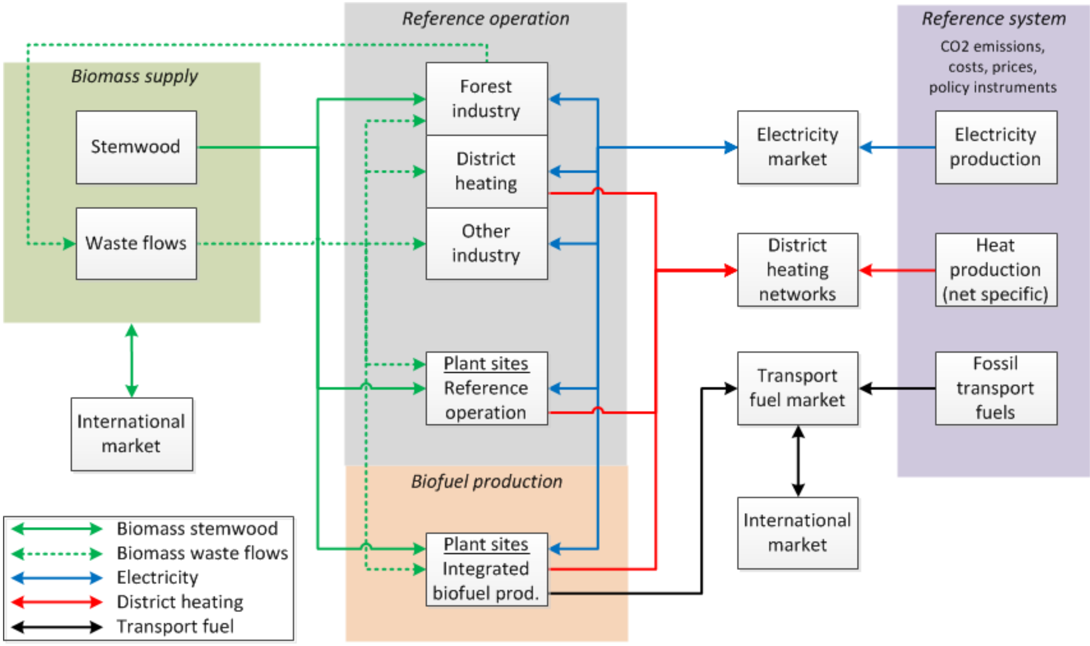

Figure A- 1. Graphical overview of the main flows in BeWhere Sweden.

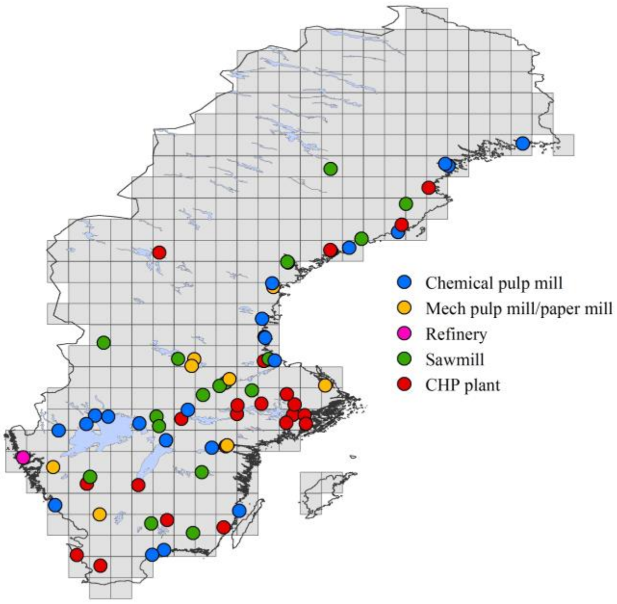

Figure A- 2. BeWhere Sweden grid division and plant sites.

MILP MODEL

BeWhere is based on mixed integer linear programming (MILP) and is written in the commercial software GAMS, using CPLEX as a solver. On a general form, a minimising MILP problem can be described as:

$$\begin{aligned} &\min_{x,y}\left[\sum_{n=1}^{N} c_n x_n + \sum_{k=1}^{K} e_k y_k\right] \\ &\text{s.t.} \sum_{n=1}^{N} a_{n,m} x_n + \sum_{k=1}^{K} d_{k,m} y_k = b_m, \quad m = 1, \dots, M \\ &\quad y_k \in Z, \quad k = 1, \dots, K \end{aligned} \tag{A.1}$$

where *N* is the number of continuous variables, *K* is the number of integer variables, and *M* is the number of constraints. *x* are the continuous variables and *y* are the integer variables. *a, b, c, d,* and *e* are parameters and *Z* is the set of all integers.

BeWhere minimises the system cost of the entire studied system. By adding the possibility to include the costs of emitting CO_2 in the objective function, the impact of fossil CO_2 emissions is internalised. The total system cost thus consists of the supply chain cost and the supply chain CO_2 emission cost.

The supply chain cost includes:

- Feedstock cost
- Cost for transportation of biomass to biofuel production plants and other biomass users
- Setup and operation and maintenance costs for new next generation biofuel plants
- Cost for biofuel transport to biofuel demand regions
- Cost of imported biomass and biofuel
- Additional cost for biofuel handling and dispensing at gas stations
- Revenue from co-produced energy carriers
- Revenue for exported biomass and biofuel
- Revenue or cost related to various policy instruments
- Cost of fossil transportation fuels used in the system

The supply chain CO_2 emissions include:

- Emissions from transportation of biomass and biofuel
- Emissions from used or produced energy carriers (including offset emissions from displaced fossil energy carriers)
- Emissions related to the use of biomass (including indirect effects, if desired)

For each emission source a separate CO_2 cost can be set, representing for example a tax or tradable emission permits, to give the total cost for supply chain CO_2 emissions. This gives the possibility to internalise the impact of fossil CO_2 emissions by including the CO_2 cost in the objective function.

The total cost is minimised subject to a number of constraints regarding, for example, biomass supply, biomass demand, import/export of biomass, production plant operation (efficiencies, capacity etc.) and biofuel demand. The model will choose the least costly pathways from one set of feedstock supply points to a specific biofuel production plant and further to a set of biofuel demand points, while meeting the demand for biomass in other sectors, over the time period chosen (in this study, 1 year). Biofuel production plants can be integrated with either industry or district heating.

The resulting output from the model consists of the location and characteristics of a set of plants, types and amounts of biomass used, biomass flows, types and amounts of biofuel produced, imported and exported biomass and biofuel, and the costs and CO_2 emissions related to various parts of the supply chain.

MODEL ARCHITECTURE AND WORKFLOW

The BeWhere Sweden model consists of the following main parts:

1. Database containing all input data
2. Input data pre-processor
3. MILP optimisation model
4. Results output post-processor

Before running the model, input data has to be treated to be expressed in the correct format and units, as well as on the appropriate geographical form. The data is stored in a database for access by the pre-processor, which reads the data and creates input files for the optimisation model.

After optimisation, the results are obtained in the form of a list of selected variables. The results are treated by a post-processor to attain the results in a more accessible form. Selected results can further be plotted geographically explicitly.

Figure A- 3 shows an overview of the model architecture and workflow, as well as the software used for each step.

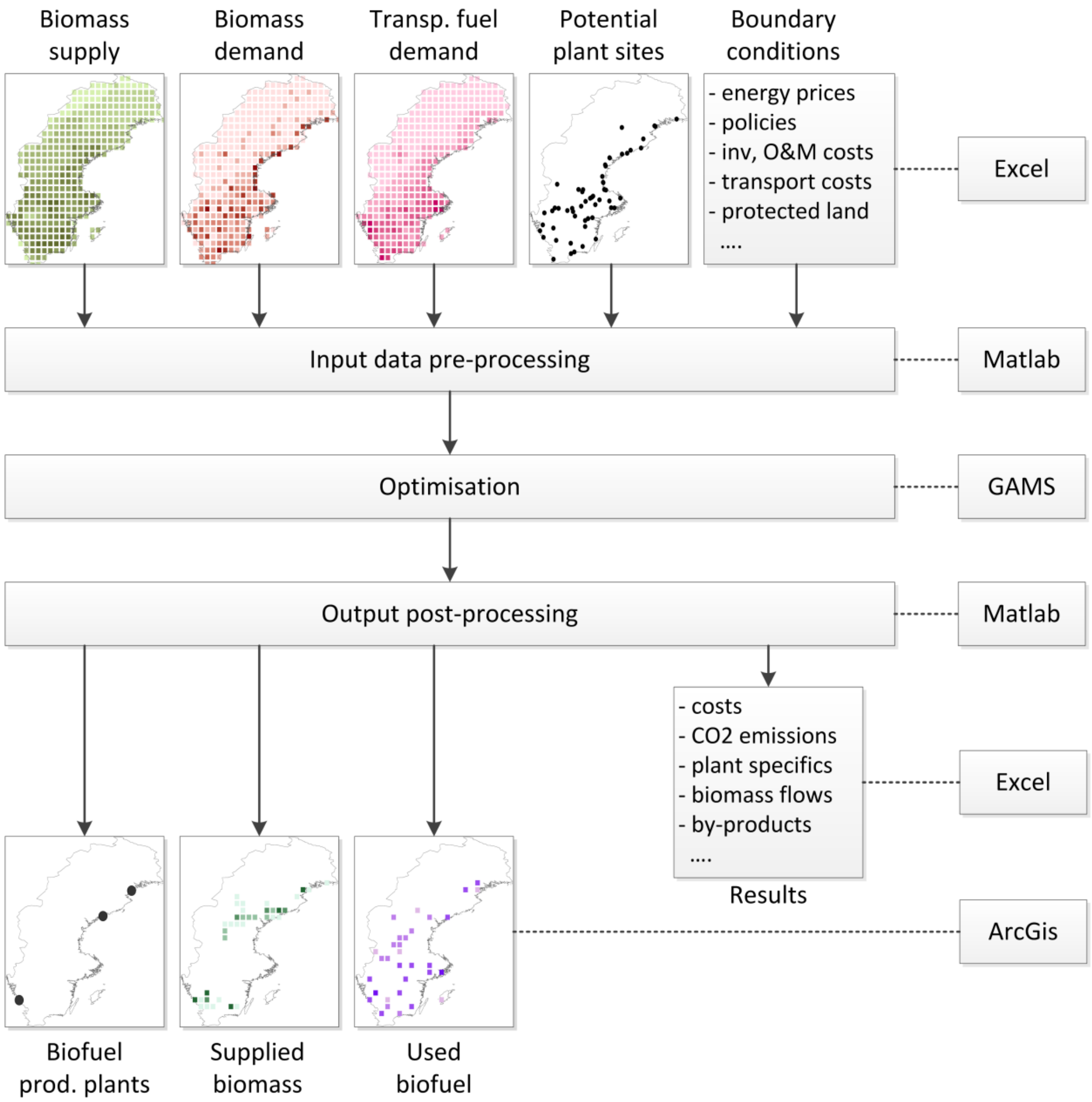

Figure A- 3. Overview of the model architecture and workflow, as well as the software used for each step.

MODEL OPERATION

The model can be run in different modes by changing various constraints. Examples are that the biofuel demand can be fixed, an explicit amount of biomass for biofuel production be defined, a certain numbers of production plants be set, or a target for CO_2 emissions be stated.

When running the model for a fixed biofuel target, a next generation biofuel demand is defined, which must be fulfilled by investment in new production facilities or biofuel import. The model chooses the least costly combination of pathways to meet the target. From the resulting system cost the cost to fulfil a specific biofuel target can be derived. The biofuel target is expressed as a share of the total fuel demand and can be defined as a lower limit, an upper limit or an interval. The target can be defined as an overall target for Sweden, as a target per county, or as a target that must be fulfilled in each demand region (grid cell).

The model can also be run without fixed biofuel target, in which case the optimal amount of biofuel is determined by the model based on boundary conditions, such as energy costs and prices. Since the model minimises the total system cost, the resulting production and use of biofuel can be zero.

In order to test specific individual plants sites' robustness to changes in boundary condition the model can be run for a fixed number of new biofuel production facilities that must be included in the solution. No target for the biofuel production is set. The model chooses the plant/s that will under the specific boundary conditions give the lowest system cost. Since the model *must* include the defined number of plants, the resulting system cost may be higher than if no or fewer plants were to be included.

APPENDIX B. INPUT VALUES FOR FOREST BIOMASS COST MODEL

Table B- 1. Input values

Variable/constant		Value	Unit [a, b]	Source
Harvester				
Final felling				
Swath width	S_f	13	meters	Brunberg (1995)
Roundwood extraction	U_f	661	stems per hectare	Brunberg (1995)
Harvester speed	K_f	25.9	meter per minute	Brunberg (1995)
Average stem volume	V_f	0.38	m^3	SFA (2012)
Secondary saw-cut	A_1	28	percent	Brunberg (1995)
Harvester-head positioning difficulty	A_2	15	percent	Brunberg (1995)
Problem trees	A_3	37	percent	Brunberg (1995)
Thinning				
Swath width	S_t	18	meters	Brunberg (1997)
Roundwood extraction	U_t	914	stems per hectare	Brunberg (1997)
Harvester speed	K_t	15.6	meter per minute	Brunberg (1997)
Average stem volume	V_t	90	dm^3	SFA (2012)
Number of trees left standing	E	1	‘000s of trees	Brunberg (1997)
Forwarder				
Load capacity	W	12.9	m^3	Brunberg (2004)
Final felling				
Miscellaneous time	M_f^f	0.37	G_{15}-min per m^3	Brunberg (2004)
Constant	$B_{f,1}$	1	--	Brunberg (2004)
Constant	$B_{f,2}$	0.86	--	Brunberg (2004)
Constant	$\alpha_{f,1}$	5.7	--	Brunberg (2004)
Constant	$\alpha_{f,2}$	11.45	--	Brunberg (2004)
Thinning				
Miscellaneous time	M_t^f	0.15	G_{15}-min per m^3	Brunberg (2004)
Constant	$B_{t,1}$	1	--	Brunberg (2004)
Constant	$B_{t,2}$	0.67	--	Brunberg (2004)
Constant	$\alpha_{t,1}$	-43	--	Brunberg (2004)
Constant	$\alpha_{t,2}$	25.9	--	Brunberg (2004)
Stump harvesting				
Miscellaneous time	M_s^f	0.37	G_{15}-min per m^3	
Constant	$B_{t,1}$	1	--	
Constant	$B_{t,2}$	0.86	--	
Constant	$\alpha_{t,1}$	5.7	--	
Constant	$\alpha_{t,2}$	11.45	--	
Other variables				
Wage (incl. social fees)	w	18.2	EUR per hour	SFA (2012)
Overhead costs (final felling)	OH_f	1	EUR per m^3	SFA (2012)
Overhead costs(thinning)	OH_t	1.4	EUR per m^3	SFA (2012)
Overhead costs (stump harvetsing)	OH_s	1	EUR per m^3	SFA (2012)
Silviculture costs (final felling)	C_{sil}	5.8	EUR per m^3	SFA (2012)
Forest roads costs (final felling)	C_{fr}	3.0	EUR per m^3	SFA (2012)
Productivity chipper	ρ^{chip}	31	m^3 solid per G_{15}-hour	Athanassiadis et al., (2009b)
Compensation to land-owner	C_{comp}	13	EUR per m^3	FRI (2012)
Stump lifting	C_{sl}	8.5	EUR per m^3	Athanassiadis et al., (2009b)
Stump crushing	C_{sc}	5.5	EUR per m^3	Athanassiadis et al., (2009b)
Productivity crusher	ρ^{crus}	31	m^3 per G_{15}-hour	Athanassiadis et al., (2009b)

[a] all m^3 measures are for solid excl. bark.
[b] when appropriate an exchange rate of 1 EUR = 9.14 SEK is used.

APPENDIX C. INPUT DATA FOR HOST INDUSTRIES

In order to estimate the plant size for the different biofuel technology cases and to estimate the consequences when different biofuel technologies are integrated to existing plant sites a number of different data is needed. Data for existing plant sites included as potential sites for integration of biofuel production has been taken from different sources. With available data and additional general assumptions, the different data necessary has been estimated. This appendix includes short descripttions of how necessary data for the different plant sites has been estimated.

CHEMICAL PULP MILLS

In order to estimate the plant size for the different biofuel technology cases and to estimate the consequences when different biofuel technologies are integrated to chemical pulp mills the following data is needed:

- Pulp production
- Pulp wood needed for pulp production
- Flow of black liquor
- Availability of falling bark and other internal fuels
- Type and amount of different fuels used for steam generation
- Electricity production
- Renewable electricity production
- Process steam demand
- Process electricity demand
- Type and amount of different fuels used for other purposes than steam generation (mainly in the lime kiln)

The data for chemical pulp mills from SFIF's environmental database (SFIF, 2012b) includes pulp production, total biomass fuel used (i.e. excl. pulp wood), fossil fuels used and how much electricity that is produced, bought and sold.

The pulp production volumes reported in SFIF's environmental database have been used to estimate the pulp wood demand for each mill, based on general wood demand ratios for different types of pulp (Swedish Forest Agency, 2012). How much bark that is debarked from the logs, the production of black liquor and the fuel use in the lime kiln for each mill have also been estimated using general ratios for different types of pulp (Delin et al., 2005b; Delin et al., 2005a). To be able to estimate this data we need to know the production of different types of pulp. From SFIF's environmental database we know how much that is unbleached (soft wood-based) kraft pulp and how much that is bleached kraft pulp. However, how much of the bleached kraft pulp that is soft wood- respectively hard wood-based are unknown. From in house data we know which types of pulp different mills produce, but not the amounts for the different types. For mills producing both, it has therefore been assumed that 3/5 is soft wood-based and 2/5 is hard wood-based kraft pulp.

At kraft pulp mills today, most of the fossil fuels used are used in the lime kiln. However, there are still some fossil fuels used for electricity and steam production. Here, it has been assumed that fossil fuels (approximated as only oil, since it is unspecified) are used as fuel in the lime kiln, and if the reported use of fossil fuels is greater than the estimated use of fuel in the lime kiln, the rest is used for electricity and steam production. On the other hand, if the reported use of fossil fuels is less than the estimated use of fuel in the lime kiln, the rest is covered by biomass fuel. The total use of biomass fuel for electricity and steam production is therefore calculated as the sum of the total biomass fuel used (incl. black liquor) and fossil fuels used, minus the estimated fuel use in the lime kiln. How much of this wood fuel that is not black liquor can then be calculated by subtracting the estimated production of black liquor from the total biomass fuel used.

The electricity production is reported in SFIF's environmental database. The electricity production and total fuel usage for electricity and steam are used to calculate the electrical efficiency. By assuming a total efficiency, thereby assuming a heat efficiency, the process steam usage is then estimated.

Since the approach in this report is that the different plant sites integrated with different biofuel technologies are compared to a case where new investments in conventional technologies (boilers and turbines) are made at the industrial plants instead of a biofuel plant, modern data for the total efficiency and the electrical efficiency is assumed (90% and 15% respectively). Thereby, the amount of fuels used for steam generation and the electricity production are changed. To assume that all mills will have the same electrical efficiency is naturally a simplification, since e.g. different types of mill have different need for steam at different pressure levels.

The data from the mapping of the pulp and paper industries energy usage 2011 performed by ÅF on behalf of SFIF's Environmental and Energy Committee (Wiberg and Forslund, 2012) includes pulp production, type and amounts of fuels used for steam production based on a standard boiler efficiency of 90%, type and amounts of fuels used for other purposes than steam generation, specification of if the fuels used are internal or external fuels, export of fuels, electricity production, steam used for electricity production and process electricity usage. Thus, these data are significantly more detailed and almost all data needed are included or could be calculated directly from the data. The exception is the pulp wood demand, which is estimated in the same way as described above for the data from SFIF's environmental database. As described above, modern data for the total efficiency and the electrical efficiency is assumed, thereby changing the amount of fuels used for steam generation and the electricity production.

MECHANICAL PULP MILLS AND PAPER MILLS

In order to estimate the plant size for the different biofuel technology cases and to estimate the consequences when different biofuel technologies are integrated to mechanical pulp mills and paper mills the following data is needed:

- Pulp production (paper production for the paper mills)
- Pulp wood needed for pulp production
- Availability of falling bark and other internal fuels
- Type and amount of different fuels used for steam generation
- Electricity production
- Renewable electricity production
- Process steam demand
- Process electricity demand

As for chemical mills, the data for mechanical pulp mills and paper mills from SFIF's environmental database includes pulp production (and paper production), total biomass fuel used (i.e. excl. pulp wood), fossil fuels used and how much electricity that is produced, bought and sold.

How much bark that is debarked from the logs has for mechanical pulp mills and paper mills been taken from home pages and annual reports. Then, the import of wood fuel is calculated. The electricity production is reported in SFIF's environmental database. By assuming a total efficiency, the heat efficiency and thereby the steam use can be estimated.

Since the mechanical mills do not have internal fuel like the black liquor that has to be combusted, the steam usage here is equal to the steam deficit. For paper mills it is the same thing except for the fact that there is no falling bark like for the pulp mills and consequently all fuel has to be purchased. The same uncertainties regarding the data for mechanical pulp mills and paper mills as for chemical pulp mills exist.

SAWMILLS

In order to estimate the plant size for the different biofuel technology cases and to estimate the consequences when different biofuel technologies are integrated to sawmills the following data is needed:

- Availability of internal by-products (wood chips, saw dust and bark)
- Type and amount of different fuels used for heating purposes
- Process heat demand

The capacities for the sawmills included have been taken from the SFIF member register (SFIF, 2012a). The heat use for different sawmills has been estimated based on a ratio between heat use and capacity from Isaksson et al. (2012b). The production of wood fuel (by-products) is calculated based on general ratios (Danielsson, 2003). The internal use (for heating purposes) is calculated by assuming a heat only boiler efficiency.