REPORT f3 2013:8

OPTIMAL LOCALISATION OF NEXT GENERATION BIOFUEL PRODUCTION IN SWEDEN

Report from an f3 R&D project

Elisabeth Wetterlund
Linköping University

Karin Pettersson
Chalmers University of Technology

Johanna Mossberg and Johan Torén
SP Technical Research Institute of Sweden

Christian Hoffstedt, Anna von Schenck and Niklas Berglin
Innventia

Robert Lundmark and Joakim Lundgren
Luleå University of Technology (Bio4Energy)

Sylvain Leduc and Georg Kindermann
International Institute of Applied Systems Analysis (IIASA), Austria

THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

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, SP Technical Research Institute of Sweden, Innventia, International Institute for Applied Systems Analysis (IIASA, Austria) and Luleå University of Technology (Bio4Energy) as project leader. The authors gratefully acknowledge the f3 Centre for the financial support and valuable comments on the report.

SUMMARY

With a high availability of lignocellulosic biomass and various types of cellulosic by-products, as well as a large number of industries, Sweden is a country of great interest for future large scale production of sustainable, next generation biofuels. This is most likely also a necessity as Sweden has the ambition to be independent of fossil fuels in the transport sector by the year 2030 and completely fossil free by 2050. In order to reach competitive biofuel production costs, plants with large production capacities are likely to be required. 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 forest industries and CHP plants (combined heat and power) 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 may be beneficial from several aspects, such as opportunities for efficient heat integration, feedstock and equipment integration, as well as access to existing experience and know-how.

This report describes the development of BeWhere Sweden, a geographically explicit optimisation model for localisation of next generation biofuel production plants in Sweden. The main objective of developing such a model is to be able 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. This report also presents current and future Swedish biomass resources as well as a compilation of three consistent future energy scenarios.

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 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 system cost is minimised subject to constraints regarding, for example, biomass supply, biomass demand, import/export of biomass, production plant operation and biofuel demand. 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.

BeWhere has previously been developed by the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and Luleå University of Technology and has been used in several studies on regional and national levels, as well as on the European level. However, none of the previous model versions has included site-specific conditions in existing industries as potential locations for industrially integrated next generation biofuel

production. Furthermore, they also usually only consider relatively few different production routes. In this project, bottom-up studies of integrated biofuel production have been introduced into a top-down model and taken to a higher system level, and detailed, site-specific input data of potential locations for integrated biofuel production has been included in the model.

This report covers the first stages of model development of BeWhere Sweden. The integration possibilities have been limited to the forest industry and a few district heating networks, and the feedstocks to biomass originating from the forest. The number of biofuel production technologies has also been limited to three gasification-based concepts producing DME, and two hydrolysis- and fermentation-based concepts producing ethanol. None of the concepts considered is yet commercial on the scale envisioned here.

Preliminary model runs have been performed, with the main purpose to identify factors with large influence on the results, and to detect areas in need of further development and refinement. Those runs have been made using a future technology perspective but with current energy market conditions and biomass supply and demand. In the next stage of model development different roadmap scenarios will be modelled and analysed. Three different roadmap scenarios that describe consistent assessments of the future development concerning population, transport and motor fuel demands, biomass resources, biomass demand in other industry sectors, energy and biomass market prices etc. have been constructed within this project and are presented in this report. As basis for the scenarios the report "Roadmap 2050" by the Swedish Environmental Protection Agency (EPA) has been used, using 2030 as a target year for the scenarios. Roadmap scenario 1 is composed to resemble "Roadmap 2050" Scenario 1. Roadmap scenario 2 represents an alternative development with more protected forest and less available biomass resources, but a larger amount of biofuels in the transport system, partly due to a higher transport demand compared to Roadmap scenario 1. Finally Roadmap scenario 3 represents a more "business as usual" scenario with more restrictive assumptions compared to the other two scenarios.

In total 55 potential biofuel plant sites have been included at this stage of model development. Of this 32 sites are pulp/paper mills, of which 24 have chemical pulp production (kraft process) while eight produce only mechanical pulp and/or paper. Seven of the pulp mills are integrated with a sawmill, and 18 additional stand-alone sawmills are also included, as are five district heating systems. The pulp and paper mills and sawmills are included both as potential biofuel plant sites, as biomass demand sites regarding wood and bioenergy, and as biomass supply sites regarding surplus by-products. District heating systems are considered both regarding bioenergy demand and as potential plant sites.

In the preliminary model runs, biofuel production integrated in chemical pulp mills via black liquor gasification (BLG) was heavily favoured. The resulting total number of required production plants and the total biomass feedstock volumes to reach a certain biofuel share target are considerably lower when BLG is considered. District heating systems did not constitute optimal plant locations with the plant positions and heat revenue levels assumed in this study. With higher heat revenues, solid biomass gasification (BMG) with DME production was shown to be potentially interesting. With BLG considered as a production alternative, however, extremely high heat revenues would be needed to make BMG in district heating systems competitive.

The model allows for definition of biofuel share targets for Sweden overall, or to be fulfilled in each county. With targets set for Sweden overall, plant locations in the northern parts of Sweden were typically favoured, which resulted in saturation of local biofuel markets and no biofuel use in the southern parts. When biofuels needed to be distributed to all parts of Sweden, the model selected a more even distribution of production plants, with plants also in the southern parts. Due to longer total transport distances and non-optimal integration possibilities, the total resulting system cost was higher when all counties must fulfil the biofuel share target. The total annual cost to fulfil a certain biofuel target would also be considerably higher without BLG in the system, as would the total capital requirement. This however presumes that alternative investments would otherwise be undertaken, such as investments in new recovery boilers. Without alternative investments the difference between a system with BLG and a system without BLG would be less pronounced.

In several cases the model located two production plants very close to each other, which would create a high biomass demand on a limited geographic area. The reason is that no restrictions on transport volumes have yet been implemented in the model. Further, existing onsite co-operations between for example sawmills and pulp mills have not always been captured by the input data used for this report, which can cause the consideration of certain locations as two separate plant sites, when in reality they are already integrated. It is also important to point out that some of the mill specific data (obtained from the Swedish Forest Industries Federation’s environmental database) was identified to contain significant errors, which could affect the results related to the plant allocations suggested in this report.

Due to the early model development stage and the exclusion of for example many potential production routes and feedstock types, the model results presented in this report must be considered as highly preliminary. A number of areas in need of supplementing have been identified during the work with this report. Examples are addition of more industries and plant sites (e.g. oil refineries), increasing the number of other production technologies and biofuels (e.g. SNG, biogas, methanol and synthetic diesel), inclusion of gas distribution infrastructures, and explicit consideration of import and export of biomass and biofuel. Agricultural residues and energy crops for biogas production are also considered to be a very important and interesting completion to the model. Furthermore, inclusion of intermediate products such as torrefied biomass, pyrolysis oil and lignin extracted from chemical pulp mills would make it possible to include new production chains that are currently of significant interest for technology developers. As indicated above, the quality of some input data also needs to be improved before any definite conclusions regarding next generation biofuel plant localisations can be drawn.

A further developed BeWhere Sweden model has the potential for being a valuable tool for simulation and analysis of the Swedish energy system, including the industry and transport sectors. The model can for example be used to analyse different biofuel scenarios and estimate cost effective biofuel production plant locations, required investments and costs to meet a certain biofuel demand. Today, concerned ministries and agencies base their analyses primary on results from the models MARKAL and EMEC, but none of these consider the spatial distribution of feedstock, facilities and energy demands. Sweden is a widespread country with long transport distances, and where logistics and localisation of production plants are crucial for the overall efficiency. BeWhere Sweden considers this and may contribute with valuable input that can be used to complement and validate results from MARKAL and EMEC; thus testing the feasibility of these model results. This can be of value for different biofuel production stakeholders as well as for government and policy makers. Further, 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.

SAMMANFATTNING

Sverige besitter goda tillgångar på skogsbiomassa och olika typer av cellulosabaserat avfall som potentiellt kan användas till framtida storskalig produktion av nästa generations biodrivmedel. Eftersom Sverige har satt som mål att vara oberoende av fossila bränslen inom transportsektorn år 2030 och helt fossilfritt 2050, är detta förmodligen också en nödvändighet. Att nå konkurrenskraftiga produktionskostnader kommer sannolikt kräva stora biodrivmedelsanläggningar. Ett råvaruintag i spannet 1-2 miljoner ton per år (motsvarande en anläggningskapacitet på 300-600 MW), kan förväntas, vilket innebär stora logistiska utmaningar. För att möjliggöra biodrivmedelsproduktion i så stora anläggningar kommer betydande infrastrukturplanering att vara nödvändigt. Den geografiska placeringen av produktionsanläggningar är därför av avgörande betydelse och måste vara strategisk för att minimera transporterna av såväl råvaror som slutprodukter. Konkurrensen om den tillgängliga råvaran från exempelvis skogsindustrin och kraftvärmesektorn, komplicerar lokaliseringsproblemet ytterligare. Eftersom potentialen för ett ökat biomassautnyttjande är begränsad, är resurseffektiviteten av stor betydelse. Integration av drivmedelsproduktion i befintliga industrier eller fjärrvärmesystem kan vara fördelaktigt ur flera perspektiv. Exempel är möjligheter till effektiv värmeintegrering, integrering av råmaterial och utrustning, samt utnyttjande av befintliga kunskaper och erfarenheter.

Denna rapport beskriver utvecklingen av BeWhere Sweden – en geografiskt explicit optimeringsmodell för lokalisering av nästa generations biodrivmedelsproduktion i Sverige. Det främsta syftet med modellen är att kunna identifiera och värdera lokaliseringar som är så robusta som möjligt i förhållande till olika randvillkor, i synnerhet gällande energimarknadsaspekter, styrmedel, investeringskostnader och råvarukonkurrens. I rapporten presenteras också en översikt av nuvarande och framtida biobränsleresurser i Sverige, samt en sammanställning av tre konsekventa framtidsscenarier.

BeWhere bygger på blandad heltalsprogrammering (Mixed Integer Linear Programming, MILP) och är skriven i den kommersiella programvaran GAMS, med CPLEX som lösare. 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. System-kostnaden minimeras under ett antal olika bivillkor som beskriver till exempel tillgång och efterfrågan på biomassa, import/export av biomassa och biodrivmedel, anläggningsdrift och efterfrågan på biodrivmedel. Modellen kommer således välja de minst kostsamma kombinationerna av råvaror, produktionsanläggningar och leveranser av biodrivmedel, samtidigt som efterfrågan på biomassa i andra sektorer tillgodoses.

BeWhere-modellen har tidigare utvecklats vid International Institute for Applied Systems Analysis (IIASA) i Laxenburg, Österrike och vid Luleå Tekniska Universitet, och har använts i ett stort antal studier på regional och nationell nivå, liksom på EU-nivå. Ingen av de tidigare modellerna har dock tagit hänsyn till platsspecifika förhållanden för potentiell integration av biodrivmedelsproduktion i exempelvis industrier. Dessutom har tidigare modeller generellt inkluderat relativt få olika produktionsalternativ. I det här projektet har bottom-up-studier av integrerad biodrivmedelsproduktion introducerats i en top-down-

modell och tagits till en högre systemnivå, med beaktande av detaljerade platsspecifika data för de potentiella lägena för integrerad biodrivmedelsproduktion.

Denna rapport omfattar de första faserna i modellutvecklingen av BeWhere Sweden. Integrationsmöjligheterna har här begränsats till skogsindustri och ett fåtal fjärrvärmenät, och råvarorna till biomassa som härrör från skogen. Produktionsteknikerna har begränsats till tre förgasningsbaserade koncept för produktion av DME, samt två hydrolys-och jäsningsbaserade koncept för produktion av etanol. Ingen av dessa tekniker är ännu kommersiell i den skala som beaktats i detta projekt.

Preliminära modellkörningar har genomförts med det huvudsakliga syftet att identifiera faktorer med stor inverkan på resultaten, samt behov av ytterligare modellutveckling och förbättring. Dessa körningar har gjorts utifrån dagens system, med nuvarande energimarknadsvillkor och tillgång och efterfrågan på biomassa, men med ett framtidsperspektiv gällande tekniker. I nästa steg av modellutvecklingen kommer olika framtidscenarier att modelleras och analyseras. Tre olika scenarier med bedömningar av framtida befolkningsutveckling, transport- och drivmedelsbehov, tillgång och efterfrågan på biomassa i olika samhällssektorer, samt marknadspriser på energi och biomassa, har skapats och presenteras i denna rapport. Naturvårdsverkets rapport ”Färdplan 2050” har använts som underlag för scenarierna, men med 2030 som tidsram. Färdplansscenario 1 är sammansatt för att efterlikna Scenario 1 i ”Färdplan 2050”. Färdplansscenario 2 representerar en alternativ utveckling med mer skyddad skog och färre tillgängliga biomassaresurser, men ed en större mängd biodrivmedel i transportsystemet, delvis beroende på en högre efterfrågan på transporter jämfört med i Färdplansscenario 1. Färdplansscenario 3 är slutligen mer av ett ”business as usual”-scenario, med generellt mer restriktiva antaganden jämfört med de andra två scenarierna.

Sammanlagt 55 potentiella platser för integrerad biodrivmedelsproduktion har inkluderats i detta skede av modellutvecklingen. Av dessa är 32 massa- och pappersindustrier, varav 24 producerar kemisk massa (sulfatmassa) och åtta tillverkar mekanisk massa och/eller papper. Sju av massabruken är även integrerade med ett sågverk. Ytterligare 18 fristående sågverk är också beaktade, liksom fem fjärrvärmesystem. Massa-och pappersbruken och sågverken ingår i modellen dels som möjliga lokaliseringar för biodrivmedelsproduktion, dels med avseende på biobränslebehov (stamved och/eller energi) som måste tillfredsställas, och dels som producenter av biobränsle (överskott av industriella biprodukter). Fjärrvärmesystemen beaktas både i form av möjliga lägen för integrerad drivmedelsproduktion, och med avseende på behov av bioenergi.

I de preliminära modellkörningarna visade sig drivmedelsproduktion integrerat i kemiska massabruk baserat på svartlutsförgasning (BLG) vara särskilt gynnsamt. När BLG beaktades var både det resulterande erforderliga antalet produktionsanläggningar och det totala biobränslebehovet för att uppnå ett visst andelsmål för biodrivmedel i transportsektorn, betydligt lägre än om BLG inte beaktades. Fjärrvärmesystem visade sig generellt inte utgöra optimala lokaliseringar med de system som innefattats och de värmepriser som antagits i denna rapport. Med högre värmeintäkter visade sig att förgasning av fasta biobränslen med DME-produktion kan vara potentiellt intressant. Med BLG-baserad produktion inkluderad som produktionsalternativ skulle dock extremt höga värmepriser behövas för att göra fastbränsleförgasning i fjärrvärmesystem konkurrenskraftigt.

I modellen kan mål för andelen biodrivmedel i transportsektorn anges för Sverige som helhet, eller som mål som måste uppfyllas i varje län. När målet angavs övergripande för Sverige gynnades anläggningslokaliseringar i norra Sverige, vilket ledde till mättnad av de lokala biodrivmedelsmarknaderna och ingen biodrivmedelsanvändning i de mer tätt-befolkade södra delarna. Om ett biodrivmedelsmål istället angavs länsvis valde modellen en jämnare geografisk fördelning av produktionsanläggningarna, med anläggningar även i södra Sverige. På grund av längre totala transportavstånd och icke-optimala integrations-möjligheter resulterade detta i en högre total systemkostnad jämfört med när målet angavs för Sverige som helhet. Den totala kostnaden för att uppfylla ett visst biodrivmedelsmål, liksom det totala kapitalbehovet, skulle också vara betydligt högre utan BLG i systemet. Detta förutsätter dock att alternativa investeringar annars skulle ha genomförts, såsom investeringar i nya sodapannor. Utan beaktande av alternativa investeringar skulle skillnaden mellan ett system med BLG och ett system utan BLG, vara mindre.

I flera körningar valde modellen två produktionsanläggningar mycket nära varandra, vilket skulle innebära en stor efterfrågan på biomassa på ett begränsat geografiskt område. Anledningen är dels att restriktioner för transportvolymer ännu inte införts i modellen, dels att befintliga samarbeten mellan exempelvis sågverk och massabruk inte alltid fångats av de indata som använts. Detta kan medföra att vissa platser betraktats som två separata anläggningar, när de i verkligheten redan har en hög grad av integrering och därmed borde betraktas som ett läge. Under arbetets gång har en del bruksspecifika data som använts (vilka erhållits från Skogsindustriernas miljödatabas) visat sig innehålla väsentliga felaktigheter. Det är därför viktigt att poängtera att detta kan påverka resultaten gällande de anläggningslokaliseringar som framstår som mest gynnsamma.

På grund av modellens tidiga utvecklingsstadium och att ett flertal potentiella produktionsalternativ och råvaror ännu inte inkluderats i modellen, måste de resultat som presenterats i denna rapport betraktas som mycket preliminära. Under arbetet har ett antal områden i behov av komplettering och vidareutveckling identifierats. Exempel är tillägg av både fler industrityper (t.ex. oljeraffinaderier) och fler potentiella anläggningsplatser, utökning av antalet produktionstekniker och drivmedel (t.ex. SNG, biogas, metanol och syntetisk diesel), inkludering av infrastrukturer för gasdistribution, samt explicit hänsyn till import och export av biomassa och biodrivmedel. Restprodukter från jordbruket och energigrödor för biogasproduktion anses också vara ett viktig och intressant tillägg till modellen. Dessutom skulle införandet av intermediärprodukter som torrefierad biomassa, pyrolysolja och lignin från kemiska massabruk göra det möjligt att inkludera ytterligare nya produktionskedjor som för närvarande är av betydande intresse för teknikutvecklare. Som diskuterats ovan behöver kvaliteten på vissa indata också förbättras innan några definitiva slutsatser kan dras om var nästa generations biodrivmedelsproduktion bör vara lokaliserad.

En vidareutvecklad BeWhere Sweden-modell har potential att utgöra ett värdefullt verktyg för simulering och analys av det svenska energisystemet, industrin och transportsektorn inkluderade. Modellen kan exempelvis användas för att analysera olika biodrivmedels-scenarier och för att identifiera och utvärdera kostnadseffektiva lokaliseringar för drivmedelsproduktion, nödvändiga investeringar, samt kostnader och biomassabehov för att möta en viss efterfrågan på biodrivmedel. Idag baserar berörda myndigheter primärt sina analyser på resultat från modellerna MARKAL och EMEC. Ingen av dessa modeller tar dock hänsyn till den geografiska fördelningen av råvaror, anläggningar och energi- och råvarubehov. Sverige är ett vidsträckt land med långa transportavstånd där logistik och lokalisering av produktionsanläggningar är avgörande för den totala effektiviteten. BeWhere Sweden beaktar dessa aspekter och kan bidra med värdefulla resultat som kan användas för att i tur komplettera och validera resultat från MARKAL och EMEC, och på så sätt testa implementerbarheten av dessa modellresultat. Detta kan vara av värde för såväl intressenter i biodrivmedelstillverkning, som för myndigheter och politiska beslutsfattare. Vidare är Sverige av stort intresse för framtida tillverkning av nästa generations biodrivmedel även ur ett europeiskt perspektiv. Genom att införa en länk till befintliga modeller som verkar på europeisk nivå, såsom BeWhere Europe och den relaterade IIASA-modellen GLOBIOM, kan BeWhere Sweden också användas för att generera resultat av värde för EU:s politik och strategier.

ABBREVIATIONS

ALK-HF-EtOH	alkaline pre-treatment followed by hydrolysis and fermentation for ethanol production
BAT	best available technology
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
CEPCI	Chemical Engineering's plant cost index
CFB	circulating fluidised bed
CHP	combined heat and power
DME	dimethyl ether
ENPAC	Energy Price and Carbon Balance Scenarios tool
EtOH	ethanol
EU ETS	European Union Emissions Trading System
HP	high pressure (steam)
HRSG	heat recovery steam generator
LHV	lower heating value
LP	low pressure (steam)
MILP	mixed integer linear programming
MP	medium pressure (steam)
NGCC	natural gas combined cycle
O&M	operation and maintenance
RB	recovery boiler
SE-HF-EtOH	steam explosion pre-treatment followed by hydrolysis and fermentation for ethanol production
SFIF	Swedish Forest Industries Federation
SNG	synthetic natural gas
SSF	simultaneous sacharation and fermentation
ST	steam turbine
WIS	water insoluble content

CONTENTS

1 INTRODUCTION

With a high availability of forest biomass and various types of cellulosic by-products, Sweden is a country of significant interest concerning future large scale production of advanced lignocellulosic biofuels[1]. In order to reach favourable economy-of-scale effects and consequently reasonable fuel production costs, large biorefinery plants will likely be required. Some of the larger biofuel plants available today (such as plants that produce ethanol from corn) require in the order of 3,000 tonnes per day of feedstock. Production facilities for the next generation of biofuels[2] are envisioned that would call for 6,000 tonnes per day or more of feedstock (World Watch Institute, 2007).

Production facilities with an annual biomass supply in the range of about 1-2 million tonnes biomass correspond to fuel input capacities of 300-600 MW. Such a large biomass intake causes major logistical challenges and to enable the 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 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 forest industries and CHP plants (combined heat and power) further complicates the localisation problem.

Since the potential for an increased biomass utilisation is limited, high overall resource efficiency is of great importance. Thus, integration of biofuel production processes in existing industries or in district heating systems may be beneficial. Options for integrating a biofuel production process into an existing industry include (Nohlgren et.al, 2010):

Feedstock integration to utilise existing internal material streams that can be used for conversion processes (black liquor, glycerol, bio-sludge and other industrial by-products)

Energy integration to utilise energy flows for example for fuel drying, pre-heating, district heating supplies etc.

Equipment integration to utilise existing or new, up-scaled equipment such as air separation unit, distillation columns, gas conditioning etc.

In a Swedish perspective, integrating a biofuel production process in existing pulp and paper industries may lead to several important techno-economic benefits. This is due to the closeness to biomass resources, long-term experience and well-developed infrastructure for handling large volumes of biomass, and access to heat sinks and/or heat sources (depending on the type of mill). Furthermore, gasification of black liquor can be applied and it is also possible to replace bark or oil boilers with a solid biomass gasifier for syngas production.

Biofuel production processes can also be co-located with other process industries with steam or hot water demands, such as sawmills or biomass-based CHP plants. Also here, biomass

[1] The term *biofuels* is in this report used to denote renewable transport fuels (liquid or gaseous).
[2] Biofuels are commonly divided into generations (first, second etc.). These terms are however difficult to define and often misleading. In this report we use the term *next generation biofuels* to denote advanced biofuels that are not yet commercial on the large scale envisioned here.

handling and logistical benefits are obtained. For biofuel plants with large amounts of low temperature excess heat, the possibility for integration with a district heating system could be crucial in order to reach profitability. In Sweden, the possibilities for delivering industrial excess heat to district heating systems is, however, quite limited. Oil refineries are also interesting from the point of view of integration, due both to the possibility to utilise existing process units and infrastructure, and to the experience and know-how concerning motor fuel products.

Suitable production site localisations can be identified by applying advanced systems analysis and modelling. By employing a spatially explicit approach, issues related to geographic factors can be addressed. A number of previous studies have addressed biofuel supply chains in a spatial context. Alex Marvin et al. (2012) used a mixed integer linear programming (MILP) model to evaluate production of lignocellulosic ethanol in a nine-state region in the USA, and Akgul et al. (2010) did the same for corn-based ethanol in Northern Italy. MILP approaches have also been used for multi-feedstock, multi-technology studies, for example by Schmidt et al. (2010a; 2011) for Austria and by Kim et al. (2011) for south-eastern USA. Hellmann and Verburg (2011) assessed a larger geographical region in their spatially explicit study of biofuel crops in Europe, employing a grid-based simulation approach.

The geographically explicit optimisation model BeWhere has been developed by the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria and Luleå University of Technology (Leduc, 2009)[3]. The model has continuously been developed during several years and has been used for regional studies such as Norrbotten (Leduc et al., 2010), national studies, for example Austria (Leduc et al., 2008; Schmidt et al., 2010a; Schmidt et al., 2010b; Schmidt et al., 2011), India (Leduc et al., 2009), Finland (Natarajan et al., 2012) and South Korea (Kraxner et al., 2012), and European studies (Wetterlund et al., 2012; Wetterlund et al., 2013). These model versions do however not include existing industrial sites as potential locations for next generation biofuel production. Furthermore, they also usually only consider relatively few different production routes.

1.1 OBJECTIVES

The main objective of this project is to develop a geographically explicit optimisation model suitable for extensive analysis of biofuel production scenarios in Sweden – *BeWhere Sweden*. The model will be a tool for finding suitable locations for lignocellulosic-based biofuel production plants in Sweden, in order to reach specific market share targets for next generation biofuels, and for analysing the consequences of establishing such production plants. The model will be used to determine suitable locations, types, sizes and operation characteristics of biomass conversion facilities at the minimum cost for the entire supply chain. Focus is on integrating the next generation biofuel production plants with other parts of the energy system, at this stage primarily in the forest industry. In this project, bottom-up studies of integrated biofuel production are introduced into a top-down model and taken to a higher system level and detailed, site-specific input data are included in the model.

[3] See the BeWhere homepage at IIASA, www.iiasa.ac.at/bewhere. Current Swedish members of the IIASA BeWhere team are Elisabeth Wetterlund (Linköping University) and Erik Dotzauer (Fortum / Mälardalen University).

This project also aims at mapping current and future Swedish biomass resources, in order to create scenarios which will be applied to BeWhere Sweden in later project phases.

The overall aim of the BeWhere Sweden project is to identify 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.

1.2 DELIMITATIONS

This report describes the first stages of model development. The integration possibilities have been limited to forest industry and a few district heating networks, and the feedstocks have been limited to biomass originating from the forest. Also the number of biofuel production technologies has been limited to three gasification based concepts and two hydrolysis and fermentation based concepts, none of which is yet commercial on the scale envisioned here. Preliminary model runs have been performed, with the main purpose to identify factors with high impact on the results, and to detect areas in need of further development and refinement concerning model input data. Those runs have been made using current energy market conditions and biomass supply and demand, but applying a future technology perspective.

1.3 WORK PROCESS AND REPORT OUTLINE

The work in this project can be divided into two parts – model development and testing, and scenario development.

Model development includes the construction of the optimisation model (described briefly in Chapter 2 and in more detail in Appendix A) as well as collection and compilation of input data. The input data needed for the model is described in a general sense in Chapter 3 as is the input data used for the preliminary runs conducted for this report. Sections 3.2 and 3.3 describes the methodology used to generate model input data regarding biofuel production technologies and integration potential at different plant sites, and Section 3.4 the methodology used to generate geographically explicit biomass supply input data. Preliminary model runs and results are presented in Chapter 4.

The scenario development is based on existing national roadmaps and strategies, and is complemented by a mapping of biomass resources. This is described in Chapter 5 and in Appendix D.

Chapter 6 contains the concluding discussion, and Chapter 7 suggestions for future work.

2 THE BEWHERE SWEDEN MODEL

With the BeWhere model total energy system optimisation calculations can be performed, that take into account locations, quantities and costs of feedstocks, demand for 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 biomass supply and demand. At the current state of model development sawmills, pulp and paper mills and district heating systems 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 demand that must be met, and as biomass supply points regarding surplus by-products. District heating systems are considered both regarding bioenergy demand and as potential plant sites.

2.1 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. 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[4]
- Additional cost for biofuel handling and dispensing at gas stations
- Revenue from co-produced energy carriers
- Revenue for exported biomass and biofuel[4]
- 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.

[4] Import and export have not been explicitly considered in this report, see Section 3.8.

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 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 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.

In this report three different modes have been applied:

1. *Fixed demand* — A fixed next generation biofuel demand is defined, which must be fulfilled by investment 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.
2. *No fixed demand* — 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 biofuel production can be zero.
3. *Fixed plants* — A fixed number of new biofuel production facilities that must be included in the solution is defined. No target for the biofuel production is set. The model chooses the plants 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.

The resulting output from the model consists of the location 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 supply chain. For a more detailed description of BeWhere Sweden, see Appendix A. The required input data, as well as the input data used for this report, are described in Chapter 3.

2.2 SPATIAL EXTENT

Sweden has been divided into a base grid consisting of 334 grid cells with a half-degree spatial resolution (approximately 50 x 50 km), as shown in Figure 1. The base grid is used to express population, biofuel demand, biomass supply and biomass demand. 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 points used at this stage of model development are also shown in Figure 1.

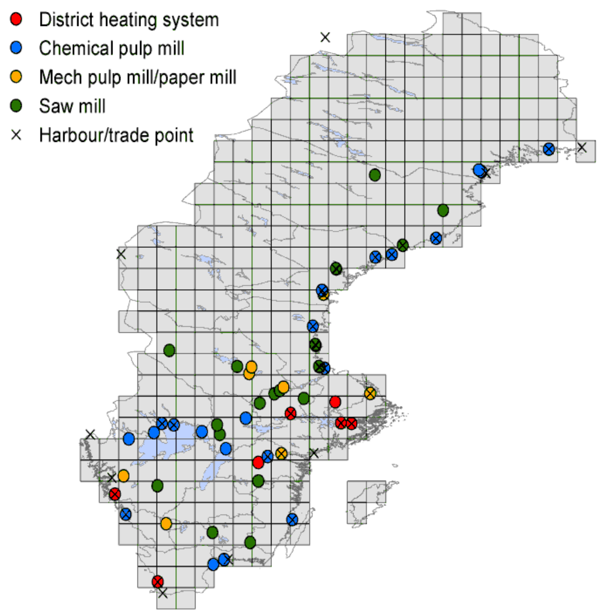


Figure 1. The BeWhere Sweden grid division and the additional points used to express plant sites and harbours.

3 INPUT DATA

In this section the required input data to BeWhere Sweden is described in general terms. Input data used for the preliminary model runs presented in this report are also described.

3.1 GENERAL MODEL 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 demand for pulp wood and sawlogs.

For this report the model has been run with a future perspective on biofuel production technologies (i.e. including technologies that are not currently commercially available at the scales assumed here), but using today's prices, costs, biomass supply and biomass demands. 2010 is used as base year.

All economic calculations have been performed using 2010 monetary value and Euro (EUR). 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%.

In the next phase of the project we intend to run the model for some selected scenarios. The construction of three roadmap scenarios for 2030 is described in Chapter 5.

3.2 BIOFUEL PRODUCTION TECHNOLOGIES

Five different biofuel technology cases have been considered at this stage of model development. Three cases are based on gasification technology and produces DME (dimethyl ether), and two cases are based on hydrolysis and fermentation technology and produces ethanol. More biofuel technology cases will be included in the next phase of model development (see Section 7). The biofuel technologies studied are:

- Solid biomass gasification with DME production (BMG-DME)
- 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)

Among the three gasification cases, one is based on gasification of black liquor (BLG-DME-BB), one is based on gasification of solid biomass (BMG-DME) and one case is based on both black liquor and solid biomass gasification (BLG-DME-BMG-DME). The two ethanol production processes differ in pre-treatment methods, where one is based on alkline pre-treatment (ALK-HF-EtOH) and one is based on steam explosion pre-treatment (SE-HF-EtOH).

Table 1 summarises the energy balances for the different technology cases, and Table 2 the investment cost functions used. Operation and maintenance (O&M) costs are set to 2-3% of the investment cost. For further explanations and references, see Sections 3.2.1-3.2.4 and Section 3.3.

Table 1. Energy balances for the different biofuel technology cases based on one unit of fuel input.

	BMG-DME	BLG-DME (-BB)[a]	BLG-DME (-BMG-DME)[a]	ALK-HF- EtOH	SE-HF- EtOH
Fuel input	1	1	1	1	1
Biofuel	0.34	0.55	0.55	0.27	0.28
Excess heat – steam	0.15	0.26	0.30	0.16	0.15
Excess heat – DH	0.04	–	–	–	0.07
Purge gas	–	0.11	–	–	–
Electricity production					
Gas turbine	0.12	–	0.03	–	–
Back-pressure ST	0.05	–	0.01	0.08	0.10
Condensing ST [b]	0.04	–	-	0.04	0.04
Electricity use	0.06	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] This is in case the excess steam is not used for heating purposes.

Table 2. 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	0.68
BLG-DME(-BB)	4.0	0.70
BLG-DME-(BMG-DME)	4.7	0.70
ALK-HF-EtOH	3.3	0.70
SE-HF-EtOH	4.6	0.70
Bark boiler (steam)	2.9	0.70
Heat water boiler (wood fuel)	2.9	0.70
Recovery boiler	2.5	0.70
Back-pressure steam turbine	1.8	0.60
Condensing steam turbine	2.9	0.60

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

The different technology cases have been dimensioned in different ways in connection to the different existing plant sites considered (see Section 3.3). Different biomass assortments give different efficiencies. For gasification there is no great influence, but for the ethanol cases this could have a quite large influence on the overall energy balance. The ethanol yield varies with the raw material and the carbohydrate (C6-sugar) content. The moisture content of the incoming biomass affect the energy needed for drying, which is done prior to gasification (of solid biomass). An average biomass composition as well as moisture content has been considered in this project (see further Sections 3.2.1-3.2.4).

3.2.1 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 a circulating fluidised bed (CFB) gasifier. 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%).

In total, there is a significant heat surplus from the BMG-DME process. This heat surplus is used to generate high pressure (HP) steam (112 bar, 540°C[5]) 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 1 is the outlet low pressure (LP) steam 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 1). There is also some heat available at lower temperatures that could be used for district heating (see Table 1).

The BMG-DME process has been considered for integration with pulp and/or paper mills having a deficit of steam, sawmills and district heating systems (see further Section 3.3).

3.2.2 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 is formed during production of kraft (sulphate) pulp. In a conventional kraft pulp mill, black liquor is fired in a recovery boiler (RB) in order to recover energy in the form of electricity and process utility steam, and pulping chemicals (see Section 3.3.1 for a description of a kraft pulp mill). Black liquor gasification is currently being developed as an alternative technology for energy and chemical recovery. In the gasification process the main part of the organic content in the black liquor is converted to a product gas and the pulping chemicals are recovered and returned to the pulping process, as for the recovery boiler case.

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,

[5] This steam data is used because it represents a future recovery boiler and the steam from the BMG-DME plant will be used in the same turbine as steam from the recovery boiler in case of integration with chemical pulp mills, see further Section 3.3.1.

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 2 shows the main energy and material flows in the BLG-DME plant.

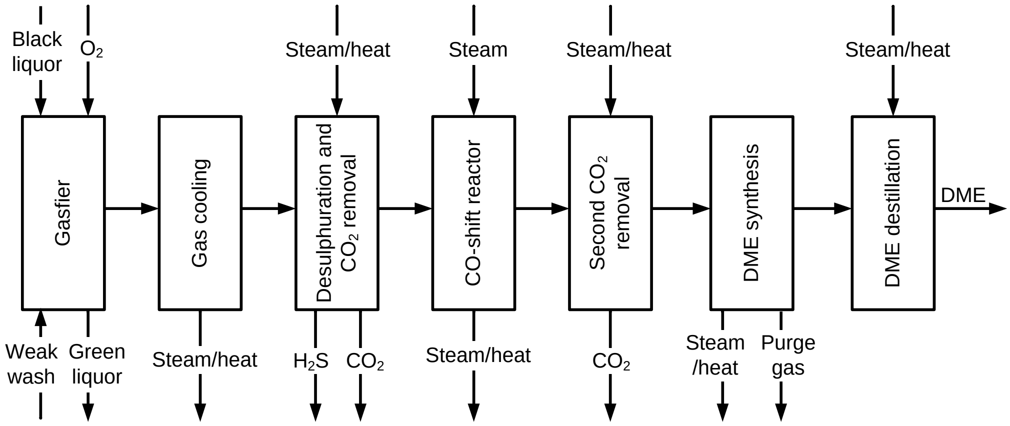


Figure 2. Main energy and material flows in the BLG-DME plant (electricity usage not included).

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 case, 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 the previous section, is used to cover the steam deficit. 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, gasified bark is used to cover the extra lime kiln load[6].

The cases based on black liquor gasification have naturally only been considered for integration with chemical pulp mills (see Section 3.3.1). In this stage of model development, only the chemical pulp mills based on kraft cooking have been included. In the sulphite process, a liquor similar to black liquor is formed which could also be used as feedstock for gasification. Due to lack of data (see Section 3.3.1), mills based on sulphite cooking have however not been included in this report.

[6] Oil is used as fuel in most lime kilns today. It could be reasonable to assume that for the time perspective assumed in this project, alternative fuels such as lignin or gasified bark will be used to cover the entire lime kiln load. This has however not been considered at this stage of model development.

3.2.3 Ethanol production with alkaline pre-treatment (ALK-HF-EtOH)

Ethanol production using SSF (simultaneous sacharation and fermentation) 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 3.

The first unit operation is the alkaline fractionation where the aim is to defibrate the raw material by degrading the lignin with hydroxide using fresh 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 from the alkaline pre-treatment is then mixed with the black liquor from the pulp mill (von Schenck et al., 2007; Berglin et al., 2009).

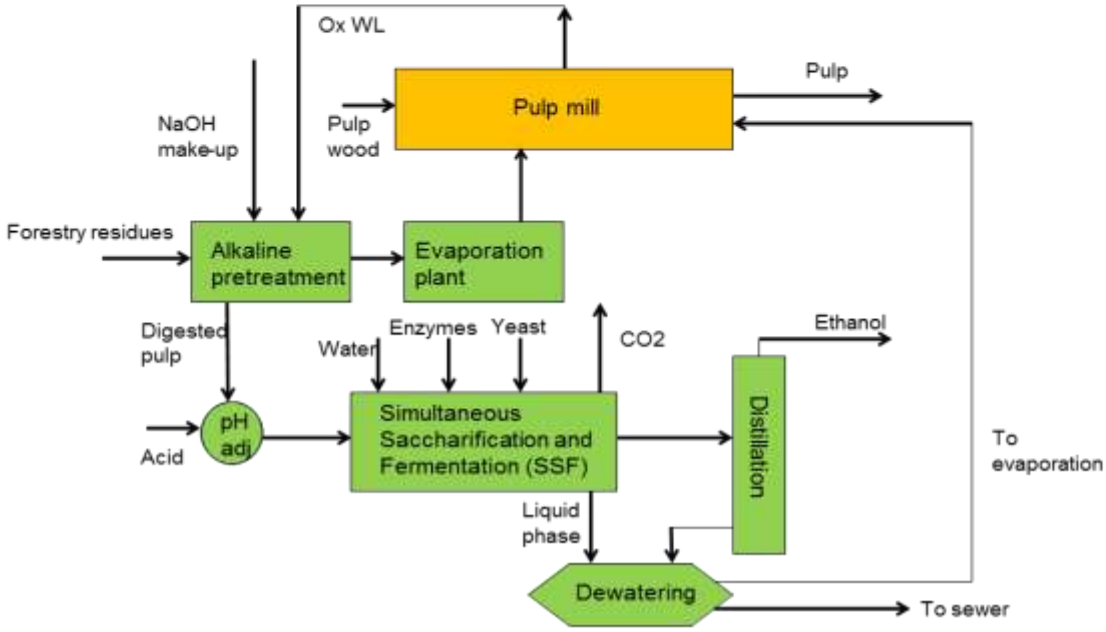


Figure 3. Process scheme of the alkaline pre-treatment concept for producing ethanol.

Since no sulphur is used in the alkaline pre-treatment, this gives an opportunity to extract sulphur free lignin from the black liquor from the ethanol production process with the LignoBoost process (Tomani P et al., 2009); this has however not been included in this work. After mixing of the black liquor it 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 (Table 2). This concept is thus most suited for integration with a mill that reduces its capacity by, for example closing one fibre line which results in free capacity in the recovery cycle. Another option is integration with a new mill, where the design for a larger recovery cycle is taken into account from the start.

The carbohydrate stream then goes to the pre-hydrolysis step where part of the cellulose is converted to glucose by the addition of enzymes. The pre-hydrolysis step is implemented in order to enable a higher WIS (Water Insoluble content) into the SSF. This is important to keep the concentration of ethanol in the distillation column at a reasonable level (normally above 4%). In the distillation, the produced ethanol is concentrated and separated from the water and other solids. Part of the concentrated stream is re-circulated back to the pre-hydrolysis step and part is mixed in with the weak black liquor, evaporated and finally burned in the recovery boiler. 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.

Several by-products from the ethanol process and delignification could be purified to give extra revenue and improve the economics of the process, such as lignin, biogas or carbon dioxide. For simplicity in this project, all lignin and solid residues have been assumed to be combusted in the mills recovery boiler to generate steam for the back-pressure steam turbine at the mill. This may not be the most beneficially 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 (given in Table 1).

Ethanol production via alkaline pre-treatment, ALK-HF-EtOH, has been considered for integration with all kraft pulp mills with a deficit of steam (see Section 3.3.1).

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

The other ethanol production process evaluated in this study begins with a steam pre-treatment procedure which is efficient on woody biomass (Wingren, 2005). Degraded materials from the pre-treatment are first 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 procedure 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. Figure 4 shows a simplified process layout of the wood-to-ethanol production process.

In the pre-treatment step sulphur dioxide and steam are used to modify the incoming raw material and by that facilitating an enzymatic reaction. The steam pre-treatment method used in this study operates with a steam pressure of 21 bars and a temperature of 215°C. LP steam (4.5 bar, 150°C) are also used in the pre-treatment step and the entire pre-treatment method is in line with what has been presented in previous studies (Wingren, 2005; Sassner, 2007). The slurry after the pre-treatment step is flash-cooled by pressure reduction before it is fed to the pre-hydrolysis and SSF steps.

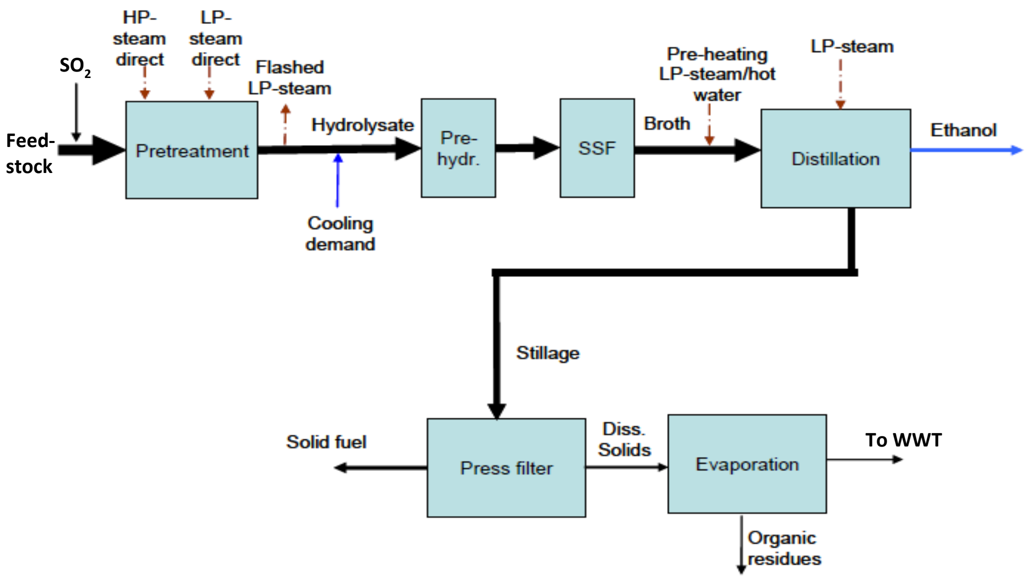


Figure 4. Process scheme of the steam explosion pre-treatment concept for producing ethanol.

In the pre-hydrolysis step part of the cellulose is converted to glucose by the addition of enzymes. The pre-hydrolysis step reduces the consistency of the material and speeds up the production of ethanol in the SSF step. The unfiltered broth from the SSF consisting of ethanol, water and solids such as lignin and yeast etc. is first preheated and then transported to a distillation procedure, which concentrates the produced ethanol and separates it from water and solids. The thin stillage contains about 3-4% dissolved solids and is evaporated and then used as a fuel.

Also for this ethanol concept, several by-products could be purified to give extra revenue and improve the economics of the process, such as lignin, biogas or carbon dioxide. For simplicity in this project, all lignin and solid residues have been assumed to be combusted in a boiler to generate steam for a back-pressure steam turbine. Some steam is used internally at the ethanol plant, but there is a significant steam surplus from the process.

The SE-HF-EtOH process has been considered for integration with pulp and/or paper mills having a deficit of steam, sawmills and district heating systems (see further Section 3.3).

3.3 INTEGRATION WITH EXISTING PLANT SITES

In total 55 potential biofuel plant sites have been included at this stage of model development (see also Figure 1). 32 pulp/paper mills have been included, of which 24 have chemical pulp production (kraft process) while eight 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 five district heating systems.

As mentioned in the introduction, oil refineries, as well as chemical process industries, could also be of interest for integration of biofuel production. This has however not been considered here, but is planned to be included in a later phase of model development (see Section 7).

3.3.1 Chemical pulp mills

The main data needed for pulp/paper mills in order to estimate the integration potential for different biofuel technologies has been calculated mainly based on data for 2010 from the environmental database of the Swedish Forest Industries Federation (SFIF) (SFIF, 2012b). All kraft pulp mills in Sweden have been included in this project, in total 24 mills. In Sweden there are also three sulphite mills. However, these mills do not currently produce any pulp/paper. Therefore, data for these mills is not included in SFIF's environmental database and they have been excluded at this stage of model development.

Figure 5 shows an overview of a conventional kraft pulp mill. After the pulp wood has been debarked and cut into wood chips, it is added to the digester where it is mixed with cooking liquor, known as white liquor, containing the cooking chemicals and water. Cellulose fibres in the wood chips are then separated from lignin (which acts as a glue between the fibres) because lignin reacts with the chemicals in the white liquor. The chemicals and lignin form a liquor called black liquor. The liquor also contains other substances, mainly hemicellulose. The fibres are separated from the black liquor in a washing step and are then screened and possibly bleached before pulp is obtained. The pulp is either dried and transported to a paper mill (this is called a market pulp mill), or processed further to paper at the mill (called an integrated pulp and paper mill).

The black liquor, which contains large amounts of water, is evaporated before it is burned in a special boiler, called a recovery boiler. In the recovery boiler, combustion of the organic compounds releases heat that is used for production of steam. The remainder of the liquor can be found at the bottom of the boiler in the form of a smelt. The smelt is dissolved to form green liquor, which is sent to the chemical preparation where white liquor for the digester is produced. Thus, the recovery boiler functions both as an energy and chemical recovery unit. In the lime kiln, which is part of the white liquor preparation, fuel oil and natural gas are the most commonly used fuels today.

The steam produced in the recovery boiler is used in a back-pressure steam turbine for electricity generation. The steam is then used to satisfy the heating requirements in the pulping process, such as in the digestion, evaporation and drying stages. In cases where the steam from the recovery boiler is not sufficient to satisfy the mill steam demand, an additional boiler (in this report called bark boiler, BB), is used to produce steam for the back-pressure turbine. The fuel in this boiler is often bark from the debarking of the logs, possibly supplemented by purchased forest residues and/or fuel oil. A surplus of steam can also occur, that is, more steam is produced by the recovery boiler than is needed at the mill. This steam could for example be used to produce additional electricity in a condensing steam turbine (as illustrated in the figure) or it enables extraction of lignin from the black liquor.

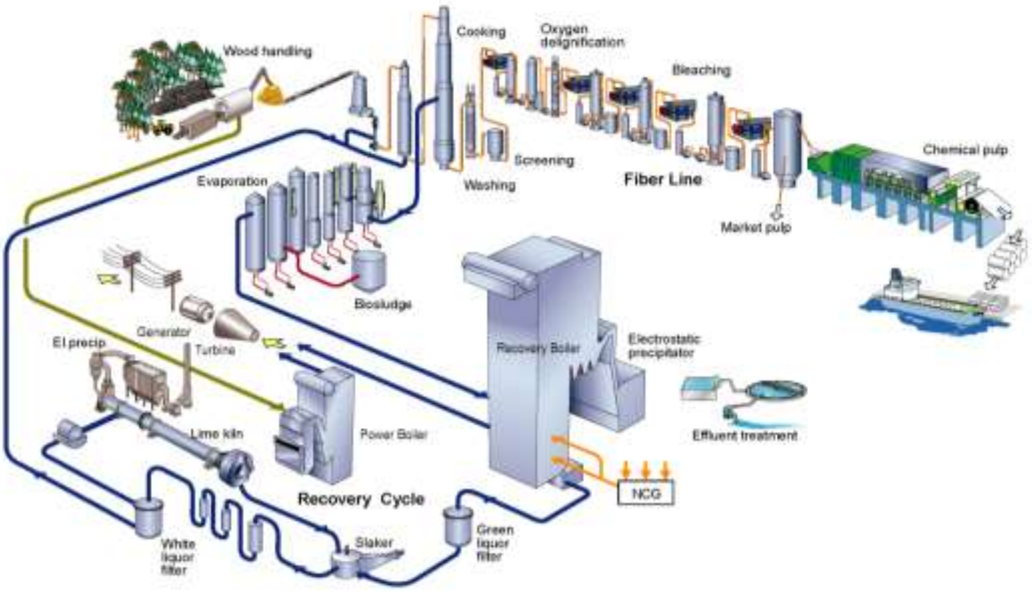


Figure 5. Overview of a conventional kraft pulp mill © 2008 Kvaerner Pulping (Pettersson et al., 2012).

Data, such as usage of pulp wood, generation of black liquor and falling bark, steam usage and wood fuel usage, needed for each mill in order to estimate the plant size for the different biofuel technology cases and the consequences of integration with chemical pulp mills can be found in Appendix C. Different data is necessary for the different technology cases since they are not dimensioned using the same criteria. Appendix C also includes a description regarding how the data is estimated.

With our knowledge about pulp and paper mills in general and some specific knowledge about certain mills, it has been concluded that some of the data estimated is 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 has been shown to not be the case for several of the mills. We believe that the main reasons for this are (1) errors in the data reported to the SFIF's environmental database (2) that different heating values have been used for the same fuel by different mills when reporting to the SFIF's environmental database. See Appendix C for more detailed discussions about this. In the next phase of model development, further investigations in order to get better estimations of mill data, required in order to estimate the biomass demand and supply and to estimate the plant size for the different technology cases and the consequences of integration with different mills, will be conducted.

BMG-DME 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 steam deficit at the mill. 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 BMG-DME plant in order to cover their steam deficit. Therefore, the incremental investment cost, as well as operating and maintenance cost, for the BMG-DME plant compared to investing in a new bark boiler has been used in the model[7]. It has been assumed that both for the BMG-DME case 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 the excess heat at district heating temperature level is not used.

The BLG-DME cases are naturally sized after the flow of black liquor. It has been assumed that the mills are in a situation where they are going to replace their recovery boiler and they have the choice between investing in a new recovery boiler or a BLG-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[7]. 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. Purge gas is used as fuel in the bark boiler together with bark and other wood fuel (purge gas is also used as fuel in the lime kiln, as was discussed in Section 3.2.2). For the BLG-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.

Ethanol production via alkaline pre-treatment, ALK-HF-EtOH, has been considered for integration with all kraft pulp mills with a steam deficit. 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 ethanol production capacities are all in a commercially acceptable range and the biomass amount should be possible to handle for all mills. As described in Section 3.2.3, there is a steam surplus from the ethanol plant that can be used in the mill processes. Thereby, the usage of wood fuel in the bark boiler can be reduced.

The steam explosion concept, SE-HF-EtOH, has also been considered for integration with all pulp and/or paper mills with a deficit of steam, with the plants sized so the excess steam would correspond to the deficit of steam at the mill, similar to the BMG-DME case, thereby replacing the bark boiler at the mill. Similar to the gasification cases, it is therefore the incremental costs that have been considered[7]. SE-HF-EtOH has also been considered for integration with sawmills and district heating systems. As in the BMG-DME case, when integrating with pulp and/or paper mills the excess heat at district heating temperature level has not been assumed to be used.

3.3.2 Mechanical pulp mills and paper mills

Six mechanical pulp mills have been included at this stage of model development. They have been selected based on the criteria that the steam use should be more than 25 MW. Two paper mills are also included based on the same criteria. This was done in order to get reasonable sizes of the biofuel plants when sized according to steam demand. As discussed, pulp mills are not just interesting because of opportunities for heat integration. Their experience and know-how concerning handling of large biomass resources is another important advantage. Thus, one can consider integration without sizing exactly according to steam use and it would therefore be interesting to include all mechanical pulp and paper

[7] A sensitivity analysis has been made with respect to this, see Section 4.2.2

mills as potential biofuel plant sites. This will be done in a later phase of model development.

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 can be found in Appendix C. The appendix also includes a description regarding how the data has been 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. This steam use/deficit is covered in the same way as for chemical pulp mills using mainly bark and other wood fuels. 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. The same assumptions as for integration with chemical pulp mills are assumed for BMG-DME plants and for the ethanol concepts.

3.3.3 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 sawmill in order to estimate the plant sizes for the different biofuel technology cases and the consequences of integration can be found in Appendix C. A description regarding how the data is estimated is also included in Appendix C.

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 too small sizes of the biofuel plants for them to be relevant.

For the BMG-DME and ethanol cases, excess heat at district heating temperature levels has been assumed to be used to cover the heat use 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). 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. The excess steam has been assumed used in a condensing steam turbine.

3.3.4 District heating systems

Five district heating systems have been considered as potential plant sites. The systems have been chosen based mainly on knowledge generated in previous research projects studying biofuel production integrated with district heating. For each system a load duration curve has been generated based on production statistics and previous research. For each system assumptions have been made regarding available heat load and where in the dispatch order a biofuel plant would be placed. For example, existing waste incineration and existing industrial excess heat have in general been assumed to constitute base production also after the introduction of biofuel plants. The available heat load has been chosen such that biofuel plants integrated with district heating would get the same annual operating time as plants integrated with industry.

BMG-DME and SE-HF-EtOH have been considered for integration with district heating systems. They have been dimensioned according to the available heat load for new plants. All excess heat has been assumed used for district heating production. It has also been assumed that the energy company will invest either in a new CHP plant or in a biofuel plant. Thus, the investment cost, as well as O&M costs, are the incremental costs compared to investing in a new biomass CHP plant.

3.4 BIOMASS SUPPLY

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 originating from the forest has been considered, divided into six different assortments:

- Sawlogs
- Pulp wood
- Branches and tops (*grot*)
- Stumps
- Wood chips (industrial by-product)
- Bark, saw dust and other low grade industrial by-products

Available quantities and costs are given for each assortment, for each grid cell. For this report, the assumed biomass availability has been based on current conditions in the Swedish forestry and forest industry. Table 3 summarises the biomass potentials from the forest and from the forest industry, as used in this report, with descriptions given in the following sections.

Table 3. Annual volumes of biomass as used in BeWhere (converted to TWh), and the corresponding reported volumes from statistics for 2010. Protected forest land has been excluded.

	BeWhere input data		Statistics[a]	
	[million m^3]	[TWh]	[million m^3]	[TWh]
Pulp wood	29	58	31	
Sawlogs	36	71	36	
Branches and tops (final felling)	8.0	19		~5[b]
Stumps	4.6	10		~0[b]
Sawmill wood chips	12	23	12	
of which surplus[c]		15		
Sawmill bark, saw dust and others	8.8		9.3	
of which surplus[c]		8.7		
Pulp mill surplus[c]		2.0		

[a] Brännlund et al. (2010), Swedish Forest Agency (2011).
[b] Only includes current use, which is significantly lower than the potential. See Appendix D.
[c] Surplus after internal use has been deducted.

3.4.1 Forest biomass

The current availability of forest biomass for biofuel production has been estimated based on forest areas and statistics regarding annual growth and felling. IIASA's Global Forest Model (G4M) was used to estimate the forest cover and share of different tree species (pine, spruce and birch, respectively) for each grid cell (for a description, see (Kindermann et al., 2013)). From the Swedish Statistical Yearbook of Forestry (Swedish Forest Agency, 2011) county specific figures for mean annual volume increment and annual felling in relation to growth, were applied to the forest area data, to give the potential annual gross felling in each grid cell. Land that is currently formally protected from forestry (national parks, nature reserves, habitat protection areas and conservation agreements) was excluded.

The potential for harvesting of branches and tops and of stumps, as used in this report, has been estimated from the final felling potential. Forest residues from thinning have not been accounted for. For branches and tops a yield of 0.11 m^3 per m^3 felled logs was used (Thuresson, 2010), and for stumps the potential was assumed to correspond to 58% of the potential for branches and tops (Lehtonen et al., 2010). For both assortments this corresponds to an increase compared to current residue removals, but is still low compared to the total potential (see Appendix D).

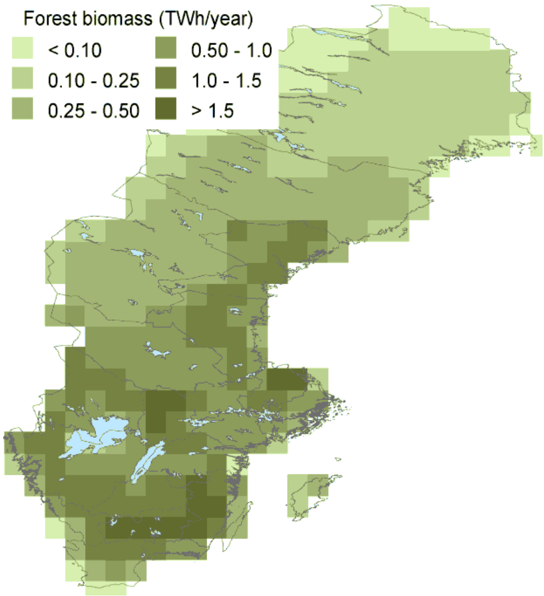
Figure 6 shows the resulting modelled geographical distribution of forest biomass, when adapted to the model grid.

3.4.2 Industrial by-products

Industrial biomass by-products from sawmills and pulp and paper mills have been estimated from production statistics. Sawmill by-products are today used for internal energy supply, pulp production (sawmill wood chips), particle and fibre board production and in the energy sector. Data for mill specific production volumes of sawn wood was obtained from the member register of the SFIF (SFIF, 2012a). The combined reported production of all SFIF mills amounts to 15 million m^3sw/year (m^3 sawn wood), which can be compared to the aggregated reported production for 2010 of 17 million m^3 sawn wood (Swedish Forest Agency, 2011).

From the production volumes, by-product amounts were estimated using reported factors from Danielsson (2003). Pulp and paper mills use the main parts of their by-products to meet internal energy demand but certain mills (mainly market chemical pulp mills) have a surplus of bioenergy, in particular bark, which is mainly sold for energy purposes. Mill specific numbers on the size of this surplus were estimated based on information from the SFIF's environmental database 2010, with the total surplus from all mills calculated to 2.0 TWh/year (see also Appendix C).

Figure 6 shows the geographical distribution of forest industry by-products, when adapted to the model grid.



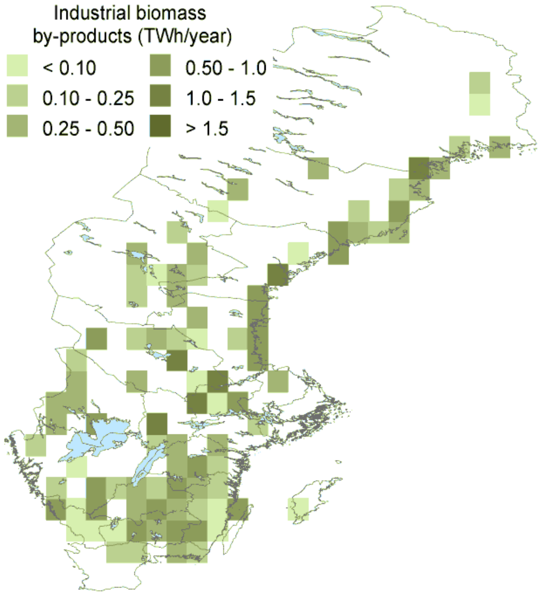


Figure 6. Geographical distribution of forest biomass (left) and industrial by-products (right), as used in BeWhere.

3.5 BIOMASS DEMAND

Biomass demands in the forest industry and in the district heating sector are considered explicitly in the model and must be met. The demands have at this stage of model development been described statically, based on current production and demand. In the model, pulp wood, sawlogs and industrial wood chips can be used to meet the wood demand in pulp mills and all feedstock types except sawlogs can be used for energy purposes, including new biofuel production plants.

Table 4 summarises the biomass demand as used in this report, with a description in the following sections.

Table 4. Annual biomass demand as used in BeWhere (converted to TWh), and the corresponding reported volumes from statistics for 2010.

	BeWhere input data		Statistics[a]	
	[million m^3]	[TWh]	[million m^3]	[TWh]
Pulp industry	46	92	45	
of which import[b]	5	10	5	
Sawmill industry	32	63	34	
District heating		32		28-38
New CHP plants		3.2		

[a] Swedish Forest Agency (2011), Swedish District Heating Association (2012).
[b] Imported pulp wood has been assumed to be used evenly in all mills and thus been subtracted from the total pulp wood demand. See also Section 3.8.

3.5.1 Forest industry

For sawmills the reported production for each SFIF mill (mentioned in the previous section) and general wood demand ratios were used to estimate the total annual demand of logs, to 32 million m^3. This can be compared to the 34 million m^3 reported in statistics (Swedish Forest Agency, 2011).

The SFIF's environmental database 2010 was used as basis for the pulp production, complemented by information from websites and annual reports where necessary. The accumulated calculated pulp production amounts to 12,000 ktonnes/year, which is in line with the 11,900 ktonnes/year reported in statistics (SDC, 2011; Swedish Forest Agency, 2011). The pulp production volumes were used to estimate the pulp wood demand for each mill, based on general wood demand ratios (Swedish Forest Agency, 2011). The total pulp wood demand in all pulp mills was calculated to 46 million m^3, which is well in line with the reported wood use of 45 million m^3 (SDC, 2011; Swedish Forest Agency, 2011).

The demand for bioenergy in pulp and paper production, excluding black liquor and internal bark, was estimated based on the SFIF's environmental database (see Appendix C).

Figure 7 shows the modelled geographical distribution of wood and bioenergy demand in the forest industry, when adapted to the model grid. The figure also shows the location of all considered sawmills and pulp and paper mills, with those included as potential plant sites marked. Since biomass supply as well as different bioenergy demands are given in TWh, the wood demands for sawmills and pulp production have also been converted to TWh.

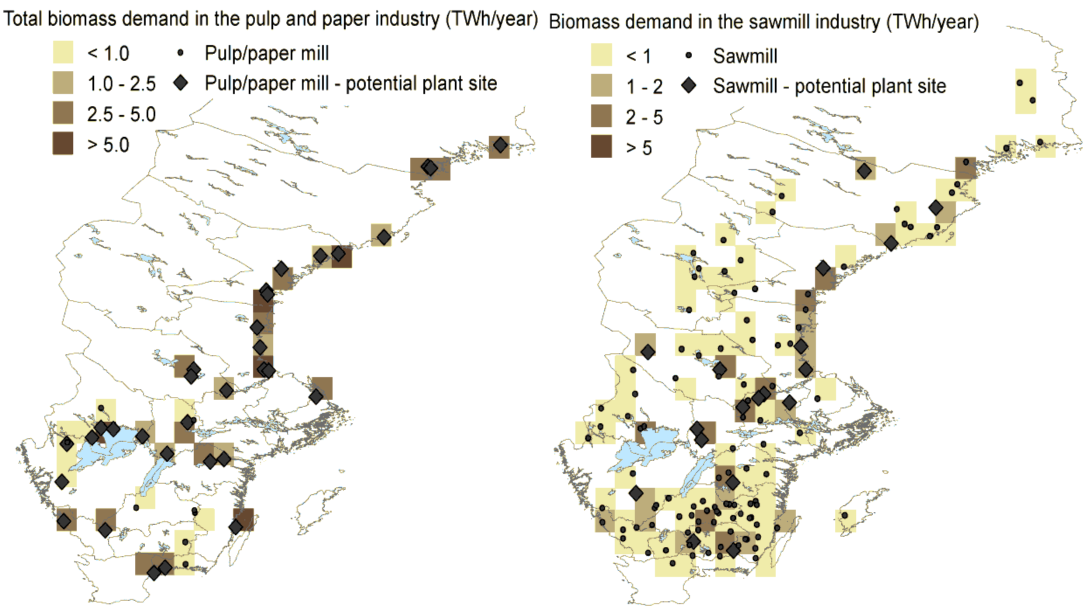


Figure 7. Biomass demand (logs and energy, adapted to the model grid) in the pulp and paper industry (left) and in the sawmill industry (right). Industries marked with a diamond have been considered explicitly as potential sites for new biofuel production plants.

3.5.2 District heating

The demand for bioenergy for district heating has been based mainly on statistics from the Swedish District Heating Association (2012). The statistics encompass over 450 district heating networks, of which around 270 utilise forest bioenergy as fuel. The bioenergy demand has been estimated from reported fuel use for 2009 and 2010, in order to account for differences in annual heat demand and in reporting methodologies. When the discrepancies have been large, statistics from 2008 have also been surveyed. The total demand for biomass for district heating (including fuel for electricity production) was calculated to 32 TWh/year, of which 6 TWh/year consists of refined wood fuel, such as pellets. This can be compared to actual use of 28 TWh in 2009 and 38 TWh in 2010[8] (Swedish Energy Agency, 2011a). In addition to existing bioenergy use in the district heating systems, bioenergy facilities planned to be taken into operation before 2014 have also been considered (Svebio, 2011). These plants account for another 3.2 TWh bioenergy.

Figure 8 shows the modelled geographical distribution of forest biomass demand in the district heating sector, as well as the location of all considered district heating systems.

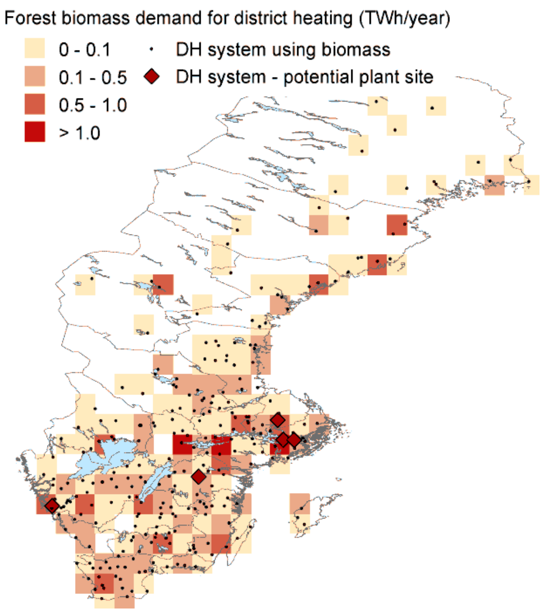


Figure 8. Forest biomass demand in the district heating sector (adapted to the model grid). Systems marked with a diamond have been considered explicitly as potential sites for new biofuel production plants.

3.5.3 Other sectors

The annual use of biomass (firewood) in smaller houses and agricultural properties amounts to around 12 TWh, of which a quarter is currently met by pellets (Swedish Forest Agency, 2011). This demand has not been regarded in the model but assumed to be satisfied by assortments not considered here.

The demand for biomass in the wood panel industry has declined steadily over the past 30 years and was in 2010 less than 1 million m^3/year (round wood and sawmill by-products) (Swedish Forest Agency, 2011). This demand has not been regarded in this study.

The use of biomass in other industry sectors is currently low. Wood could be used in for example the iron and steel industry to reduce fossil CO_2 emissions, or in the chemical industry as raw material. The potential to consider future demand from new industry sectors has been implemented in the model, but with the demand currently set to zero. This is discussed further in Chapter 5 where scenarios for 2030 are described.

[8] 2010 was an unusually cold year.

3.6 TRANSPORT FUEL DEMAND

The total energy use in road transport in 2010 amounted to 88 TWh, which has been used as a basis for the modelled transport fuel demand (Swedish Energy Agency, 2011b; Statistics Sweden, 2013b). The geographical distribution of the transport fuel demand was assumed to be proportional to the population, and thus the total fuel demand per county was downscaled based on grid cell population. The demand per capita was assumed equal in all cells of each county. Population per county was in turn obtained from Statistics Sweden and downscaled to the model grid based on data from CIESIN (2011). The total population in 2010 was 9.42 million people.

Figure 9 shows the resulting transport fuel demand, as modelled in BeWhere. County specific populations and transport fuel demands are given in Table E- 1 and Table E- 2 in Appendix E.

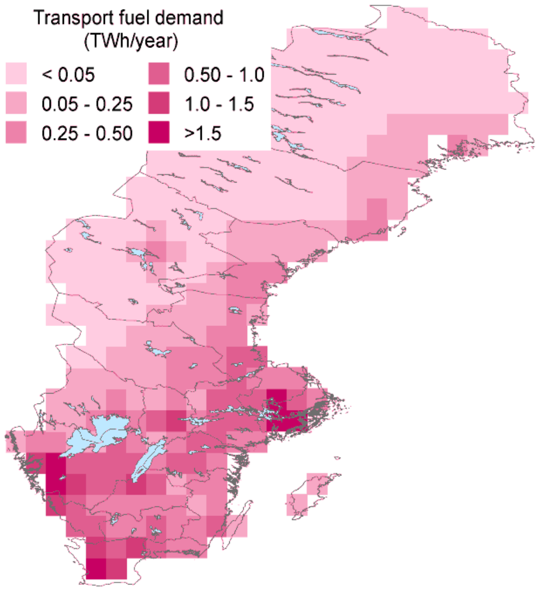


Figure 9. Modelled geographical distribution of total fuel demand in road transport (2010).

In the model 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). For the preliminary model runs in this report different biofuel targets have been analysed.

Future demand for energy in transport, including biofuels, is discussed in Chapter 5.

3.7 DEMAND FOR AND PRODUCTION OF OTHER ENERGY CARRIERS

Demand for other energy carriers has not been modelled explicitly, except when affected by the biofuel production plants.

Surplus co-produced electricity has been assumed possible to sell to the grid, without restrictions. For plants integrated with an industry, co-produced heat has been assumed possible to use in the industrial process, as has been described in Section 3.3. For plants integrated with a district heating system, co-produced heat has been assumed to replace alternative heat production. This heat production has for each district heating system been estimated based on the existing heat mix with an assumed new CHP plant (see Section 3.3.4).

Also other energy carriers, such as coal, oil and natural gas, that could be affected by new biofuel production plants can be included in the model. However, since none of the industries considered in this report use any significant amounts of those energy carriers they have not been included here.

3.8 IMPORT AND EXPORT

The option to import or export biomass or biofuels has been included in the model. Import and export can be done by ship at harbours or by truck at a selection of road points, as shown in Figure 1. For every trade point the goods possible to trade are defined by a trade limit (import and/or export) as well as the price associated with the trade.

At this stage of model development import and export have not been explicitly considered. The 6.3 million m^3 logs (of which 90% pulp wood) that were imported in 2010 (Swedish Forest Agency, 2011) have been excluded from the total wood demand, i.e. all mill have been assumed to use an equal share of imported wood.

3.9 TRANSPORTATION 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.

At this stage of model development a simplified transport cost model has been applied, with linear cost functions for all transport means. Transport cost functions of different biomass feedstocks using truck and train have been obtained from Johansson and Mortazavi (2011), and converted to cost per GWh instead of per tonne. The transport cost of biomass using ship was adapted from Börjesson and Gustavsson (1996) to give a similar relation between the different transportation means. Transport cost functions for biofuels were also modified from Börjesson and Gustavsson, in order to reflect biofuel transport costs estimations from other sources, e.g. (Börjesson and Ahlgren, 2012).

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 to 0.87 EUR/MWh, which was here assumed equivalent for dispensing ethanol. For DME the cost was assumed to be 20% higher.

Table 5 presents the transport and dispensing costs applied for feedstocks and biofuels.

Table 5. Transport costs [EUR/GWh] for feedstocks and biofuels, as well as dispensing costs for biofuels [EUR/GWh]. d is the transport distance in km.

Energy carrier	Truck	Train	Ship	Biofuel disp.
Pulp wood, saw logs[a]	2,160 + 59.0*d*	4,650 + 7.57*d*	6,470 + 3.42*d*	–
Branches and tops[a]	3,140 + 79.9*d*	5,580 + 9.09*d*	6,470 + 3.42*d*	–
Stumps[a]	3,420 + 76.6*d*	4,650 + 7.57*d*	6,470 + 3.42*d*	–
Industrial by-products[a]	1,770 + 44.8*d*	4,650 + 7.57*d*	6,470 + 3.42*d*	–
DME[b]	940 + 20.8*d*	2,890 + 4.5*d*	3,160 + 1.01*d*	1,040
Ethanol[b]	832 + 18.4*d*	2,550 + 3.98*d*	2,790 + 0.89*d*	868

[a] Adapted from (Johansson and Mortazavi, 2011) for truck and train and from (Börjesson and Gustavsson, 1996) for ship

[b] Transport costs based on (Börjesson and Gustavsson, 1996; Börjesson and Ahlgren, 2012). Dispensing costs based on (Leduc, 2009).

3.10 ENERGY PRICES AND COSTS

3.10.1 Biomass

The harvesting of forest resources is a series of operations that are relatively straightforward and does not require exceedingly complex procedures. Therefore, the harvesting is technically feasible in a wide range of production configurations, including manual chain-saw fellings as well as sophisticated, high-volume mechanised fellings. Along with the set of feasible technical configurations, the per-unit harvesting production cost also varies. This section summarises the methodology followed to estimate the harvesting costs for various types of forest biomass. A full description is given in Appendix A.

Following the economic-engineering approach in estimating the cost structure for each type of forest resource, three procedural steps have been followed. These steps include: (1) a description of the used harvesting system, including a specification of alternative techniques that are technically feasible; (2) estimation of the productivity functions for each stage of the harvesting process, and accumulation of the productivity functions into a production function and; (3) calculation of the harvesting cost functions by applying input factor prices. Thus, the harvesting costs for each forest resource were calculated from the combination of estimated productivity functions and average input factor prices.

Standard economic cost procedures were used to calculate the total cost functions, including a long term fixed cost component and variable operating cost. The cost functions represent the underlying cost structure and emphasise the importance of geography (terrain), type of forest resource, technology and the management regime on the competitiveness of the industry sectors using forest resources as a feedstock.

Forest residue chipping may take place at the source, at the road-side or landing (at a terminal) or at the plant where the chips are to be used. Road-side chippers do not operate off-road and can therefore be heavier, stronger and more efficient than terrain chippers. Therefore, the production of forest residues was assumed to be chipped at road-side.

To the grid cell specific forest harvesting costs, expenditure and handling costs from forest to end-user have been added (Johansson and Mortazavi, 2011; Skogforsk, 2012). For pulp wood used for energy purposes or for biofuel production an additional chipping cost was also added. Bioenergy and stemwood price statistics for 2010 (Swedish Forest Agency, 2011; Swedish Energy Agency, 2012b) were used to calculate calibration factors (region specific) in order to be able to estimate the resulting biomass costs for the biofuel production plants. Table 6 summarises the average biomass costs used in this report (excluding transport costs).

Table 6. Biomass costs (excluding transport costs, see Section 3.9) for use for energy purposes and in the forest industry, as used in this report [EUR/MWh]. Note that biomass costs are expressed grid cell specifically in the model. The numbers presented here are average values.

	Energy use (biofuel production, district heating, industry)	Forest industry use (pulp and paper production, sawmills)
Pulp wood	19	16
Sawlogs	27	–
Branches and tops (final felling)	14	–
Stumps	19	–
Sawmill wood chips	13	13
Sawmill bark, saw dust and others	13	–

3.10.2 Transport fuels and other energy carriers

The model allows for county specific declaration of energy costs and prices. Here average energy prices for the entire country have been used, with 2010 as base year.

It has been assumed that all produced electricity is sold and generates revenue for the sold electricity. When applicable, sold electricity also generates revenue from a policy instrument incentive scheme promoting production of green electricity (see Section 3.12). Consumed electricity is purchased for the price of non-green electricity. Average electricity spot prices have been used here.

For district heating system specific prices, based on the current heat production have been used. It has been assumed possible to sell heat at 50% of the reported consumer prices in 2010 (EKAN-gruppen, 2010). In future work the pricing of district heating will be refined to also consider the alternative investment in new CHP.

For transport fuels, average pump prices for petrol and diesel have been used. Pricing of produced biofuels has been assumed to be done so the end consumer gets the same cost as when using fossil fuels. The prices are given in Table 7.

Table 7. Energy prices used for this report [EUR/MWh].

Transport fuel[a]	Electricity[b]	District heating[c]
110 (55)	47	29-34

[a] Average petrol and diesel pump prices for the year 2010 (SPI, 2013). Price excluding taxes in parentheses.
[b] Average spot prices in Sweden for the years 2009-2011 (Nord Pool, 2012). Includes taxes.
[c] District heating system specific prices (2010) (EKAN-gruppen, 2010).

3.11 CO_2 EMISSIONS

The cost of emitting fossil CO_2 is internalised in the model by including the possibility to apply a CO_2 cost, representing for example a CO_2 tax or tradable emission permits, to the various emissions of the supply chain. For each emission source a separate CO_2 cost can be set, to represent differences in how CO_2 emissions are valued in different sectors. Emissions from transportation of biomass and biofuel are included, as are emissions from used or produced energy carriers (including offset emissions from displaced fossil energy carriers). CO_2 emissions from the use of biomass can also be considered, to be able to include indirect effects. In this report, however, CO_2 emissions from the use of biomass are not considered.

For electricity, it has in this report been assumed that a net surplus or deficit affects the marginal electricity production. A European perspective on the electricity market has been adopted, assuming coal condense power as marginal production. In future work assumptions regarding the assumed reference system can be further analysed, e.g. employing CO_2 factors of various average electricity mixes.

Emission factors used in this report are given in Table 8.

Table 8. CO_2 emissions from transportation of feedstocks and biofuels and from energy use.

	Use[a]	Transport emissions [g CO_2/MWh,km][b]		
Energy carrier	[kg CO_2/MWh]	Truck	Train	Ship
Pulp wood, saw logs	0	20.2	10.3	5.3
Branches and tops, stumps	0	29.4	12.4	5.3
Industrial by-products	0	20.2	10.3	5.3
DME	0	7.16	3.65	1.88
Ethanol	0	6.51	3.32	1.71
Fossil transport fuels[c]	282	–	–	–
Electricity[d]	723	–	–	–
District heating[e]	system specific	–	–	–

[a] Emissions related to energy use, including offset emissions from displaced fossil energy carriers.
[b] Adapted from (European Commission, 2010).
[c] Biofuels are assumed to replace fossil fuels on a 1:1 energy ratio. CO_2 emission factor concerns average of petrol and diesel (Gode et al., 2011).
[d] Assuming European electricity market with coal condense power as marginal electricity (Axelsson and Harvey, 2010).
[e] Depends on the heat production mix of the respective district heating system. Changes in CHP production are also considered, which means that the emission factor for electricity influences the emissions for displaced heat.

3.12 POLICY INSTRUMENTS

BeWhere Sweden includes the possibility to apply various economic policy instruments to the studied system. Currently three different instruments have been included – green electricity certificates, CO_2 emission charge and biofuel policy support.

The CO_2 emission charge encompasses both taxes and tradable emission permits (European Union Emissions Trading System, EU ETS). The EU ETS covers companies in energy-intensive industries as well as producers of electricity and heat and embraces all combustion plants larger than 20 MW. Sweden has also included combustion plants smaller than 20 MW output that supply heat to district heating networks. Sweden also applies a CO_2 tax on fossil fuels, based on the emitted amount of CO_2 per used unit of fuel. Reductions or exemption from the CO_2 tax apply to sectors covered by the EU ETS, as well as to electricity and CHP production.

The electricity certificate system is a policy instrument incentive scheme promoting production of green electricity, which was introduced in Sweden in 2003. Electricity producers receive one certificate per MWh produced electricity from approved renewable sources[9]. The certificates are traded between the suppliers and consumers. A quota obligation for consumers creates a demand for the certificates and thus provides them with an economic value. New renewable electricity suppliers receive certificates for the first 15 years of operation. Biomass-based electricity currently makes up the largest part (over 60%) of the total renewable electricity production entitled to certificates. In this report all new sold green electricity is assumed entitled to electricity certificates.

Sweden applies a number of policy measures intended to encourage a shift towards a more sustainable transport sector. Biofuels for transport are currently exempt from energy and CO_2 taxes, if they meet the sustainability criteria for biobased motor fuels. Two of the sustainability criteria are that the fuels should lead to a reduction in greenhouse gas emissions by at least 35% compared with the use of fossil fuels, and that certain uses of land for the production of the fuels are not permitted. In this report produced biofuels are considered exempt from energy as well as CO_2 tax.

Table 9 summarises the policy instruments used in this report.

Table 9. Economic policy instruments used in this report. Average for 2010.

Policy instrument	Value
Green electricity certificates	25 EUR/MWh
CO_2 tax fossil transport fuels	114 EUR/tonne CO_2 30 EUR/MWh
Energy tax fossil transport fuels	25 EUR/MWh

[9] Wind energy, solar energy, geothermal energy, wave energy, certain types of bioenergy, and certain types of hydropower.

4 PRELIMINARY MODEL RUNS

For this report a number of preliminary model runs have been performed. The runs have been based on the input data presented in Chapter 3. In principle the model has been run with a future perspective on biofuel production technologies, but using today's prices, costs, biomass supply and biomass demands with 2010 as base year. As has been described, mainly incremental investment costs have been used, i.e. it has been assumed that the investment in biofuel production is done instead of investment in alternative technology.

The main purposes of the model runs performed for this report are to identify factors with high impact on the results, and to detect areas in need of further development and refinement concerning model and input data. In the next stage of the project, model runs will be performed using the scenarios for 2030 which are presented in Section 5.

4.1 TESTED CASES

The model runs have to a large extent been performed using an exploratory approach, where the results from one set of runs have been used to devise the net set of runs. The model has been run in each of the three different basic modes described in Section 2.1:

1. *Fixed demand* – a fixed next generation biofuel demand is defined, which must be fulfilled
2. *No fixed demand* – the amount of biofuel is determined by the model (which minimises the total system cost) based on boundary conditions, such as energy costs and prices
3. *Fixed plants* – a fixed target of the number of new biofuel production facilities that must be included in the solution is defined, with no biofuel target set

4.2 GEOGRAPHICAL RESULTS

4.2.1 Fixed demand

In the *Fixed demand* mode the model was run for targets for next generation biofuel ranging from 1 to 10 TWh[10] (corresponding to approximately 1.1 to 11% of the total road transport energy demand). Figure 10 shows the results for a biofuel demand of 2, 4 and 6 TWh, respectively. The figure shows the optimal plant positions and biofuel production technologies, biofuel production per plant, site type, where the biomass used for biofuel production originates and where the produced biofuel is used.

[10] When necessary, the assumed availability of biomass (branches and tops and stumps) was increased compared to the levels discussed in Section 3.4, in order to be able to meet high biofuel demands.

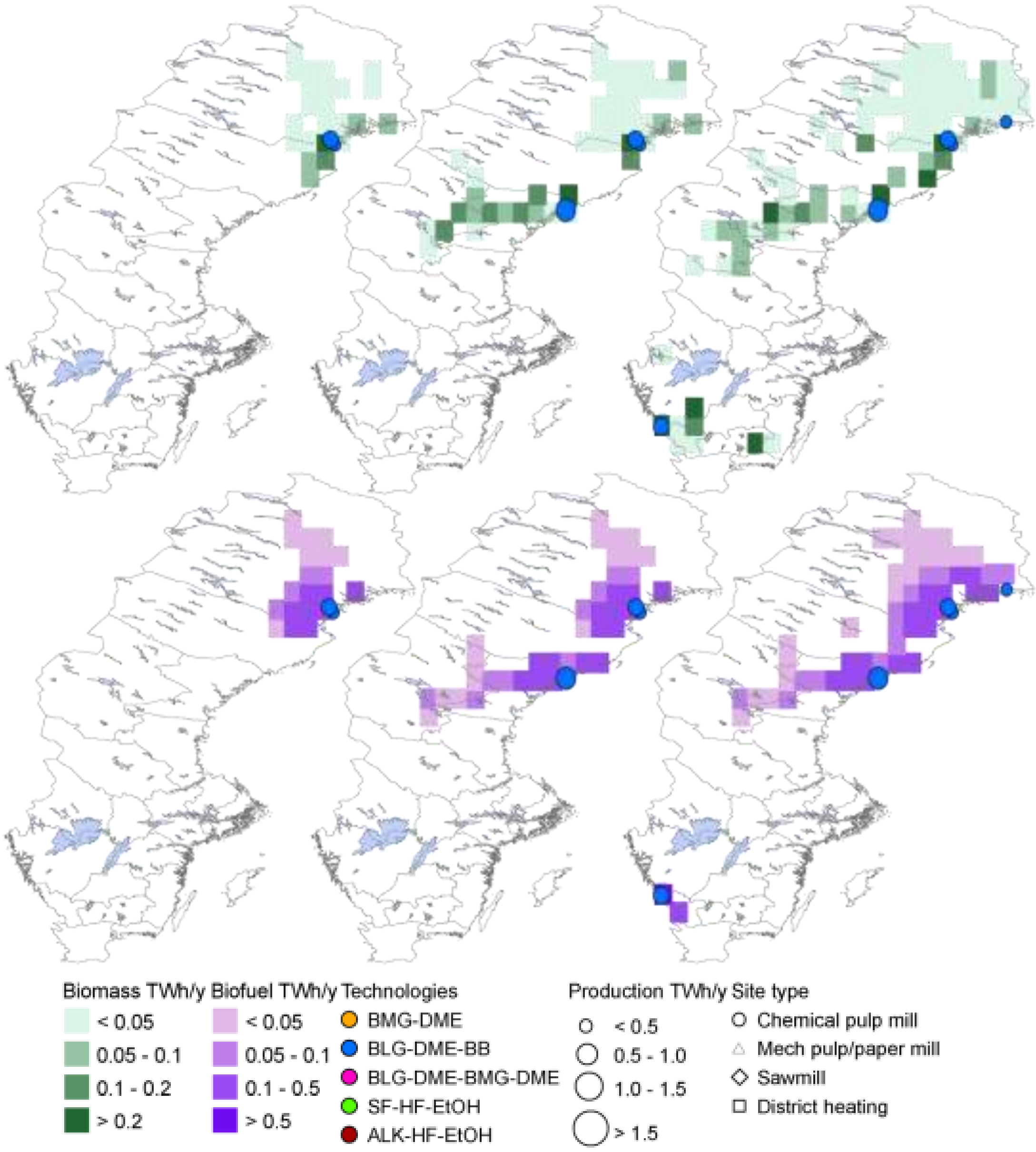


Figure 10. Results for fixed biofuel demand of 2 TWh (left), 4 TWh (centre) and 6 TWh (right).

As can be seen, BLG-DME-BB (black liquor gasification with DME production and bark boiler) is the preferred technology, with the same mills as the optimal positions in all three cases, but with addition of more plants at higher demands levels. For BLG, the needed input of additional biomass to the mills in relation to produced biofuel is low compared to the other technologies (see Appendix C). Thus, the required harvesting area for each plant is small and the average biomass transport distance moderate (100-140 km). Since the regions surrounding the optimal plant positions are sparsely populated the produced biofuel must be transported some distance (80-100 km on average).

Figure 11 shows the same three biofuel target cases, but with black liquor gasification excluded as investment options.

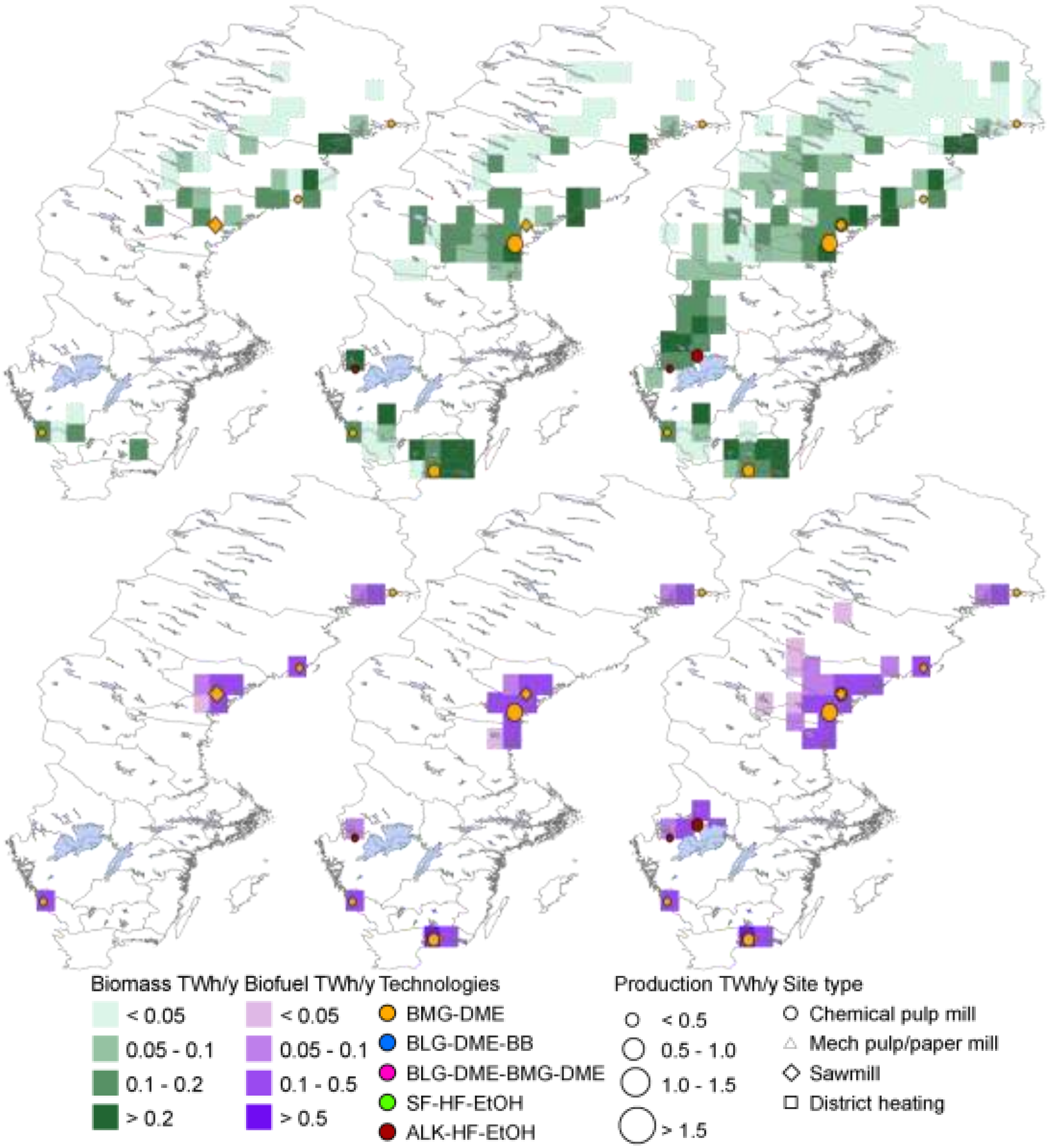


Figure 11. Results for fixed biofuel demand of 2 TWh (left), 4 TWh (centre) and 6 TWh (right) when BLG is excluded as investment option.

When BLG is not considered, BMG-DME (solid biomass gasification with DME production) is the prioritised technology. More plants are needed to meet the same biofuel demand, due to generally smaller plant sizes for non-BLG technologies (see Appendix C). Since the non-BLG biofuel technologies included in this report all have relatively low biomass-to-biofuel efficiency (see Table 1), the needed number of plants and the required amount of biomass increase significantly when BLG is not considered. Figure 15 shows the biomass used for biofuel production as function of produced biofuel, when BLG is considered as well as when BLG is not considered. As can be seen, the total biomass demand is about twice as high when BLG is excluded.

Without BLG the average biomass transport distances also increase, to 130-160 km. On the other hand, the larger dispersion of production plants gives shorter biofuel transport distances (25-45 km).

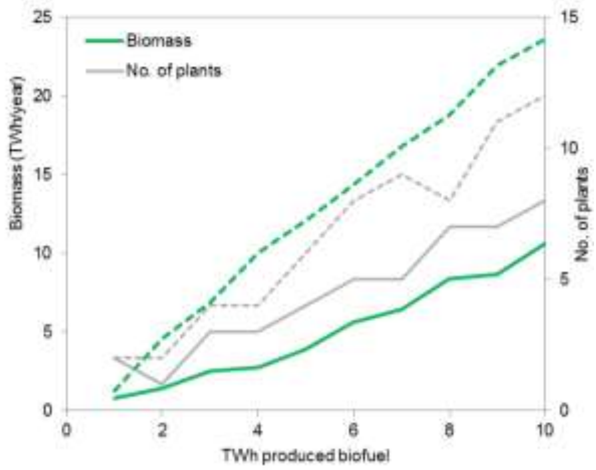


Figure 12. Biomass used for biofuel production. Solid lines represent model runs where BLG is considered and dashed lines runs when BLG is excluded. Total numbers of plants for each case are also shown.

Since the demand by default is defined as a demand to be met in Sweden overall, the produced biofuel is used as close to the production plant as possible. This results in high shares of biofuel in transport in the producing counties, and zero shares in the rest of Sweden. Table 10 summarises the biofuel shares reached in each county for the six cases shown above. The northern counties reach considerable biofuel shares in all *Fixed demand* cases, with no case resulting in any biofuel use in the most densely populated counties.

Table 10. Biofuel as share of total fuel demand for road transport in six different *Fixed demand* cases.

County	2 TWh BLG	4 TWh BLG	6 TWh BLG	2 TWh no BLG	4 TWh no BLG	6 TWh no BLG
Blekinge					61%	61%
Dalarna						
Gävleborg					5%	12%
Gotland						
Halland			43%	10%	10%	10%
Jämtland		19%	19%			6%
Jönköping						
Kalmar						
Kronoberg						
Norrbotten	49%	49%	73%	6%	6%	6%
Örebro						
Östergötland						
Skåne						
Södermanland						
Stockholm						
Uppsala						
Värmland					2%	24%
Västerbotten	22%	52%	59%	15%		19%
Västernorrland		26%	26%	24%	60%	70%
Västmanland						
Västra Götaland						

To test the effects of changing the demand definition (see Section 3.6), the two 4 TWh cases above (with and without BLG, respectively) were also run with the demand defined per county and per grid cell (see Section 3.6). The results are shown in Figure 13 and Figure 14.

The figures show that the optimal plant locations shift towards southern Sweden when the produced biofuel is forced to be distributed to more parts of Sweden than just the area closest to the production plant. Similarly, the transportation distances for biofuel increase significantly when changing the demand definition.

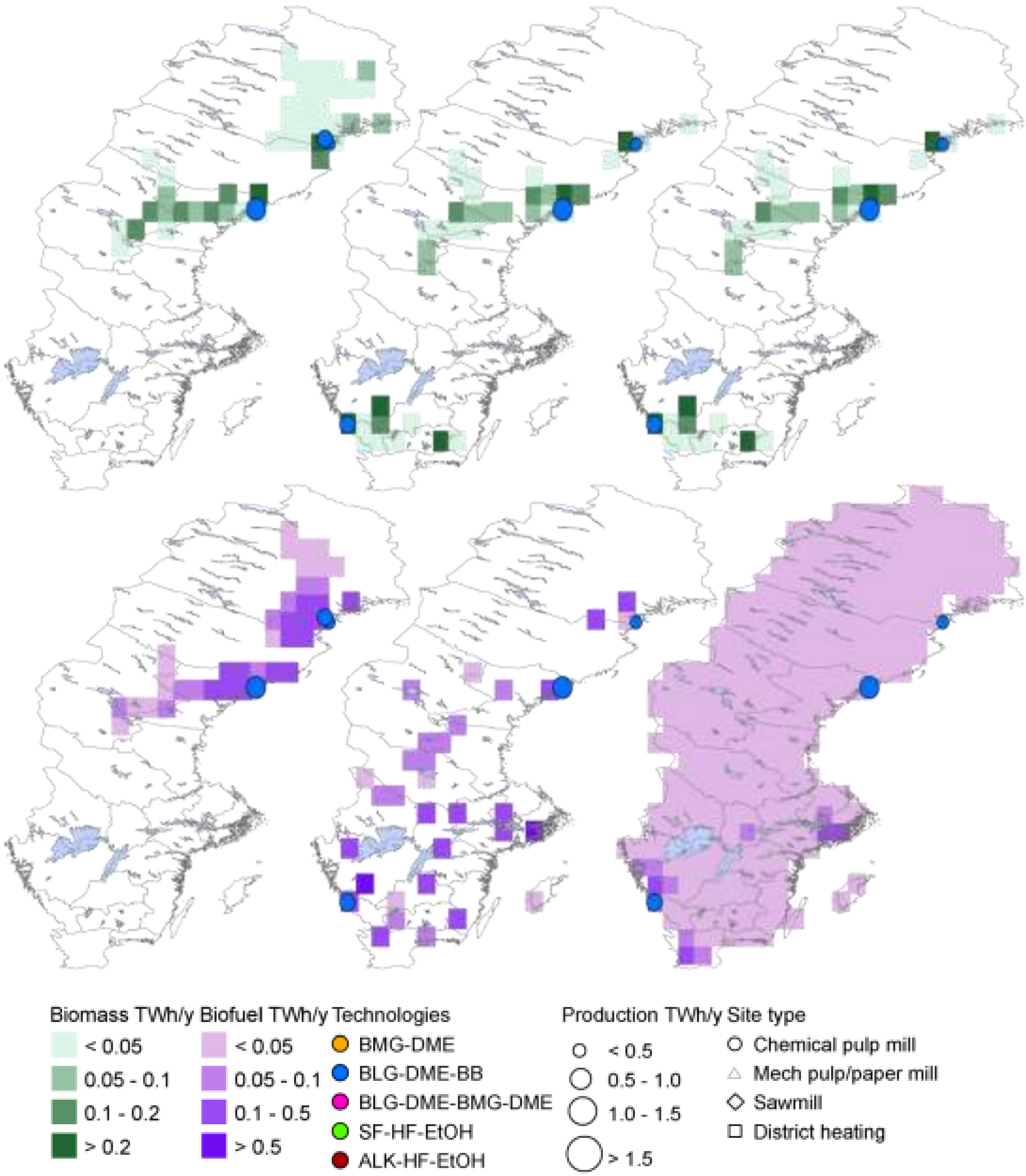


Figure 13. Results for a fixed biofuel demand of 4 TWh with the demand to be fulfilled for Sweden overall (left), each county (centre) and each grid cell (right), when BLG is included as investment option.

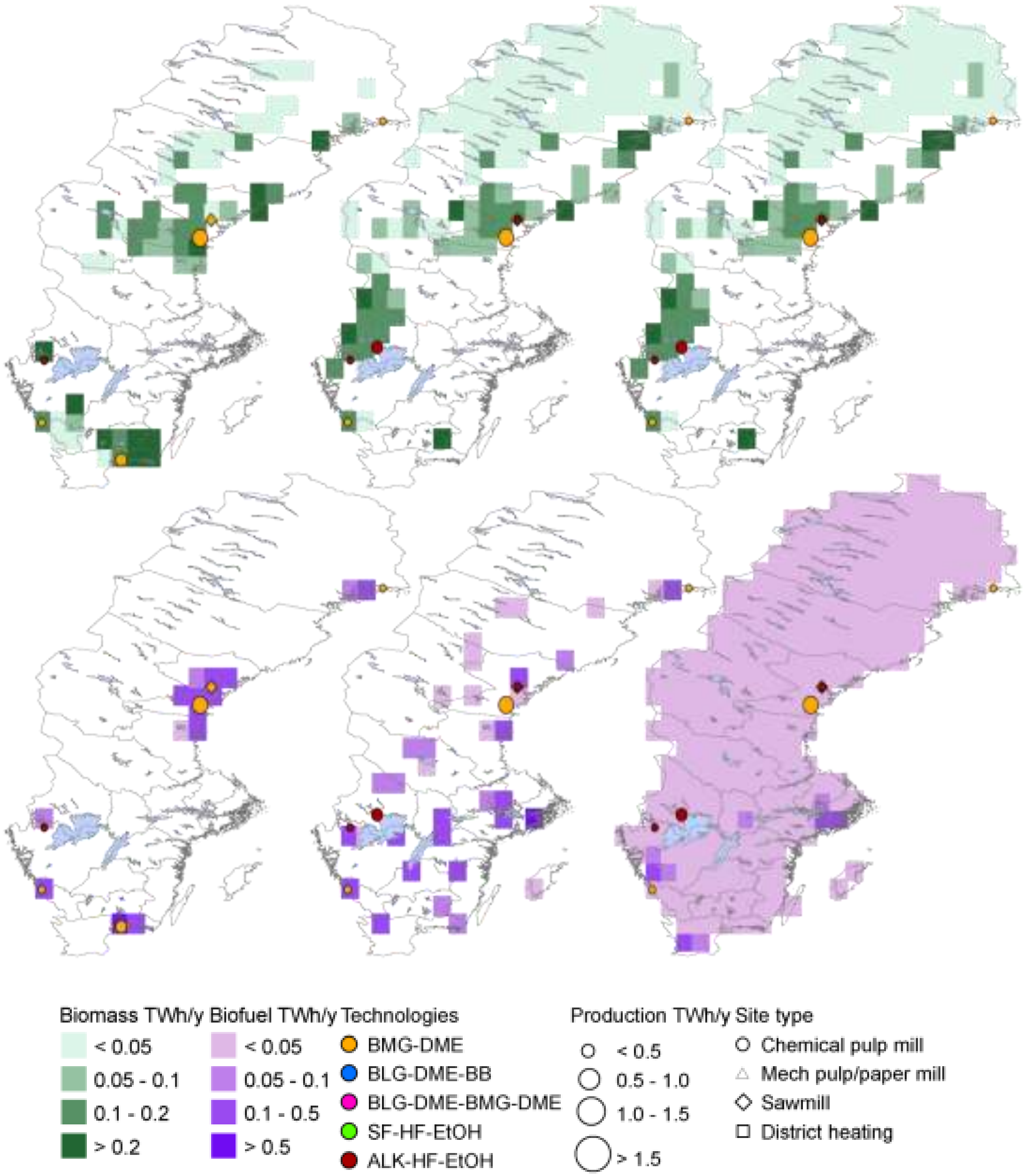


Figure 14. Results for a fixed biofuel demand of 4 TWh with the demand to be fulfilled for Sweden overall (left), each county (centre) and each grid cell (right), when BLG is excluded as investment option.

Figure 15 shows the average transport distances of biomass and biofuel as function of produced biofuel, when BLG is considered as well as when BLG is not considered. As the figure shows, the average biomass transport distance is relatively constant at around 100 km when BLG is considered, regardless of demand definition and total biofuel demand. When BLG is not considered the average biomass transportation distance increases with an increased biofuel demand.

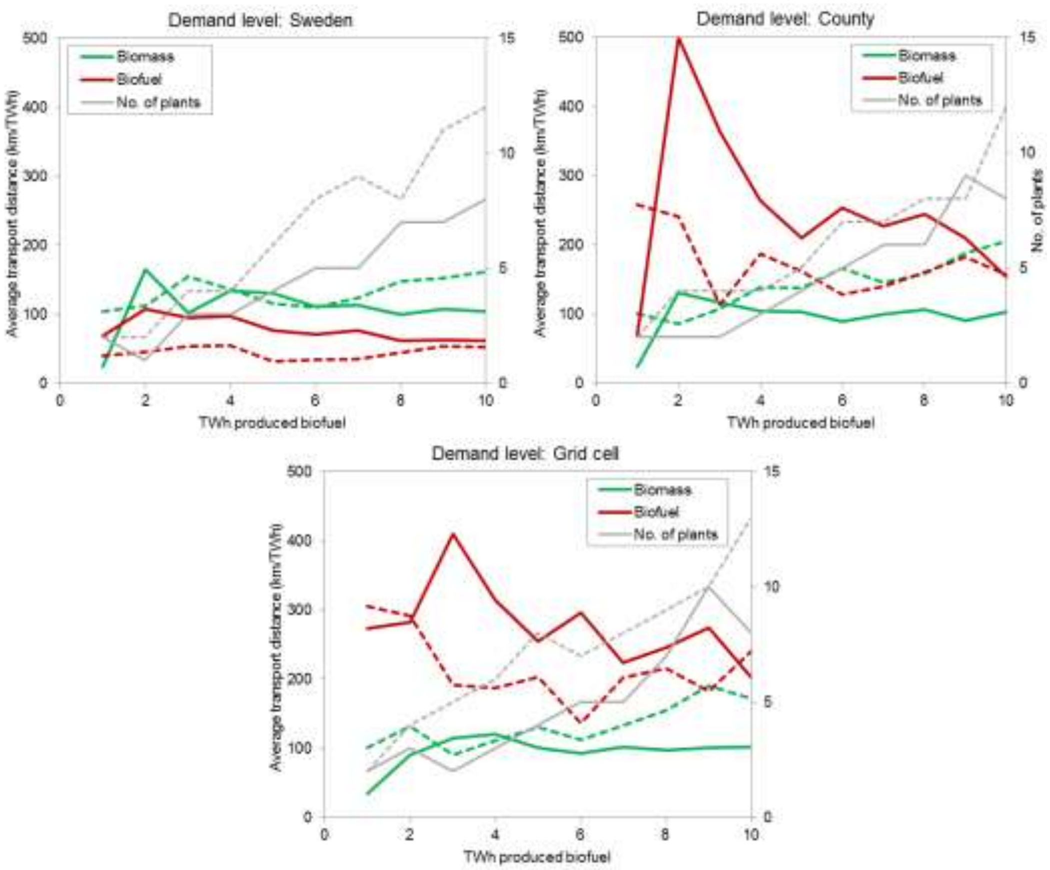


Figure 15. Average transport distances for biomass and biofuel when the biofuel demand is defined for Sweden overall, per county or for each demand region (grid cell). Solid lines represent model runs where BLG is considered and dashed lines runs when BLG is excluded. Total number of plants for each case is also shown.

For biofuel, the average transport distances decrease with higher biofuel demand. The reason is that more plants are needed to cover the total demand, which leads to more plants closer to more densely populated areas. This effect is particularly obvious for lower biofuel levels when BLG is considered and when the demand is defined per county, which gives few plants and very long biofuel transport distances. Biofuel transport distances are correspondingly typically shorter when BLG is not considered, again due to that more plants are needed.

4.2.2 No fixed demand

When running the model in the *No fixed demand* mode, without fixed biofuel demand, the optimal biofuel production is determined by the profitability to invest in and run new production plants, which in turn depends on the assumed boundary conditions (costs, prices, policy instruments). Produced biofuel has been assumed possible to sell at a price that gives the end consumer the same cost as when using fossil fuels, which means that biofuel production is considered profitable when the cost of producing and delivering biofuel is lower than the corresponding cost for fossil transport fuels. For this report, the model was run with no fixed demand with BLG considered as well as with BLG not considered. It was also run for both those cases using incremental investment and O&M costs (i.e. assuming that investment in biofuel production is done instead of investment in alternative technology) as well as absolute investment and O&M costs (i.e. assuming no alternative investments).

The results (shown in Figure 16) show that with the assumed energy market prices and costs, and using incremental investment and O&M costs, all available biomass (approximately 10 TWh) would be used to produce biofuels (8 TWh), with BLG. With absolute investment and O&M costs, investment in biofuel production would still be profitable, but in fewer positions. With BLG not considered, biofuel production would only be profitable to a very low extent, and only when assuming incremental investment costs. The optimal plant locations naturally correspond to the same positions as in the *Fixed demand* cases.

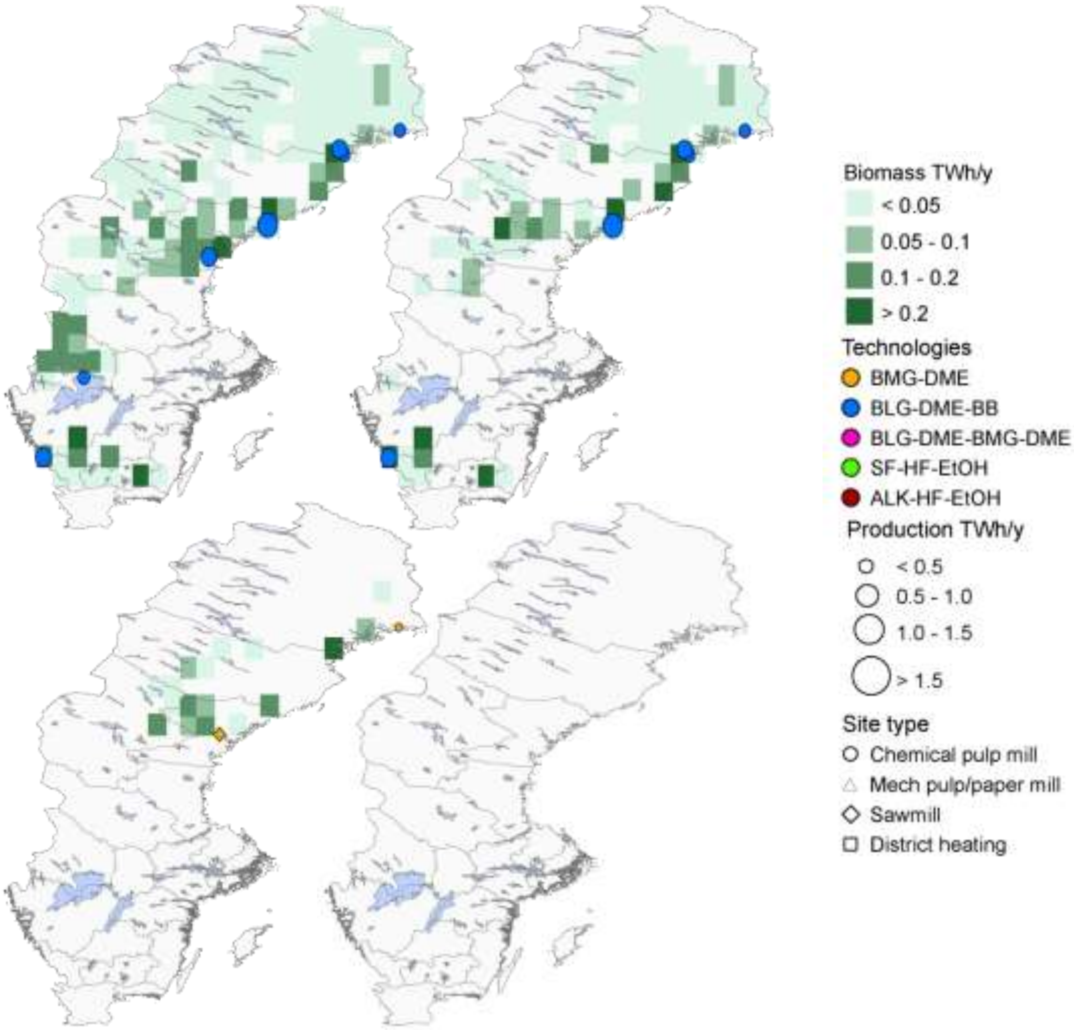


Figure 16. Results for the *No fixed demand* cases with BLG considered (top) and not considered (bottom). At the left are the results when applying incremental investment and O&M costs and at the right the results when applying absolute costs.

4.2.3 Fixed plants

In the *Fixed plants* mode no biofuel demand is defined. Instead the model has to include a fixed number of biofuel plants in the solution. Here the model was run for a target of one biofuel plant. This mode can for example be used to test individual plants sites' robustness to changes in boundary condition.

The model was run with all technologies included at the same time, as well as for one technology at a time. To investigate the effects of the assumed energy market parameters on the plant locations, a number of runs were made for each case, varying one parameter at a time. The parameter values were varied also relatively far outside the range that can be assumed realistic. Each parameter variation run was performed for both the base amount of assumed available biomass feedstock (see Section 3.4) and for an assumed 50% increase in availability of branches and tops and stumps. **Table 11** summarises the parameter variations.

Table 11. Parameter variation values. Parameters have been varied one at a time.

Parameter	Unit	Base value	Min	Max	No. of runs
Green electricity support	EUR/MWh	25	0	100	5
CO_2 emission cost[a]	EUR/tonne	0	0	300	5
Fossil transport fuel price[a]	EUR/MWh	110	0	210	5
District heating revenue[b]	EUR/MWh	31	0	300	5
Feedstock cost[c]	–	1	0.5	3	4
Feedstock availability[d]	–	1	1	1.5	2 x 24

[a] Applied to the entire supply chain emissions, see Section 2.1.
[b] Including energy and CO_2 tax that biofuels are exempt from.
[c] District heating system specific revenues. Average revenue shown here.
[d] Cost multiplier added to all biomass assortments.
[e] Each of the 24 parameter variation runs has been performed for two levels of assumed biomass availability – the base level and an assumed 50% increase in availability of branches and tops and stumps.

Figure 17 shows the resulting plant positions over the 48 parameter variation cases. The left side of the figure shows the results when running the model for one technology at a time. The right side of the figure shows the optimal plant positions when all technologies have been included simultaneously. Some positions are shown to be far more likely to be included in the solution and certain plant positions are also favourable for more than one technology (shown as overlapping markers or pie charts). As in the *Fixed demand* and *No fixed demand* cases BLG is the preferred technology when all technologies are included at the same time.

Plant positions favourable for BLG based biofuel production have in common that they have high conversion efficiency from external biomass to biofuel. With bark boiler (BLG-DME-BB) one chemical pulp mill stands out. The same position was also shown to be of interest when running the model in the *Fixed demand* and *No fixed demand* modes. The reason is the size of the mill, which gives good scale effects, and the large surplus of biomass for the mill base case. However, we have identified errors and quality problems in the SFIF database, why the outstanding performance of this particular mill could be an effect of corrupt input data, as discussed in Section 3.3.1 and further in Chapter 7.

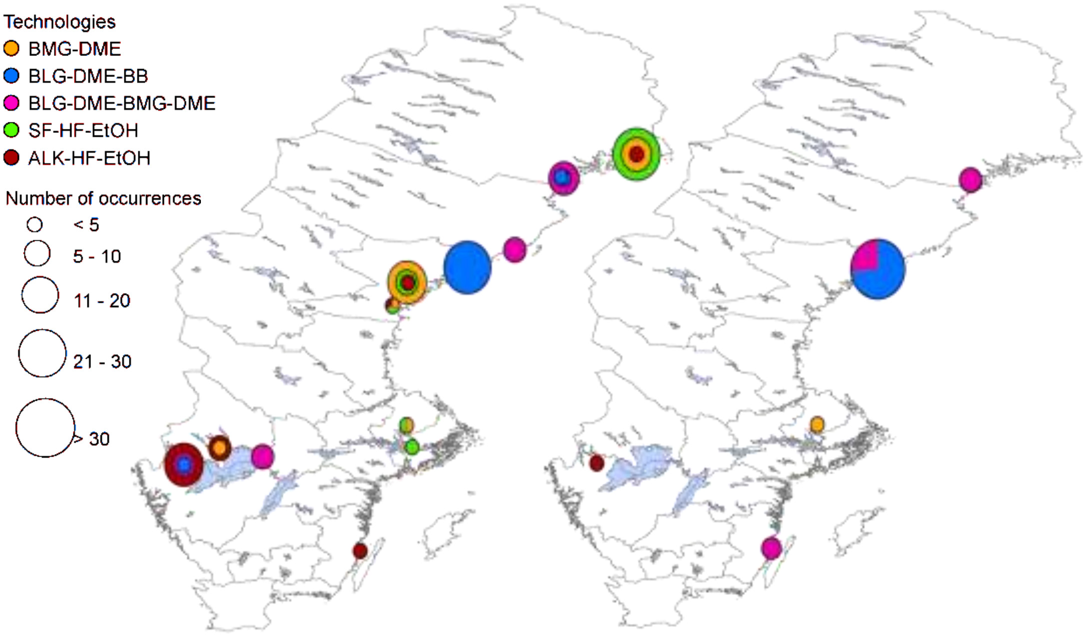


Figure 17. Resulting plant positions when running in *Fixed plants* mode. The left part shows the results when running for one biofuel technology at a time over 48 parameter variation cases. The right part shows the results when including all technologies at the same time. The marker sizes indicate how frequently a position appears as the optimal location.

If instead looking at BLG-DME with BMG-DME, the optimal position shifts towards smaller plants, as the biomass demand increases considerably (see Appendix C). This technology is characterised by a large biofuel production and a corresponding large biomass demand, which makes the assumed available biomass insufficient to cover the demand of the biggest plants[11]. When running the model with more available biomass, the optimal plant positions for BLG-DME-BMG-DME shift towards positions with larger plants. Similarly, when running the model with all technologies included simultaneously, higher biomass availability stimulates a technology shift from BLG-DME-BB towards BLG-DME-BMG-DME, with a higher resulting biofuel production. This indicates that if more biomass would be available for biofuel production, the combined BLG/BMG gasification plant could become more advantageous.

For the non-BLG technologies the profitability of investing in biofuel plants is low, as was shown when running in *No fixed demand* without BLG, for which reason the model chooses the smallest and cheapest plants connected to pulp/paper mills and the cheapest plant connected to sawmills when forced to invest in one plant. With high revenues for biofuel (high fossil fuel price or high policy support), high CO_2 charges or low biomass costs the optimal plant position shifts towards large plants. When running the model with all technologies simultaneously, non-BLG technologies only enter the solution when very high heat prices are applied (BMG-DME in district heating system) or at either very low biofuel revenues or high biomass costs (smallest and cheapest possible plant is chosen).

[11] The largest possible BLG-DME-BMG-DME plant produces 7.7 TWh biofuel per year and uses 16 TWh biomass.

Figure 18 shows the distribution of the resulting biofuel production levels for the different technologies when running the model in *Fixed plants* mode for the 48 parameter variation cases described in Table 11. Each marker represents the resulting biofuel production from one model run, i.e. the production in one production plant. As has been discussed, the biofuel production of the largest BLG-DME-BMG-DME plants by far surpasses that of any other technology.

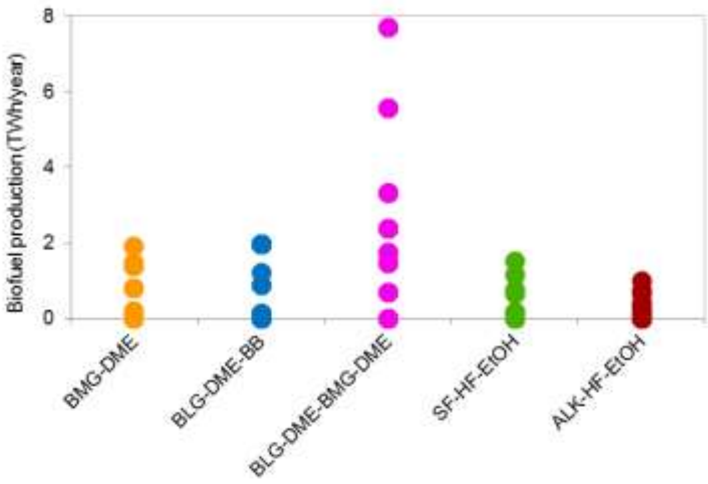


Figure 18. Resulting biofuel production for each technology when running the model in *Fixed plants* mode over the 48 parameter variation cases.

4.3 HEAT AND ELECTRICITY PRODUCTION

All included technologies are net producers of electricity, but with varying electricity efficiencies. It could be expected that higher electricity revenues would shift the optimal plant locations or technologies towards options with higher net production of electricity. When running the model in *Fixed plants* mode small effects could be seen when increasing the electricity certificate levels.

Regarding heat production all included biofuel production technologies have a surplus of heat that can be used either in an industrial process or for district heating, but an external revenue has only been defined when selling the heat as district heating. Of the five district heating networks that have been considered, none was shown to be the optimal location in either of the *Fixed demand* and *No fixed demand* cases tested (Figure 13, Figure 14 and Figure 16). In the *Fixed plants* runs (Figure 17) the heat revenue was varied and only at very high revenues the optimal plant location shifted to district heating networks.

Figure 19 shows the net electricity production and the district heating production as functions of the electricity certificates and heat revenue levels respectively, for two different *Fixed demand* cases (2 and 6 TWh biofuel), with and without BLG included. As the figure shows, the electricity production is higher for a certain biofuel production when BLG is not considered. The reason is that the non-BLG technologies have higher co-production of electricity (see Table 1 in Section 3.2). At high electricity certificates the optimal biofuel technology shifts towards BMG-DME, since that technology has the highest net electricity production. Also the optimal plant positions shift towards positions with higher net production of electricity. The effect is however rather modest when BLG is not considered, compared to the effect when BLG plants can also be included. When BLG is included the technology shift towards BMG-DME at high electricity certificate levels is considerable.

With the base assumed heat revenue level, district heating systems did not constitute optimal plant locations for any of the cases shown in the figure above. When doubling the assumed revenue for sold heat the optimal plant positions include district heating systems when BLG is not considered. When BLG plants are possible, heat revenues at least four times the base assumptions were needed to stimulate a shift towards BMG in district heating systems.

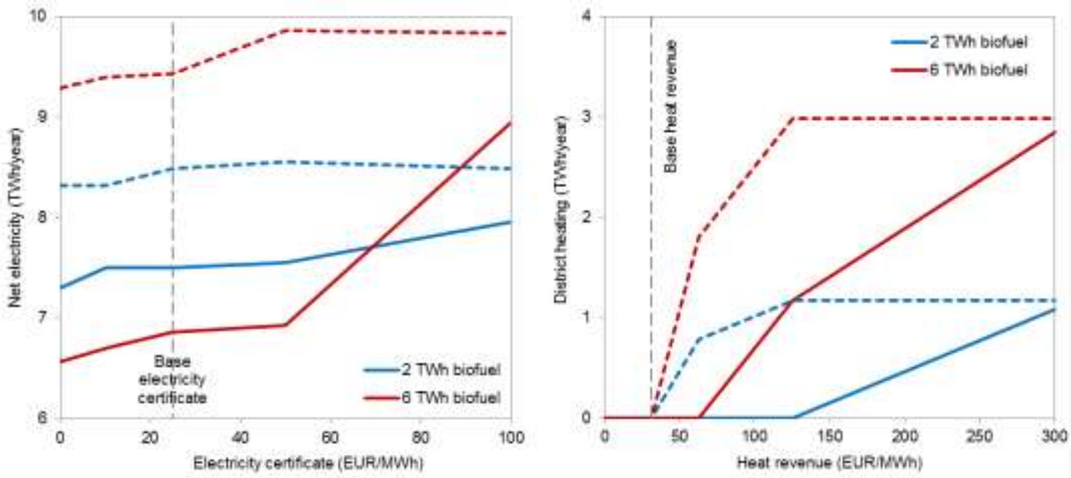


Figure 19. Net electricity production and production of heat for district heating, as function of the electricity certificate level and heat revenue respectively, for different *Fixed demand* cases. Solid lines represent model runs where BLG is considered and dashed lines runs when BLG is excluded.

4.4 CO_2 EMISSIONS

Figure 20 shows the resulting net CO_2 emissions as a function of the produced biofuel for *Fixed demand* model runs from 1 to 10 TWh biofuel, with BLG considered as well as not considered. The figure also shows the annual net electricity and heat (district heating) production. The emissions and energy carrier productions are shown in relation to a reference case with no biofuel production. From the figure it can be seen that the introduction of next generation biofuel plants could lead to a substantial CO_2 emission reduction, in particular when BLG plants are not considered. Since the non-BLG plants, as discussed above, have a larger electricity production compared to the BLG based plants, and since replaced electricity has higher emissions than replaced fossil transport fuels, this is not surprising. However, here coal condensing power was used to value the CO_2 effect of displaced electricity. If a different approach for valuing the effects of a changed electricity balance would be used, applying e.g. average electricity mix or a different marginal technology with lower associated CO_2 emissions, the effects related to replaced electricity would be correspondingly lower.

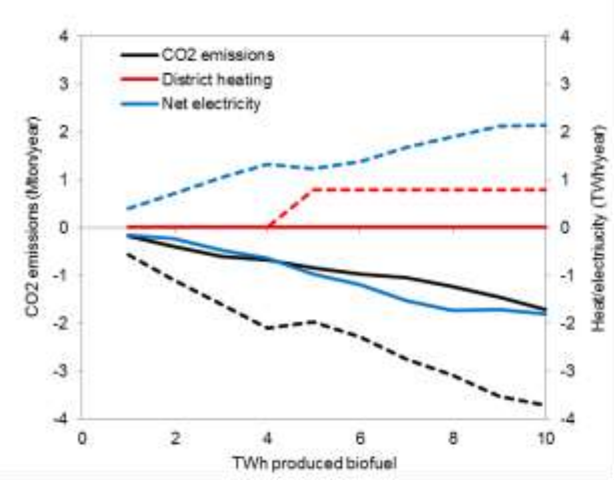


Figure 20. CO_2 emissions, district heating production and net electricity. Solid lines represent model runs where BLG is considered and dashed lines runs when BLG is excluded. Negative values mean a reduction compared to a reference case with no biofuel plants.

4.5 ECONOMIC RESULTS

Figure 21 shows the resulting annual costs to meet different biofuel targets (*Fixed demand*), for demands from 1 to 10 TWh (to be fulfilled in Sweden overall). The total annual cost is considerably higher when BLG is not considered, than when it is, regardless of whether incremental (blue plots) or absolute (red plots) investment and O&M costs are assumed. The penalty for assuming absolute instead of incremental costs is significantly more noticeable when BLG is included, due to the high alternative cost for BLG-based plants (new recovery boiler in chemical pulp mills).

It should be noted that the costs shown in Figure 21 represent the total cost for the system from a communal perspective, and do not reflect the profitability for the individual plant sites included in the solutions.

Figure 22 shows the biofuel production and supply costs[12] for six different *Fixed demand* cases, with incremental and absolute costs considered. As can be seen the biomass cost makes up the largest share of the production cost, especially when BLG is not considered, followed by the capital cost. Revenues for co-produced electricity substantially brings down the production cost for in particular the non-BLG cases, and without the revenue from electricity certificates the production cost would for those cases increase by around 20%.

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

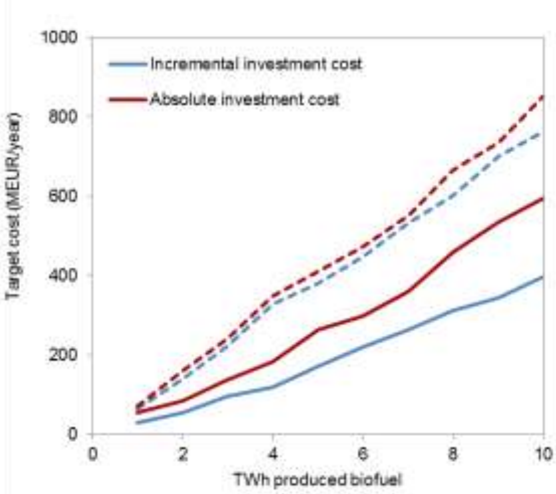


Figure 21. Total annual cost to meet different fixed biofuel demands, with BLG considered (solid lines) and not considered (dashed lines). The red plots show the cost when applying absolute investment and O&M costs instead of incremental (blue plots).

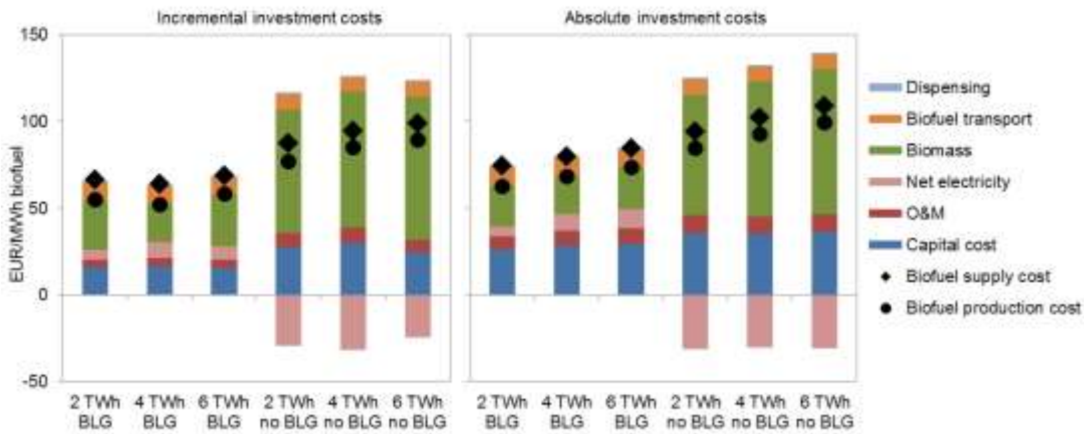


Figure 22. Biofuel production and supply costs when applying incremental (left) and absolute (right) investment and O&M costs.

The capital cost constitutes a considerable share of the total biofuel production costs, in particular when absolute investment costs have been applied. Figure 23 shows the total capital requirement as function of produced biofuel, for *Fixed demand* model runs from 1 to 10 TWh biofuel, with BLG considered as well as not considered and for both investment cost assumptions.

Since the alternative investment to the BLG-based technologies is a new recovery boiler, which in itself is a very costly investment, the total capital requirement increases considerably when applying absolute costs and when considering BLG. The alternative investments to non-BLG technologies are boilers and CHP plants with relatively lower investment costs, for which reason the effect of considering absolute instead of incremental costs is less drastic when BLG is not considered.

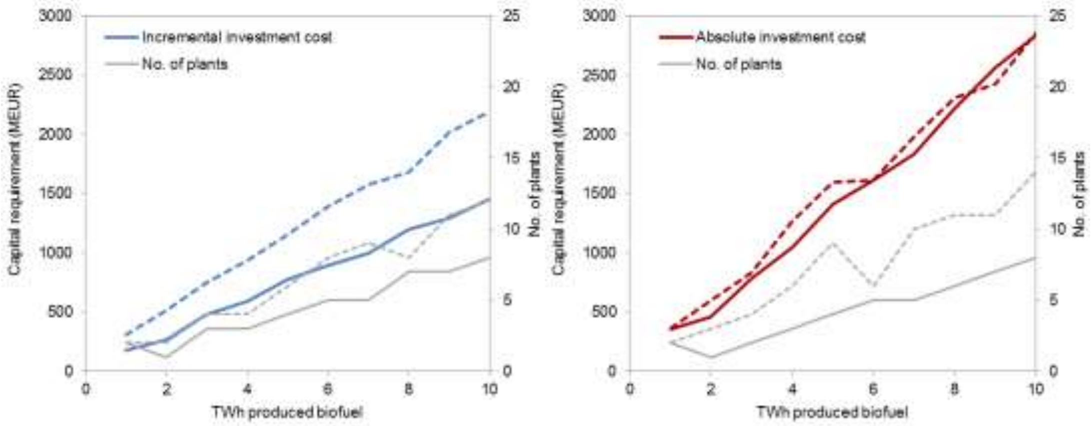


Figure 23. Total capital requirement for different levels of biofuel production (*Fixed demand*) using incremental investment costs (left) and absolute investment costs (right). Solid lines represent model runs where BLG is considered and dashed lines runs when BLG is excluded. Total number of plants for each case is also shown.

The total capital requirement for a next generation biofuel target of 2 TWh (approximately 2% of the current road transport energy demand) ranges from 270 MEUR when considering incremental costs for BLG technology, to 600 MEUR when applying absolute costs and when not considering BLG based biofuels.

4.6 SUMMARY

The initial model runs showed that biofuel production based on black liquor gasification (BLG) was heavily favoured, due mainly to the high conversion efficiency from external biomass to biofuel compared to the other technologies included here. In general, BLG-DME-BB (DME plant with bark boiler) was chosen over BLG-DME-BMG-DME (DME plant with gasification of both black liquor and solid biomass). Higher biomass availability stimulated a technology shift towards BLG-DME-BMG-DME, with a higher resulting biofuel production. This indicates that if more biomass would be available for biofuel production, combined BLG/BMG gasification could become more advantageous.

With BLG considered, both the required number of production plants and the required amount of biomass feedstock were lower than if BLG was not considered. Without BLG the average biomass transportation distance would increase, but due to a higher number of required plants and a corresponding larger dispersion of production plants, the average biofuel transport distance would concurrently decrease. It should be noted that the non-BLG technologies considered here all have relatively low biomass-to-biofuel conversion efficiency compared to efficiencies reported in other studies. Higher biomass-to-biofuel conversion efficiency, however, usually means low or negative net electricity efficiency, which is also important to consider.

When a biofuel target was set for Sweden overall, plant locations in the northern part of Sweden were typically favoured. This was shown to lead to saturation of the local biofuel markets and no biofuel use in the southern parts. If biofuel instead needed to be distributed to all parts of Sweden, the model selected a more even distribution of production plants, with the optimal plant locations shifting towards the southern parts.

District heating systems did in general not constitute optimal plant locations with the base heat revenue levels assumed. A relatively modest increase of the revenue for sold heat shifted the optimal plant positions towards district heating systems when BLG was not considered. With BLG plants included, heat revenues at least four times the base assumptions were needed to stimulate a shift towards inclusion of district heating systems.

The resulting total annual cost to meet a next generation biofuel target of 2 TWh (approximately 2% of the current road transport energy demand) ranged from 55 MEUR when regarding BLG and assuming alternative investments, to 140 MEUR when not considering BLG. When the biofuel targets were instead set for each county instead of for Sweden overall, the cost to meet a specific target was shown to increase due to longer total transport distances and non-optimal integration possibilities.

Regarding the resulting total capital requirement, a biofuel target of 2 TWh require investments ranging from 270 MEUR (BLG considered) to 520 MEUR (BLG not considered), when assuming alternative investments. With no alternative investments considered the corresponding numbers would be 460-600 MEUR. The resulting biofuel production cost was correspondingly dependent on whether incremental or absolute investment and O&M costs were assumed. With BLG considered the resulting production cost was 52-73 EUR/MWh, and with BLG not considered 77-99 EUR/MWh, for biofuel targets in the range of 2-6 TWh. The production cost was more affected by the assumption of alternative investment than by the biofuel target level. Due to higher capital cost of the alternative investment (new recovery boiler), BLG was more affected by whether incremental or absolute costs were applied. The application of absolute instead of incremental costs can also be seen as a sensitivity analysis of investment and O&M costs.

In several cases the model has included two plant positions very close to each other, which would create very high biomass demands on a limited geographic area. The reason is that no restrictions on transport volumes have yet been implemented in the model. Further, existing onsite co-operations between for example sawmills and pulp mills have not always been captured by the input data used for this report, which can cause the consideration of certain locations as two separate plant sites, when in reality they are already integrated. As has been mentioned, some of the mill specific data obtained from the SFIF's environmental database has also been identified to contain considerable errors. This could affect the results, for which reason too much weight should not be placed on the actual plant positions identified in this report.

5 SCENARIO DEVELOPMENT

The purpose of the developed scenarios is to provide a basis for the future modelling using the BeWhere Sweden model. Thus, the scenarios describe different options for the future development of different parts of the studied system, e.g. development of transport demand, transport fuel demand, demand for next generation biofuels, biomass available for industrial purposes, biomass usage in other industrial sectors, etc. The target year for the scenarios is 2030 and, when possible, the data is 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).

For this purpose scenarios for different parts of the studied system are defined in the subsequent sections; Population, Transport – demand and fuel mix, Biomass resources, Development of biomass utilisation in other industry sectors, Energy and biomass market prices. These “scenario parts” can be combined into different roadmap scenarios and thereby describe different developments of the studied system and its surroundings; at the end of this section three different roadmap scenarios constructed this way are presented. This approach resembles the approach used in the Swedish EPA report; where sector specific scenarios are combined into two target scenarios.

5.1 POPULATION

The year 2011 the total population in Sweden amounted to 9,482,855 individuals (Statistics Sweden, 2013a). By the year 2030 the Swedish population will have grown. Both Statistics Sweden (2009) and independent consultants (Nilsson, 2011) have made prognoses for the population development until 2040/2050, for which the estimates for 2030 are presented in Table 12. Two population scenarios, *Low* and *High*, are presented.

As can be seen in the table, the prognosis made by Nilsson (2011) foresees a larger population compared to Statistics Sweden. In principle, it is only the assumption about future immigration that differs between SCB's forecast and the forecast made by Nilsson. However, that difference has implications for both future re-emigration and the future number of births. The population in Sweden 2030 assumed by Swedish EPA in their report is 10,342,000, based on data from Statistics Sweden in 2011 (Swedish EPA, 2012c). As can be seen when comparing this estimation and the other estimations made by Statistics Sweden presented in Table 12, the estimation for the Swedish population made by Statistics Sweden are rising when updated (the prognoses are published in 2009 and 2012 (on-line) respectively), closing the gap between the estimates made by Statistics Sweden and the higher estimate made by Nilsson (2011).

Table 12. Population scenarios for the population in Sweden 2030.

Population scenario	Estimated population 2030	Reference
Low	10,660,344	(Statistics Sweden, 2013a)
High	11,021,000	(Nilsson, 2011)
(for comparison)	10,219,000	(Statistics Sweden, 2009)

The regional population distributions by 2030 are based on the assumptions described by Nilsson (2011) for different regions but have been adapted to the county level to fit the BeWhere Sweden model. In principle, the demographic patterns observed in 2006-2010 are the basis for the county projections. Thus, the urbanisation continues and the counties comprising the three metropolitan areas of Sweden (Stockholm, Göteborg and Malmö) increase their population the most whereas the forest counties in northern Sweden is expected to experience only a marginal increase in population. For immigration, the county's share for the years 2006-2010 has been applied to the national immigration 2011-2040. On a general level, these assumptions agree with the assumptions made by Trafikverket (2012) who states that the continuously increased urbanisation will result in that by 2030 fewer people will live in rural areas and more in cities. Apart from the populations influence on total transport demand, the regional distribution of the population affects the amount of transport fuel needed since e.g. people living in densely populated areas to a greater extent can utilise public transport solutions. The regional distribution of population is presented in Table E- 1 in Appendix E.

5.2 TRANSPORT – DEMAND AND FUEL MIX

For the development of transport demand and transport fuel demand two different scenarios are presented. The first scenario, *Fossil free transport sector*, is based on Roadmap Scenario 1 from the "Basis for a roadmap for Sweden without greenhouse gas emissions in 2050" (Swedish EPA, 2012c) and the related background report concerning the transport sector published by Trafikverket (Trafikverket, 2012). This scenario represents a fossil free transport sector by 2030 achieved through a transport lean society and implementation of best available technology (BAT).

The second scenario, *Best available technology (BAT)*, assumes only implementation of BAT and is based on a report by Profu (Profu, 2011).

5.2.1 Fossil free transport sector scenario

This scenario represents a transport lean future where societal, behavioural and technical changes/improvements coincide and drastically reduce the transport fuel demand compared to the future demand of transport fuels based on extrapolations of the present situation. The scenarios assumes "Scenarios 1" presented by Trafikverket (2012) as their interpretation of the development needed for the transport sector to contribute to Sweden's national climate goal as well as the climate goal for the transport sector (including the goal/vision of a fossil free transport sector by 2030). Compared to the scenario presented by Trafikverket, we have made some smaller adaptions such as defining the amount of next generation biofuels by 2030 and fitted the changes in transport demands described to fit the geographically explicit BeWhere model.

The total travelling is about the same level as today, however, more travels are constituted by public transport, bicycles and walk. 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.

A development towards reaching the high levels of efficiency assumed in this scenario, as well as reducing the transport demand to the assumed extent (see data in Table 13 below), is something which will not occur spontaneously; very powerful policy instruments will be required, to achieve the technological development as well as the changed behaviour.

5.2.2 Best available technology (BAT) scenario

The second scenario for transport demand and transport fuel demand assumes the scenario described by Profu (2011). This scenario is a “best available technology” scenario with a very fast exchange rate of vehicles to reach technical efficiency levels deemed possible. The scenario foresees a very large proportion of biofuels and electricity. Yet, since no behavioural or societal changes are implemented towards a transport lean society, the transport demand is larger than for the Fossil free transport sector scenario and the transport sector will, despite the high share of biofuels and electricity, not be completely fossil free. As mentioned in the previous section, a development towards reaching high levels of efficiency, as well as high shares of biofuels and electricity in the transport sector, will not occur spontaneously, for which reason powerful policy instrument will be required. Thus, the scenario illustrates how far one could theoretically come by applying technology measures. The assessments made for both first and next generation biofuels are deemed to be feasible using almost only domestic biomass raw materials. The only imported fuel is sugarcane ethanol for which it is assumed that the future level of import is in line with the import today.

Since no significant societal and/or behavioural changes are assumed, the regional patterns regarding transport fuel demand per capita 2030 are assumed to replicate the current demand patterns, adjusted to fit the total forecasted demand and the foreseen population (see Table 13 below).

5.2.3 Data for the two scenarios

Data for the two scenarios for transport fuel demand and share of biofuels and next generation biofuels are presented in Table 13. As can be seen in the table the scenarios vary quite a bit. For example, the transport fuel demand is about 70% higher and the demand for next generation biofuels more than double in the BAT scenario compared to the Fossil free transport sector scenario.

Table 13. Transport fuel demand 2030 [TWh/year] for the Fossil free transport sector scenario and the BAT scenario compared to the current (2010) transport fuel demand.

	Scenario 2030		2010
	Fossil free transport sector	BAT	
Transport fuel demand – total[a]	33	50	88
Electricity for transport[a]	4	4.5	0
Biofuel demand – total	14	31	5.0
of which next generation biofuels	4[b]	9	0

[a] Excluding maritime, air and rail transport.
[b] The share of next generation biofuels in the fossil free transport sector scenario was not clearly defined by Trafikverket (2012). Instead the same share of next generation biofuels out of the total amount of biofuels has been assumed as for the BAT scenario (Profu, 2011).

For the two scenarios, the estimated amounts of biofuels (both first and next generation) are 14 and 31 TWh respectively. For next generation biofuels the estimates are 4 and 9 TWh. These levels can be compared with possible levels of national production of biofuels estimated in other studies. For example, IVL (2010) estimates a potential of 25 TWh of biofuels based on domestic raw material supply. Grahn and Hansson on the other hand estimate a lower potential of 10-18 TWh by 2030. The lower part of the interval representing the potential with only existing and planned facilities (2009) and the higher part of the interval including also further investments in biogas and next generation biofuels. An earlier estimate for 2030 by Sandebring (2004) gives domestic potentials of more than 35 TWh biofuels, where the largest contributions are made by next generation biofuels in the form of DME/Methanol (largely based on black liquor gasification). However, looking back at the past years technology development and slow rate of commercialisation of next generation biofuels it is not likely that such large amounts are produced as early as by 2030.

Some counties have visions to have a fossil free transport by 2030 (county level). For the BeWhere model and the future scenario modelling it is thus of interest to have good estimations of the transport fuel demand on the county level. Already today, people living in different counties show different transportation demand in kWh/capita where people in the larger metropolitan areas show a lower transport demand in kWh/capita compared to people living in rural dwellings (due to e.g. better access to public transport systems). These pattern will most definitely be strengthened by the year 2030 since people who live in metropolitan areas and between regions a larger potential to reduce their car travels compared to rural dwellers, much due to better access to public transport and shorter average distances between home and work.

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 (Trafikverket, 2012). For the two transport fuel demand scenarios presented in this report the county specific transport demand per capita has been adjusted to fit the total transport demand presented in Table 13. About half of the reduction in transport fuel demand, representing the reduction in passenger transports, have been distributed based on type of county (Rural, Region or Metropolitan area where metropolitan areas show the larger reduction following the assumptions by Trafikverket (2012)), the remaining reduction has been distributed evenly. Table E- 2 in Appendix E shows the county specific fuel demand. As can be seen in the table the difference in transport fuel demand between rural areas and metropolitan areas increase by the year 2030.

5.3 BIOMASS RESOURCES

The demand for forest and forest products are increasing and a number of studies have examined the Swedish potential to increase the yield of different assortments of forest biomass. However, identified potentials vary significantly between different studies (compiled in Appendix D). However, even though studies show different absolute potentials they all agree in that there is a significant potential to increase the yield/harvest of biomass from Swedish forest. However, the potential is relatively limited to certain regions of the country. Since there is also a great potential for increased usage in these areas biomass logistics might play an even more important role by 2030. In addition to the discussion in

Appendix D, Nohlgren et al. (2010) provides a good summary of some resent studies on a national level.

For the scenario development we have assumed two different futures for the availability of biomass for industrial purposes – the *Restrictive scenario* and the *Extensive development scenario* (described in the following sections). As visualised in Figure 24, the potential available forest for industrial purposes depend on a number of assumptions regarding theoretical potential, technical potential, environmental/economic potential and assumptions regarding the amount of forest protected from forestry. For example, how much of the possible potential that is realised depend partly on policy measures and market prices as well as demand for biobased products and forest industry development (economic and technical potential). In addition to this, existing technologies for harvesting and logistics decide the viable economical take out as well as environmental factors such as biodiversity conservation, public opinion, etc. (technical and environmental potential and protection of forest).

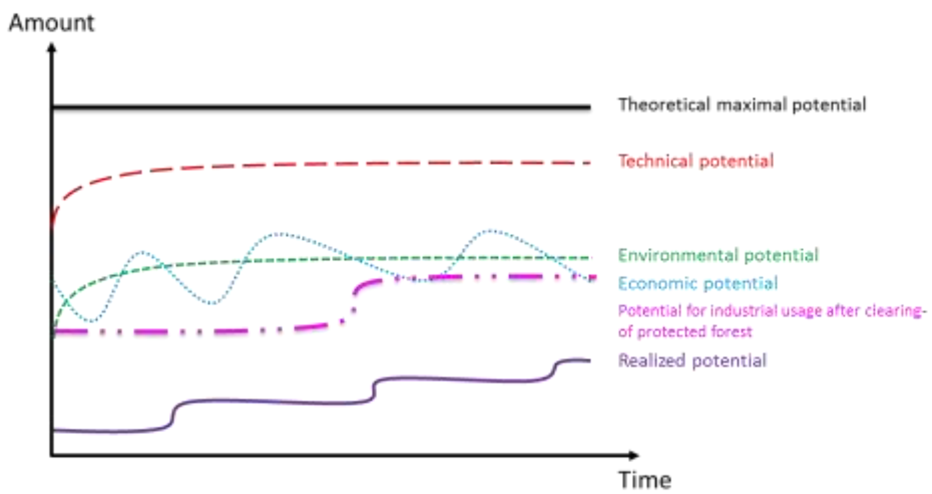


Figure 24. Explanation of different potential concepts (translated version of figure first published in SOU (2007), adapted for this project)

In the scenarios three different forest assortments are considered, stemwood, branches and tops and stumps. The available amounts of branches, tops and stumps are directly related to final felling of stemwood (and possibly thinnings). Today, about 67 million m^3 (around 150 TWh) stemwood (including 16 TWh firewood and discarded pulpwood) and about 10 TWh/year of branches and tops are harvested; stumps on the other hand are only marginally utilised today (Paulrud et al., 2010; Thuresson, 2010).

Regarding protected forest, today, about 25% – 7 million ha – of the area of forest land is protected from forestry. Out of these 25% about 20% are formally protected land and about 5% are voluntary protected. Formally protected forests are national parks, nature reserves, habitat area, wildlife conservation areas and “unproductive forest land”. The majority of the formally protected forest is unproductive forest land. Voluntary protected forest land is forest which is voluntarily protected by the landowner without any compensation. According to the Swedish Forest Agency, today about 1.2 million ha of forest land are voluntarily protected (Swedish Forest Agency, 2012). It should be noted that certification of forestry affects the amounts of voluntary protected forest since a certified forest owners have to set aside 5% of his/her forests in order to maintain high environmental values.

5.3.1 Restrictive scenario

The Restrictive scenario represents a future where the forests are viewed both as resources for raw material but also as an important resource for other types of value creation such as conservation of biodiversity, recreation and tourism. The theoretical potential assumed for 2030 equals the theoretical potential estimated for present conditions (Nohlgren et al., 2010) and it is assumed that the forest resources are located in the same areas and regions as today. Thus, it is assumed that no significant changes are made regarding new afforestation or deforestation certain regions. Also, since the productivity (in harvested tonnes) is not the one main priority forest fertilisation is assumed to be at present levels and new cultivars are assumed not to increase the total theoretical potential by any significance.

For stemwood, both the technical and economic/ecological potential is assumed to be 95% of the theoretical potential. For branches, tops and stumps the technical potential is lower since the forest machinery and logistics for these assortments are less developed. In order to maintain the soil carbon content, uptake of nutrients, soil moisture, etc. it has been assumed that at least 40% of the branches and tops are left in the forest and that only 30% of the stumps are harvested. As can be seen in Table 14, these assumptions give an economic/environmental potential of about 241 TWh/year.

Table 14. Biomass potentials 2030 – Restrictive scenario.

Year 2030 [TWh]	Stemwood	Branches and tops	Stumps	Total
Theoretical potential	188	68	72	328
Technical potential	179	61	50	290
Economic/environmental potential	179	41	22	241
Available potential for industrial usage after clearing-off protected forest	152	35	18	205

In the Restrictive scenario it has been assumed that a fair amount of forest is protected from forestry and set aside for conservation of biodiversity, recreation, tourism, etc. Apart from the forest land protected today (both formally and voluntary protected) the Restrictive scenario assumes protection from forestry also for the following areas:

- Natura 2000 areas which are protected according to the Habitats directive (European Commission, 1992 (updated 2007))[13].
- Key habitats on private land
- Urban woodlands of interest for recreation[14]

Data for these areas are based on data from the Swedish Forest Agency (2012). As can be seen in Table 14, this protection of forest land reduces the potential available for industrial usage by 36 TWh to 205 TWh/year. It should be noted that the share of protected forest land

[13] The areas which are not already included due to formal protection already today (national parks and nature reserves).

[14] Only areas of national interest for recreation near urban areas.

(out of total forest land) varies quite a bit between different counties in Sweden; from about 6% in Västernorrland to about 72% for Gotland.

In Figure 25 the different biomass potentials are visualised when adapted to the BeWhere Sweden model grid.

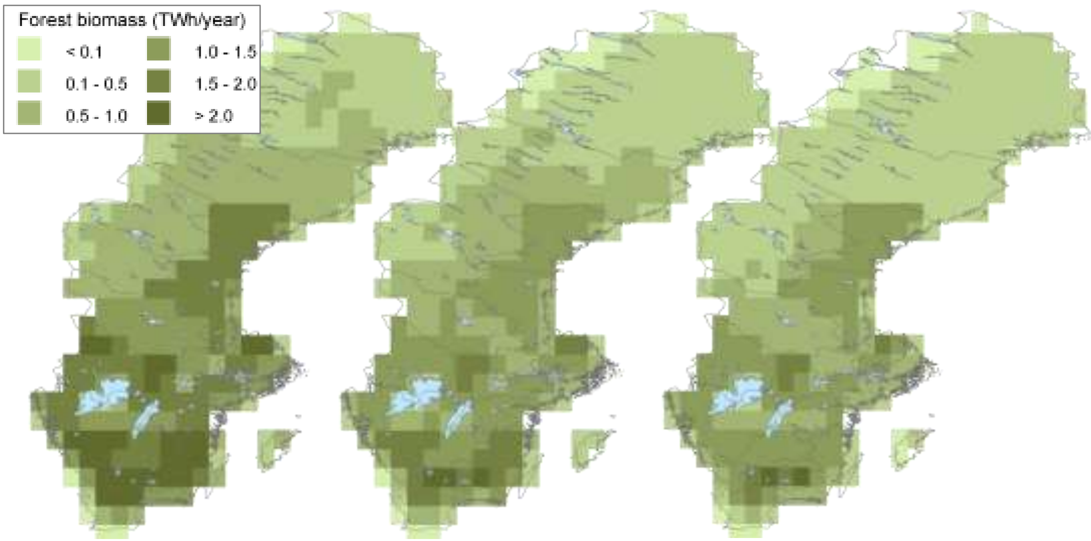


Figure 25. Biomass potentials 2030 – Restrictive scenario, when adapted to the BeWhere model grid. Theoretical potential (left), economic/environmental potential (centre) and available potential after clearing-off protected forests (right).

5.3.2 Extensive development scenario

The Extensive development scenario represents a future where forestry is significantly developed and high productivity in the form of output in tonnes or TWh are prioritised over recreation and other values. It is assumed that advances in forest fertilisation and new/improved cultivars increase the theoretical forest potential by 15% compared to today's estimates. This increase of forest productivity is larger in the south of Sweden – below the Dal River (Dalälven) – than in the north of Sweden. Table 15 presents the different forest biomass resource potentials for the Extensive development scenario. As can be seen in the table the theoretical potential amounts to 377 TWh/year in this scenario compared to 328 TWh/year in the Restrictive scenario.

Since, in this scenario, forestry is viewed as a national strength area for Sweden significant advances are made regarding forest machinery, logistics etc. These advances contribute to increasing the technical and economic potential for harvest of branches and tops to 95% and stumps to 80% (compared to 90% and 70% in the Restrictive scenario). The amounts of branches, tops and stumps left in the forest to maintain the soil carbon content, uptake of nutrients, soil moisture, etc. is kept at minimum; 15% of the branches and tops and 30% of the stumps are left in the forest). Harvest of stumps is rather expensive since large clear-cuts/deforested areas are needed to achieve economy of scale for transport and use of the machinery needed. To achieve as large a harvest as presented by the potential in this scenario significant technology advances in the machinery are is needed.

Table 15. Biomass potentials 2030 – Extensive development scenario.

Year 2030 [TWh]	Stemwood	Branches and tops	Stumps	Total
Theoretical potential	216	78	83	377
Technical potential	205	74	66	346
Economic/environmental potential	205	66	58	330
Available potential for industrial usage after clearing-off protected forest	199	64	56	320

In this scenario only the forest land formally protected today is assumed to be protected by 2030. The voluntary protection has vanished due to the shift in value base for forest land from biodiversity and recreation to added-value and production. As can be seen in the table the protection of forest reduces the potential available forest land for industrial usage by 10 TWh in this scenario, compared to 36 TWh in the Restrictive scenario.

If the Restrictive scenario represents a future where national forest biomass is more limited due to environmental concerns and prioritising of additional value, this scenario represents a high availability scenario where the focus is on providing as large a potential as possible for industrial usage, possibly chipping the biodiversity and recreational values away at the edges.

In Figure 26 the different biomass potentials are visualised when adapted to the BeWhere Sweden model grid.

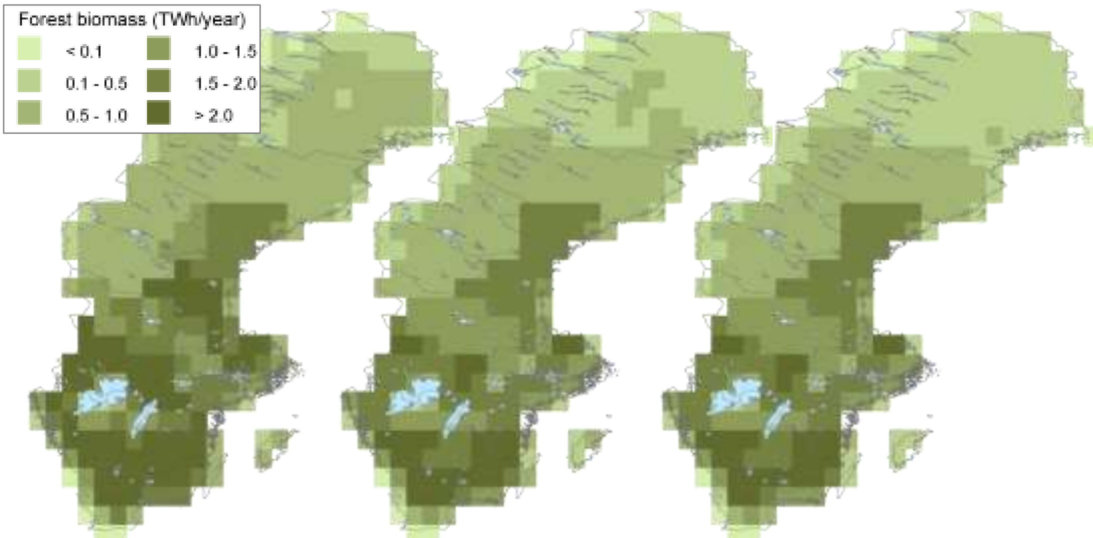


Figure 26. Biomass potentials 2030 – Extensive development scenario, when adapted to the BeWhere model grid. Theoretical potential (left), economic/environmental potential (centre) and available potential after clearing-off protected forests (right).

5.4 DEVELOPMENT OF BIOMASS UTILISATION IN OTHER INDUSTRY SECTORS

The three different scenarios presented below – *Green process industry scenario*, *Expansive forest industry scenario* and *Conservative technology development scenario* – are based on the scenarios presented by the Swedish EPA (2012a). However, some adaptions/ supplementations have been made and these are presented in the text below. The scenarios presented by the Swedish EPA focus on the year 2050 and encompass the development of many different energy carriers. In this report, the assumed year is 2030 and the focus is on changes in industrial biomass usage (both as feedstock and for energy purposes). An increased usage of biomass in other industry sectors implies an increased competition for the biomass resources available for production of next generation biofuels. In the BeWhere model this is handled geographically explicit by allocating the changes in usage to the large industrial sites.

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 shrink. 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 the scenarios below, the pulp and paper industry is assumed to show economic growth until 2030[15] and increase its production volumes. However, the growth is assumed to be less than growth demand globally and thus the Swedish pulp and paper industry will decrease its market share.

Introduction of large shares of biomass in industry will, for most sectors, impose significant structural changes. The different industry sectors vary when it comes to both incentives and motivations for such structural change. Further, these structural changes will bring new value chains and value chain cooperations and thus there will be a strong connection between different industry sectors. For example, in the future the chemical industry may demand raw materials from the pulp and paper industry. However, just as for the changes described for the transport sector (Section 5.2) these changes will probably not occur spontaneously. For the industry sectors currently using fossil fuels and fossil feedstock, the demand for biobased raw materials and fuels have to be strong enough to justify the substitution of fossil fuels and feedstock and the development of biobased products. Also, the additional costs associated with the biogenic feedstock/fuel/product have to be possible to pass on to the final customer, which means that there must be a strong market demand for biobased products and materials.

5.4.1 Green process industry scenario

This scenario builds on Goal Scenario 1, as described by the Swedish EPA (2012c; 2012a). The economic development of the industry is in line with development in the business as usual scenario. However, due to a stronger willingness to invest in energy efficient technologies the energy use in industry is about 7% lower in 2030 in this scenario compared to the business as usual scenario.

In the “green” process industry scenario it has been assumed that for the technologies and processes where it is technically feasible today or where a technological breakthrough can be envisaged in the near future, biomass and electricity will replaces fossil fuels. With respect to an increased industrial usage of biomass, black liquor gasification, torrefied biomass, bio-based raw materials in the chemical and refinery sector are all technologies

[15] The economic growth is estimated to 1.4% annually for the *Green process industry scenario* and the *Expansive forest industry scenario* and 0.9% annually for the *Conservative technology development scenario*.

assumed to be commercial by 2030. The assumptions and resulting biomass demands for this scenario are presented in Table 16 and Table 17.

A conversion towards more chemical products based on biogenic raw materials could lead to increased prices of these products (e.g. resins). Would the price of plastic products increased sharply, it could strengthen the demand for cardboard/packaging. Consequently, the mechanical pulping industry could benefit from such a rebound effect and it might lead to a shift back towards more cardboard-based packaging solutions instead of plastic based solutions. This has, however, not been included in the projections made for the pulp and paper industry in this scenario.

The industrial biomass usage (for energy purposes) in 2030 is assumed to be 72 TWh, including waste and peat (an increase by 17.1 TWh compared the usage 2010 (Swedish Energy Agency, 2012a)). The biomass usage for production of heat and power is assumed to remain at constant levels compared to 2010. In addition the biomass usage for feedstock purposes will also increase by 2030, both in the pulp and paper industry and in the chemical industry (including refineries).

Table 16. Development of industry and development of biomass usage in industry – Green process industry scenario.

	Pulp and paper industry (incl. saw mills)	Iron and steel	Chemical industry incl. refineries	Heat and power
Development of industry	Good economic growth but limited increase in energy usage due to structural changes in the industry Increased production of chemical pulp and decreased production of mechanical pulp The production of back-pressure power decrease somewhat due to the implementation of black liquor gasification	Marginal increase in energy use	The relative energy use is reduced compared to the business as usual scenario. In absolute numbers, however, the energy use is increased, mainly due to strong economic growth Fossil fuels are not completely replaced by other energy carriers	Electricity generation from biomass heat and power in district heating networks decrease as a result of a decline in demand for district heating but also the increased competition for biomass raw materials This is a “low electricity use” scenario
Development of biomass usage in industry	Black liquor gasification is commercially available All fossil fuels used are replaced by 75% biomass and 25% electricity The use of biomass is significantly increased whereas the use of electricity only show an marginal increase	Some coal, coke and oil are replaced by biomass	Considerable increase in the use of biomass and electricity Fossil fuels are replaced by 75% biomass and 25% electricity Fossil-based raw materials are replaced by bio-based raw materials, both in refineries and in other chemical process industries New technologies that enable a more efficient use of biomass is assumed to be available on the market and used by the chemical industry (e.g. torrefaction)	Constant levels of biomass usage for heat and power production (due to a combination of lower district heating demand and phase out of fossil fuels for production of district heating) Significant increase in electricity produced based on biogenic feedstock, the majority of the increase is however not in the heat and power sector but in other industry sectors such as the pulp and paper industry (industrial back pressure power)

Table 17. Increase in biomass demand in different industry sectors – Green process industry scenario.

	Pulp and paper industry (incl. saw mills)	Iron and steel	Chemical industry incl. refineries	Heat and power
Increased biomass demand comp. to 2010[a] (TWh)	55	3	25	0
Biomass used for	Feedstock and energy	Energy	Feedstock and energy	Energy
Comment	Assuming an increase of biomass for feedstock purposes of ~1.4% and that 75% of the fossil fuels used are replaced by biomass.	Some of the fossil fuels used are replaced by biomass.	Assuming that about two thirds of the increase is for feedstock purposes and the rest is replacing fossil fuels for energy purposes. Almost 100% of the feedstock in the chemical cluster in Stenungsund is replaced by biomass.	The increase in biogenic electricity production solely takes place in industry (back pressure power).

[a] Feedstock and energy purposes

5.4.2 Expansive forest industry scenario

This scenario is somewhat similar to Goal Scenario 2, as described by the Swedish EPA (2012c; 2012a). The similarities lie in the assumptions regarding to what extent fossil fuels and fossil feedstock will be replaced by biomass in different industry sectors. However, the assumptions made in this report are marginally stricter, and fossil feedstock is only assumed to be very marginally replaced by biomass. 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 pulp and paper industry and the saw mill industry are assumed to experience a steady economic growth and their production capacity is increased.

The assumptions and resulting biomass demands for this scenario are presented in Table 18 and Table 19.

For this scenario the industrial biomass usage in 2030 is assumed to be 65 TWh, including waste and peat (an increase by 10.1 compared the usage 2012). The use of biomass for heat and power production is assumed to increase to 69 TWh.

Table 18. Development of industry and development of biomass usage in industry – Expansive forest industry scenario.

	Pulp and paper industry (incl. saw mills)	Iron and steel	Chemical industry incl. refineries	Heat and power
Development of industry	Good economic growth but limited increase in energy usage due to structural changes in the industry Increased production of both mechanical and chemical pulp	Significant electrification bring radical increase in electricity and hydrogen usage	Slower economic growth gives a modest increase in energy demand	An increased electrification in e.g. industry give a significant increase in the total use and production of electricity District heating demand remains constant at today’s levels. Phase out of fossil fuels gives a higher share of biomass This is a “high electricity use” scenario
Development of biomass usage in industry	All fossil fuels used are replaced by 75% biomass and 25% electricity Increased use of biomass, both for pulp production and for energy purposes Black liquor gasification is assumed to be commercially available	No significant substitution of fossil fuels for biomass	No significant substitution of fossil feedstock for biomass	Modest increase in the use of biomass for heat and power production (~+15% compared to 2009) Significant increase in electricity produced based on biogenic feedstock, the majority of the increase is however not in the heat and power sector but in other industry sectors such as the pulp and paper industry (industrial back pressure power)

Table 19. Increase in biomass demand in different industry sectors – Expansive forest industry scenario.

	Pulp and paper industry (incl. saw mills)	Iron and steel	Chemical industry incl. refineries	Heat and power
Increased biomass demand comp. to 2010[a] (TWh)	55	0	2	9
Biomass used for	Feedstock and energy	Energy	Energy	Energy
Comment	Assuming an annual increase of biomass for feedstock purposes of ~1.4% and that 75% of the fossil fuels used are replaced by biomass.	No significant substitution of fossil fuels for biomass	Some fossil fuels are replaced by biomass.	Biomass replaces fossil fuels for district heating production (including heat and power production).

[a] Feedstock and energy purposes

5.4.3 Conservative technology development scenario

This scenario builds on the reference scenario presented by the Swedish EPA (2012c; 2012a). The development of the industry in this scenario is based on current policy instruments and the assumption of no major technology breakthrough.

In the business as usual scenario the biomass usage is increasing rapidly. This increase is mainly due to the large growth in the forest industry and the substitution of fossil fuels, mainly oil into biofuel. The substitution of fossil fuels occurs in several industry sectors but is greatest in the forest industry.

In 2012 the industry (excluding the heat and power sector) used 152 TWh out of which 56 TWh was biomass and 52 TWh was electricity. In reference scenario the total energy use 2050 is estimated to 190 TWh out of which 75 TWh is biomass and 71 TWh is electricity.

The assumptions and resulting biomass demands for this scenario are presented in Table 20 and in Table 21.

In some industry sectors, e.g. aluminium industry, the historical data suggests that there has been a "decoupling" between value added and energy use. However, in other industry sectors, such as the iron and steel industry and the pulp and paper industry, historical data suggests that there is a stronger link between value added and energy consumption. Thus, in this scenario the assumption when the value added increases the energy demand will increase as well.

Table 20. Development of industry and development of biomass usage in industry – Conservative technology development scenario.

	Pulp and paper industry (incl. saw mills)	Iron and steel	Chemical industry incl. refineries	Heat and power
Development of industry	Total increase of production and moderate increase in energy use Closure of inefficient and/or small mills in benefit of expansion of competitive and/or large mills Increase in chemical pulp production and decrease of mechanical pulp production Investments in production capacity, energy efficiency and fuel substitution	Increased production as well as increased energy use	Economic growth, increased production and increased energy use Decrease in use of oil, increase in use of natural gas	The fuel mix changes: the use of waste, biomass and wind increases and the use of oil and coal decrease Sweden is a large net exporter of electricity The demand for district heating decrease due to increased user efficiency competition with heat pumps
Development of biomass usage in industry	Increased use of biomass, both for pulp production and for energy purposes Black liquor gasification is assumed not to be implemented	Some coal, coke and oil are replaced by biomass	No significant substitution of fossil feedstock for biomass	The usage of biomass increases and the share of biomass in the district heating mix increase

Table 21. Increase in biomass demand in different industry sectors – Conservative technology development scenario.

	Pulp and paper industry (incl. saw mills)	Iron and steel	Chemical industry incl. refineries	Heat and power
Increased biomass demand comp. to 2010[a] (TWh)	36	2	8	12
Biomass used for	Feedstock and energy	Energy	Energy	Energy
Comment	Assuming an annual increase of biomass for feedstock purposes of ~0.9% and that 75% of the fossil fuels used today are replaced by biomass.	Some of the fossil fuels used are replaced by biomass.	Fossil fuels are replaced by biomass.	Biomass replaces fossil fuels for district heating production (including heat and power production).

[a] Feedstock and energy purposes

5.5 ENERGY AND BIOMASS MARKET PRICES

5.5.1 Energy market prices

The future economic performance, as well as the global emissions of CO_2, associated with the different modelled systems and next generation biofuel plants is dependent on the development of the energy market. Consequently, to identify robust investment options, the performance of the different investment options should be evaluated for varying future energy market conditions. For this purpose, energy market scenarios that reflect a variety of possible future energy market conditions could be used.

The energy market prices presented in Table 22 are summarised based on the report by the Swedish EPA (2012c) including background reports and annexes (e.g. (Profu, 2011; Swedish EPA, 2012a; Swedish EPA, 2012b; Trafikverket, 2012)). 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 (Swedish EPA, 2012b).

Table 22. Energy market prices for the year 2030.

		Scenario 2030		
Energy market price		Fragmented action	Global action	Reference scenario
Oil	EUR/barrel	97	60	83
Gas	EUR/MWh	34	26	
Coal	EUR/MWh	13	11	
Electricity	EUR/MWh	78	72	
Biomass (wood chips)	EUR/MWh	31	31	
CO_2	EUR/tonne	51	60	38

To achieve reliable results from an evaluation using prices based on energy market scenarios, the energy market parameters within a given scenario must be consistent, i.e. the energy prices must be related to each other (i.e. accounting for energy conversion technology characteristics and applying suitable substitution principles). Consequently, a systematic approach for constructing such consistent scenarios is facilitated by the use of a suitable calculation tool. For such purposes researchers at Chalmers University of Technology have developed the Energy Price and Carbon Balance Scenarios tool (the ENPAC tool) (Axelsson et al., 2009; Axelsson and Harvey, 2010). 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 CO_2. Based on these inputs, the probable marginal energy conversions technologies in key energy markets are determined, which in turn yield consistent values for energy prices and CO_2 emissions associated with marginal use of fossil fuels, electricity, wood fuel and heat for district heating.

Table 23 presents electricity and biomass prices generated by the ENPAC-tool when giving the fossil fuel prices and CO_2 emission prices presented in Table 22 as input. As can be seen in the table the consistent electricity and biomass prices generated by applying the tool differ somewhat compared to the electricity and biomass prices presented by the Swedish EPA (Swedish EPA, 2012c; Swedish EPA, 2012a).

The biomass prices are adapted for use in the BeWhere model using calibration factors for different assortments, and geographical factors for felling and residue harvesting. This will be described more in detail in the future work where these scenarios will be modelled.

Table 23. Energy market prices generated by applying the ENPAC-tool to the fossil fuel prices and CO_2 charges defined for the scenarios presented in Table 22.

		Scenario 2030		
Energy market price		Fragmented action	Global action	Comment
Oil	EUR/barrel	97	60	input data
CO_2	EUR/tonne	51	60	input data
Electricity	EUR/MWh	89	88	incl. cost for CO_2
Biomass (wood chips)	EUR/MWh	40	40	incl. cost for CO_2
Electricity	EUR/MWh	50	66	excl. cost for CO_2
Biomass (wood chips)	EUR/MWh	40	40	excl. cost for CO_2

5.5.2 Import and export of biomass and biofuels

Biomass and biofuels are traded today. For example, first generation ethanol from sugarcane or corn is imported and used in the transport sector today, Göteborg Energi has on occasion imported Canadian wood chips for fuel purposes and some Swedish pulp mills use e.g. Russian hardwood. The use of wood pellets for heating purposes has also increased during the last years and a large share of the pellets is imported. Yet, for some biomass fractions (mainly those with lower market value) there is not yet a fully working international market in place. By 2030, however, it can be assumed that the competition regarding biomass will have increased; something which ought to stimulate trade and development of larger markets also for the more low value segments.

The estimated levels of biofuel production (both first and next generation) presented in Section 5.2.3 are feasible to reach by using domestic raw materials only (Profu, 2011). Thus, if no other major changes occur in the biomass supply and demand compared to the present situation these levels of biofuels can be produces without any major changes in the import/export occurring for biomass and biofuels today. However, if the higher levels of next generation biofuels are to be reach at the same time as process industry is significantly increasing its biomass usage and if a restrictive scenarios regarding domestic biomass supply is assumed (see 5.3.1) biomass (or biofuels) might have to be imported. In the BeWhere model this is by handled import of suitable biomass (or biofuels) fractions through one of the main harbours points. Since an international market for biomass is not yet in place and thus hard to predict and model, import is only assumed to occur when the domestic biomass resources are insufficient. International markets, import and export of biomass and biofuels are parts which could be further developed when improving the model.

5.6 SUMMARY

As stated in the introduction to this Chapter, scenarios for different parts of the studied system can be combined into different roadmap scenarios and thereby describe different developments of the studied system and its surroundings. Table 24 presents three different roadmap scenarios constructed this way. Roadmap scenario 1 is composed to resemble Scenario 1 in the Swedish EPA's report "Roadmap 2050" (Swedish EPA, 2012c). Roadmap scenario 2 represents an alternative development with less biomass resources available (due to a larger share protected forest) but with a larger amount of biofuels in the transport system (partly due to a higher transport demand compared to Roadmap scenario 1). Finally Roadmap scenario 3 represents a more "business as usual" scenario with more restrictive assumptions compared to the other two scenarios. In the future modelling using the BeWhere model also other compositions of roadmap scenarios could be defined and modelled.

Table 24. The three roadmap scenarios

	Roadmap scenario 1	Roadmap scenario 2	Roadmap scenario 3
Population	Low	High	Low
Transport and transport fuel demand	Fossil free transport sector	Best available technology	Best available technology
Biomass resources	Development	Restrictive	Restrictive
Biomass utilisation in other sectors	Green process industry	Expansive forest industry	Conservative technology development
Import/Export	If needed	If needed	If needed
Energy market prices	Global action	Fragmented action	Fragmented action

6 CONCLUDING DISCUSSION

Ambitious targets for renewable motor fuels boost the interest in next generation biofuels, in particular in forest rich regions such as Sweden. Sweden has the ambition to be independent of fossil fuels in the transport sector in year 2030 and completely fossil free in the year 2050. Large production capacities and feedstock competition makes the geographic plant localisation important. In this report, the development of a techno-economic, geographically explicit biofuel production plant localisation model (BeWhere Sweden) has been presented together with scenarios regarding biomass supply potentials and biofuel demand.

The main objective for this report has been model and scenario development, with the overall aim of the BeWhere Sweden project being to identify 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.

Examples of model results from BeWhere Sweden have been shown. Those results must be considered as highly preliminary as many production technologies, feedstocks, biofuel types and plant sites are not considered at this stage of model development. However, from the preliminary results a number of parameters have been identified as important and some conclusions have been drawn:

- Biofuel production based on black liquor gasification (BLG) is heavily favoured, due mainly to the high conversion efficiency from external biomass to biofuel compared to the other technologies included here.
- Low requirement for external biomass input is important in the choice of plant location.
- If BLG plants are commercialised and installed, both the required number of production plants and the required amount of biomass feedstock are lower than if BLG is not considered.
- District heating systems do not constitute optimal plant locations with the base heat revenue levels assumed, even though the plants were assumed to be able to operate for the same number of hours each year as if integrated with industry. With higher heat revenues, solid biomass gasification with DME production could be introduced in district heating systems. If BLG is considered, however, extremely high heat revenues would be needed.
- When a biofuel target is set for Sweden overall, plant locations in the northern part of Sweden are typically favoured, which leads so saturation of the local biofuel markets and no biofuel use in the southern parts.
- When biofuel needs to be distributed to all parts of Sweden, the model selects a more even distribution of production plants, with plants also in the southern parts.
- Due to longer total transport distances and non-optimal integration possibilities, the total system cost is higher when all counties should fulfil the biofuel share target.
- The total annual cost to fulfil a biofuel target would be considerably lower with BLG in the system, as would the total capital requirement. This however presumes that alternative investments would otherwise be undertaken, such as investment in

new recovery boilers. Without alternative investments the difference between a system with BLG and a system without BLG would be less pronounced.

BeWhere Sweden has the potential for being a valuable tool for simulation and analysis of the Swedish energy system, including the industry and transport sectors. The model can be used to analyse different biofuel scenarios and estimate cost effective biofuel production plant locations, required investments and costs to meet a certain biofuel demand etc. Today, concerned ministries and agencies base their analyses primary on results from the models MARKAL[16] and EMEC[17], but none of these consider the spatial distribution of feedstock, facilities and energy demands. Sweden is a widespread country with long transport distances and where logistics and localisation of production plants are crucial for the overall efficiency. BeWhere Sweden considers this and may thus contribute with valuable input that can be used to complement and validate results from MARKAL and EMEC; thus testing the feasibility of these model results. This can be of value for different biofuel production stakeholders as well as for government and policy makers.

[16] MARKet Allocation, generic dynamic, process oriented optimisation model tailored by the input data to represent the evolution over a certain time period of a specific energy system. The model is a partial-equilibrium, bottom-up model with perfect foresight.

[17] Environmental Medium term EConomic model, computable general equilibrium model of the Swedish economy developed and maintained by the National Institute of Economic Research for analysis of the interaction between the economy and the environment.

7 FUTURE WORK

This report has described the first stages of model development of BeWhere Sweden. The integration possibilities have been limited to the forest industry and a few district heating networks, the feedstocks to biomass originating from the forest, and the number of biofuel production technologies to three gasification-based concepts and two hydrolysis- and fermentation-based concepts, neither of which is yet commercial on the scale assumed here.

Regarding input data, a number of areas in need of supplementing have thus been identified, before and during the work with this project. Examples are:

- Additional industries and plant sites, e.g. oil refineries and more district heating systems
- More detailed description of district heating systems, e.g. multiple time steps and production based heat pricing
- Other production technologies and biofuels, e.g. SNG, biogas, methanol, synthetic diesel
- Biofuel distribution, e.g. inclusion of gas distribution infrastructure
- Additional feedstocks, e.g. wood from thinning, agricultural feedstocks, other types of waste
- Import/export – quantity limits, prices and costs

Agricultural residues and energy crops for biogas production are considered to be a very important and interesting completion to the model. Furthermore, inclusion of intermediate products such as torrefied biomass, pyrolysis oil and lignin extracted from chemical pulp mills would make it possible to include new production chains that are currently of significant interest for technology developers.

Given the high relevance of bioresources globally and in Sweden, there is a strong and urgent need for new and comprehensive studies at the national level, and indeed global level, that fully address, in an integrated manner, the sustainable implementation potential for biomass resources; taking into account both global and local dynamics of all aspects affecting the forestry system.

During this work, a number of other important areas to improve the BeWhere Sweden model have also been identified. For example, an increased level of detail on the potential amounts, spatial distribution and costs of the feedstock are of great importance. The used transport cost model is rather simplified, with linear costs assumed and no volume restrictions, and would benefit greatly from improvements.

The quality of some input data and statistics may also be considered as highly uncertain. For example, with our knowledge about pulp and paper mills in general and some specific knowledge about certain mills, we can conclude that some of the mill specific data obtained from the SFIF's environmental database contains considerable errors. In the next phase of model development, further investigations in order to get better estimations of mill data will be included. This would strongly improve the model and ensure more reliable results. A more thorough mapping could also be used to identify and quantify existing onsite co-operations between for example sawmills and pulp mills, which has not always been captured by the input data used for this report.

Following the review of the existing literature of biomass resources it is also clear that there is a strong need for further development of data for biomass resource assessments, as well as data on current biomass use, to facilitate the identification of biomass resources still available for energy. Two levels of data development needs have been identified:

i. Data assessing the current production and use of biomass and bioenergy;
ii. Data needed to perform assessments of the current and future potential of biomass for energy;

Three overarching areas of data pertaining to biomass and bioenergy need to be augmented and improved:

i. Supply: including forestry and biomass processing industries;
ii. Demand: including the main demand sectors, i.e. heat and power generation (both domestic and large scale), saw mills and the pulp and paper industry and biofuel production;
iii. Trade: including imports and exports of all kinds of biomass and biofuels.

With the above mentioned improvements, the BeWhere Sweden model can be used for more comprehensive strategic system studies of future biofuel production. It will also be possible to use the model to analyse the effect of different policy instruments, such as CO_2 charges and biofuel production incentives, which makes it highly relevant for policy makers and government. It would also be highly interesting and valuable to add quantitative measures of the economic and social dimensions as a modelling output (i.e. required work force, creation of new job opportunities etc.).

The roadmap scenarios constructed within this project will be used as a starting point for the utilisation of BeWhere Sweden. The scenarios will be implemented into the model and analysed, with focus on implementability and feasibility.

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[18], BeWhere Sweden could also be used to provide results of value for EU policies and strategies.

[18] Global model that is used to analyse the competition for land use between agriculture, forestry, and bioenergy. Developed and operated at Ecosystems Services and Management, IIASA.

8 REFERENCES

Akgul, O., Zamboni, A., Bezzo, F., Shah, N., Papageorgiou, L.G. (2010). Optimization-Based Approaches for Bioethanol Supply Chains. *Industrial & Engineering Chemistry Research* 50(9), 4927-4938.

Alex Marvin, W., Schmidt, L.D., Benjaafar, S., Tiffany, D.G., Daoutidis, P. (2012). Economic Optimization of a Lignocellulosic Biomass-to-Ethanol Supply Chain. *Chemical Engineering Science* 67(1), 68-79.

Axelsson, E., Harvey, S. (2010). *Scenarios for assessing profitability and carbon balances of energy investments in industry*. AGS Pathways report 2010:EU1, Pathways to sustainable european energy systems – AGS, the Alliance for Global Sustainability, Göteborg.

Axelsson, E., Harvey, S., Berntsson, T. (2009). A tool for creating energy market scenarios for evaluation of investments in energy intensive industry. *Energy* 34(12), 2069-2074.

BEE (2010). *Status of Biomass Resource Assessments, Version 3*. Rettenmaier, N., Schorb, A. Köppen, S., Biomass Energy Europe Project, Heidelberg.

Berglin, N., Björk, M., Hägglund, A. (2009). *Ethanol from wood via alkaline fractionation – pilot plant trials*. Presentation at Etanolprogrammets konferens 2009, Stockholm.

Berndes, G., Hoogwijk, M., van den Broek, R. (2003). The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy* 25(1), 1-28.

Brolin, M., Böhlmark, E. (2011). *Energikombinat – en studie inom Carpe Futurum*. MSc thesis, LIU-IEI-TEK-A - 11/01090--SE. Division of Energy Systems, Linköping University, Linköping.

Brännlund, R., Lundmark, R., Söderholm, P. (2010). *Kampen om skogen – koka, såga, bränna eller bevara? (in Swedish)*. Stockholm, SNS Förlag.

Börjesson, M., Ahlgren, E.O. (2012). Modelling transport fuel pathways: Achieving cost-effective oil use reduction in passenger cars in Sweden. *Technological Forecasting and Social Change* 79(5), 801-818.

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

Center for International Earth Science Information Network (CIESIN) (2011). *Global Rural-Urban Mapping Project, version 1 (GRUMPv1): Settlement Points*. Center for International Earth Science Information Network (CIESIN)/Columbia University, International Food Policy Research Institute (IFPRI), The World Bank Centro Internacional de Agricultura Tropical (CIAT). Palisades, NY, USA, NASA Socioeconomic Data and Applications Center (SEDAC). Available at: http://sedac.ciesin.columbia.edu/data/set/grump-v1-settlement-points.

Dahlroth, B. (2009). *Öppnade fjärrvärmenät i Storstockholm (in Swedish)*. E.ON, Fastighetsägarna, Vattenfall, Stockholm.

Danielsson, B.-O. (2003). *Uppskattning av sågverkens produktion av trädbränslen inom mål 1-området i Dalarna-Gävleborg (in Swedish)*. Bioenergi i WX Mål 1. Ett strukturfondsprojekt inom Mål 1, Södra skogslänsregionen. Projektbilaga 2, GDE-Net.

Delin, L., Berglin, N., Lundström, A., Samuelsson, Å., Backlund, B., Sivard, Å. (2005a). *Bleached market kraft pulp mill, Reference and type mill, FRAM 09*. STFI-Packforsk, Stockholm, Sweden.

Delin, L., Berglin, N., Samuelsson, Å., Lundström, A., Backlund, B., Sivard, Å., Åberg, M. (2005b). *Kraftliner mill, FRAM 11*. STFI-Packforsk, Stockholm, Sweden.

Difs, K., Wetterlund, E., Trygg, L., Söderström, M. (2010). Biomass gasification opportunities in a district heating system. *Biomass and Bioenergy* 34(5), 637-651.

Djuric Ilic, D., Dotzauer, E., Trygg, L. (2012). District heating and ethanol production through polygeneration in Stockholm. *Applied Energy* 91(1), 214-221.

Dotzauer, E. (2012). *Production data Fortum*. Personal communication (August 2012).

EKAN-gruppen (2010). *Fastigheten Nils Holgerssons underbara resa genom Sverige – En avgiftsstudie (in Swedish)*. Nils Holgersson-gruppen, Stockholm.

European Commission (1992 (updated 2007)). *Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*.

European Commission (2010). *European Reference Life Cycle Database (ELCD)* European Commission, Joint Research Centre, Available at: http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm (2010-07-24).

Fahlén, E., Ahlgren, E.O. (2009). Assessment of integration of different biomass gasification alternatives in a district-heating system. *Energy* 34(12), 2184-2195.

Gode, J., Martinsson, F., Hagberg, L., Öman, A., Höglund, J., Palm, D. (2011). *Environmental facts 2011. Estimated emission factors for fuels, electricity, heat and transport in Sweden (Miljöfaktaboken 2011, in Swedish)*. Report 1183, Värmeforsk, Stockholm.

Hellmann, F., Verburg, P.H. (2011). Spatially explicit modelling of biofuel crops in Europe. *Biomass and Bioenergy* 35(6), 2411-2424.

Isaksson, J., Pettersson, K., Mahmoudkhani, M., Åsblad, A., Berntsson, T. (2012). Integration of biomass gasification with a Scandinavian mechanical pulp and paper mill – Consequences for mass and energy balances and global CO_2 emissions. *Energy* 44(1), 420-428.

IVL (2010). *Biobaserade drivmedel: analys av potential, förutsättningar marknad, styrmedel och risker. möjligheter och risker - projektet BIODRIV. Slutrapport*. IVL Rapport B1884, Göteborg.

Johansson, J., Mortazavi, R. (2011). *Transport av skogsenergisortiment - Företags- och samhällsekonomiska kostnader (in Swedish)*. Projekt SWX-Energi, rapport nr 17.

Kim, J., Realff, M.J., Lee, J.H., Whittaker, C., Furtner, L. (2011). Design of biomass processing network for biofuel production using an MILP model. *Biomass and Bioenergy* 35(2), 853-871.

Kindermann, G.E., Schörghuber, S., Linkosalo, T., Sanchez, A., Rammer, W., Seidl, R., Lexer, M.J. (2013). Potential stocks and increments of woody biomass in the European

Union under different management and climate scenarios. *Carbon Balance and Management* 8(2), doi:10.1186/1750-0680-1188-1182.

Kraxner, F., Aoki, K., Leduc, S., Kindermann, G., Fuss, S., Yang, J., . . . Obersteiner, M. (2012). BECCS in South Korea – Analyzing the negative emissions potential of bioenergy as a mitigation tool. *Renewable Energy*, In press, http://dx.doi.org/10.1016/j.renene.2012.1009.1064.

Landälv, I., Granberg, F., Nelving, H. (2010). Production of Di Methyl Ether from Kraft Black Liquor for Use in Heavy Duty Trucks. International Chemical Recovery Conference, 29 March - 1 April Williamsburg, Virginia, USA, Volume 2, pp. 179-186.

Leduc, S. (2009). *Development of an Optimization Model for the Location of Biofuel Production Plants*. PhD thesis. Division of Energy Engineering, Luleå University of Technology, Luleå.

Leduc, S., Lundgren, J., Franklin, O., Dotzauer, E. (2010). Location of a biomass based methanol production plant: A dynamic problem in northern Sweden. *Applied Energy* 87(1), 68-75.

Leduc, S., Natarajan, K., Dotzauer, E., McCallum, I., Obersteiner, M. (2009). Optimizing biodiesel production in India. *Applied Energy* 86(SUPPL. 1), S125-S131.

Leduc, S., Schwab, D., Dotzauer, E., Schmid, E., Obersteiner, M. (2008). Optimal location of wood gasification plants for methanol production with heat recovery. *International Journal of Energy Research* 32(12), 1080-1091.

Lehtonen, A., Anttila, P., Puolakka, P. (2010). *Biomass Energy Europe: Illustration Case for Finland*. D 6.1 - Annex III, Metla, Finland.

Mantau, U. (2005). *Development of methods to generate market information and linkages between biomass supply and demand*. INFRO - Information Systems for Resources, Hamburg.

Mantau, U., Steierer, F., Hetsch, S., Prince, C. (2008). *Wood resources availability and demands - Part 1 National and regional wood resource balances 2005*. United Nations Economic Commission for Europe (UNECE), Geneva.

Natarajan, K., Leduc, S., Pelkonen, P., Tomppo, E., Dotzauer, E. (2012). Optimal Locations for Methanol and CHP Production in Eastern Finland. *BioEnergy Research* 5(2), 412-423.

Nilsson, Å. (2011). *Befolkningsprognos för Sverige 2011-2040 (in Swedish)*. Demografikonsulten, Upplands Väsby.

Nohlgren, I., Lundqvist, P., Liljeblad, A., Hylander, N. (2010). *Förutsättningar för svensk produktion av Fisher-Tropsch diesel (A general feasability study on the production of Fisher-Tropsch motor-fuels from biomass in Sweden) (in Swedish)*. Report No. 320497-01, Ångpanneföreningens forskningsstiftelse.

Nord Pool (2012). *Nord Pool spot prices*, Available at: http://www.nordpoolspot.com/Market-data1/Elspot/ (January 2013).

Paulrud, S., Lundgren, J., Jonsson, Å. (2010). *Framtida behov och system för småskalig värmeproduktion med biobränsle (in Swedish)*. Slutrapport till Energimyndigheten, IVL.

Pettersson, K., Harvey, S. (2012). Comparison of black liquor gasification with other pulping biorefinery concepts – Systems analysis of economic performance and CO2 emissions. *Energy* 37(1), 136-153.

Pettersson, K., Mahmoudkhani, M., von Schenck, A. (2012). *Opportunities for biorefineries in the pulping industry*. Systems Perspectives on Biorefineries, Björn A. Sandén (ed.), pp. 48-58.

Profu (2011). *Fossilbränsleoberoende transportsektor 2030 – hur långt når fordonstekniken?* Slutrapport, Profu.

Sandebring, H. (2004). *Slutbetänkandet från utredningen om förnybara fordonsbränslen: Introduktion av förnybara fordonsbränslen*. Statens offentliga utredningar (SOU) 2004:133.

Sassner, P. (2007). *Lignocellulosic Ethanol Production based on Steam Pretreatment and SSF – Process Development through Experiments and Simulations*. PhD thesis. Department of Chemical Engineering, Lund University, Lund.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E. (2010a). Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. *Applied Energy* 87(7), 2128-2141.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E. (2010b). Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. *International Journal of Energy Research* 34(11), 970-985.

Schmidt, J., Leduc, S., Dotzauer, E., Schmid, E. (2011). Cost-effective policy instruments for greenhouse gas emission reduction and fossil fuel substitution through bioenergy production in Austria. *Energy Policy* 39(6), 3261-3280.

SDC (2011). *Skogsindustrins virkesförbrukning samt produktion av skogsprodukter 2007-2011 (in Swedish)*. SDC, Uppsala.

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

SFIF (2012b). *Skogsindustriernas miljödatabas (in Swedish)*, Swedish Forest Industries Federation (March 2012).

Skogforsk (2012). *Skogsbränslets metoder, sortiment och kostnader 2011 (in Swedish)*, Skogforsk nr. 10.

Smeets, E., Lemp, D., Dees, M. (2010). *Methods & Data Sources for Biomass Resource Assessments for Energy*. Utrecht University.

SOU (2007). *Bioenergi från jordbruket - en växande resurs*. Statens offentliga utredningar (SOU) 2007:36.

SPI (2013). *Price statistics*, Svenska Petroleum och Biodrivmedel Institutet, Available at: http://spbi.se/statistik/priser/ (February 2013).

Statistics Sweden (2009). *The future population of Sweden 2009–2060 (in Swedish)*. Demographic reports 2009:1, Örebro.

Statistics Sweden (2013a). *Folkmängd efter tid*, Statistikdatabasen: Befolkning: Befolkningsstatistik (2013-02-11).

Statistics Sweden (2013b). *Slutanvändning (MWh), efter region, förbrukarkategori och bränsletyp, år 2009-2010*, Statistikdatabasen: Energi: Kommunal och regional energistatistik (January 2013).

Svebio (2011). *Biokraftkartan 2011*, Available at: http://www.svebio.se/publikationer/biokraftkartan-2011 (October 2012).

Swedish District Heating Association (2012). *Statistics over fuels and deliveries in Swedish district heating systems 2008-2010*, Available at: http://www.svenskfjarrvarme.se/Statistik--Pris/Fjarrvarme/Energitillforsel/ (August 2012).

Swedish Energy Agency (2011a). *Facts and Figures 2011 (Energiläget i siffror 2011)*. ET 2011:42, Swedish Energy Agency, Eskilstuna.

Swedish Energy Agency (2011b). *Transportsektorns energianvändning 2010 (in Swedish)*. ES 2011:05, Swedish Energy Agency, Eskilstuna.

Swedish Energy Agency (2012a). *Facts and Figures 2012 (Energiläget i siffror 2012)*. ET 2012:34, Swedish Energy Agency, Eskilstuna.

Swedish Energy Agency (2012b). *Wood fuel- and peat prices (Trädbränsle- och torvpriser)*, Eskilstuna, Swedish Energy Agency and Örebro, Statistics Sweden, No. 3 / 2012.

Swedish EPA (2012a). *Sektorsunderlag industri – Underlag till Färdplan 2050 (in Swedish)*. Report no. 6537, Swedish Environmental Protection Agency, Stockholm.

Swedish EPA (2012b). *Underlag till en färdplan för ett Sverige utan klimatutsläpp 2050 - Bilagor till rapport 6537 (in Swedish)*. Report no. 6525, Swedish Environmental Protection Agency, Stockholm.

Swedish EPA (2012c). *Underlag till en färdplan för ett Sverige utan klimatutsläpp 2050 (in Swedish)*. Report no. 6537, Swedish Environmental Protection Agency, Stockholm.

Swedish Forest Agency (2011). *Skogsstatistisk årsbok 2011 (Swedish Statistical Yearbook of Forestry 2011)*. Swedish Forest Agency, Jönköping.

Swedish Forest Agency (2012). *Skogsstatistisk årsbok 2012 (Swedish Statistical Yearbook of Forestry 2012)*. Swedish Forest Agency, Jönköping.

Thuresson, T. (2010). *Bioenergi från skog – Uppdaterad bedömning av potentialer och förutsättningar för svenskt Skogsbruk att producera främst primära Skogsbränslen - vintern 2009/2010 (in Swedish)*. Zephyr Skogskonsult, Kumla.

Tomani P, Berglin N, Axegård P (2009). *The LignoBoost process and use of lignin as a new biofuel*. Proceedings of TAPPI Engineering, Pulping and Environmental Conference, Memphis, TN.

Trafikverket (2012). *Delrapport transporter - underlag till färdplan 2050*. Report no. 2012:224, Trafikverket.

Wetterlund, E., Leduc, S., Dotzauer, E., Kindermann, G. (2012). Optimal localisation of biofuel production on a European scale. *Energy* 41(1), 462-472.

Wetterlund, E., Leduc, S., Dotzauer, E., Kindermann, G. (2013). Optimal use of forest residues in Europe under different policies—second generation biofuels versus combined heat and power. *Biomass Conversion and Biorefinery* 3(1), 3-16.

Wingren, A. (2005). *Ethanol from Softwood – Techno-economic evaluation for development of enzymatic process*. PhD thesis. Department of Chemical Engineering, Lund University, Lund.

von Schenck, A., Axelsson, E., Berglin, N. (2007). *System study of ethanol production in a pulp mill converted to a biorefinery*. Swedish Energy Agency Project no. P30141-1, STFI-Packforsk report no. 266.

World Watch Institute (2007). *Biofuels for transport – global potential and implication for sustainable energy and agriculture*. London, Earthscan.

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[19] and has been used for regional, national and European studies.

BeWhere Sweden[20] 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 50 x 50 km). 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 specific points are shown in Figure A- 2.

[19] BeWhere homepage at IIASA: www.iiasa.ac.at/bewhere. Current Swedish members of the IIASA BeWhere team are Elisabeth Wetterlund (Linköping University) and Erik Dotzauer (Fortum / Mälardalen University).
[20] BeWhere Sweden homepage: www.liu.se/bewhere

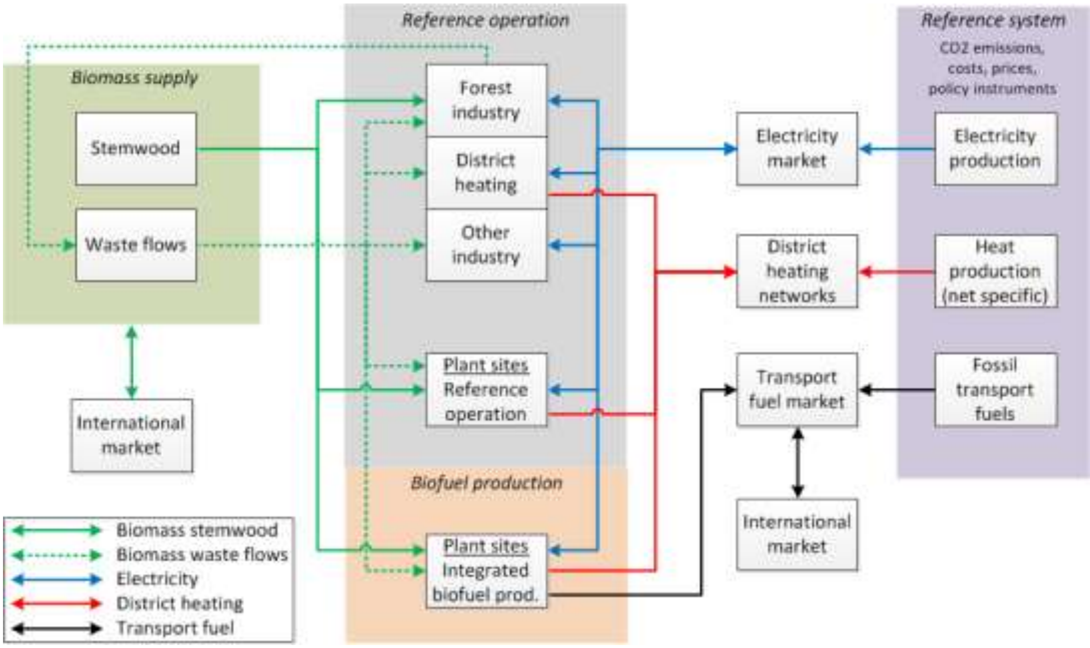


Figure A- 1. Graphical overview of the main flows in BeWhere Sweden.

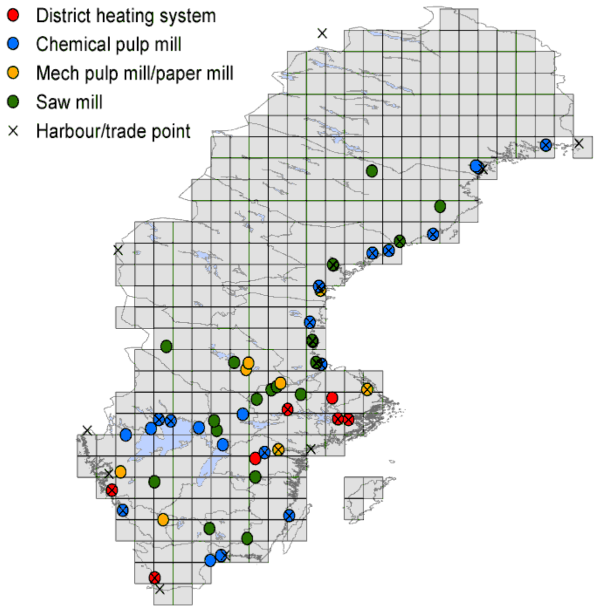


Figure A- 2. BeWhere Sweden grid division, plant sites and harbours.

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.

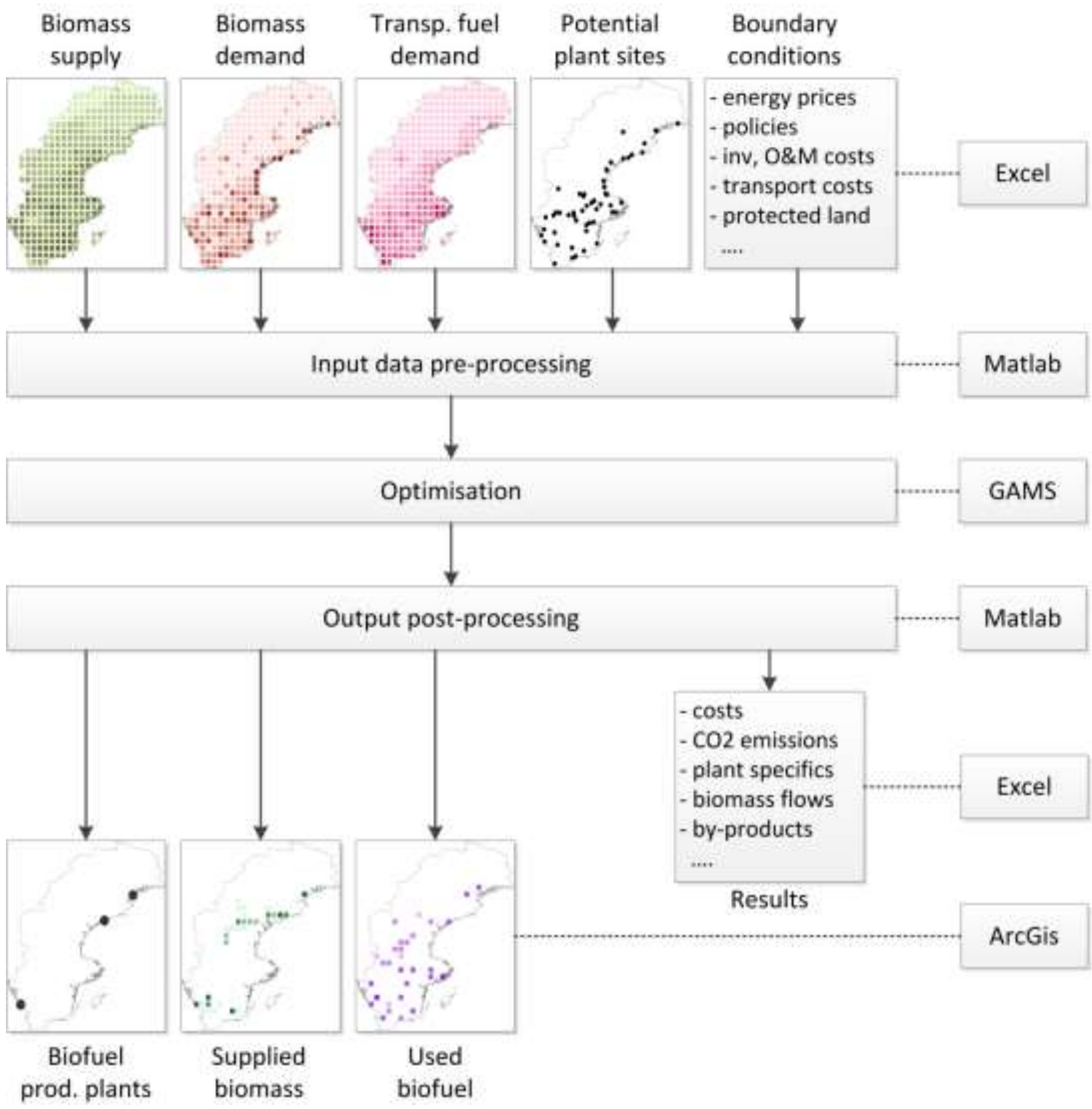


Figure A- 3. Overview of the model architecture and workflow, as well as the software used for each step.

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. FOREST BIOMASS COST CALCULATIONS

COST STRUCTURE

The harvesting of forest resources is a series of operations that are relatively straightforward and does not require exceedingly complex procedures. Therefore, the harvesting is technically feasible in a wide range of production configurations, including manual chain-saw fellings as well as sophisticated, high-volume mechanised fellings. Along with the set of feasible technical configurations, the per-unit harvesting production cost also varies.

Following the economic-engineering approach in estimating the cost structure for each type of forest resource, three procedural steps were followed. These steps include: (1) a description of the using harvesting system, including a specification of alternative techniques that are technically feasible; (2) estimation of the productivity functions for each stage of the harvesting process, and accumulation of the productivity functions into a production function and; (3) calculation of the harvesting cost functions by applying input factor prices. Thus, the harvesting costs for each forest resource are calculated from the combination of estimated productivity functions and average input factor prices.

The analysis of the cost structure is carried out through the estimation of harvesting costs using harvester-forwarder technology. That is, the same harvesting technology is assumed to be used in all harvesting operations. Technical harvesting conditions vary widely and the variations are reflected in the productivity and cost of the work. The effects of cost factors associated with the operating environment depend on the scale of operation, the technology applied, and the source and quality requirements. The effect of factors such as stand conditions and transportation distances most be known for a number of reasons: (1) to identify the most advantageous stands for production; (2) to estimate the change in costs when demand increases or quality requirements are tightened; (3) to focus on the key problems in machine and method development; and (4) to collect relevant material for practitioners for decision making.

For each category of forest resources, i.e., wood (logs) and forest residues, the economic-engineering approach was used to develop a total cost per unit of output. No subsequent transportation beyond road-side delivery by the forwarders is included at this point (see Section 3.9). In general, four stages are defined in the harvesting process. The stages include: (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.

Standard economic cost procedures were used to calculate the total cost functions, including a long term fixed cost component and variable operating cost. The cost functions represent the underlying cost structure and emphasize the importance of geography (terrain), type of forest resource, technology and the management regime on the competitiveness of the industry sectors using forest resources as a feedstock. Fixed costs include capital costs, depreciation and maintenance of machinery and equipment. Machinery and equipment investment costs are based on the purchase of new machinery and equipment without consideration of the cost and availability of used equipment. A straight line depreciation method is used to calculate depreciation cost of the machinery and equipment to be fully depreciated over a useful life of ten years with zero salvage value. This approach represents a maximum depreciation cost estimate since major components of machinery and equipment will have a useful life of more than ten years (or have a positive salvage value at the end of ten years). Annual maintenance cost was calculated at 2% of the initial machinery and equipment investment cost. Variable operating costs include labour, additive materials and overhead costs and are synthesized from the component productivity.

A harvesting residue production system is built around the chipping component. The position of the chipper or crusher in the procurement chain largely determines the state of residues during transportation and consequently whether subsequent machines are dependent on each other. Chipping may take place at the source, at the road-side or landing (at a terminal) or at the plant where the chips are to be used. Road-side chippers do not operate off-road and can therefore be heavier, stronger and more efficient than terrain chippers. Therefore, the production of forest residues is assumed to be chipped at road-side. Transportation to the end-users is covered in Section 3.9.

COST CALCULATIONS

The cost calculations have been done in SEK, with subsequent conversion of the results into EUR (2010). Values for all exogenous variables are given in Table B- 1.

Total cost for final felling

Total harvesting costs (TC^{Log}) per unit of output final felling and for road-side delivery are calculated based on labour costs per unit $\left(C_L^{Log}\right)$; capital costs per unit $\left(C_K^{Log}\right)$; fuel and material costs per unit $\left(C_M^{Log}\right)$ and; overhead costs per unit (C_{OH}), which are expressed as a percentage of the other costs.

$$TC^{Log} = C_L^{Log} + C_K^{Log} + \overline{C_M^{Log}} + \overline{C_{OH}}$$

Labour cost final felling

The labour costs for harvesting a m^3 of stem in the final felling operation can then be expressed as:

$$C_L^{Log} = \overline{w}\left(\frac{1}{\rho^H}\right) + \overline{w}N_F^{Log}$$

where *w* is the industry specific wage rate, N_F^{Log} is the number of forwarders needed and ρ^H is productivity of harvesters and can be expressed as (Brunberg, 1995):

$$\rho^H = \frac{6000\overline{dt}}{\overline{sut} + 56V_{average}^{Log} + 80\overline{pt}}$$

where *dt* is down-time per hour; *sut* is set-up time between trees; *pt* is the share of problem trees; $V_{average}^{Log}$ is the average log volume.

Based on Marklund (1988) biomass functions and the actual distribution of harvested tree types the following log volume function has been constructed:

$$V_{Pine}^{Log} = \frac{1.116}{1000} e^{11.3264\left(\frac{d_{Pine}}{d_{Pine}+13}\right)-2.3388}$$

$$V_{Spruce}^{Log} = \frac{1.116}{1000} e^{11.3341\left(\frac{d_{Spruce}}{d_{Spruce}+14}\right)-2.0571}$$

$$V_{Birch}^{Log} = \frac{1.116}{1000} e^{11.0735\left(\frac{d_{Birch}}{d_{Birch}+8}\right)-3.0932}$$

where V_X^{Log} is the timber volume and *d* is the average diameter of harvested timber in final felling of pine, spruce and birch respectively. The first term in the volume functions is transforming the unit from kg to m^{3}ub.

The weighted average of timber volume where $V_{average}^{Log}$ can be calculated as:

$$V_{average}^{Log} = \%_{Pine} V_{Pine}^{Log} + \%_{Spuce} V_{Spruce}^{Log} + \%_{Birch} V_{Birch}^{Log}$$

Given the harvester productivity and the average volume of logs the number of trees cut per hour (N^{Log}) can be expressed as:

$$N^{Log} = \frac{\rho^H}{V_{average}^{Log}}$$

For simplicity it is assumed that sufficient numbers of forwarders are used to keep up with the harvesters. The number of forwarders needed can be expressed as:

$$N_F^{Log} = \frac{\rho^H}{\rho^F}$$

where N_F^{Log} is the number of forwarders needed to keep up with the harvesters in collecting logs. The productivity of forwarders (ρ^F) can be expressed as:

$$\rho^F = \frac{\overline{kf} * \overline{sf}}{df}$$

where *kf* is the average rated capacity of forwarders; *sf* is average working speed of forwarders; *df* is the average terrain traveling distance measured by the inverse of the kilometre of roads in the grid.

Capital cost final felling

The unit capital cost can be expressed as:

$$C_K^{Log} = \left(\frac{\bar{\delta}}{8760}\right)\left(\frac{1}{\rho^H} * \overline{K_H} + N_F^{Log} * \overline{K_F}\right)$$

Where K_H and K_F is the capital cost (purchase price) of a harvester and a forwarder respectively. The first term in the capital cost function is the hourly depreciation of the capital equipment since the productivity variables are expressed in m^{3}ub per hour.

Total cost for extracting forest residues

Total costs (TC^{Res}) per unit of output and for road-side delivery are calculated based on labour costs per unit (C_L^{Res}); capital costs per unit (C_K^{Res}); fuel and material costs per unit (C_M^{Res}) and; overhead costs per unit (C_{OH}), which are expressed as a percentage of the other costs.

$$TC^{Res} = C_L^{Res} + C_K^{Res} + \overline{C_M^{Res}} + \overline{C_{OH}}$$

Labour cost forest residues

The construction of the unit labour functions for forest residues follows the same principal as for logs harvesting. However, the number of chippers needed $\left(N_C^{Res}\right)$ and their capital costs (purchase price) is now also included in the functions.

$$C_L^{Res} = \overline{w}N_F^{Res} + \overline{w}N_C^{Res}$$

The extra number of forwarders needed to collect the forest residues are calculated with the same principle as for log harvesting. It is assumed that a sufficient number of forwarders are used to keep up with the production of residues from the harvester.

$$N_F^{Res} = \frac{V_{average}^{Res}}{\rho^F}$$

where N_F^{Res} is the number of forwarders needed to keep up with the harvesters in collecting forest residues. The technology assumed for forest residues is that the residues are chipped at road-side. Therefore, it is important to include the cost of chippers in the cost calculation. For simplicity it is assumed that the productivity of the chippers is exogenous. The number of chippers needed to keep up with the volume brought back with the forwarders can be expressed as:

$$N_C^{Res} = \frac{V_{average}^{Res}}{\overline{\rho^C}}$$

where N_C^{Res} is the number of chippers needed and ρ^C is the productivity of the chippers. The number of chippers is calculated based on the residue volume harvested and the productivity of the chippers, which is assumed to be exogenous.

The biomass functions for forest residues are also estimated by Marklund (1988) and are calculated from the following functions, which have been modified to reflect that residues can only be collected from harvested trees:

$$V_{Pine}^{Res} = \frac{3.34N^{Log}}{1000}e^{9.1015\left(\frac{d_{Pine}}{d_{Pine}+10}\right)-2.8604}$$

$$V_{Spruce}^{Res} = \frac{3.34N^{Log}}{1000}e^{8.5242\left(\frac{d_{Spruce}}{d_{Spruce}+13}\right)-1.2804}$$

$$V_{Birch}^{Res} = \frac{3.34N^{Log}}{1000}e^{10.2806\left(\frac{d_{Birch}}{d_{Birch}+10}\right)-3.3633}$$

where the V^{Res} indicate the volume of forest residues from pine, spruce and birch respectively.

Capital cost forest residues

The unit capital cost can be expressed as:

$$C_K^{Res} = \left(\frac{\bar{\delta}}{8760}\right)\left(N_F^{Res} * \overline{K_F} + N_C^{Res} * \overline{K_C}\right)$$

where K_C and K_F is the capital cost (purchase price) of a chipper and a forwarder respectively. The first term in the capital cost function is the hourly depreciation of the capital equipment since the productivity variables are expressed in m^3ub per hour.

SPATIALLY EXPLICIT DATA SET

IIASA's Global Forest Model (G4M) was used to give the share of different tree species (pine, spruce and birch, respectively) for each grid cell (for a description, see (Kindermann et al., 2013)). From the Swedish Statistical Yearbook of Forestry (Swedish Forest Agency, 2011) data on average diameters for each tree species in different parts of the country was obtained and down-scaled to the model grid. The average terrain travelling distance for each grid cell was estimated from the road density in each cell.

Table B- 1. Assumed values of exogenous variables

	Notation	Final felling (FF)	Commercial thinning (CT)
Material cost final felling (SEK per m^3ub)	C_M^{Log}	40	40
Overhead costs (%)	C_{OH}	20	20
Gross wage including social fees (SEK/h)	w	134.4	134.4
Set-up time harvester	sut	0.2	0.3
Down-time per hour (%)	dt	15	20
Share of problem trees (%)	pt	0.14	0.16
Capacity forwarder (m^3ub)	kf	6.22	6.22
Working speed forwarder (km/h)	sf	5	5
Depreciation rate (%)	δ	10	10
Capital cost harvester (SEK)	K^H	4,250,000	4,250,000
Capital cost forwarder (SEK)	K^F	3,187,500	3,187,500
Material cost forest residue harvesting (SEK/m^3ub)	C_M^{Res}	55	55
Capital cost chipper (SEK)	K^C	585,000	585,000
Productivity chipper (m^3ub/hour)	ρ^C	35	35
Average diameter of pine timber	d_{Pine}	Data set	Data set
Average diameter of spruce timber	d_{Spruce}	Data set	Data set
Average diameter of birch timber	d_{Birch}	Data set	Data set
Share of pine in grid cell	$\%_{Pine}$	Data set	Data set
Share of spruce in grid cell	$\%_{Spruce}$	Data set	Data set
Share of birch in grid cell	$\%_{Birch}$	Data set	Data set
Terrain traveling distance	df	Data set	Data set

APPENDIX C. DATA FOR BIOFUEL PLANT SITES

This appendix presents the data for the biofuel plant sites and explains the integration between the biofuel production technologies and the biofuel plant sites more in detail.

Table C- 1 presents name, type and id number for the different biofuel plant sites considered at this stage of model development.

Table C- 1. Name, type and id number for the different biofuel plant sites.

Name	Type	Id nr
Södra Cell Mörrum, Karlshamn	Chemical pulp mill (market)	10
Södra Cell Mönsterås, Kalmar	Chemical pulp mill (market) (+sawmill)	32
Södra Cell Värö, Varberg	Chemical pulp mill (market) (+sawmill)	33
Billerud Skärblacka, Norrköping	Chemical pulp mill (integrated)	79
Munksjö Aspa Bruk, Askersund	Chemical pulp mill (market)	96
Munksjö Paper, Billingsfors	Chemical pulp mill (market/integrated)	97
Nordic Paper Bäckhammar, Kristinehamn	Chemical pulp mill (market/integrated)	101
Stora Enso Packaging, Skoghall	Mechanical/Chemical pulp mill (integrated)	116
Billerud Gruvöns Bruk, Grums	Chemical pulp mill (integrated) (+sawmill)	118
Korsnas Frövi, Lindesberg	Chemical pulp mill (integrated)	121
Stora Enso Pulp, Skutskärs Bruk	Chemical pulp mill (market)	158
Korsnas Gävle	Chemical pulp mill (integrated)	160
Vallviks Bruk, Söderhamn	Chemical pulp mill (market)	175
Holmen Iggesunds Bruk, Hudiksvall	Chemical pulp mill (integrated) (+sawmill)	186
SCA Östrands Massafabrik, Timrå	Mechanical/chemical pulp mill (market) (+sawmill)	209
Mondi Dynäs AB, Väja	Chemical pulp mill (integrated)	222
M-real Sverige Husum, Örnsköldsvik	Chemical pulp mill (integrated)	240
SCA Packaging Obbola, Umeå	Chemical pulp mill (integrated) (+sawmill)	243
SCA Packaging Munksund, Piteå	Chemical pulp mill (integrated) (+sawmill)	309
Smurfit Kappa Kraftliner, Piteå	Chemical pulp mill (integrated)	310
Billerud Karlsborg, Kalix	Chemical pulp mill (market/integrated)	330
Stora Enso Publication Paper, Hylte Bruk	Mechanical pulp mill (integrated)	31
Holmen Braviken, Norrköping	Mechanical pulp mill (+sawmill)	80
SCA, Edet Bruk, Lilla Edet	Paper	64
Holmen Hallsta, Hallstavik	Mechanical pulp mill (integrated)	141
Stora Enso Fors, Avesta	Mechanical pulp mill (integrated)	143
Stora Enso Kvarnsveden	Mechanical pulp mill (integrated)	157
Grycksbo Paper	Paper	159
SCA Ortvikens Pappersbruk, Sundsvall	Mechanical pulp mill (integrated)	208
Södra Timber Långasjö	Sawmill	19
Vida Vislanda, Alvesta	Sawmill	30
Vida Borgstena	Sawmill	61
Södra Timber, Kisa	Sawmill	62
Setra Hasselfors, Laxå	Sawmill	98
Moelven Valåsen, Karlskoga	Sawmill	117
Setra Skinnskatteberg	Sawmill	137
Setra Heby	Sawmill	139
Karbenning Sågverk & Hyvleri, Norberg	Sawmill	140

Table C- 1, continued.

Karl Hedin, Krylbo	Sawmill	142
Bergkvist-Insjön	Sawmill	161
Setra Kastet, Gävle	Sawmill	162
Fiskarhedens Trävaru, Transtrand	Sawmill	174
Stora Enso Timber, Ljusne	Sawmill	176
SCA Timber, Bollsta Sågverk	Sawmill	223
SCA Timber, Rundviks Sågverk	Sawmill	242
Martinsons Såg, Bygdsiljum	Sawmill	276
Setra Malå	Sawmill	292
Göteborg	District heating	45
Linköping	District heating	78
Sthlm city-söder	District heating	119
Sthlm nordvästra	District heating	120
Uppsala	District heating	138

In the explanations below on how the integration between the different technologies and the different plant sites are done, some equations are used. Table C- 2 shows the biofuel technologies with used designations.

Table C- 2. Energy balances for the different biofuel technology cases based on one unit of fuel input.

		BMG-DME	BLG-DME (-BB)[a]	BLG-DME (-BMG-DME)[a]	ALK-HF-EtOH	SE-HF-EtOH
Fuel input		1	1	1	1	1
Biofuel	n_{bf}	0.34	0.55	0.55	0.27	0.28
Excess heat – steam	n_{ehs}	0.15	0.26	0.30	0.16	0.15
Excess heat – DH	n_{ehdh}	0.04	–	–	–	0.07
Purge gas	n_{pg}	–	0.11	–	–	–
Electricity production	n_{el}					
Gas turbine		0.12	–	0.03	–	–
Back-pressure ST		0.05	–	0.01	0.08	0.10
Condensing ST[b]		0.04	–	-	0.04	0.04
Electricity use	n_{elu}	0.06	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 plants have different sizes in relation to the BLG-DME plant depending on the specific mill.
[b] This is in case the excess steam is not used for heating purposes.

CHEMICAL PULP MILLS

Table C- 3 includes data extracted for chemical pulp mills from SFIF's environmental database (SFIF, 2012b).

Table C- 3. Data extracted for chemical pulp mills from SFIF's environmental database.

Id nr	Total kraft pulp production [1000 Adt/y]	Unbleached kraft pulp production [1000 Adt/y]	Other pulp production [1000 Adt/y]	Total wood fuel used (incl. black liquor) [GWh/y]	Fossil fuels used [GWh/y]	Electricity produced [GWh/y]
9	0	0	336	1,936	157	256
10	405	0	0	2,973	230	338
32	708	0	0	5,581	239	773
33	430	0	0	3,098	62	393
79	316	156	60	1,928	106	224
96	175	0	0	1,136	55	70
97	61	61	0	374	65	23
100	0	0	40	149	9	0
101	196	196	0	1,026	62	123
116	302	146	237	2,504	236	384
118	385	0	209	3,525	131	280
121	259	148	0	1,739	77	184
158	513	0	0	3,739	41	328
160	625	305	0	2,876	36	0
175	184	54	0	1,389	39	115
186	322	0	0	2,252	213	210
209	409	0	90	3,403	299	439
222	258	258	0	1,567	58	137
240	655	0	0	3,813	185	265
243	228	228	178	1,093	151	113
309	364	148	0	1,679	115	189
310	494	323	115	2,503	42	287
330	279	0	0	1,988	51	227

Table C- 4 presents the data needed for each mill in order to estimate the plant size for the different technology cases and the consequences of integration with chemical pulp mills. Different data is necessary for the different technology cases since they are not dimensioned using the same criteria.

Table C- 4. Data needed for each mill in order to estimate the plant size for the different technology cases and the consequences of integration with chemical pulp mills. Pulp wood in [m^3/y]. All energy flows in [GWh/y].

					Steam		Wood fuel (ecxl. black liquor)		Electricity	
Id nr	Pulp wood	Bark	Black liquor	Lime kiln fuel	Use	Deficit[a]	Use[b]	Net	Prod.	Eff.
	f_{pw}	q_{bark}	q_{bl}	q_{lk}	q_{su}	q_{sd}	q_{wfu}	q_{wfn}	$q_{el,m}$	$\eta_{el,m}$
9	1,449	0	0	0	0	0	0	0	0	0.000
10	808,920	374	2,215	160	2,024	387	524	-150	304	0.111
32	1,414,112	655	3,872	248	3,567	813	1,143	-488	696	0.139
33	891,820	371	2,500	178	1,927	132	184	9	354	0.132
79	642,211	277	1,451	107	1,273	208	284	-7	201	0.116
96	362,950	151	1,017	72	793	-8	-10	161	63	0.063
97	98,241	39	225	17	303	123	155	-116	20	0.054
100	133,333	0	0	0	0	0	0	0	0	0.000
101	315,658	125	723	56	679	150	205	-81	111	0.119
116	805,152	329	1,446	106	1,669	651	924	-595	346	0.146
118	1,017,681	459	2,106	135	2,442	819	1,063	-604	252	0.079
121	443,038	210	1,077	82	1,161	360	484	-274	166	0.106
158	1,024,632	474	2,806	202	2,441	314	414	60	296	0.092
160[c]										
175	346,620	154	910	67	938	241	315	-161	104	0.085
186	635,982	303	1,729	111	1,612	296	389	-86	189	0.089
209	941,864	391	2,378	150	2,321	594	818	-427	395	0.124
222	415,509	164	952	73	1,064	338	444	-280	123	0.088
239	1,260	0	0	0	0	0	0	0	0	0.000
240	1,308,253	606	3,582	258	2,623	-169	-216	822	239	0.071
243	367,194	145	841	58	805	170	226	-81	102	0.096
309	636,658	321	1,579	106	1,121	-44	-60	380	170	0.112
310	874,846	353	2,186	163	1,564	-31	-43	395	258	0.120
330	578,646	241	1,622	115	1,268	80	110	131	204	0.118

[a] Steam use not covered by steam from the recovery boiler. (-) indicate a steam surplus.
[b] A negative value here corresponds to a steam surplus, i.e. more steam is produced by the recovery boiler than is needed at the mill. Here, it is assumed that the steam surplus enables extraction of lignin from the black liquor. This lignin is then included in the net export of wood fuel indicted in the next column.
[c] This mill has been excluded in this stage due to its special characteristics.

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 (Delin et al., 2005a; Delin et al., 2005b; Swedish Forest Agency, 2011). 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., 2005a; Delin et al., 2005b).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 2/3 is soft wood-based and 1/3 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 (oil) are used as fuel in the lime kiln, while only wood fuel is used for electricity and steam production. The total use of wood fuel for electricity and steam production is therefore calculated as the sum of the total wood 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 wood fuel used. The net import (-) or export (+) is calculated as the difference between the falling bark and the total wood fuel usage (excluding black liquor).

The electricity production is reported in SFIF's environmental database. The electricity production and total wood fuel usage for electricity and steam are used to estimate the electrical efficiency. By assuming a total efficiency, thereby assuming a heat efficiency, the steam usage is then estimated. The steam deficit is defined as the steam use not satisfied by combustion of the black liquor. It has been assumed that all mills implement steam savings, reducing the total steam usage by 10%. Thereby, the net import/export of wood fuel and electricity produced is recalculated.

With our knowledge about pulp and paper mills in general and some specific knowledge about certain mills, it can be concluded that some of the data estimated in Table C- 4 is not of sufficiently good quality. We thought that publically available data from the SFIF's environmental database together with some general correlations would generate sufficiently good estimates of for example a mill's steam balance. Since some general assumptions together with some general correlations are used, there are source of errors. However, for several of the mills there are relatively large deviations in the estimates compared to what we know of the mills, that neither the known sources of errors, or the combination of them, can explain. We believe that the main reasons for this are (1) errors in the data reported to the SFIF's environmental database (2) that different heating values have been used for the same fuel by different mills when reporting to the SFIF's environmental database.

Investing in a new recovery boiler and bark boiler will for most mills likely mean a change of both the total efficiency and the electrical efficiency. This has however not been taking into consideration at this stage of model development.

BMG-DME plants are considered for integration with chemical mills having a deficit of steam and are sized so the excess steam from the plant covers the steam deficit at the mill. Thus, the size of the biofuel plant, q_{bp}, (i.e. fuel input) is for this technology case, calculated according to q_{sd}/n_{ehs}. It is assumed that the mills are in a situation where they are going to replace their bark boiler and they 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 BMG-DME plant compared to investing in a new bark boiler is used in the model (a sensitivity analysis is made with respect to this). Both in the mills base and in the case where a BMG-DME plant is considered, a back-pressure steam turbine accommodating all steam (i.e from both the recovery boiler and the bark boiler or the BMG-DME plant) is considered. In case of integration with pulp and/or paper mills the excess heat at district heating temperature level is not used.

The BLG-DME cases are naturally sized after the flow of black liquor, q_{bl}. The excess steam from the BLG-DME plant, $q_{ehs,BLG-DME}$, is calculated according to $q_{bl} \times n_{ehs}$ and then the steam deficit of the biorefinery, $q_{sd,br}$, is calculated according to q_{su} - $q_{ehs,BLG-DME}$. For the BLG-DME-BB case, the size of the bark boiler, q_{bb}, can then be calculated according to $q_{sd,br}/n_{heat,CHP}$, where $n_{heat,CHP}$ is the heat efficiency of the new CHP plant (i.e. bark boiler and back-pressure steam turbine)[21]. Purge gas is used as fuel in the bark boiler together with bark and other wood fuel (purge gas is also used as fuel in the lime kiln). The electricity production in the new CHP plant can be calculated using the electrical efficiency, $n_{el,CHP}$, according to $q_{bb} \times n_{el,CHP}$[22]. For the BLG-BMG-DME case, the size of the BMG-DME plant, $q_{BMG-DME}$, is calculated according to $q_{sd,br}/q_{ehs, BMG-DME}$.

Ethanol production via alkaline pre-treatment, ALK-HF-EtOH, has been considered for integration with all kraft pulp mills with deficit of steam. 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. In Table C5 the fuel input, q_{bp}, is 50% of the pulp wood flow, q_{pw}, to the pulping process. This way, the ethanol production capacities are all in a commercially acceptable range and the biomass amount should be possible to handle for all mills. There is a steam surplus from the ethanol plant that can be used in the mill processes. Thereby, the usage of wood fuel in the bark boiler can be reduced.

The steam explosion concept, SE-HF- EtOH, has been considered both for integration with all pulp and paper mills and the plants were sized so the heat in excess would correspond to the deficit in heat at the mill, similar to the BMG-DME case. All residues (lignin, non-fermented carbohydrates, hemi-cellulose etc.) are sent to a power boiler and a back-pressure turbine for steam and electricity generation. The produced steam with lower pressure is then used in the pulp mills. As in the BMG-DME case, when integrating with pulp and/or paper mills the excess heat at district heating temperature level is not used.

Table C- 5 present an example of a mill, where the energy balance for the mill base case is presented together with the energy balances for the mill integrated with each of the different technology cases considered for integration with chemical pulp mills.

[21] $n_{heat,CHP}$ is assumed to be 0.73.
[22] $n_{el,CHP}$ is assumed to be 0.12.

Table C- 5. Energy balance for the mill base case together with the energy balances for the mill integrated with the different technology cases that are considered for integration with chemical pulp mills. Balances are shown using one mill (id number 118) as example.

Mill tech. case	Net wood fuel[a] [GWh/y]	Electricity production [GWh/y]	Incremental el use [GWh/y]	Biofuel [GWh/y]	Incremental inv. cost [MEUR]	Incremental O&M cost [MEUR/y]
Base case	q_{wfn}	$q_{el,m}$				
	-604	252	-	-	-	-
BMG-DME	$q_{bark} - q_{bp}$	$q_{bp} \times n_{el,bp} + q_{el,m} - q_{wfu} \times n_{el,m}$	$q_{bp} \times n_{elu}$	$q_{bp} \times n_{bf}$		
	-5,151	1,127	314	1,891	377	13
BLG-DME-BB	$q_{bark} + q_{bl} \times n_{pg} - q_{lk} \times 0.25 - q_{bb}$	$q_{bb} \times n_{el,CHP}$	$q_{bl} \times n_{elu}$	$q_{bl} \times n_{bf}$		
	-1,949	312	155	1,158	156	5
BLG-BMG-DME	$q_{bark} - q_{lk} \times 0.25 - q_{BMG\text{-}DME}$	$q_{bl} \times n_{el,BLG\text{-}DME} + q_{BMG\text{-}DME} \times n_{el,BMG\text{-}DME}$	$q_{bl} \times n_{elu,BLG\text{-}DME} + q_{BMG\text{-}DME} \times n_{elu,BMG\text{-}DME}$	$q_{bl} \times n_{bf,BLG\text{-}DME} + q_{BMG\text{-}DME} \times n_{bf,BMG\text{-}DME}$		
	-12,000	1,731	851	5,344	775	26
ALK-HF-EtOH	$q_{bark} - q_{pw} \times 0.5$	$q_{pw} \times 0.5 \times n_{el,bp} + q_{el,m} - q_{wfu} \times n_{el,m}$	$q_{pw} \times 0.5 \times n_{elu}$	$q_{pw} \times 0.5 \times n_{bf}$		
	-2,510	462	89	712	198	6
SE-HF-EtOH	$q_{bark} - q_{bp}$	$q_{bp} \times n_{el,bp} + q_{el,m} - q_{wfu} \times n_{el,m}$	$q_{bp} \times n_{elu}$	$q_{bp} \times n_{bf}$		
	-5,190	704	215	1,582	367	15

[a] (-) indicates import to plant, (+) indicates export from plant

MECHANICAL PULP MILLS AND PAPER MILLS

Table C- 6 includes data extracted for mechanical pulp mills and paper mills from SFIF's environmental database.

Table C- 6. Data extracted for mechanical pulp mills and paper mills from SFIF's environmental database.

Id nr	Wood fuel used [GWh/y]	Fossil fuels used [GWh/y]	Electricity produced [GWh/y]
31	742	121	133
64	158	52	10
141	384	75	15
143	699	11	78
157	776	98	64
159	251	3	16
208	722	0	55

Table C- 7 presents the data needed for each mill in order to estimate the plant size for the different technology cases and the consequences of integration with mechanical pulp mills and paper mills.

Table C- 7. Data needed for each mill in order to estimate the plant size for the different biofuel technology cases and the consequences of integration with mechanical pulp mills and paper mills. All numbers in [GWh/y].

		Wood fuel			
Id nr	Steam use	Bark	Use	Net	Electricity prod.
	q_{su}	q_{bark}	q_{wfu}	q_{wfn}	$q_{el,m}$
31	540	182	776	-594	120
64	152	0	189	-189	9
80	588	154	1063	-604	252
141	337	184	413	-229	13
143	474	77	640	-563	70
157	612	292	787	-495	57
159	180	0	229	-229	15
208	503	235	650	-416	50

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. The use of wood fuel has been calculated as the sum of the wood fuel usage and fossil fuel usage reported in SFIF's environmental database (i.e. assuming the same as for chemical mills, that all fuels used for steam and electricity production are wood fuel). 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. As for chemical mills, a 10% reduction of the steam use is assumed and imported wood fuel and electricity production is recalculated.

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.

The same assumptions as for integration with chemical pulp mills are assumed for BMG-DME plants and for the ethanol concepts. Table C- 8 present an example of a mill, where the energy balance for the mill base case is presented together with the energy balances for the mill integrated with the different technology cases that are considered for integration with mechanical pulp mills and paper mills.

Table C- 8. Energy balance for the mill base case together with the energy balances for the mill integrated with the different technology cases that are considered for integration with mechanical pulp mills and paper mills. Balances are shown using one mill (id number 143) as example.

Mill tech. case	Net wood fuel[a] [GWh/y]	Electricity production [GWh/y]	Incremental el. use [GWh/y]	Biofuel [GWh/y]	Incremental inv. cost [MEUR]	Incremental O&M cost [MEUR/y]
Base case	q_{wfn} -563	$q_{el,m}$ 70	-	-	-	-
BMG-DME	$q_{bark} - q_{bp}$ -3,168	$q_{bp} \times n_{el,bp}$ 555	$q_{bp} \times n_{elu}$ 182	$q_{bp} \times n_{bf}$ 1,093	245	8
SE-HF-EtOH	$q_{bark} - q_{bp}$ -3,190	$q_{bp} \times n_{el,bp}$ 310	$q_{bp} \times n_{elu}$ 124	$q_{bp} \times n_{bf}$ 915	248	8

[a] (-) indicates import to plant, (+) indicates export from plant.

SAWMILLS

Table C- 9 shows the capacities for the (stand-alone) sawmills included. The numbers have been taken from the SFIF member register (SFIF, 2012a). The table also presents the data needed for each sawmill in order to estimate the plant size for the different technology cases and the consequences of integration with sawmills.

Table C- 9. Capacities for the included sawmills and data needed for each sawmill in order to estimate the plant size for the different technology cases and the consequences of integration with sawmills.

			Wood fuel [GWh/y]		
Id nr	Capacity [1000 m^3/y]	Heat use [GWh/y] q_{hu}	Prod. q_{wfprod}	Use q_{wfu}	Net q_{wfn}
19	250	58	648	64	584
30	250	58	648	64	584
61	255	58	648	64	584
62	240	62	703	69	634
98	271	58	648	64	584
117	250	58	648	64	584
137	250	51	571	56	514
139	253	55	622	61	561
140	220	129	1,452	143	1,309
142	205	47	532	52	479
161	300	69	778	77	701
162	217	50	563	55	507
174	270	62	700	69	631
176	405	93	1,050	104	947
223	560	39	436	43	393
242	240	53	597	59	538
276	230	58	656	65	591
292	168	55	622	61	561

The heat use for different sawmills has been estimated based on a ratio between heat use and capacity from Isaksson et al. (2012). The production of wood fuel is calculated based on general ratios (Danielsson, 2003). The internal use (for heating purposes) is calculated by assuming a heat water boiler efficiency. Then, the export (+) from the saw mill can be calculated.

Table C- 10 presents an example of a sawmill, where the energy balance for the sawmill base case is presented together with the energy balances for the sawmill integrated with the different technology cases that are considered for integration with sawmills.

All biofuel plants that are considered for integration with a sawmill have a size of 300 MW, corresponding to 2,352 GWh/y (q_{bp}). This is because sizing the plant according to heat use would give too small sizes of the biofuel plants to be relevant.

For the BMG-DME and ethanol cases, excess heat at district heating temperature levels, q_{ehdh}, is assumed to be used to cover the heat use at the sawmill, thereby replacing a heat water boiler (there is always a sufficient amount of excess heat to cover the heat use at all sawmills). As for integration with pulp/paper mills, it is the incremental investment and O&M costs that are considered compare to investing in a new heat water boiler. The excess steam, q_{ehs}, is used in a condensing steam turbine.

Table C- 10. Energy balance for the sawmill base case is presented together with the energy balances for the sawmill integrated with the different biofuel technology cases that are considered for integration with sawmills. Balances are shown using one mill (id number 161) as example.

Mill tech. case	Net wood fuel[a] [GWh/y]	Electricity production [GWh/y]	Incremental el. use [GWh/y]	Biofuel [GWh/y]	Incremental inv. cost [MEUR]	Incremental O&M cost [MEUR/y]
Base case	q_{wfn} 701	-	-	-	-	-
BMG-DME	$q_{wfprod} - q_{bp}$ -1,573	$q_{bp} \times n_{el,bp}$ 489	$q_{bp} \times n_{elu}$ 132	$q_{bp} \times n_{bf}$ 792	251	8
SE-HF-EtOH	$q_{wfprod} - q_{bp}$ -1,573	$q_{bp} \times n_{el,bp}$ 223	$q_{bp} \times n_{elu}$ 89	$q_{bp} \times n_{bf}$ 659	233	7

[a] (-) indicate import to plant, (+) indicate export from plant

DISTRICT HEATING

For each included district heating system a load duration curve is generated based on production statistics (Swedish District Heating Association, 2012) and previous research (Dahlroth, 2009; Fahlén and Ahlgren, 2009; Difs et al., 2010; Brolin and Böhlmark, 2011; Djuric Ilic et al., 2012; Dotzauer, 2012).

Assumptions are made regarding available heat load and where in the dispatch order a biofuel plant would be placed. For example, existing waste incineration and existing industrial excess heat are in general assumed to constitute base production also after the introduction of biofuel plants. The available heat load is chosen such that biofuel plants integrated with district heating get the same annual operating time as plants integrated with industry. The inclusion of a new biofuel production plant affects the heat mix, which in turn affects the CO_2 consequences of integrating biofuel in the system.

BMG-DME and SE-HF-EtOH are considered for integration with district heating systems. They are dimensioned according to the available heat load for new plants. All excess heat is used for district heating production.

Table C- 11 summarises the key data including the data needed for each district heating system in order to estimate the plant size for the different biofuel technology cases.

Table C- 11. Key input data for the included district heating systems.

Id nr	Heat production [GWh/y]	Wood fuel use [GWh/y]	Electricity production [GWh/y]	Heat load [MW] Total	Heat load [MW] New plants q_{dhhl}	Heat production mix[a]
45	4,300	636	977	1,400	50	waste, ind. waste heat, NG, wood HOB, HP
78	1,700	559	259	500	80	waste, wood CHP[b], coal CHP[b], wood HOB, oil CHP
119	9,900	2,091	1,542	3,600	100	wood/waste CHP, coal CHP, HP, wood HOB, bio oil
120	2,400	1,222	528	840	50	wood/oil CHP, HP, wood HOB, bio oil
138	1,500	78	266	550	100	waste, wood/peat CHP[b], HP, HOB

[a] NG = natural gas, HOB = heat only boilers, CHP = combined heat and power, HP = heat pumps.
[b] Plant planned to be taken out of operation in the near future.

It is assumed that the energy company either will invest in a new CHP plant or in a biofuel plant. Thus, the investment cost, as well as the O&M costs, are the incremental costs compared to investing in a new biomass CHP plant.

APPENDIX D. BIORESOURCE MAPPING

In this Appendix definitions and estimations of potentials regarding Swedish forest biomass resources are presented.

FORESTRY AND FORESTRY RESIDUES

Forestry biomass can be subdivided into woody biomass (harvested products) and residues from forestry. Table D- 1 gives an overview of all subcategories and included types of biomass.

Table D- 1. Woody biomass and residues from forestry and trees outside forests: Biomass subcategories, origin and included types of biomass. Adapted from BEE (2010).

Biomass subcategory	Origin	Type of biomass
Woody biomass		
From forestry	Forests and other wooded land incl. tree plantations	Harvests from forests and other wooded land incl. tree plantations, i.e. stemwood
From trees outside forests (landscape)	Trees outside forests incl. orchards and vineyards, public green spaces and private residential gardens	Harvests from trees outside forests incl. orchards and vineyards, excl. residues
Woody residues		
Primary residues	Cultivation and harvesting / logging activities in all of the above incl. landscape management	Cultivation and harvesting / logging residues (twigs, branches, thinning material and stumps), pruning from fruit trees and grapevines etc.
Secondary residues	Wood processing, e.g. industrial production	Wood processing by-products, i.e. sawdust, bark, black liquor, tall oil etc.

Woody biomass from forestry includes all biomass from forests (or other wooded land), tree plantations, and trees outside forests. Woody forestry residues include both primary residues, i.e. leftovers from cultivation and harvesting / logging activities (twigs, branches and tops, thinning material, stumps etc.), and secondary residues, i.e. those resulting from industrial processing (sawdust, bark, black liquor etc.). Tertiary residues, i.e. used wood (wood in household waste, end-of-life wood from industrial and trade uses, waste paper, discarded furniture, demolition wood etc.) are considered organic waste and are not treated in this report.

BIOMASS AT DIFFERENT LEVELS

When assessing biomass resources, the type of biomass potential to be considered is an important parameter, as it to a large extent determines the approach and methodology, and thereby also the data requirements. Five types of biomass potentials can be distinguished:

1. Theoretical potential
2. Technical potential
3. Economic potential
4. Implementation potential
5. Sustainable implementation potential

Theoretical potential

The theoretical potential is the overall maximum amount of terrestrial biomass which can be considered theoretically available for bioenergy production within fundamental bio-physical limits. The theoretical potential is usually expressed in joule primary energy, i.e. the energy contained in the raw, unprocessed biomass. Primary energy is converted into secondary energy, such as electricity and liquid and gaseous fuels. In the case of biomass from forests, the theoretical potential represents the maximum productivity under theoretically optimal management taking into account limitations that result from e.g. soil, temperature, solar radiation and rainfall. In the case of residues, the theoretical potential equals the total amount that is produced.

Technical potential

The technical potential is the fraction of the theoretical potential which is available under the regarded techno-structural framework conditions, with the assumed technological possibilities (such as harvesting techniques, infrastructure and accessibility, and processing techniques). It also takes into account spatial confinements due to other land uses (recreation, fibre production etc.) as well as ecological (e.g. nature reserves) and possibly other non-technical constraints. The technical potential is usually expressed in joule primary energy, but can sometimes also be expressed in secondary energy carriers.

Economic potential

The economic potential is the share of the technical potential which meets criteria of economic profitability within the given framework conditions. The economic potential generally refers to secondary energy carriers, although primary bioenergy can also sometimes be considered.

Implementation potential

The implementation potential is the fraction of the economic potential that can be implemented within a certain time frame and under defined socio-political framework conditions, including economic, institutional and social constraints, as well as policy incentives. Studies that focus on the feasibility or the economic, environmental or social impacts of bioenergy policies typically consider this type of potential.

The classification into different types of biomass potentials helps the reader to understand and categorise what information is presented in the potential estimations. For instance, some biomass types show high technical potentials while their economic potential is rather limited, due to the high costs of extraction and transport. In existing resource assessments, it is often difficult to distinguish between theoretical and technical potentials, and between economic and implementation potentials. However, even more important than making this distinction between different types of potentials is the provision of insight into explicit conditions and assumptions made in the assessment.

Sustainable implementation potential

There is a strong demand for inclusion of sustainability aspects in bioenergy potentials. Since bioenergy in general and biofuels in particular have lost some of their good reputation due to the food versus fuel debate, and due to an increased awareness of land use change effects, both industry and politics strive for more sustainable practices. The concept of sustainable biomass contains multiple environmental, economic and social aspects. However, integration of these aspects may be very complex.

The sustainable implementation potential is not a potential on its own but rather the result of integrating environmental, economic and social sustainability criteria into biomass resource assessments. This means that sustainability criteria act like a filter on the theoretical, technical, economic and implementation potentials, which leads to a sustainable implementation potential. Depending on the type of potential, sustainability criteria can be applied to different extents. For example, for deriving the technical potential, mainly environmental constraints and criteria are integrated that either limit the area available and/or the yield that can be achieved. Applying economic constraints and criteria leads to the economic potential and for the sustainable implementation potential, additional environmental, economic and social criteria may be integrated, as illustrated in Figure D- 1.

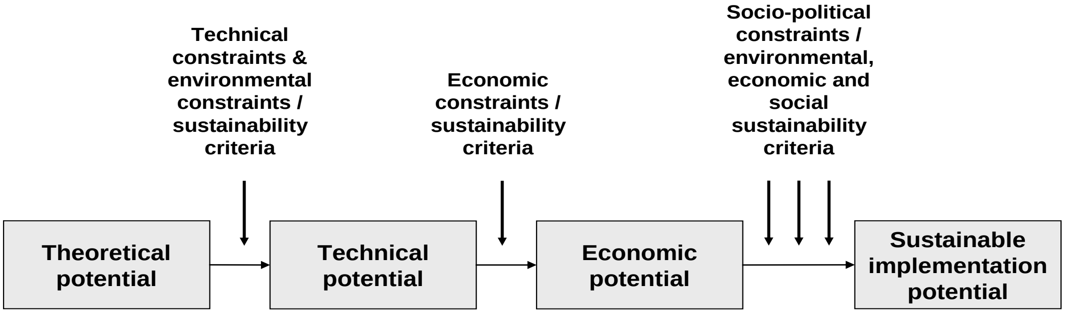


Figure D- 1. The integration of sustainability criteria in biomass potential assessments.

APPROACHES AND METHODOLOGIES FOR FORESTRY BIOMASS ASSESSMENTS

A number of general approaches for quantification of biomass resources are commonly applied to make future projections, see e.g. Smeets et al. (2010).

A *resource-focused approach* is applied in assessments that focus on the total bioenergy resource base and on the competition between different uses of the resources (supply side).

In contrast, a *demand-driven approach* is typically applied by studies that analyse the competitiveness of biomass-based electricity and biofuels, or that estimate the amount of biomass required to meet exogenous targets on climate-neutral energy supply (demand side). For an illustration of the two approaches, see Figure D- 2.

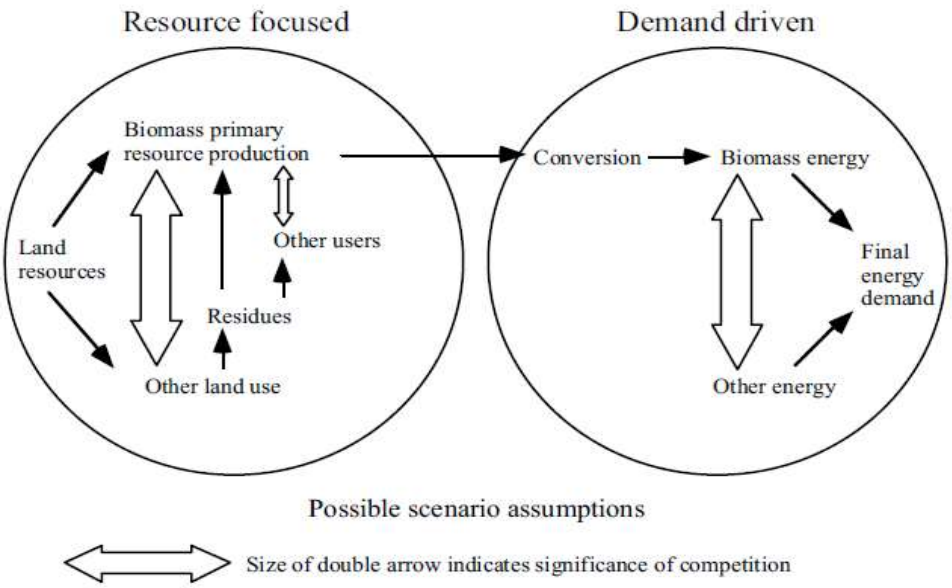


Figure D- 2. The classification of 'demand-driven' and 'resource-focussed' (Berndes et al., 2003).

Other types of approaches are the *integrated assessment approach*, in which a combined demand-driven and resource-focused approach is used, and the *feasibility and impact approach*, in which the technical, economic or environmental feasibility or impacts of a certain bioenergy policy target or scenario are investigated.

A recently developed approach focusing on forestry biomass called *wood resource balance* (Mantau, 2005) is based on available production and trade statistics, with a consumption analysis based on statistics supplemented with field research. This approach facilitates assessment of inter-sectorial trade flows, and estimates demand and possible supply for wood simultaneously, taking into account multiple use of wood (Mantau et al., 2008).

Correspondingly, different methodologies for biomass resource assessments can be identified (Smeets et al., 2010).

Statistical analysis is used for the least complex kind of studies. With statistical analysis, the energy potential is estimated based on assumptions concerning the yield per hectare, which in turn is based on expert judgment, field studies or a literate review, as well as on assumptions concerning the fraction of forest biomass available for energy purposes, accounting for the use of land and biomass for other purposes and environmental or social barriers. Frequently, results from other studies are utilised, but scenario analysis is also sometime applied. The potential of residues is generally calculated based on projections of the production of wood, multiplied by residue generation coefficients and factors that account for the fact that many residues cannot be collected in practice. Some studies also assess the use of residues for other purposes.

Spatially explicit analysis is used for the most advanced resource-focused assessments, which include spatially explicit data on forest availability in combination with calculations of forest yields. The scenario analysis it is based on typically takes into account forestry policies, technological development, population growth, income growth, and so forth.

Cost-supply analysis begins with a bottom up analysis of the potential, based on assumptions regarding the availability of forestry and forestry residues. The demand of land and biomass for other purposes, as well as environmental and other (social, technical) limitations, are included, ideally by scenario analysis. The resulting bioenergy cost-supply curves are then combined with estimates of the costs of other energy systems or policy alternatives, often with specific attention being put on policy incentives (e.g. tax exemptions, carbon credits, and mandatory blending targets).

Energy-economics and *energy-system models* simulate the dynamics of the demand and supply of energy, including bioenergy, by investigating economic and non-economic correlations, and by for example projecting the energy demand per sector. Technological learning is typically considered and scenarios usually applied.

Integrated assessment models include, in theory, all different aspects of sustainability related to biomass production, including relevant feedback mechanisms as well as synergies and trade-offs, and allow for the use of multi-dimensional scenarios. In this kind of analysis, bottom-up data on land use and productivity is combined with energy models and agricultural economics models. Integrated assessment models provide an appropriate framework to estimate the potential of biomass resources, as well as the impacts on agricultural markets and food security, greenhouse gas emissions and land use. However, these models are very complex, which makes them relatively non-transparent and expensive to develop.

Each approach and methodology has specific advantages and disadvantages, which are summarised in Table D- 2. Statistical analyses only offer very limited possibilities to account for environmental or social needs, as those needs can only be included via general reduction factors. These factors usually refer to average conditions, and thus cannot reflect specific local conditions. Static spatially explicit analyses are more adequate to reflect biomass potentials that are adapted to local or regional conditions, which make consideration of environmental or social aspects significantly easier. In this kind of analysis different layers containing relevant and local information regarding e.g. soil, water and climate can be combined. Static spatially explicit analyses, as statistical analyses, do not offer any possibility to include feedback mechanisms, trade-offs and synergies between different sustainability dimensions. Furthermore, it is not possible to adequately account for the economic dimension, which is especially important when evaluating the feasibility of changes in technology and thus the availability of forest biomass for e.g. fibre purposes.

Table D- 2. The advantages and disadvantages of different methodologies used in existing biomass resource assessments (Smeets et al., 2010).

Methodology	Advantages	Disadvantages
Statistical analysis	Simple, transparent, cheap, data is easily available	No economic mechanisms, no spatially explicit information, no integration, based on crude assumptions, sometimes inaccurate
Spatially explicit analysis	Spatially explicit, transparent, based on data on land use and climate, soil characteristics	No economic mechanisms, no integration, complex tool
Cost-supply analysis	Cheap, transparent	No economic mechanisms, no integration
Energy-economics /energy-system model analysis	Economics mechanisms are included	No integration with other markets, not spatially explicit, no integration, no validation based on bottom-up data on land use and climate, soil characteristics, untransparent
Integrated assessment model analysis	Integrated/consistent, spatially explicit	Complex, untransparent, expensive, results are difficult to interpret, model is user unfriendly, level of details is limited

ESTIMATIONS OF POTENTIALS REGARDING SWEDISH FOREST BIOMASS RESOURCES

This section presents different published forestry biomass estimations for Sweden. The considered studies were selected from a broad field of scientific and grey literature on biomass potential estimates. The criteria for selection are divided into two groups. The first group of criteria concerns the types of biomass resources that are assessed by a study. Selected studies have to cover, but need not be limited to, all sorts of woody biomass derived from forest and forest plantations during wood harvesting; e.g. stem wood and harvest residues (twigs, branches, stumps, thinning materials etc.), as well as residues of wood processing industry, i.e. sawdust, bark, black liquor etc. The second group of criteria sets the spatial levels to be included in the review. The selected biomass resource assessments have to cover Sweden in its entirety. Additional criteria for the selection were clearly presented results, as well as wide recognition of the authors by a scientific and policy making community.

Potential for primary forest residues

The studies listed in Table D- 3 present the potential for primary forests residues, also referred to branches and tops. See also Figure D- 3.

Table D- 3. Potential for primary forest residues in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Asikainen et al 2008	Total	102.5					
Asikainen et al 2008	Available	64.2					
Börjesson et al 2010	High	21.9	65.3				
Börjesson et al 2010	Low	20.0	52.8				
Elforsk 2008			36.0	54.0			
EEA 2007	Max	24.8	28.5	29.8	30.6		
EEA 2007	Protected area	24.8	33.3	31.3	34.8		
Hagstrom 2006	Protected area & Biodiversity	24.8	25.8	27.7	27.9		
		57.1					
Hektor et al 1995	High	68.0		81.0			
	Low	63.0		65.5			
Jacobssen 2005		15.0					
Kommissionen mot Oljeberoende 2006		20.0		40.0			52.0
Mantau et al 2010			63.5	68.1	71.2		
Panoutsou et al 2009		46.7	51.5	56.9			
Profu 2012			34.0	42.0			
Skogsindustrierna 1995		14.0					
Skogsstyrelsen & SLU 2008	Nivå 1		36.3				
	Nivå 2		25.0				
	Nivå 3		15.5				
SOU 2000:23	High	55.0					
	Low	50.0					
SOU 1992:90	High	40.0					
	Low	36.0					
STEM 2013				34.0	42.0		
STEM 2009	Ekonomisk, 110 SEK/MWh	5.0					
Svebio 2004			64.0				
Svebio 2008		68.0					
Swedish EPA 2012	Miljöscenario		8.0	16.0	16.0		18.0
	Produktionsscenario		8.0	16.0	16.0		18.0
Thuresson 2010		7.6		16.5			
Number of assessments		20	15	14	7		3
Minimum		5.0	8.0	16.0	16.0		18.0
Maximum		68.0	65.3	81.0	71.2		52.0

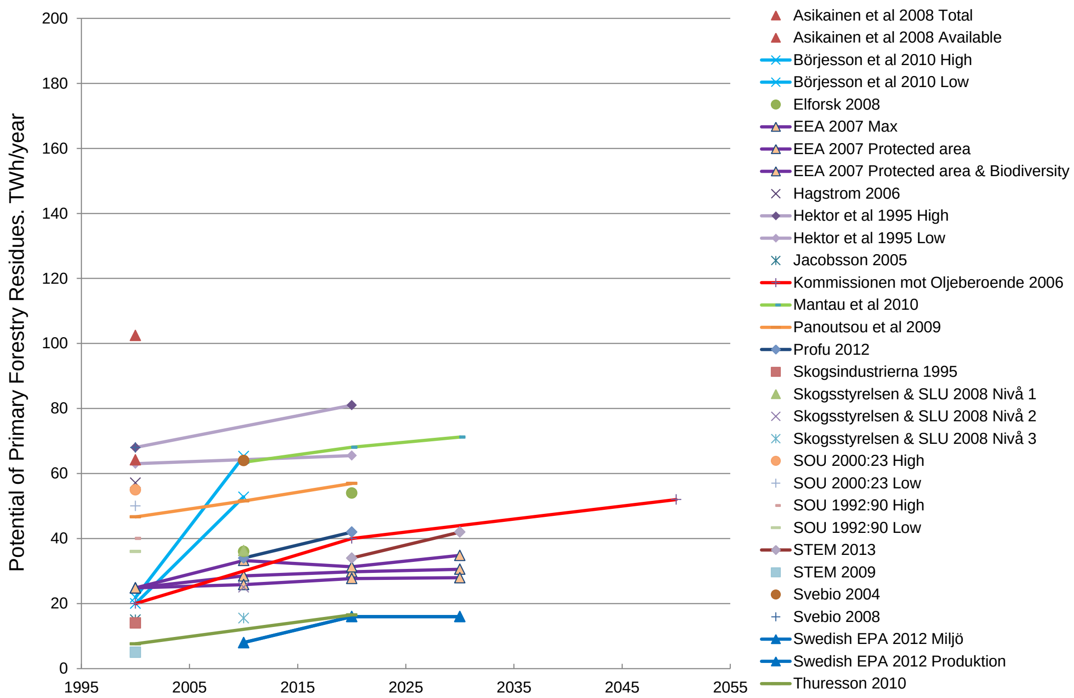


Figure D- 3. Potential for primary forest residues in Sweden [TWh/year].

Potential for stumps

The studies listed in Table D- 4 present the potential for stumps. See also Figure D- 4. Stumps are by definition included in primary forest residues but as they are yet to be commercially harvested on any larger scale they are reported separately in this review.

Table D- 4. Potential for stumps in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Asikainen et al 2008	Total	56.8					
	Available	6.7					
Jacobssen 2005		5.1					
Skogsstyrelsen & SLU 2008	Nivå 1		57.5				
	Nivå 2		33.7				
	Nivå 3		20.7				
STEM 2009	Ekonomisk, vid 110 SEK/MWh	8.0					
Svebio 2004			10.0				
Thuresson 2010		0.3		10.0			
Number of assessments		5	4	1			
Minimum		0.3	10.0	10.0			
Maximum		8.0	57.5	10.0			

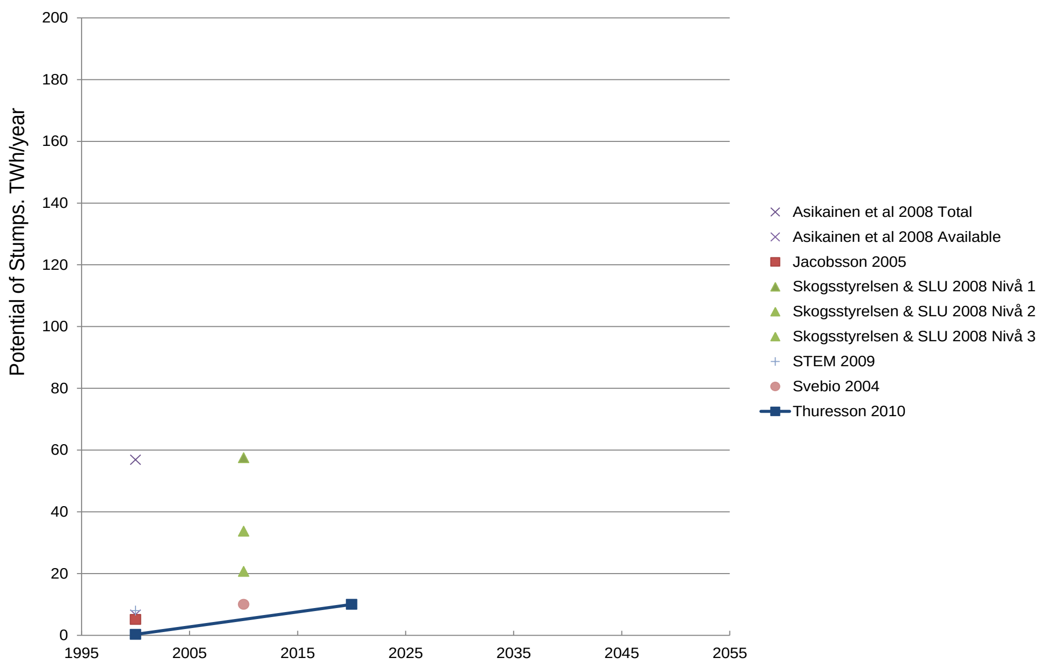


Figure D- 4. Potential for stumps in Sweden [TWh/year].

Potential for fuelwood

In Table D- 5 the potential for fuelwood is listed, see also Figure D- 5. Fuelwood is traditionally used for small scale heating of single family houses.

Table D- 5. Potential for fuelwood in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Elforsk 2008			12	12			
Hagstrom 2006		17.9					
Jacobsson 2005		9					
Skogsindustrierna 1995		12					
SOU 2000:2	High	11					
	Low	11					
SOU 1992:90	High	29					
	Low	24					
STEM 2013				11	11		
STEM 2009	Ekonomisk, vid 110 SEK/MWh	3					
Svebio 2004			6				
Svebio 2008		7.5					
Thuresson 2010		8.5		8.5			
Number of assessments		10	2	3	1		
Minimum		3.0	6.0	8.5	11.0		
Maximum		29.0	12.0	12.0	11.0		

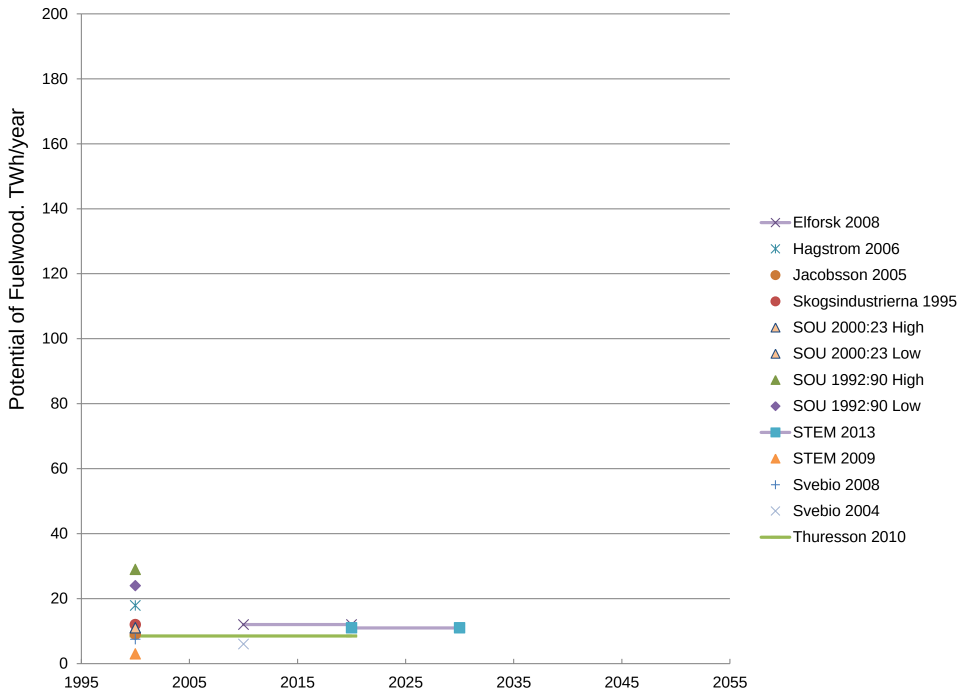


Figure D- 5. Potential for fuelwood in Sweden [TWh/year].

Potential for stemwood for energy

Additional fellings of stemwood for energy is assessed in some forestry biomass potential estimates. Levels of stemwood fellings are presented in Table D- 6 and corresponding Figure D- 6.

Table D- 6. Potential for stemwood for energy in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
EEA 2007 Max	Max		16.6	13.2	16.7		
	Protected area		1.2	0.6	1.1		
	Protected area & Biodiversity		0.0	0.0	0.0		
Hagstrom 2006		12.4					
Hektor et al 1995	High	45.5		45.0			
	Low	33.0		26.0			
Jacobsson 2005		6.8					
Svebio 2004			31.0				
Svebio 2008		15.2					
Thrän et al 2006		83.2	90.3	80.6			
Thuresson 2010		7.8		13.8			
Number of assessments		7	5	7	3		
Minimum		6.8	0.0	0.0	0.0		
Maximum		83.2	90.3	80.6	16.7		

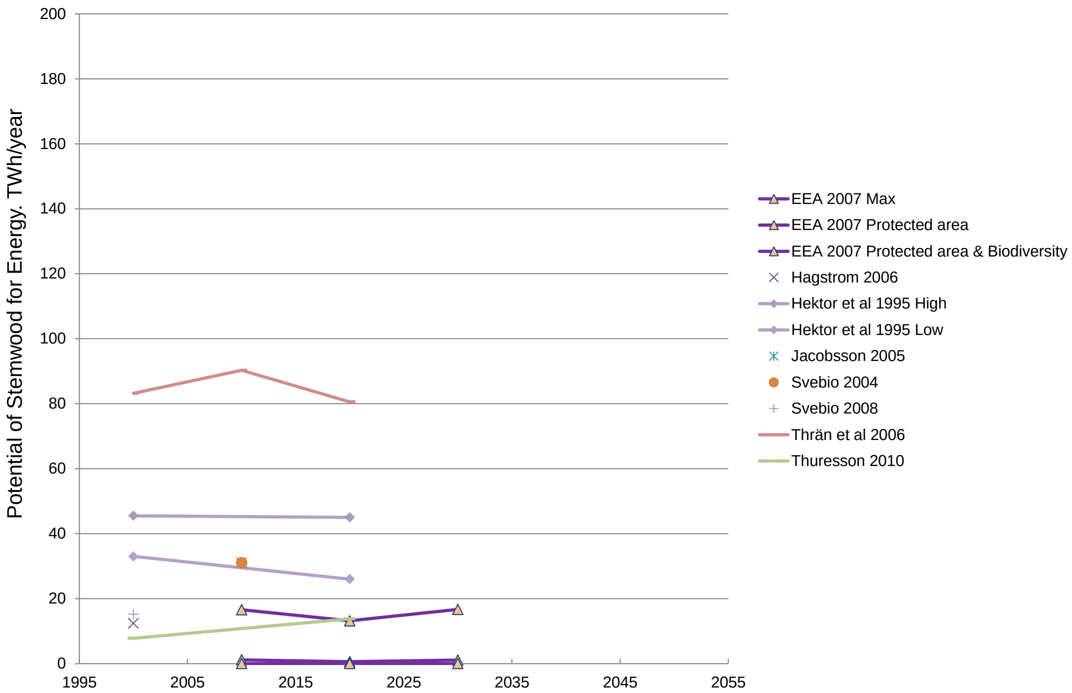


Figure D- 6. Potential for stemwood for energy in Sweden [TWh/year].

Potential for total primary forest biomass

The total primary forest potential consists of previous 4 forestry biomass categories combined, i.e. primary forest residues, stumps, fuelwood and stemwood, see Table D- 7 and Figure D- 7. Note that not all biomass potential estimates assess all biomass categories.

Table D- 7. Potential for total primary forest biomass in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Asikainen et al 2008	Total	102.5					
	Available	64.2					
Börjesson et al 2010	High	21.9	65.3				
	Low	20.0	52.8				
Elforsk 2008			36.0	54.0			
EEA 2007	Max	24.8	28.5	29.8	30.6		
	Protected area	24.8	33.3	31.3	34.8		
	Protected area & Biodiversity	24.8	25.8	27.7	27.9		
Hagström 2006		57.1					
Hektor et al 1995	High	68.0		81.0			
	Low	63.0		65.5			
Jacobsson 2005		15.0					
Kommissionen mot Oljeberoende 2006		20.0		40.0			52.0
Mantau et al 2010			63.5	68.1	71.2		
Panoutsou et al 2009		46.7	51.5	56.9			
Profu 2012			34.0	42.0			
Skogsindustrierna 1995		14.0					
Skogsstyrelsen & SLU 2008	Nivå 1		36.3				
	Nivå 2		25.0				
	Nivå 3		15.5				
SOU 2000:23	High	55.0					
	Low	50.0					
SOU 1992:90	High	40.0					
	Low	36.0					
STEM 2013				34.0	42.0		
STEM 2009	Ekonomisk, vid 110 SEK/MWh	5.0					
Svebio 2004			64.0				
Svebio 2008		68.0					
Swedish EPA 2012	Miljöscenario		8.0	16.0	16.0		18.0
	Produktionsscenario		8.0	16.0	16.0		18.0
Thuresson 2010		7.6		16.5			
Number of assessments		23	14	16	7		3
Minimum		16.0	25.8	16.0	16.0		18
Maximum		113.5	111.0	126.0	71.2		52

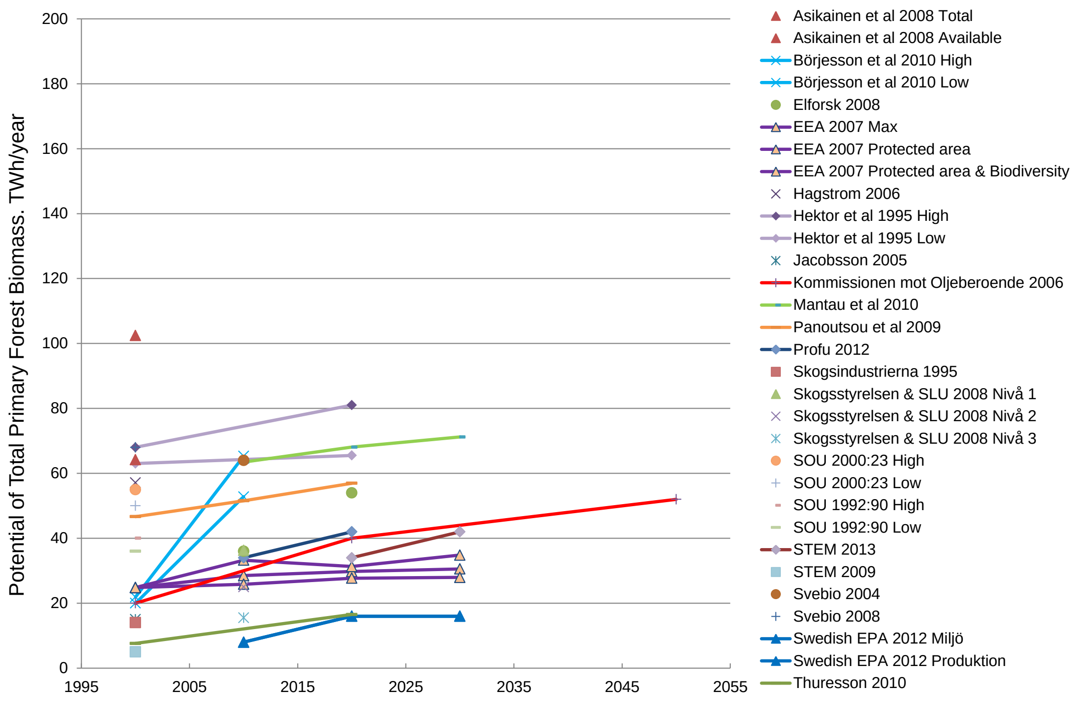


Figure D- 7. Potential for Total Primary Forest Biomass in Sweden [TWh/year].

Potential for secondary forest residues

The studies listed in Table D- 8 presents the potential for secondary forests residues, see also Figure D- 8. Black liquor is not included in these figures but presented separately in the next section.

Table D- 8. Potential for secondary forest residues in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Elforsk 2008			20	20			
Hagstrom 2006		27					
Hektor et al 1995	High	17		19			
	Low	16		17			
Kommissionen mot Oljeberoende 2006		16		22			35
Mantau et al 2010			60	64	68		
Panoutsou et al 2009		20	22	24			
Profu 2012			32	40			
Skogsindustrierna 1995		17					
SOU 2000:23	High	24					
	Low	24					
SOU 1992:90	High	13					
	Low	12					
STEM 2013				32	40		
STEM 2009		44					
Svebio 2004			20				
Svebio 2008		20					
Thrän et al 2006		37	40	43			
Number of assessments		13	6	9	2		1
Minimum		12.0	20.0	16.8	40.0		35.0
Maximum		44.0	59.6	63.7	68.1		35.0

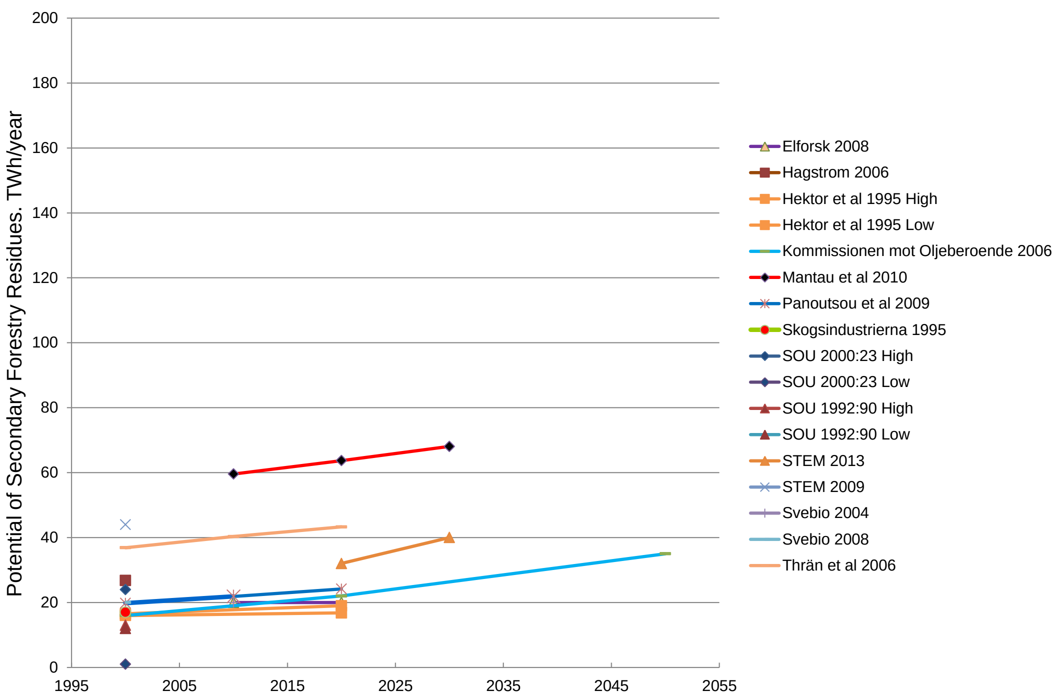


Figure D- 8. Potential for secondary forest residues in Sweden [TWh/year].

Potential for black liquor

Black liquor is by definition a secondary forest residue but is presented separately because of its special characteristics in relation to the biofuel system. Potentials of black liquor is listed in Table D- 9 and visualised in Figure D- 9.

Table D- 9. Potential for black liquor in Sweden [TWh/year].

Study	Scenario	Time frame					
		2000	2010	2020	2030	2040	2050
Kommissionen mot Oljeberoende 2006		44		45			45
Mantau et al 2010			44	50	56		
Profu 2012			45	50			
STEM 2013				45	50		
Thrän et al 2006		40	43	46			
Number of assessments		2	3	5	2		1
Minimum		39.6	43.2	45.0	50.0		45.0
Maximum		44.0	45.0	50.0	55.9		45.0

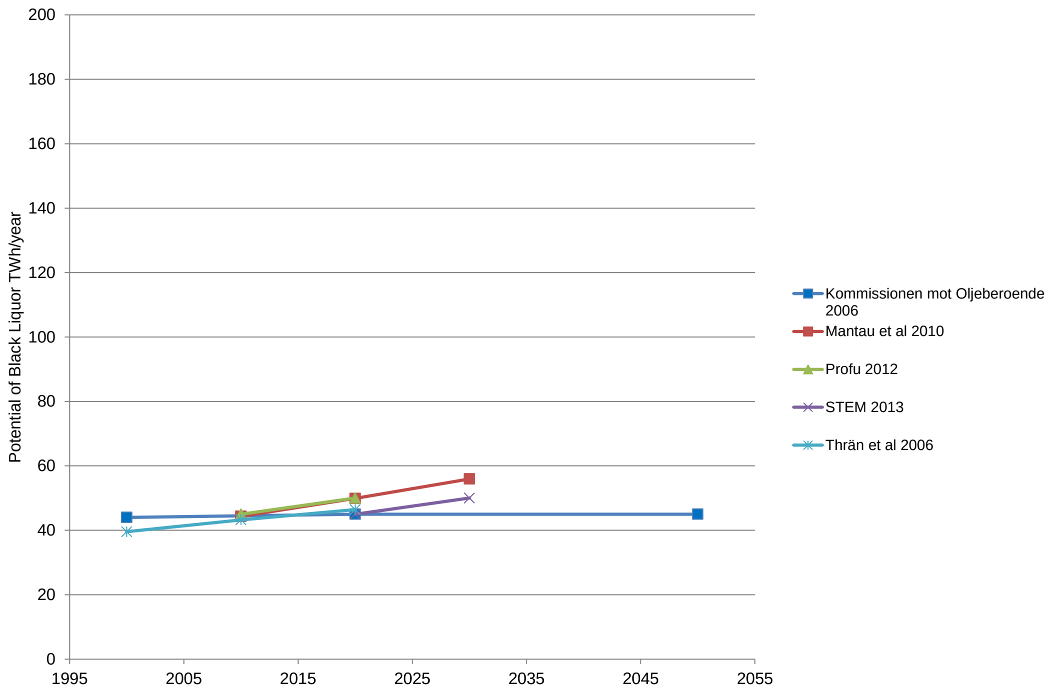


Figure D- 9. Potential for black liquor in Sweden [TWh/year].

Potential for total forest biomass

Only a limited number of biomass potentials estimates cover what can be defined as the total forest biomass available for energetic uses, also note that all does not cover all biomass categories but are sufficiently complete to be included none the less. The potential estimates are presented in Table D- 10 and Figure D- 10.

Table D- 10. Potential for total forest biomass in Sweden [TWh/year].

Study	Scenarios	Time frame					
		2000	2010	2020	2030	2040	2050
Kommissionen mot Oljeberoende 2006		80.0		107.0			132.0
LRF, SNF, Tällberg Foundation 2009		112.6		140.6			
Mantau et al 2010			167.4	181.7	195.2		
Profu 2012			111.0	132.0			
STEM 2013				122.0	143.0		
Thrän et al 2006		159.6	173.8	170.3			
Number of assessments		3	3	6	2		1
Minimum		80.0	111.0	107.0	143.0		132
Maximum		159.6	173.8	181.7	195.2		132

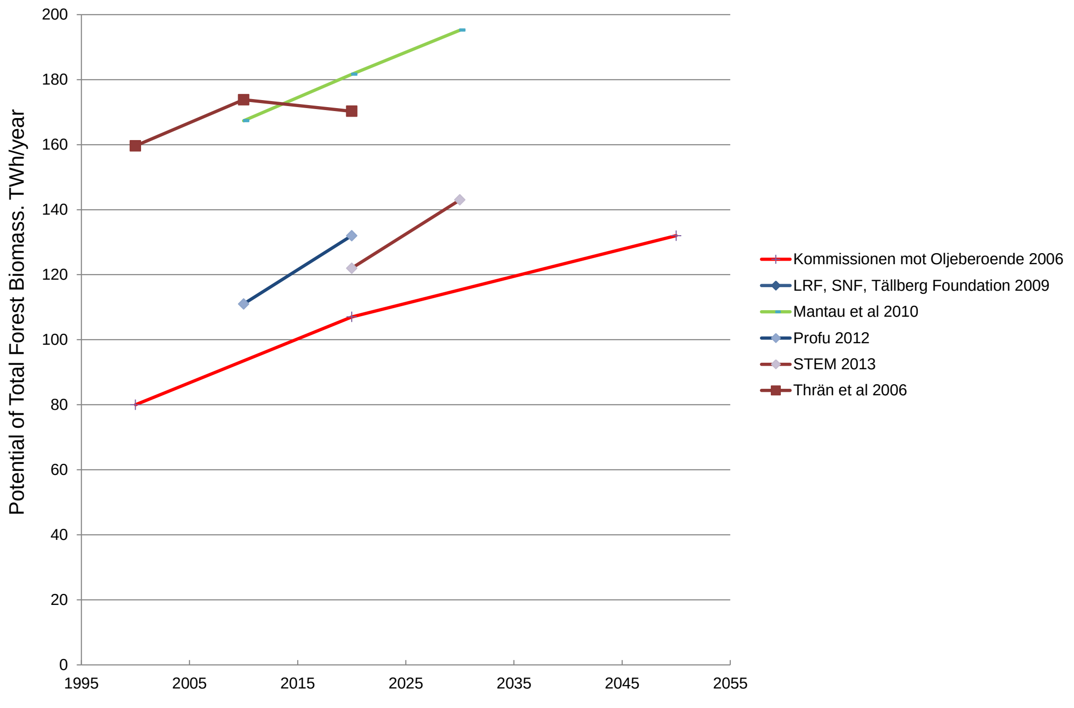


Figure D- 10. Potential for total forest biomass in Sweden [TWh/year].

APPENDIX E. SCENARIO DATA

This Appendix presents county specific data for the scenarios described in Chapter 5.

Table E- 1 shows the regional distribution of population by 2030. The regional population distributions by 2030 are based on assumptions described by Nilsson (2011) for different regions but have been adapted to the county level to fit the BeWhere Sweden model. In principle, the demographic patterns observed in 2006-2010 are the basis for the county projections. Thus, the urbanisation continues and the counties comprising the three metropolitan areas of Sweden (Stockholm, Göteborg and Malmö) increase their population the most whereas northern Sweden counties are expected to experience only a marginal increase in population. For immigration, the county's share for the years 2006-2010 has been applied to the national immigration 2011-2040. On a general level, these assumptions agree with the assumptions made by Trafikverket (2012) who states that the continuously increased urbanisation will result in that by 2030 fewer people will live in rural areas and more in cities. Apart from the populations influence on total transport demand, the regional distribution of the population affects the amount of transport fuel needed since e.g. people living in densely populated areas to a greater extent can utilise public transport solutions.

Table E- 1. County specific population 2030 and average annual change.

County	Population 2010[a]	Population 2030: High[b]	Population 2030: Low[c]	Average annual change 2010-2030
Blekinge	153 227	171 195	165 593	+900
Dalarna	277 047	292 813	283 231	+800
Gävleborg	276 508	292 243	282 680	+800
Gotland	57 269	63 984	61 890	+300
Halland	299 484	352 426	340 894	+2 900
Jämtland	126 691	132 185	127 859	+400
Jönköping	336 866	376 368	364 052	+2 000
Kalmar	233 536	260 921	252 383	+1 400
Kronoberg	183 940	205 509	198 784	+1 100
Norrbotten	248 609	262 756	254 157	+700
Örebro	280 230	325 327	314 681	+2 200
Östergötland	429 642	480 023	464 315	+2 500
Skåne	1 243 329	1 533 105	1 482 935	+15 000
Södermanland	270 738	314 307	304 021	+2 200
Stockholm	2 054 343	2 657 513	2 570 547	+32 000
Uppsala	335 882	389 935	377 175	+2 700
Värmland	273 265	288 815	279 364	+800
Västerbotten	259 286	274 041	265 073	+700
Västernorrland	242 625	256 432	248 040	+700
Västmanland	252 756	293 431	283 829	+2 000
Västra Götaland	1 580 297	1 797 671	1 738 844	+12 000
Sweden total:	*9 415 570*	*11 021 000*	*10 660 344*	

[a] Statistics Sweden (2013a)
[b] Calculations based on Nilsson (2011)
[c] Statistics Sweden's totals for 2030 adopted to counties based on Nilsson (2011)

Table E- 2 shows the county specific fuel demand. In a report by Trafikverket (2012) the assumed reductions for car travels for people living in metropolitan areas, regions and rural dwellings are given as 25%, 21% and 13% of passenger kilometres per person respectively (Trafikverket, 2012). For the two transport fuel demand scenarios presented in this report the county specific transport demand per capita has been adjusted to fit the total transport demand presented in Table 13. About half of the reduction in transport fuel demand, representing the reduction in passenger transports, has been distributed based on type of county (Rural, Region or Metropolitan area where metropolitan areas show the larger reduction following the assumptions by Trafikverket (2012)), the remaining reduction has been distributed evenly.

Table E- 2. County specific transport fuel demand per capita for the different transport fuel demand scenarios compared to the year 2010

		2030[a]				2010
		Fossil free transport sector		Best available technology		
	County type[b]	Transport fuel demand/capita [kWh/capita]	Reduction compared to 2010	Transport fuel demand/capita [kWh/capita]	Reduction compared to 2010	Transport fuel demand/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] Assuming the high population scenario presented in Section 5.1.
[b] Judgement 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 demand per capita).