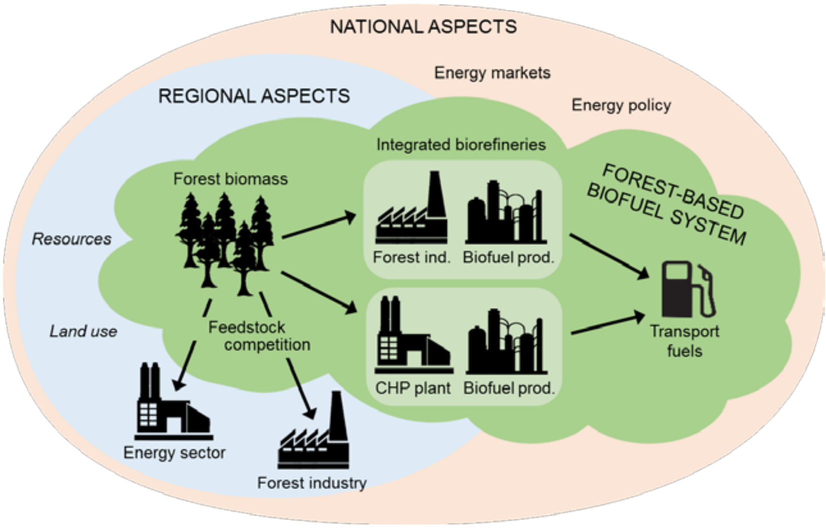
BEWHERE - STAKE-HOLDER ANALYSIS OF BIOFUEL PRODUCTION IN SWEDEN

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

October 2017



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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project has been carried out within the collaborative research program *Renewable transportation fuels and systems* (Förnybara drivmedel och system), Project no. 39118-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

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

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

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

The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

The project has been a collaboration between seven f3 partners and one external company, as follows: Bio4Energy / Luleå University of Technology (Elisabeth Wetterlund, Joakim Lundgren, Robert Lundmark); Bio4Energy / SLU (Dimitris Athanassiadis); Linköping University (Magdalena Fallde); Lund University (Pål Börjesson, Johanna Olofsson); RISE Research Institutes of Sweden (former SP) (Karin Pettersson (previously at Chalmers University of Technology), Johan Torén); RISE Research Institutes of Sweden (former Innventia) (Marie Anheden, Valeria Lundberg); E.ON (Björn Fredriksson Möller); Perstorp (Lars Lind); SEKAB (Marlene Mörtsell).

This report is based on two scientific papers, with additional analysis in this report:

- Fallde M, Torén J, Wetterlund E (2017). Energy system models as a means of visualising barriers and drivers of forest-based biofuels: an interview study of developers and potential users. Sustainability 2017, 9, 1792, doi:10.3390/su9101792.
- Wetterlund, E, Pettersson K, Olofsson J, Einarsson R, Börjesson P, Lundgren J, Dotzauer E, Leduc S (2017). Towards a fossil free transport sector – the costs of meeting ambitious targets for biofuels in Sweden. Manuscript, to be submitted for publication.

This report should be cited as:

Wetterlund E, et al. (2017). *BeWhere – Stake-holder analysis of biofuel production in Sweden*. Report No 2017:15, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

SUMMARY

BeWhere Sweden is a spatially explicit energy system model, which has been developed to analyse future biofuel production opportunities in Sweden. In this study, we investigated the usefulness of BeWhere Sweden for relevant actors and stakeholders in the biofuel area. This was done by (1) model development and model runs based on dialogue with relevant actors, and (2) interviews and workshops with actors representing potential users of the model and/or results from it.

The results showed that there are many different ways to reach high levels of biofuel production in Sweden, at reasonable costs, and that the dependency on specific locations or technologies is not particularly strong. Economy-of-scale and high conversion efficiencies were shown to provide the largest production cost reductions, which benefitted large-scale production of gasification based biofuels for use as high-blend or pure fuels. This would, however, require substantial investments in capital-intensive production concepts, which contradicts the current trend, which is towards less capital intensive pathways and drop-in fuels. This contradiction was stressed in the actor analysis, where the large investment requirements associated with gasification based fuel pathways were discoursed as insurmountable barriers to actual implementation. It was also emphasised that model result presentations must be complemented with interpretations, and that, in order to use the results from models as a basis for decision-making, it is essential to understand the assumptions that have been integrated in the model. The results confirmed that BeWhere Sweden can help to illustrate opportunities and obstacles for forest-based biofuel production in Sweden. Nevertheless, many of the barriers identified as critical are due to aspects that are not easily included in this type of parameterised energy system model – such as social, political and (perceived) risk related factors.

The overall conclusion is that BeWhere Sweden has the potential to be a useful part of a larger toolbox in the transformation towards forest-based biofuel production. A number of lessons have been learned, and both strengths and shortcomings of the model have been identified. The main strengths of the model lie in the spatial representation, and in the possibility to model different value chain options in detail. One important usefulness is, thus, the potential to identify regional "hot-spots" for new production, which can be used to create knowledge about factors that affect the costs and environmental impacts from biomass based supply chains. This can in turn aid in the design of robust policies in order to facilitate effective development. A major obstacle for useful model application lies in the timing aspect. In order to be useful for the intended actors, the model must be relevant in the contemporary scope. From an actor's perspective, this typically means the inclusion of the production technologies currently in the spotlight, and the exclusion of technologies where the investment appetite is low (or non-existent) even though they may be more technologically mature. However, for early stage emerging technologies, available data of sufficient quality is typically lacking. This creates a contradiction between fundamental research of new processes, current state-of-the-art systems analysis knowledge, and the actual momentum and interest regarding biofuel investments. Future studies using BeWhere Sweden should involve relevant actors at an early stage, in order to clearly identify the scope of the analysis, what technologies to include, and how to operate the model. A relatively frequent, iterative process is recommended in order to ensure confidence in the final results from the model analysis.

A final conclusion is that researchers and experts involved with energy system modelling would benefit from reforming how models are designed, operated and presented, and also from deeper interaction with different actors in order to more explicitly make society the subject of the work.

SAMMANFATTNING

BeWhere Sweden är en geografiskt explicit energisystemmodell, som har utvecklats för att analysera framtida möjligheter för biodrivmedelsproduktion i Sverige. I denna studie har vi undersökt modellens användbarhet för relevanta aktörer inom biodrivmedelsområdet. Detta har gjorts genom (1) modellutveckling och modellanalys baserat på aktörsdialog, och (2) intervjuer och workshops med aktörer som representerar potentiella användare av modellen och/eller dess resultat.

Resultaten visade att det finns många olika sätt att uppnå höga nivåer av biodrivmedelsproduktion i Sverige till rimliga kostnader, och att detta inte är särskilt starkt beroende av specifika tekniker eller lokaliseringar. Skalekonomi och höga verkningsgrader visade sig ha störst effekt vad gäller möjligheter att minska produktionskostnaderna, vilket gynnade storskalig förgasningsbaserad produktion av biodrivmedel för användning som höginblandade eller rena bränslen. Detta skulle emellertid kräva betydande investeringar i kapitalintensiva produktionskoncept, vilket står i motsats till den nuvarande trenden som går mot mindre kapitalintensiva koncept och drop-in-bränslen. Denna motsats diskuterades i aktörsanalysen, där det enorma investeringsbehovet för förgasningsbaserad drivmedelsproduktion framhölls som ett närmast oöverstigligt hinder för faktisk implementering. Det betonades också att presentation av modellresultat måste kompletteras med tolkningar, och att för att kunna använda modellresultat som grund för beslutsfattande är det viktigt att förstå de antaganden som har integrerats i modellen eftersom dessa har avgörande inverkan på resultaten. Studien bekräftade att BeWhere Sweden kan bidra till att illustrera möjligheter och hinder för skogsbaserad biodrivmedelsproduktion i Sverige, men att många av de hinder som identifierades som kritiska beror på aspekter som är svåra att implementera i denna typ av parametriserad energisystemsmodell – som sociala och politiska faktorer, samt aspekter relaterat till (upplevda) risker.

En övergripande slutsats är att BeWhere Sweden kan vara en användbar del av en större analysverktygslåda inför omställningen till skogsbaserad biodrivmedelsproduktion. Modellens huvudsakliga styrkor ligger i den spatiala representationen, och i möjligheten att kunna modellera olika värdekedjor i detalj. Ett viktigt användningsområde är möjligheten att identifiera regionala ”hot-spots” för ny produktion, vilket kan användas för att ta fram ny kunskap om faktorer som påverkar kostnaderna och miljöpåverkan från biobaserade värdekedjor. Detta kan i sin tur hjälpa till i utformningen av robusta strategier och policies, och för att underlätta utvecklingen av exempelvis ny teknik och infrastruktur. Ett huvudsakligt hinder för modellens användbarhet ligger i tidsaspekten. För att kunna vara till nytta för de avsedda aktörerna måste modellen vara nutidsrelevant. Detta innebär ur ett aktörsperspektiv typiskt inkludering av de produktionstekniker som för tillfället är i fokus, och exkludering av de tekniker där investeringsaptiten är låg (eller obefintlig), även om dessa har högre teknikmognadsgrad. För framväxande tekniker med låg teknikmognad saknas dock vanligtvis tillgängligt data av tillräcklig kvalitet. Detta skapar en motsägelse mellan utveckling av nya processer, state-of-the-art systemanalyskunskaper, och det aktuella intresset för investeringar i biodrivmedel. Framtida studier där BeWhere Sweden-modellen används bör därför redan i ett tidigt skede involvera relevanta aktörer för att tydligt identifiera analysens syfte och omfattning, vilka tekniker som ska inkluderas, och hur modellen ska användas. En relativt frekvent, iterativ process rekommenderas för att skapa förutsättningar för förtroende för de slutliga resultaten från analysen.

En sista övergripande reflektion är att forskare och experter inom energisystemmodellering skulle främjas av att dels reformera hur vi arbetar med och presenterar modellresultat, dels interagera mer med aktörer från olika sektorer, för att mer uttryckligen göra samhället till mottagare av resultaten.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

Sweden has an extensive history of research and development of biofuel production technologies using lignocellulosic (woody) or waste biomass feedstocks. The total production potential has been estimated to at least 20-30 TWh biofuel from woody biomass [1, 2] and 2-8 TWh biogas from anaerobic digestion [3], in addition to the current production of biofuels which amounts to around 5 TWh (grain-based ethanol, biodiesel/FAME, tall oil-based HVO and biogas) [4]. Biofuel production based on woody biomass, in particular integrated with different types of industry, would appear to be attractive from a Swedish perspective. Nonetheless, biofuel production based on forest feedstocks has so far only been realized on any significant scale for tall oil based HVO production, and is otherwise mainly limited to technology development activities.

In a recent study, Peck et al. [5] investigated the system of forest-derived transport biofuels in Sweden, with particular focus on the systems' actors as well as on systemic constraints and drivers for the emergence of a significant biofuel production industry. Peck et al. showed that a number of factors can be identified as barriers to forest-based biofuel production. In particular, various policy-related issues, such as policy instability, 'short-termism' and low predictability, have hindered biofuel initiatives from moving forward. This has resulted in eroded confidence and trust levels among industrial biofuel actors, which in turn results in even higher investment hurdles. Peck et al. also concluded that the forest sector stands divided regarding the view on forest-based biofuels, which likely undermines the efforts of biofuel proponents to secure the necessary support. Hellsmark et al. [6] also identified the lack of appropriate policies as a key barrier or a system weakness. Hellsmark et al. concluded, among other things, that knowledge about e.g. the current biorefinery development status should be increased among policy makers, and that policy initiatives aimed at the industry are critical.

The contradiction between, on the one hand, visions among policy makers as well as within the research community, and, on the other hand, the lack of actual momentum regarding forest-based biofuel production, raises the question of if and how research results can be and are used in order to achieve such goals.

1.2 BEWHERE SWEDEN

The BeWhere Sweden model has been developed to investigate biofuel production opportunities in Sweden. The model is a techno-economic, spatially explicit optimisation model, with focus on forest biomass and design of forest-based value chains. The model has been constructed to analyse how future bio-based value chains can be implemented cost-efficiently from a system perspective, what role the existing energy infrastructure can play, and how different parameters affect e.g. the choice of conversion technologies, localisation and integration, in a system where the same limited resource (biomass) is also in demand from other sectors. The parameters considered include e.g. policy instruments, future scenarios for energy market conditions, technological development and industrial investment opportunities. The results are envisioned to be useful as decision support for stakeholders in, for example, biofuel production, as well as for policy makers.

BeWhere Sweden was initially developed and used within two previous f3 projects [7, 8], but has subsequently been used also in research projects outside the scope of f3 [9–14]. This study is a continuation of the previous two f3 projects and has primarily been aimed at investigating if and how the model can be useful for various actors and stakeholders in the biofuel area.

1.3 AIM AND OBJECTIVES

The overall aim of this project was to investigate the usefulness of the BeWhere Sweden model for relevant actors and stakeholders, in the transformation towards large-scale forest-based biofuel production. This was done by (1) model development and model runs based on the outcome of dialogues with industry representatives and other relevant actors, and (2) interviews with actors representing potential users[1] of the model and/or results from it.

Specific objectives were divided into two parts:

1) Model development and techno-economic analysis:
    a. Update and further develop the BeWhere Sweden model[2].
    b. Use the BeWhere Sweden model to identify and analyse types of locations of interest for production of advanced biofuels, under different scenarios and conditions.
    c. Develop supply curves that describe the costs (total as well as specific) to reach certain levels of domestically produced biofuels in Sweden, under different scenarios and conditions.
2) Actor analysis regarding how the BeWhere Sweden model and its results are interpreted among its potential users:
    a. Provide understanding of how potential users interpret energy system models concerning forest-derived biofuel production in general, and BeWhere Sweden in particular.
    b. Investigate what barriers and drivers concerning forest-derived biofuel production in Sweden that the interviewed actors identity, and whether the BeWhere Sweden model can be used to visualise and analyse those barriers and drivers.
    c. Identify discrepancies between the scope of and results from BeWhere Sweden, and the potential users' interpretations and expectations of it.

[1] The term "users" is in this report used to denote users/recipients of the model results, rather than the actual model users/operators, as the BeWhere Sweden model has not been adapted for use by non-experts.
[2] Including, but not limited to, the addition of agriculture based fuels and feedstocks.

2 METHODS

The work in this project has been divided into two main parts, following the objectives outlined above: (1) techno-economic analysis (model development and operation), and (2) actor analysis (interviews and workshops). The work in the two parts has been connected, as outlined in Figure 1. This study has also incorporated results from a number of previous f3 projects, which is also shown in the figure. The model development was done in an iterative manner, based on the input from the dialogue with actors in the project workshops, and to some extent, on the interviews.

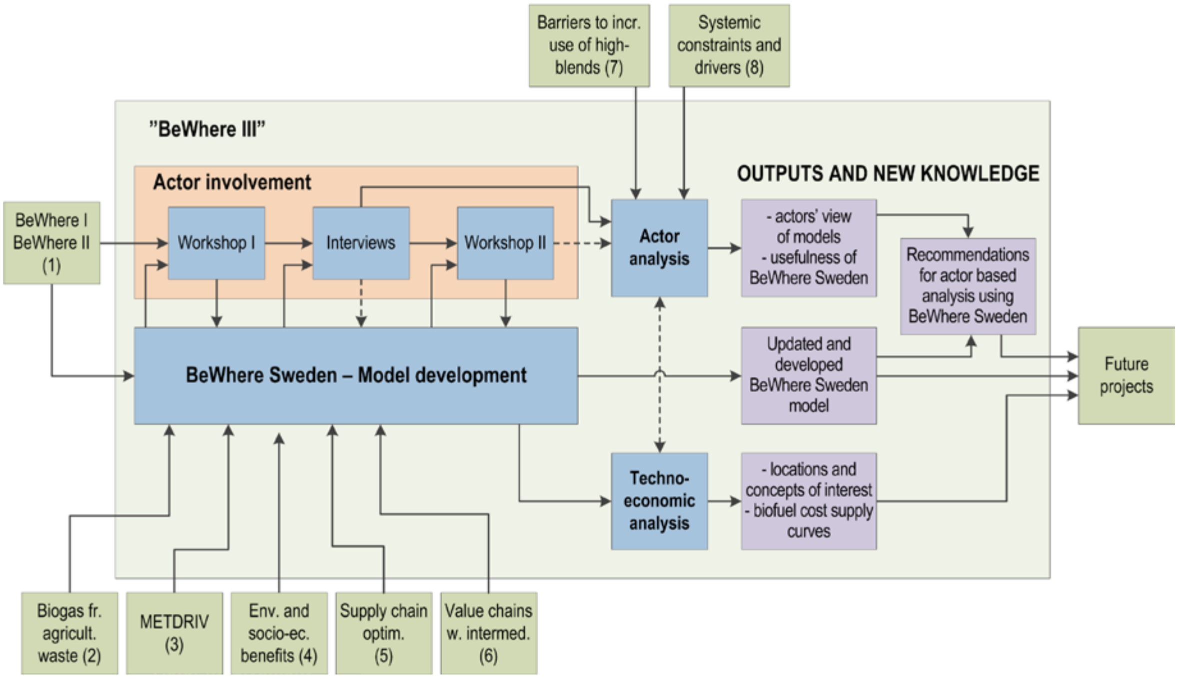

Figure 1. Overview of project work flow. Green boxes indicate projects, blue indicate actions or processes within this project, and purple indicate outputs. Numbers in parentheses refer to previous projects within f3 or the collaborative research program Renewable transportation fuels and systems:
(1) Optimal localisation of next generation biofuel production in Sweden – Part I & II [7,8]
(2) Biogas from agricultural wastes and residues - Where and how much? [15]
(3) Methane as vehicle fuel - a gate-to-wheel study (MetDriv) [16]
(4) Environmental and socio-economic benefits from Swedish biofuel production [4]
(5) Optimization of biofuel supply chains based on liquefaction technologies [17]
(6) Value chains for production of renewable transportation fuels using intermediates [18]
(7) Barriers to an increased utilisation of high biofuel blends in the Swedish vehicle fleet [19]
(8) Examining systemic constraints and drivers for production of forest-derived transport biofuels [5]

2.1 TECHNO-ECONOMIC ANALYSIS

The BeWhere Sweden model minimises the total system cost to meet a certain demand of produced biofuels, while simultaneously meeting the demand for biomass from other users (forest industries and the stationary energy sector). In previous studies, the model has been focused only on biofuels from forest biomass. In order to be able to analyse the total costs for meeting increasing levels of biofuel production, the model was for this study complemented with other domestic feedstocks and biofuels, as outlined in the following sections and in Appendix A. Figure 2 gives an overview of the main biomass flows and geographic scope of BeWhere Sweden as used in this study, with new additions highlighted.

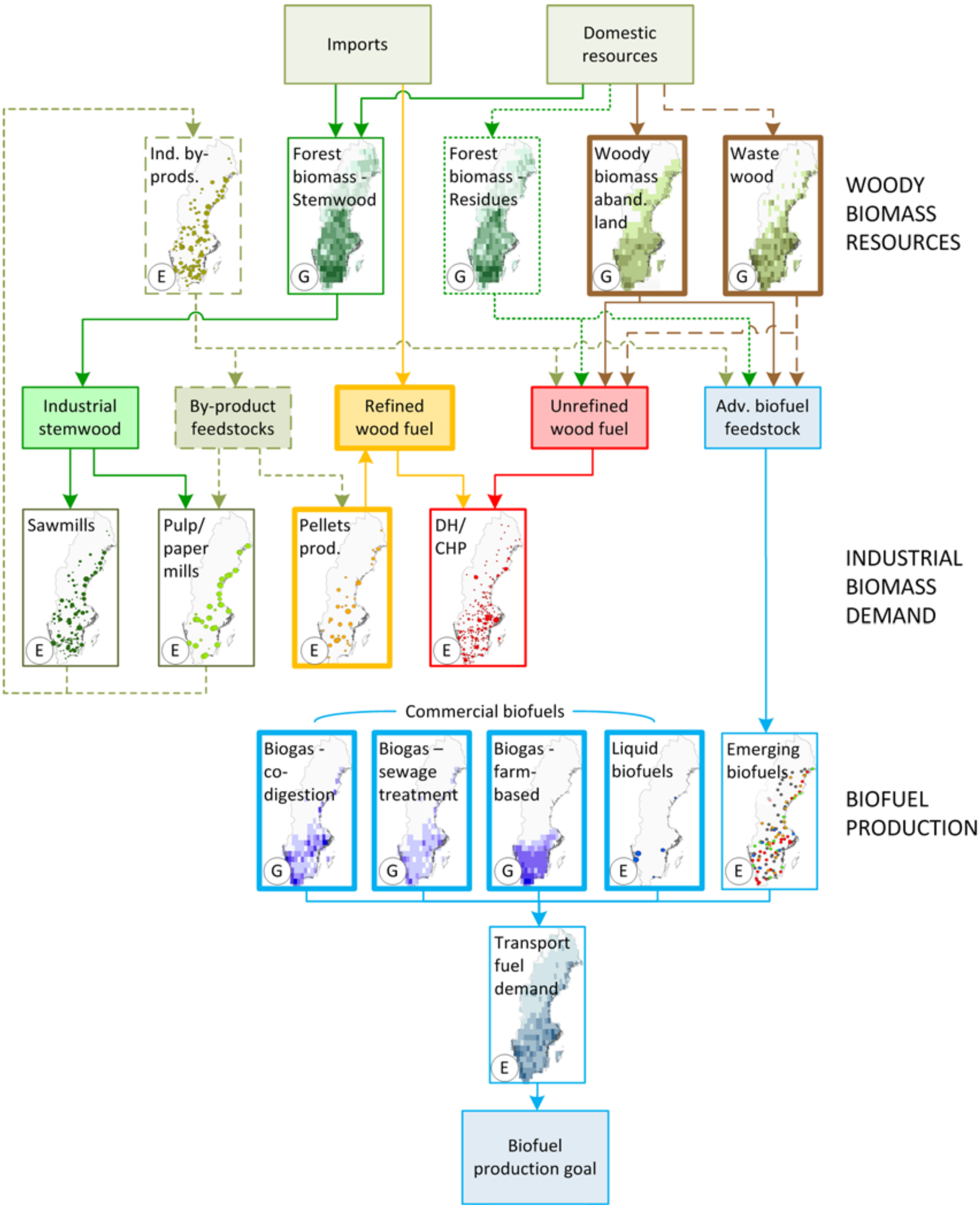

Figure 2. Overview of main biomass flows and geographical scope of BeWhere Sweden. Residue flows are represented by dashed lines, while virgin biomass flows are represented by solid lines. Elements marked with "G" are represented on the base model grid, elements marked with "E" are represented using explicit locations. Feedstocks and fuels that were added within this project are marked with thick lines.

2.1.1 Model description

BeWhere Sweden is based on mixed integer linear programming (MILP) and has been written in GAMS, using CPLEX as a solver. The system cost to be minimised includes the costs for existing and new biofuel production, biofuel distribution costs to end-users, policy costs and revenues, and biomass procurement costs for competing users. The model is geographically explicit regarding biomass supply, competing biomass demand, existing and potential new biofuel production, transportation infrastructure, and biofuel demand. Two different geographic representations have been used: a base model grid with 0.5 degree spatial resolution (“G” in Figure 2), and explicit locations (“E” in Figure 2). The model is run statically over one year, for the medium-term future (2030). The model output includes a set of new and existing biofuel production options to meet the defined production target, supply chain configurations, feedstock sources, as well as costs related to the various parts of the supply chain. For a more complete model description, the reader is referred to previous publications [7, 8, 20, 21].

Model development

The major model developments for this report are summarised in Table 1, with further descriptions of key elements in the following sections and with key input data given in appendix a – summary of model development.

Table 1. Summary of development of the BeWhere Sweden model, compared to in previous publications.

Model development	Model area	New / updated	Also described in
Emerging biofuel production technologies			
SNG production via solid biomass gasification	biofuel technologies	updated	
Methanol production via solid biomass gasification	biofuel technologies	updated [a]	
Methanol production via black liquor gasification	biofuel technologies	updated [a]	
Co-production of cellulosic ethanol and biogas	biofuel technologies	updated [b]	
Stand-alone facilities	plant localisation	new	
Integration with district heating networks	plant localisation	updated	
Agriculture based feedstocks and biofuels			
Farmed wood from abandoned arable land	feedstocks	new	[22]
Liquid biofuel production (ethanol, FAME)	biofuel technologies	new	[4]
Farm-based biogas production from anaerobic digestion	biofuel technologies	new	[15,23]
Biogas production from co-digestion / waste water treatment	biofuel technologies	new	
Other feedstocks and biofuels			
Waste wood	feedstocks	new	
Refined wood pellets	feedstocks	new	
Liquid biofuel production (tall oil-based HVO)	biofuel technologies	new	[4]
Transportation and distribution			
Intermodal transportation using road, rail and short sea shipping	logistics	updated	[17]
Gas grid distribution (natural gas grid or local biogas grids)	logistics	new	
Fuel blending terminals for fuel distribution	logistics	new	[17]
Competing biomass demand			
Sawmill, pulp and paper industry	competition	updated	
District heating and CHP plants	competition	updated	[10]
Pellets production	competition / feedstocks	new	

[a] Previously dimethyl ether (DME) was considered, but has here been replaced by methanol. The production pathways are similar, for which reason this is considered an update rather than a new feature.
[b] In previous model versions, residues from cellulosic ethanol production were assumed to be used for heat and electricity production, which gave a low biofuel yield for the ethanol technologies. Here, suitable residues have been assumed to undergo anaerobic digestion for co-production of biogas as a secondary biofuel product.

Biofuel production technologies

Two general groups of biofuel production technologies were considered.

Commercial biofuel production technologies cover concepts that are currently in place in Sweden. This includes biogas from anaerobic digestion, grain-based ethanol, RME (rape methyl ester, or biodiesel), and tall oil based HVO (hydro-treated vegetable oils). For ethanol, RME and HVO, current production levels were modelled as the base production with the existing production facilities modelled explicitly. For biogas, the production was modelled spatially explicitly on an aggregated level (individual plants not modelled explicitly) divided into three production categories: sewage treatment plants, farm-based biogas plants and co-digestion plants. For all commercial technologies, existing production capacities as well as modelled production capacity increases were included in the model

Emerging biofuel production technologies cover production technologies and concepts that have the potential to be commercialised on the time-frame considered here. The scope was limited to technologies that have reached pilot or demonstration scale and where plans for actual commercial operation either exist or have existed in Sweden. This includes fuels based on gasification (methanol and synthetic natural gas, SNG, were considered for this study), as well as cellulosic ethanol based on enzymatic hydrolysis and SSF (simultaneous saccharification and fermentation) with co-production of biogas, but excludes e.g. fuels based on depolymerisation and upgrading of lignin[3]. The emerging biofuel technologies were considered on individual plant level. It was assumed that production plants can be either operated as stand-alone facilities, or integrated with existing industry (sawmills, pulp and paper mills, CHP plants) or district heating networks.

Biomass feedstocks

As in previous BeWhere Sweden studies, the main focus has continued to be on woody biomass resources. The production of agricultural biomass feedstocks for crop-based biofuel, as well as of tall oil for HVO, has not been considered explicitly. The reason is that these biomass assortments are not subject to resource competition (e.g. land) on the geographical scale and within the scope considered here. Virgin forest biomass as well as by-products from the forest industry have been considered previously in BeWhere Sweden, while farmed wood from abandoned arable land, waste wood, and refined wood pellets are results from the model development within this project.

For forest biomass, the supply potential was estimated based on modelled scenarios from SKA 15 [25] ("Today's forestry" scenario). The supply and cost assessment methodology has been described in [8,21]. The potential for wood from abandoned arable land[4] was estimated using a bottom-up GIS-based approach, as described in [22]. First, suitable land areas were identified using various GIS databases. Next, the potential production capacity for fast-growing broadleaf trees, such as poplar and hybrid aspen, was estimated based on land productivity data. Finally, the production costs were estimated based on cost estimations for short rotation forestry. Waste wood quantities were estimated based on [26]. For wood pellets, both domestic production and import were considered. The costs for waste wood and pellets were derived from statistics [27].

Regarding biomass trade, Sweden today imports a certain amount of forest industry feedstock. In this study, sawlogs and pulpwood were as assumed possible to import to supplement the domestic wood supply. A cap on the import was set to 5 and 15 TWh per year for sawlogs and pulpwood, respectively, which can be compared to current net import volumes of 2.5 and 12 TWh per year [28].

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[3] While those fuels have been pinpointed as a short term priority [24], together with other drop-in fuels, and are currently hot topics on the research and development agenda, the technology readiness level is still relatively low (lab scale). As a consequence, publically available techno-economic data is missing.

[4] Land that has been cultivated before and is not currently occupied but could be cultivated again. Abandoned pasture land was excluded from the analysis, in order to reduce the risks for negative effects on biodiversity.

Transportation and distribution

For transport of biomass feedstocks and produced liquid biofuels, road, rail and short sea shipping was considered. The transportation costs between all possible origins and destinations were calculated with a geographically explicit intermodal transport model, as described in [17]. For SNG, grid injection was considered for locations with gas grid connections (local grids or the national gas grid in the south-western parts of Sweden). For locations without grid connection, road transportation as CBG (compresses biogas) was instead assumed.

2.1.2 Description of model runs

The model was evaluated in discrete steps of 1 TWh, starting from the current annual domestic biofuel production of 5 TWh, to 40 TWh[5]. In order to evaluate the impact of various key parameters, a number of scenarios were included in the analysis. The scenarios were selected partly based on discussions with the involved actors, partly based on previous experience from analyses using BeWhere Sweden. Special focus was put on technology related assumptions (max production capacity, availability of particular technologies, and investment costs), as well as on future feedstock availability. The scenarios are summarised in Table 2.

In three scenarios (Scenarios 5-6, 9) it was assumed that the potential host industries are facing major energy investments, where they have the choice between investing in either conventional energy technology, or biofuel production plants that can fulfil the same utility services and in addition produce biofuels. With this approach, new biofuel production plants are only burdened with the incremental biofuel plant costs compared to alternative investments in conventional technology, which allows for an estimation of the potential role of existing industrial infrastructure in mitigating future biofuel production costs.

In scenarios with limited biomass availability (Scenarios 10-11), the SKA 15 scenario “Double conservation areas” [25] was applied. In addition to this, further restriction was put on the stump harvest potential, according to [30]. This reduced the potential for stemwood by 9%, for harvesting residue by 11% and for stumps by 72%, which represents a system with stricter focus on environmental quality objectives that may be impacted negatively by increased use of forest biomass for energy purposes.

[5] This can be compared to the total energy use in the domestic transport sector, which amounted to 87 TWh in 2015, of which 94% was used in road transport [29].

Table 2. Summary of scenarios included in this report. BLG = black liquor gasification, RB = recovery boiler, alt. inv. = alternative investment. Capacities refer to biomass input feed (MW_{th} LHV).

	Scenario	Technology availability	Capacity restriction	Investment costs	Alt. inv. considered	Biomass availability
1	Base scenario	No BLG	400 MW_{th}	Base	No	Base
2	No capacity restriction	No BLG	No	Base	No	Base
3	BLG in old RB	All	400 MW_{th}	Base	No	Base
4	BLG in all RB	All	400 MW_{th}	Base	No	Base
5	Base scenario, alt. inv.	No BLG	400 MW_{th}	Base	Yes	Base
6	BLG in old RB, alt. inv [a]	All	400 MW_{th}	Base	Yes	Base
7	No gasification	No gasification	400 MW_{th}	Base	No	Base
8	Base scenario, capex +50%	No BLG	400 MW_{th}	Base +50%	No	Base
9	BLG in old RB, alt. inv., capex +50% [a]	All	400 MW_{th}	Base +50%	Yes	Base
10	Base scenario, limited biomass [b]	No BLG	400 MW_{th}	Base	No	Limited
11	BLG in old RB, limited biomass [b]	All	400 MW_{th}	Base	No	Limited

[a] "Old RB" here means all recovery boilers estimated to be older than 25 years at the modelled year (2030) [31].
[b] Only evaluated up to 28 TWh biofuel/y, which is the upper boundary for the production potential from domestic feedstocks, without significantly increasing the imports of e.g. industrial wood.

2.1.3 Evaluation of biofuel production and supply costs

The total *biofuel supply cost* presented here consists of the costs for producing commercial biofuels (expressed per produced unit of each biofuel type, see Appendix A), as well as the costs for producing biofuels from emerging production technologies, and the biofuel distribution costs to end-users. For the emerging technologies, the production cost includes feedstock costs (including upstream transportation), conversion costs (capital and O&M costs, assuming N^{th} plant costs), and credits for by-products. Investment costs for new plants were annualised using a capital recovery factor of 0.13, which represents e.g. an economic lifetime of 15 years and an interest rate of 10%.

In addition to the absolute biofuel supply cost, a *biofuel system supply cost* has also been derived from the model results. This cost was, for each scenario and each biofuel production model run (5-40 TWh biofuel per year), calculated as the difference between the total system cost for the scenario reference model run (0 TWh biofuel production per year) and the system cost for the specific model run, divided by the total biofuel production of the model run. While admittedly omitting a number of relevant system effects of biofuel production (e.g. job creation), this biofuel system supply cost can nonetheless be seen as a measure of two major biomass system related effects: (1) increased biomass costs for competing users in the studied system, and (2) the impact of plant integration in existing industry. The latter includes both the effects of considering alternative industrial investments (Scenarios 5, 6, 9), and the physical benefits of integration (such as efficient use of surplus heat and internal by-product flows). This can thus be seen as a representation of the value of the potential contribution of existing industry to reduced biofuel supply costs.

2.2 ACTOR ANALYSIS

The methodology and theoretical framework for the second group of objectives, related to how the BeWhere Sweden model and its results are interpreted among its potential users, has been described in detail in [32]. The data collection was mainly based on semi-structured interviews, with the goal to capture the interviewees' reflections and interpretations in relation to two themes:

(1) barriers to and drivers for forest-based biofuel production, and
(2) the use of energy system models in general, and the BeWhere Sweden model in particular, to visualise and analyse barriers to and drivers for forest-based biofuel production.

One part of the interviews was also dedicated to giving an overview of BeWhere Sweden. This part was adapted according to the interviewees' previous knowledge and understanding of the model. The study was framed as an example of expertise, problematising how energy system models and the results from them can be used and are interpreted among expected users.

The selection of actors to be interviewed was made in order to represent both the most relevant parts of the studied core system (forest-based biofuel production), and the surrounding systems, as illustrated schematically in Figure 3. As such, the selection of interviewees was broadened from "the usual suspects" (i.e. actors more directly related to the biofuel production industry), whose views on barriers and drivers for forest-based biofuels have already been extensively analysed by e.g. Peck et al. [5].

Two groups of actors were interviewed, with a total of eight interviewees (Table 3). The first group consisted of potential *users* of the model results, representing several sectors: the forestry and forest industry, the energy sector, and national and regional authorities (U1-U6). The second group of interviewees consisted of researchers that have been involved with the BeWhere model as *developers* (D1-D2)[6].

[6] The developers have been connected to the BeWhere model family in general, not only specifically to the BeWhere Sweden model. See also the official BeWhere webpage: www.iiasa.ac.at/bewhere.

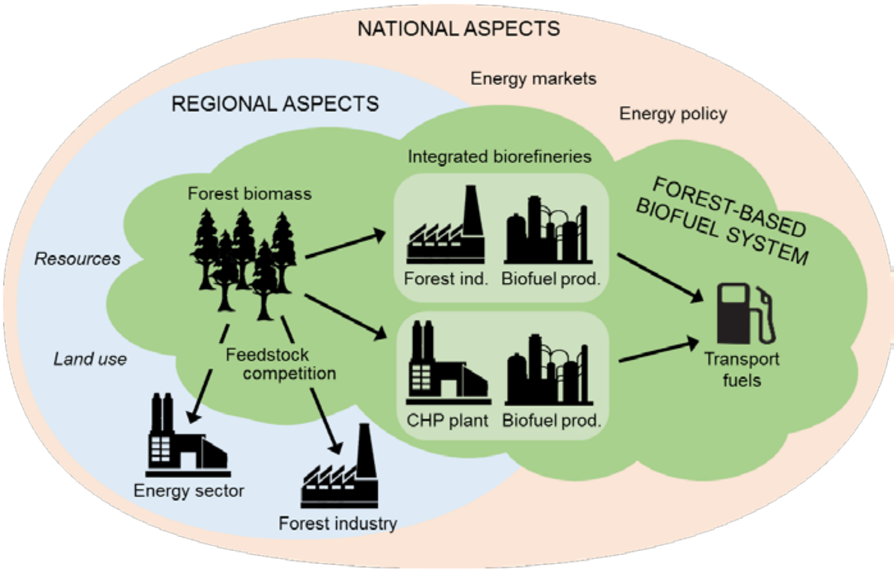

Figure 3. Overview of the forest-based biofuel system in focus in this study, including important surrounding systems (regional as well as national) [32]. Aspects in italics are not covered by BeWhere Sweden, but came up in the interview study.

Table 3. List of interviewees and their respective areas of competence (varying levels within each competence area). Interviewees marked with * under "Previous BeWhere experience / knowledge" are or have been involved in the BeWhere project as reference group participants.

		Areas of expertise and competence							
Designation	**Sector / Organization**	**Forestry / forest industry**	**Energy sector / energy systems**	**Biofuel prod.**	**Local / regional aspects**	**National aspects**	**Energy policy**	**Energy system models**	**Previous BeWhere experience / knowledge**
U1	Regional authority	x			x	x			low
U2	Regional authority	x			x				none
U3	State authority		x			x	x	x	low *
U4	Energy sector		x	x	x				medium *
U5	Forest industry	x	x						low
U6	Forest industry	x		x					none
D1	Research institute		x	x			x	x	high
D2	University / energy sector		x		x	x	x	x	high *

3 RESULTS

3.1 TECHNO-ECONOMIC RESULTS

This section provides a summary of the results from the model runs performed for this study. The results presented here have been selected in order to highlight some key conclusions. Further results and analysis can be found in the forthcoming journal publication by Wetterlund et al. [33].

3.1.1 Biofuel production

The results from the model runs showed that forest-based biofuel production would be needed to meet annual biofuel production levels over around 7 TWh. The threshold for the introduction of forest-based biofuels was higher in the scenarios with lower biomass supply (Scenarios 10-11). Exclusion of gasification (Scenario 7), and higher investment costs for emerging biofuel technologies (Scenarios 8-9), also led to a higher threshold for forest-based fuels. In general, solid biomass gasification with SNG production dominated the model output, with the exception of three scenarios. When alternative industrial investments were considered and black liquor gasification (BLG) was assumed to be available, BLG based biofuel production was clearly favoured (Scenarios 6, 9). When no gasification based technologies were assumed to be available, cellulosic ethanol/biogas was instead the only allowed forest-based technology (Scenario 7), with obvious impact on the results.

Figure 4 shows the resulting range of total number of plants needed to meet the modelled biofuel production levels in the analysed scenarios. As the figure indicates, removing the capacity constraints (Scenario 2) results in significantly fewer required plants than in the scenarios where the maximum plant capacity was restricted at 400 MW_{th} (biomass input).

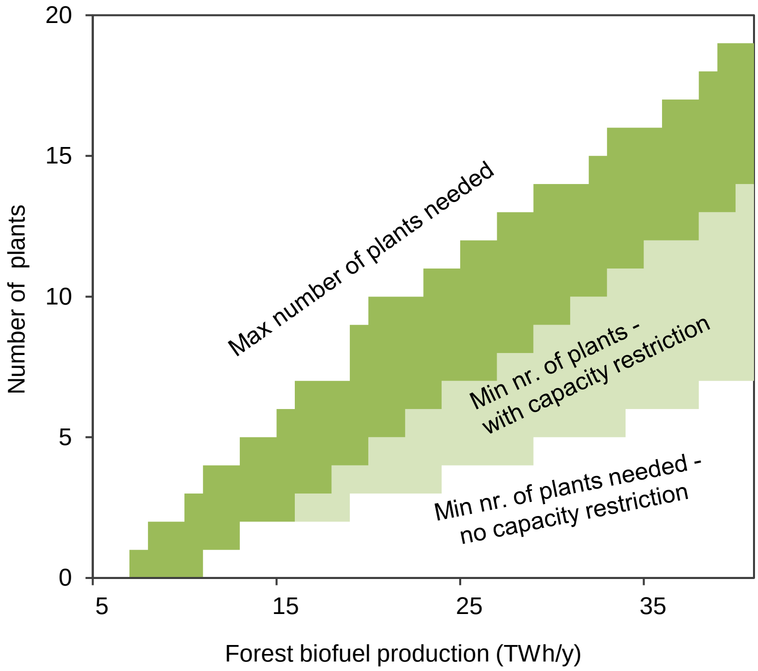

Figure 4. Range of total number of forest-based biofuel production plants needed in the 11 analysed scenarios. The darker green area shows the span of plants required when the scenario without capacity restriction (Scenario 2) was omitted, while the lighter green area includes also that scenario.

Figure 5 further highlights this, in showing resulting average plant capacities in terms of MW biofuel production. The results show a clear tendency of the model to maximise production plant capacities, which is due to the strong advantage of economy-of-scale effects. Figure 5 also shows that all scenarios except Scenario 2 exhibit a similar trend, with average production capacities at or near the set maximum capacity.

Three scenarios show lower average capacities: the no gasification scenario (Scenario 7), which has lower biomass-to-biofuel conversion efficiency (ethanol / biogas); and the BLG scenarios with alternative investments (Scenarios 6, 9), where the production plants' capacities were limited by natural feedstock restrictions (black liquor).

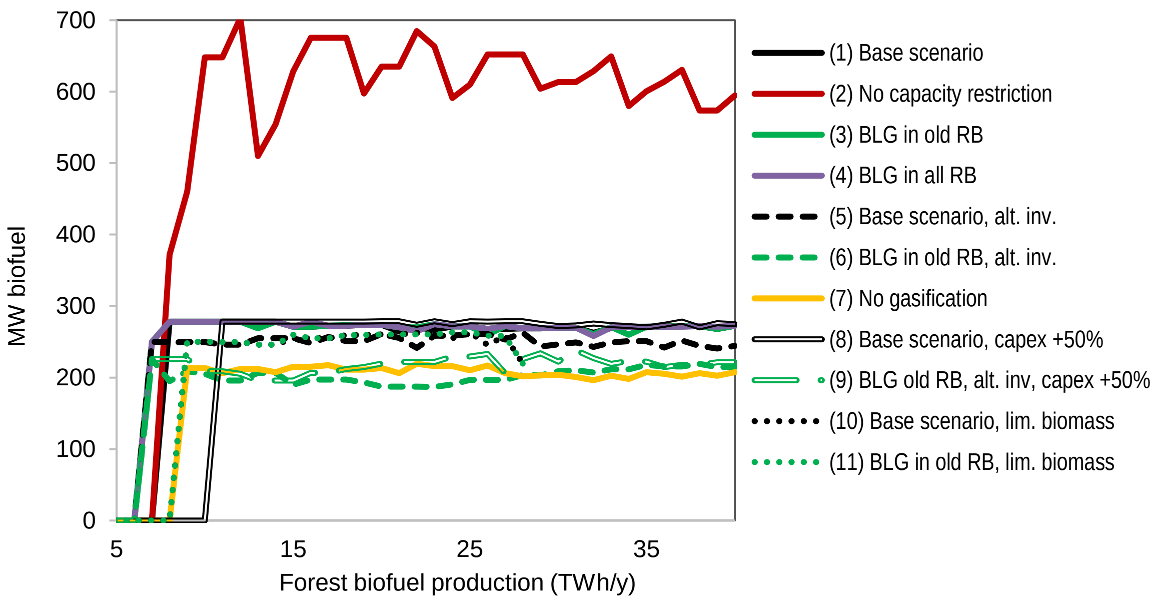

Figure 5. Average production plant capacity (MW biofuel production) for new forest-based biofuel production plants in the modelled scenarios. Dashed lines represent scenarios where alternative industrial investments are considered, dotted lines scenarios with limited biomass supply, and double lines scenarios with higher investment costs for emerging biofuel production technologies.

In general, the scenarios resulted in similar biofuel production mix profiles, with the commercial technologies playing a decreasing role with increasing production levels. The resulting biofuel mixes for four of the modelled scenarios are shown in Figure 6. As can be seen, even with methanol from BLG production in the biofuel mix (Scenarios 6, 9), SNG still played an increasingly important role, due to high conversion efficiency and, on relative terms, lower specific investment cost.

In the scenarios with higher investment costs for emerging production technologies (Scenarios 8-9), commercial biofuels represented a larger share of the total biofuel production. Nonetheless, forest-based biofuels were shown to be needed in order to reach high production levels, with a relatively similar total number of new biofuel plants.

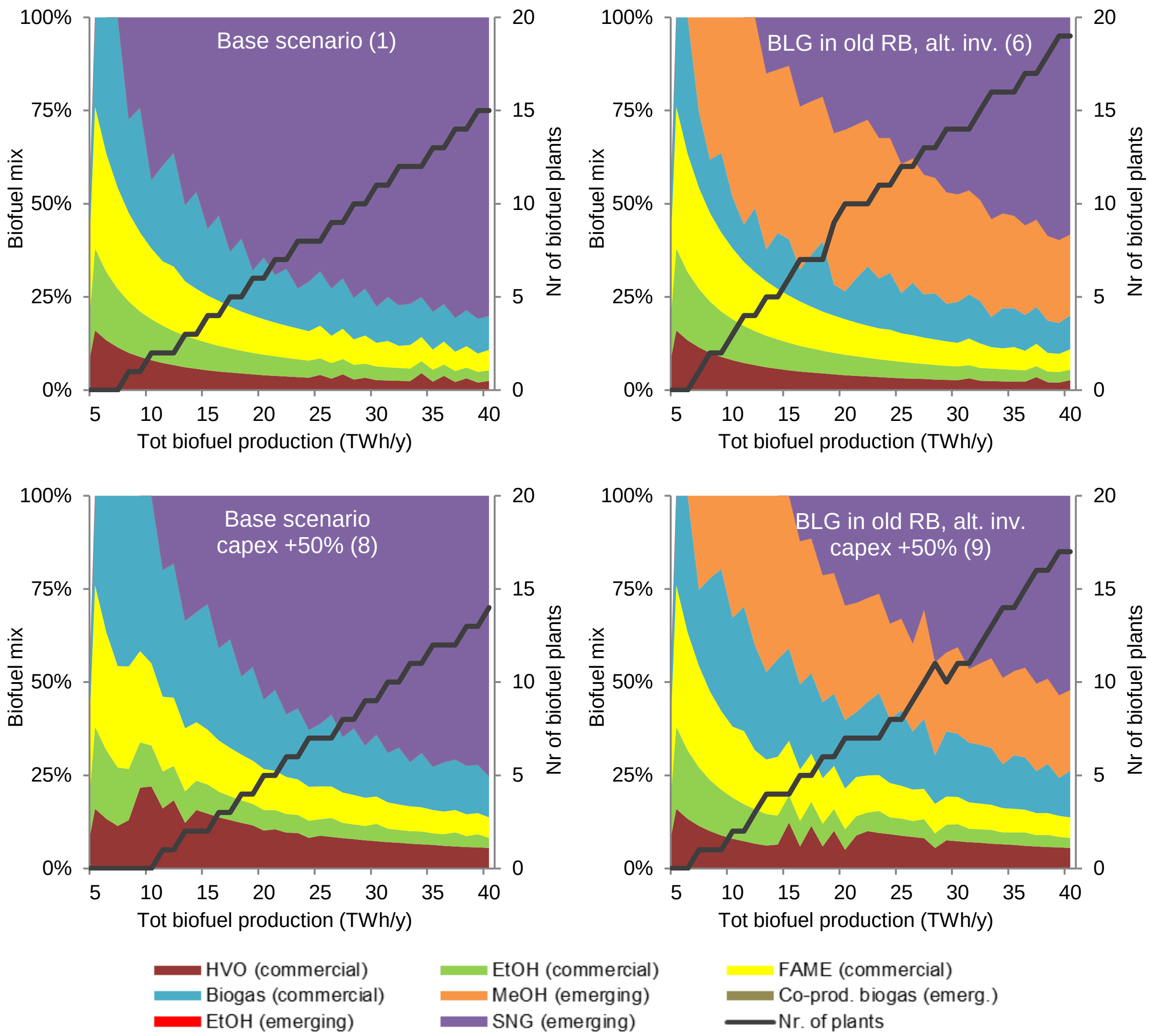

Figure 6. Resulting biofuel production mix for four of the modelled scenarios.

3.1.2 Biofuel supply costs

As described in Section 2.1.3, two different indicators of the biofuel supply cost have been applied in this study – the absolute biofuel supply cost, and the system biofuel supply cost. The results are shown in Figure 7. For the SNG dominated scenarios with the base investment costs (Scenarios 1-5 and 10-11) the biofuel supply cost (left side of figure) can be seen to follow a decreasing trend at lower biofuel production levels, which flattens at higher production levels. The supply cost of forest-based biofuels in those scenarios is relatively similar, in the range of approximately 72-80 EUR/MWh. This puts the costs from this study in the lower range of what has been reported by Landälv and Waldheim (Sub Group on Advanced Biofuels, European Commission, Sustainable Transport Forum) [34]. The absolute biofuel supply cost in the BLG dominated scenarios (Scenarios 6, 9) can be noted as markedly higher, at 85-90 EUR/MWh.

When instead looking at the system biofuel supply cost (right side of the figure) it can be seen that for most scenarios, the system supply costs are of a similar size as the absolute supply costs. Here, the BLG dominated scenarios stand out, as the system supply cost is considerably lower than the absolute biofuel supply cost. The reason is that when alternative industrial investments are considered, the BLG based biofuel production is credited with the alternative investment cost of a new recovery boiler, which has a significantly higher investment cost than the alternative investments for the other biofuel production technologies (typically bio-boilers and/or turbines). Also the scenarios with limited biomass resources (Scenarios 10-11) showed a discrepancy between the absolute biofuel supply cost, and the system supply cost, but in these cases the system cost was higher. This can be explained by that more costly biomass resources need to be taken into use with the assumed resource restriction in place.

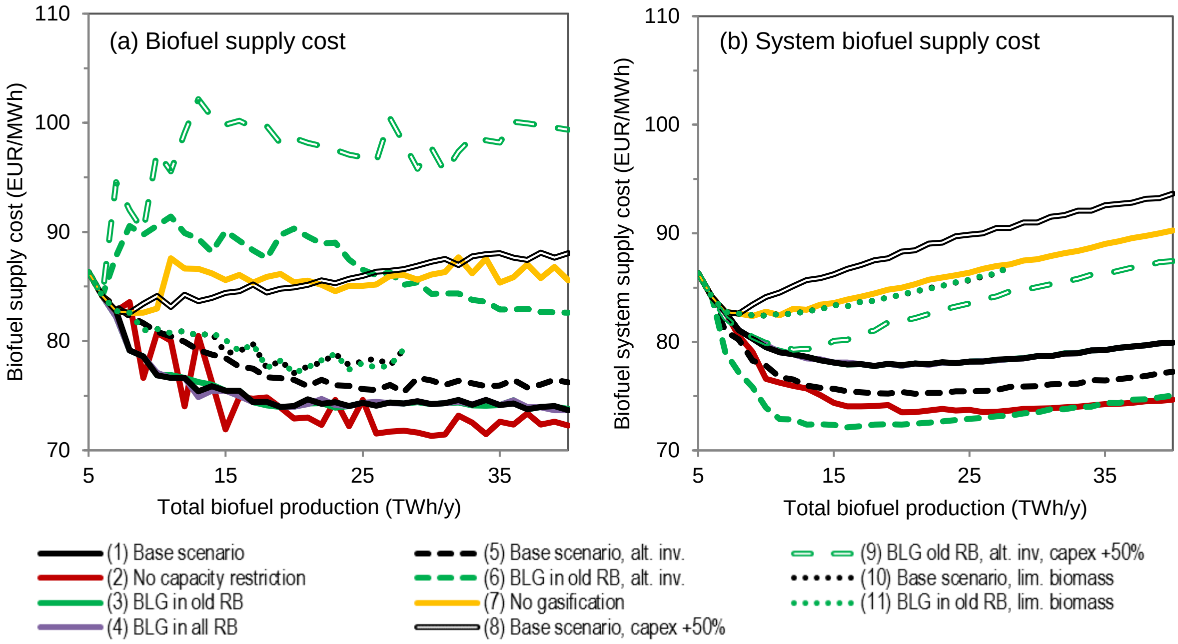

Figure 7. Resulting biofuel supply cost (left) and biofuel system supply cost (right). Dashed lines represent scenarios where alternative industrial investments are considered, dotted lines scenarios with limited biomass supply, and double lines scenarios with higher investment costs for emerging biofuel production technologies. Note that the results for Scenarios 1, 3 and 4 coincide to a large extent, for which reason some resulting cost curves are hidden.

3.1.3 Locations of interest for biofuel production

Figure 8 gives an overview of the frequency with which specific plant locations appear in the model solution over the 11 analysed scenarios, for four selected biofuel production levels. It was found that compared to in previous analyses using BeWhere Sweden, there was a less strong tendency to favour industrial integration in this analysis. Instead, also stand-alone locations appeared frequently in the results. The exception was the scenarios where alternative industrial investments were considered (Scenarios 5, 6, 9), where integration with industries or district heating systems was always preferred, due to the investment credit resulting from the assumed need for alternative investments. This emphasises the complexity in the potentially important role of the existing industry in mitigating future biofuel production costs, as this potential synergy benefit must be shared between the host industry operation and the biofuel production (here the entire gain is shown as attributed to the biofuel production). This aspect is lacking in current policy, and will likely be difficult to capture in any policy design.

Another explanation for the “new” preference for also non-integrated production locations, lies in the capacity restriction (400 MW_{th} biomass input), which leads to relatively small quantities of excess heat, which in turn gives a relatively small credit to the biofuel production. Consequently, the scenario with no capacity constraint (Scenario 2) shows a significantly larger preference for integrated production in pulp mills as well as in district heating systems.

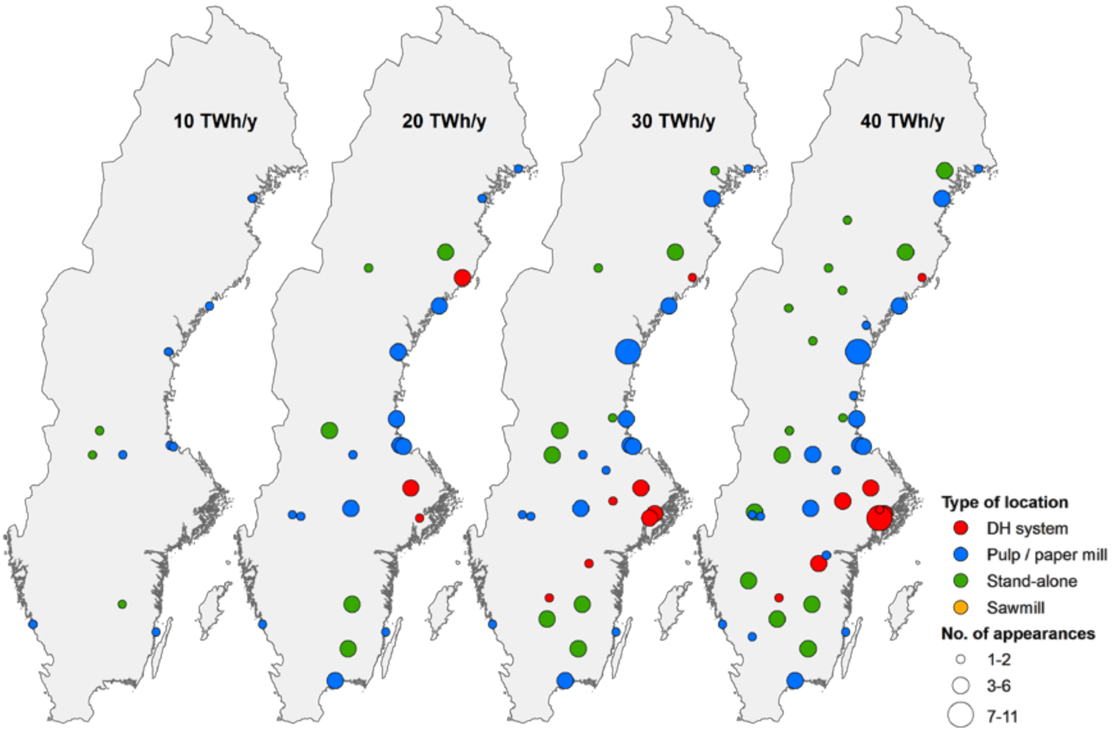

Figure 8. Number of times each potential location appears in the model results for four different biofuel production levels. The sizes of the markers correspond to the frequency of appearances for a particular location, while the colours indicate which type of location each marker represents.

3.1.4 Comments from actors and stakeholders

The results from the model runs were discussed in a final workshop where relevant actors and stakeholders from the industry and energy sector participated, together with representatives from academia and research institutes. A number of aspects were discussed, as summarised below. The results were subsequently subject to some refinement before inclusion in this report.

Plausibility of specific model results

A central point of discussion concerned the plausibility of the specific results that were presented, in particular in relation to the contemporary areas of interest in the real world. Three main observations were made. Firstly, the model clearly favours large, centralised biofuel production plants, due mainly to economy-of-scale effects. However, the current tendency regarding biofuel investments is the opposite – that is, smaller plants with lower capex are in favour. This is, for example, an important driver behind the current interest in biofuels based on depolymerisation and upgrading of lignin. Secondly, since a fundamental constraint in the model work has been to only include production technologies at a relatively high technology readiness level, gasification based pathways have been heavily favoured. Again, this does not accurately reflect the current level of interest in investing in large-scale gasification based biofuel concepts (which are, at the time being, virtually non-existent). Thirdly, the selection of specific gasification based biofuels to include was done in order to maximise the biofuel output, which resulted in the inclusion of methanol and SNG (both of which are high-yield fuels). However, the current focus is heavily inclined towards drop-in fuels, which would have made it relevant to also (or instead) include synthetic fuels (e.g. Fischer-Tropsch or FT fuels). It should be noted that refinery integrated FT fuel production has previously been considered in the BeWhere Sweden model [8], but due to high fuel production costs compared to other analysed pathways, it was subsequently omitted from later model versions.

Applicability of analyses

The biofuel system supply cost was highlighted in the analysis in order to be able to (1) further elucidate the increased biomass costs for competing users in the system, as increasing shares of the total biomass supply would be allocated to the transport sector at high biofuel production levels, and (2) evaluate the potential contribution of required alternative industrial investments as a means to reduce biofuel production costs. As pointed out in the workshop discussion, a number of other relevant system related aspects have been left out from the biofuel system supply cost, which would make it less (or not at all) relevant as a measure of e.g. different technologies' performance.

A similar discussion concerned the scenarios where alternative industrial investments were considered (Scenarios 5, 6, 9). This in particular regards the investment in black liquor gasification (BLG) as an alternative to investment in a new recovery boiler, which was shown in the results to be an absolute prerequisite for the profitability of BLG based biofuel production. It was noted that this reasoning would demand that (1) alternative investments are required, (2) the entire benefit for the recovery boiler investment is credited to the biofuel production, and (3) the mutual dependency between the two technologies is accepted. As a consequence, this type of investment would require either that it is the host pulp mill that invests in biofuel production, or the development of a highly complex business model in order to split the benefit of the recovery boiler credit between the pulp mill and the biofuel plant.

It should be noted that the intention of including both the absolute biofuel supply cost and the system supply cost in the analysis was to assess the value of further development of existing industrial infrastructure in an overall systems perspective, and not to analyse the benefits for individual actors in the system. It was thus concluded that it is extremely important to clearly define not only the technological scope of the model, but also the scope of the analysis, as well as the intended recipient(s) of the results of the analysis. The analysis in this study could be of interest at an academic as well as on a policy maker level, but would probably be of less relevance within the industrial scope.

Aspects of interest to analyse further

The focus in this study has been heavily production oriented, with no explicit consideration of where or how the produced fuel would be used (domestically or exported, in road transports or shipping, etc.). In the workshop, several biofuel market aspects were also discussed, that could be of interest to analyse using BeWhere Sweden. A potential scope of analysis would be to model and analyse the new reduction obligation, which would require explicit consideration of e.g. international trade and CO_2 emission performance of different fuels. Much of the discussion was focused on markets for biofuels and how they are actually created, which further emphasised the value of performing model based systems analysis in collaboration with relevant stakeholders, in order to capture impacts of and effects on different parts of the studied system. It would also be relevant to explicitly take risk related factors into account in the model. Examples could be lower plant availability during early years of operation, higher capital costs for first-of-a-kind plants, or real-option theory based approaches [35–37][7].

While industrial integration is a core concept in BeWhere Sweden, that, as the results showed, may help mitigate biofuel production costs, it would be of interest to broaden the scope of industrial integration pathways. As Holmgren et al. [38] showed, and as was discussed in the workshop, integration with chemical industries or oil refineries could provide benefits for gasification based pathways. This has indeed previously been included in BeWhere Sweden, but was later excluded due to inferior performance compared to other pathways and integration options.

It was further noted that the biomass costs for the forest industry would increase with increasing biofuel production levels[8]. At the same time, this is the industrial sector that, according to the model results, could be expected to carry a large part of the necessary new investments in forest-based biofuel production. This could, thus, lead to potential conflicts of interest – in particular for pulp mills that today use large shares of sawmill chips as fibre feedstock. This aspects was also discussed in the interview analysis (Section 3.2.1), and could be of interest for future analysis – again preferably in collaboration with relevant actors and stakeholders.

3.1.5 Concluding comments on the techno-economic analysis

The results showed that there are many different ways to reach high levels of biofuel production in Sweden, at reasonable costs. The resulting system costs, as well as the biofuel supply costs, for the different alternatives are relatively similar, which shows that the dependency on specific locations or technologies is not particularly strong. The results confirmed the findings from previous studies in that economy-of-scale and biomass-to-biofuel conversion efficiencies provide the largest potential for decreased biofuel production costs, when it concerns the emerging production technologies. Further, as has been mentioned, gasification based biofuels were favoured already in the design of the model runs, and as such turned out as promising pathways in the model results, both as regards production costs and conversion efficiency. Black liquor gasification followed by synthesis to methanol provides the opportunity for high efficiency conversion at competitive costs, but was shown to be completely dependent on the need for alternative industrial investments (new recovery boilers) in order to be competitive. Gasification based fuel pathways, however, come with very large investment requirements, which are in turn associated with seemingly insurmountable barriers to actual implementation, as was also discussed among the actors and stakeholders.

It can be commented that the biofuel technology options included in this study are not necessarily the most relevant in the short time perspective, but rather represent technologies that have been

[7] This will be analysed in a project starting at LTU during 2018.

[8] A similar effect was noticed concerning the stationary energy sector (i.e. heat and power production). For the energy sector the possibility to compensate by increasing the price to the final customer is, however, likely higher, as the energy sector operates on a local market, contrary to the forest industry that operates on an international market.

shown in previous studies to offer competitive long-term costs and high biomass-to-biofuel conversion efficiency (see e.g. [34]). FT fuel production, which was discussed among the actors in the workshop, is based on similar technology, but with lower conversion efficiency and higher production costs (at least 20 EUR/MWh higher than SNG/methanol, according to Landälv and Waldheim [34]). Nevertheless, it should also be noted that no additional costs for new infrastructures, vehicles, etc. have been considered here, which would be needed with SNG and/or methanol in the fuel mix. If this was to be included explicitly, in addition to the inclusion of e.g. gasification based drop-in fuels (FT fuels), the results could benefit FT fuels to some extent.

3.2 ACTOR ANALYSIS RESULTS

This section summarises the main results from the actor analysis, with focus on results relevant for the overall aim of this project, of investigating the usefulness of BeWhere Sweden for relevant actors. For more details, see Fallde et al. [32].

3.2.1 Drivers for and barriers to forest-based biofuel production

The interviewed actors' perspectives of *drivers* for forest-based biofuel production can be divided into three main categories, of different relative importance for the actors. First, *climate change mitigation* was mentioned as a driver for engaging in biofuel production. This driver was most pronounced as regards the actors representing authorities, but was also mentioned by industrial representatives. A second driver was found regarding *the changed market and conditions for pulp and paper mills*. The perspectives regarding changed market conditions as a driver were, however, found to be strongly ambivalent. On the one hand, changed market conditions have made the industry (in particular the forestry sector) search for new markets and new products. On the other hand, the forest industry can be seen as being skeptical regarding new markets that differ from the traditional markets, and the concern was also expressed that new products (such as biofuels) would result in higher pulping feedstock prices. Finally, a third driver was discerned that concerns not only new markets, but rather *the already established production*, where biofuel production was interpreted as a part of the waste-management system for handling by-products from the forest industry. Biofuel production could also be used as a way to utilise existing process equipment more efficiently, and to possibly generate extra revenues from activities that currently generate low or no extra income (such as lignin separation to debottleneck the recovery boiler).

Even though new markets were regarded as a possibility among the interviewed actors, they were complemented or outdone by different *barriers*. *Technical barriers* were discussed among all interviewees, related to the fact that mature technologies for large-scale forest-based biofuel production are largely missing today. Nevertheless, obstacles related to technology readiness levels were overshadowed by what can be summarised as *financial barriers.* The interviews showed that the industries' perception of risk has increased during the last decade. These risks are, to a high degree, connected to policies and, for example, stability and predictability with regard to supporting regulations, but also to investments and the expected costs for producing biofuels. The perceived risks were also found to be enhanced by the competition between different biofuels, and by the lack of long-term market stability. The comparison was made with E85, which saw a rapid increase, and an even quicker decline. For E85, the lack of political perseverance contributed to a loss of legitimacy, economic losses for investors, and reduced willingness to invest in renewable fuels, which subsequently led to an increase in the perceived risks in investing in this type of systems (see [19]). Finally, a third type of barrier concerns *interest contradictions regarding forest and land use*. This barrier was only emphasised among the interviewed authorities, and not by the interviewees representing model developers or industrial representatives. Here, focus is turned from presuming that biomass residues from forests should be used, e.g. for biofuel production, to instead problematising forests as resources. The conflicts involve several different aspects, in particular environmental values other than climate change mitigation (especially biodiversity related issues), but also other geographical aspects. In the forest-rich areas of northern Sweden, the geographical areas involve a multitude of different interests: the forest as industrial raw material, the possibility to use it for example for biofuel production, the forest as tourism, the forest as home for the Sami, etc., which creates interest contradictions, as high-lighted by the interviewed regional authority representatives.

3.2.2 BeWhere Sweden and interpretations of its results

Model usefulness – how and for whom?

When asked what aspects of the BeWhere Sweden model that could be used and why, several interviewees mentioned the geographically explicit function. According to the interviewed developers, this function was one of the reasons why the model was developed: in order to shape a tool to investigate potential localisations of, for example, biofuel production; and also to complement other energy system models. Further, the geographical function also serves as a tool for calculating the total production costs of the produced biofuels. In order to evaluate such costs, the geographical function can be used to calculate expected transportation costs, depending on where production plants would be located. One expectation highlighted in the interviews, and which was also discussed in the project workshops (see Figure 1), also lies in the progress and continued development of the model, and the assumed goal of producing a model close to reality. As explained by interviewee D1, the model is updated for every ‘new’ scope or area that is studied, in order to include and evaluate specific components in the model.

The results from the interviews showed that when describing the model and the reasons for using it, it is important to also problematise who the intended users of the model and the model results are. Among the interviewees, it was clear that potential users of results from the model mainly consist of civil servants investigating biofuel production in a national or regional context. This was also the aim when initially developing the original BeWhere model, and the intention is that the model will progress from being used only for research, to also being used as a tool for policy makers. Nevertheless, the interviewees representing the forest industry also saw themselves as potential users of the results presented from the model.

The model as a means to illustrate barriers to and drivers for forest-based biofuels

The interviewed actors found BeWhere Sweden to be useable as part of the investigation needed for decision-making – e.g., as an exemplifying scenario. In general, energy system models are good for identifying and analysing various economic barriers for the introduction of, for example, renewable energy technologies. In contrast, they usually over-simplify or omit the relationships between the energy system being studied and other issues (see e.g. Nakata et al. [39]). In this regard, BeWhere Sweden is no exception. The model has thus mainly been focused on and developed to analyse opportunities and barriers related to geographical localisation, and strategies for reducing supply chain costs in order to minimise the cost gap to fossil fuels, as well as to investigate necessary policy support in order to make investments feasible.

Even though BeWhere Sweden could help to illustrate different scenarios and support decision-making, the obstacles that the interviewed actors foresee concerning forest-derived biofuel production are, however, mainly to be found outside of the components that influence the results of the model. The barriers identified as most critical focus mainly on social and, to a certain extent, political factors that are not acknowledged in the model. Whereas interviewees representing the forest industry identified unpredictable policy instruments as an obstacle that influences future action (compare [5]), interviewees representing regional and state authorities also recognised issues concerning land and resource use competition as critical. Policy instruments on the state and EU level constantly change, but can (and are already to a certain extent) acknowledged in the BeWhere model. On the contrary, issues like land use competition involve a multitude of actors and interests connected to ecosystems and ecosystem services, interests and rights of indigenous people, interests of business and enterprises, all affecting the interest of producing biofuels based on forests. That is, as several interests compete for a limited resource in a confined geographical area, the result is a complex mess of interests, which illustrates how the reality studied in a model can never be understood as a ‘closed system’ [40]. Similarly, that many actors’ perception of risks (e.g., political, technological and economic risks) has increased over time is not captured by BeWhere Sweden, but may have a large influence on the willingness to invest. The timing aspect was thus mentioned by several interviewees, as well as during the project workshops, and confirms findings by Peck et al. [5] and Kastensson and Börjesson [19].

3.2.3 Reflections on models and how they could (and should?) be used

A general view among the actors, in interviews as well as in project workshops, was that models and the results from models can and should be used in investigations and as a basis for decision-making. However, using models was also seen to be associated with a complexity, mainly concerning what has been referred to as “the black box”. Models are thus often seen as black boxes, giving results that might be (too) complex to understand without analysing the data that goes into the model, and with an output that is highly sensitive concerning the input.

Even though the interviewees stated that BeWhere Sweden (as well as other models) could be used for e.g. decision-making and governmental investigations, they were nevertheless very concerned regarding models in general and how they are used. Mainly, this concerns the use of models where the results are interpreted as ‘facts’ or truth. The point was made that a model can never be understood without the input from researchers working with it, and can never become better that the input and the assumptions made. This means that a model and the results from the model must be understood as a synthesis from the different assumptions made by the developers of the model. The different assumptions that become the model input could be a strength for the model because it considers many different perspectives when the results are calculated. Conversely, erroneous assumptions might harm the results considerably. That is, the more assumptions that are included in a model, the higher the probability of a flawed output from the model.

The potential BeWhere Sweden users, as well as the model developers, expressed awareness during the interviews of the limitations of what a model can illustrate and what questions it might answer. However, in order to make the model realistic, BeWhere Sweden is constantly under development, including the addition of more parameters to be able to answer further questions and better illustrate the real world (see also Section 2.1.1). This, however, risks leading to the so called "complexity paradox", as described by Oreskes [40]. That is, the effort to create a model that is close to reality actually risks making it more unsecure. In order to be more realistic, and thus to result in an output that takes a multitude of different components into consideration, the input must in turn consist of many different parameters. At the same time, all variables that go into the model involve a certain amount of uncertainty. The more complex the model is with all these variables, the more unsecure it becomes. Or "the 'truer' the model, the more difficult it is to show that it is 'true'" [40, p. 20]. The complexity paradox thus means that every new variable that is added into the model also makes it more unsecure.

In this study, the actors showed a certain amount of ambivalence regarding this aspect. On the one hand, the actors expressed awareness of and caution regarding the fact that models are highly dependent on the quality of the input assumptions. On the other hand, they also expressed a certain belief in added components and increased complexity as factors that might improve the BeWhere Sweden model.

3.2.4 Concluding comments on the actor analysis

The results have confirmed that the BeWhere Sweden model could, at least to some extent, help to illustrate opportunities and obstacles regarding forest-derived biofuel production in Sweden. The main users of the model results were expected to be e.g. representatives of authorities, investigating biofuel production in a national or regional context, which matches the original intention of the model developers. It was emphasised among the interviewees that presentations of model results must be complemented with an interpretation, and that, in order to use the results from models as a basis for decision-making, it is essential to understand the assumptions that have been integrated in the model, and which have thereby influenced the results. A further consequence of this is that, in a broader scope of use of energy models, it is important to critically investigate who has developed the model and why, before even starting to analyse the results from it. Models developed in academia or models used within governmental authorities should thus also be critically evaluated before being exercised in a public authority.

This study has also illustrated the complexity that characterises biofuel policy area, where a multitude of different interests interact and where an energy system model can answer only a part of the possible 'what if…?'-questions. The study also showed that the greatest concerns for actors involved in investigations regarding forest-derived biofuel production are due to aspects that are not easily included in a parameterised energy system model, such as BeWhere Sweden.

4 CONCLUSIONS

This project aimed at investigating the usefulness of the BeWhere Sweden model for relevant actors and stakeholders. This was done by, on the one hand, model development and model runs based on dialogue with relevant actors, and, on the other hand, interviews with actors representing potential users of the model and/or results from it.

4.1 USEFULNESS OF BEWHERE SWEDEN AND LESSONS LEARNED

Two overall conclusions can be drawn from this study:

(1) The BeWhere Sweden model indeed has the potential to be a useful part of a larger toolbox in the transformation towards large-scale forest-based biofuel production, *but…*

(2) …this requires careful consideration of the scope of the model for the particular analysis, as well as early contact and communication with the involved actors and intended stakeholders and users of the model results.

A number of lessons have been learned during this work, and both strengths and shortcomings of the model have been identified. From this, some recommendations for future work involving the BeWhere Sweden model have been compiled.

4.1.1 Strengths and intended areas of use

A main conclusion was the importance of clearly showing how the BeWhere Sweden model can be used, and for which types of analyses. This minimises the risk of misunderstanding between the model operator(s) and the intended users of the results, regarding e.g. what the model can be used for, and conversely, where it is inappropriate. The main strength of the model (in relation to other energy system models) lies in the geographical representation of supply and demand of biomass resources, and the options to model different value chain alternatives in detail. One important usefulness of the model thus lies in the potential to identify e.g. regional “hot-spots” for new production. This can be used to create knowledge about factors that affect e.g. the costs and environmental impacts from biomass based supply chains, which can in turn aid in the design of robust policies in order to facilitate effective technological, infrastructural and behavioural development.

BeWhere Sweden is thus intended to be used at a strategic decision making level. This type of decision making refers to long term decisions that usually involve investment intensive decisions, and which typically pertains to the design of the biomass supply network and policies affecting this. The intention is thus to use results from the model as strategic decision support (in combination with other decision support systems), in order to facilitate market penetration for biomass based value chains.

Examples of aspects that can be analysed using BeWhere Sweden include comparison of the performance of different supply chain configurations (e.g. centralised vs. distributed) under varying system conditions, impact of policies on the performance of different technology options, strategies for reducing supply chain costs in order to minimise the cost gap to fossil fuels, and trade-offs between e.g. supply chain costs and supply chain related CO_2 emissions. By connecting BeWhere Sweden to an economic market model, local and regional biomass market effects can also be analysed, as is currently being done by Ouraich et al. [12,13].

A main lesson learned was that the BeWhere Sweden model can be used in collaboration with relevant actors, but that a different type of process setup than what was applied here would be required. The exploratory approach applied in this project showed that BeWhere Sweden was not particularly well suited for use in the originally intended workshop format, due both to run-time and inertia related issues, and to lack of fast and simple model result visualisation options.

A better approach would thus be to outline a more iterative process, with regular meetings involving the model operator(s)/analysists, as well as relevant experts, actors and stakeholders. In particular, early definition of (1) appropriate actors and stakeholders to include for a particular analysis, and (2) the purpose and scope of the analysis, were identified as keys for a successful process.

4.1.2 Shortcomings and risks

The results from both the interview study, and the actor workshops where model results were discussed, showed that a discrepancy exists between the actors' "model wish list", and aspects that actually are (and can be) covered by BeWhere Sweden. As such, many of the main obstacles regarding forest-derived biofuel production that the interviewed actors anticipated, are not acknowledged in BeWhere Sweden and also not covered by the overall intended scope of analysis using the model.

A major obstacle for useful application of the BeWhere Sweden model lies in the timing aspect, which in turn connects to issues regarding input data availability vs. input data requirements. In order to be useful for the intended actors and stakeholders, the model must be relevant in the contemporary scope. From an actor's perspective, this typically means the inclusion of the biofuel production technologies that are currently in the spotlight within, in particular, the policy agenda, and the exclusion of technologies that may have been demonstrated technologically but where the investment appetite is currently low (or non-existent). However, for emerging technologies on an early stage, publically available data on the form and of the quality required for inclusion in a parameterised model such as BeWhere Sweden, is typically scarce (at best). This creates a contradiction between current fundamental research of new technology and processes, current state-of-the-art knowledge from the systems analysis research community, and the actual momentum and interest regarding biofuel investments.

Another obstacle can be found regarding understanding of and expectations on the model. Both the workshops and the interviews showed a tendency among the actors to advocate model improvement and addition of e.g. new parameters and technologies, in order to get "closer to reality". However, this approach risks leading to loss of transparency, reliability and model robustness (the so called complexity paradox [40]).

Lack of previous model knowledge and understanding can also lead to excessively long "run-in periods", which, at best, is only time-consuming, but which also risks leading to misunderstanding and miscommunication of essential aspects of the analysis.

4.1.3 Recommendations for future use of BeWhere Sweden

The boxes below summarise the key success factors and obstacles, respectively, for an actor based analysis setup using BeWhere Sweden, that have been identified within this project.

Success factors

- **Well defined aim** of analysis and model scope (technologies, scenarios etc.)
- **Flexible and robust** model structure – ability to adapt model quickly
- **Regular iterative process** between model operator / analyst and involved actors and stakeholders
- **Communication and mutual understanding** – previous model knowledge desirable and timesaving, but not required
- **Openness and awareness** – for model operators as well as involved actors and stakeholders
- **Let it take time** – important in order to build necessary mutual system and model understanding

Obstacles and risks

- **Misunderstandings and miscommunication** – risks of for example trying / wanting to use the model outside its intended context
- **Poorly defined aim** early in the process risks leading to eroded confidence in model results later
- **Timing aspects** – long lead times and process inertia risk making the analysis outdated before it is even finished
- **Lack of available data** – difficult (or impossible) to implement emerging technologies at an early stage
- **Complexity paradox** – risks of losing transparency and robustness when adding new variables and parameters

4.2 CONCLUDING COMMENTS

The results from the techno-economic analysis using BeWhere Sweden showed that there are many different ways to reach high levels of biofuel production in Sweden, at reasonable costs, and that the dependency on specific locations or technologies is not particularly strong. Economy-of-scale and high biomass-to-biofuel conversion efficiencies were shown to provide the largest potentials for decreased production costs, which benefitted large-scale gasification based biofuel production, which in turns would require substantial investments in capital intensive production concepts. The results, however, stand in sharp contradiction against the current actual development regarding investments in biofuel production, where the trend is towards less capital intensive technology tracks, as well as towards drop-in fuels that can be upgraded in existing refinery infrastructure.

A final overall conclusion from this study is that researchers and experts involved with energy system modelling would benefit from reforming the way they design, operate and present models and model outputs, and also from engaging in deeper interaction with actors from different sectors in order to more explicitly make society the subject of the work. Future studies using the BeWhere Sweden model should, therefore, involve relevant actors and stakeholders at an early stage in the process, in order to clearly identify the scope of the intended analysis, what technologies to include, and how to operate the model. A relatively frequent, iterative process is recommended in order to ensure confidence in the final results from the model analysis. Of general interest for future studies would also be to further investigate how energy system models are actually interpreted among their users, and how they are actually used for policy-making – not just how they are intended to be interpreted and used.

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APPENDIX A – SUMMARY OF MODEL DEVELOPMENT

In this appendix, the key input data that has been updated or added within this project is summarised. For a more thorough description of the BeWhere Sweden model, the reader is referred to previous publications [7, 8, 20, 33].

GEOGRAPHIC SCOPE

Two different geographic representations were used: a base model grid (0.5 degree spatial resolution), and explicit locations. The geographical scope was limited to current land-use. This means that no land use change from e.g. agriculture to forestry was considered. Further, the geographical representation is relatively coarse, for which reason changes between e.g. different types of crops on arable land can not be captured by the model. Table A-1 summarises the geographic representations for the different types of parameters.

Table A-1. Overview of the geographic model representation (see also Figure 2).

Modelled parameters	**Geographic representation**
Biomass supply	
Crop-based feedstocks (grains, rapeseed)	N/A (see the text for details)
Tall oil for HVO production	N/A (see the text for details)
Forest biomass (stemwood and residues)	Grid-based, bottom-up aggregation
Farmed wood from abandoned arable land	Grid-based, bottom-up aggregation
Waste wood	Grid-based, top-down disaggregation
Industrial by-products	Explicit locations, bottom-up estimation
Industrial biomass demand	
Sawmills	Explicit locations, bottom-up estimation
Pulp and paper mills	Explicit locations, bottom-up estimation
Pellets production plants	Explicit locations, bottom-up estimation
District heating (DH) and combined heat and power (CHP)	Explicit locations, bottom-up estimation
Biofuel production	
Commercial liquid biofuel production (HVO, RME, ethanol)	Explicit locations, bottom-up estimation
Biogas production	Grid-based, bottom-up aggregation
Emerging biofuel production plants	Explicit locations, individual modelling
Transport fuel demand	Grid-based, top-down disaggregation

BIOFUEL PRODUCTION

Two general groups of biofuel production technologies were considered – commercial biofuel production technologies and emerging biofuel production technologies. Table A-2 gives an overview of the considered production technologies and concepts, with more details in the following sections.

Table A-2. Included biofuel production technologies. Localisation options include stand-alone (SA) or integrated with chemical pulp mills (cPoP), mechanical pulp mills/paper mills (mPoP), sawmills (SM), or district heating networks (DH).

Biofuel production technologies		**Biofuel/s**	**Existing prod. (TWh/y)**	**Modelled max cap. [a] (TWh/y)**	**Localisation options [b]**
Commercial biofuel production technologies					
Biogas, co-digestion	BG-codig	biogas	0.75	2.1	(SA)
Biogas, sewage treatment	BG-wwtp	biogas	0.43	0.70	(SA)
Biogas, farm-based	BG-farm	biogas	0.01	2.2	(SA)
Ethanol, grain-based	EtOH-grain	ethanol	1.1	1.4	(SA)
Ethanol, brown liquor based	EtOH-brl	ethanol	0.13	0.13	(SA)
Biodiesel (RME)	RME	RME	1.9	2.7	(SA)
HVO, tall oil based [c]	HVO	HVO	0.85	2.1	(SA)
Emerging biofuel production technologies					
Methanol via black liquor gasification	MeOH-blg	methanol	0	(no limit)	cPoP
Methanol via solid biomass gasification	MeOH-bmg	methanol	0	(no limit)	SA, cPoP, mPoP, SM, DH
SNG via solid biomass gasification	SNG-bmg	biogas [d]	0.03	(no limit)	SA, cPoP, mPoP, SM, DH
Ethanol + biogas via SSF and anaerobic digestion	EtOH/BG-ssf	ethanol + biogas	0	(no limit)	SA, cPoP, mPoP, SM, DH

[a] For existing production, 2015 has been used as a base year. Maximum production capacities for commercial technologies have been estimated based on a combination of a mapping of actual current and planned biofuel production, and a review of scenarios and projections for future transport sector development in Sweden [4,15]. No max total production capacities are defined for new advanced biofuel technologies. This is instead determined endogenously by the model, as described in the text.

[b] Several existing biofuel production plants are partly or fully integrated with industry or district heating networks. The effects of these integrations have not been explicitly considered in this analysis, for which reason they are labelled SA (stand-alone).

[c] A small share of this originates from other feedstocks than tall oil, mainly from tallow methyl ester and RME. Here it has been aggregated as one type of biofuel.

[d] SNG is here considered as equivalent to upgraded biogas from anaerobic digestion.

Commercial biofuel production technologies

For commercial biofuel production, concepts that are currently in place in Sweden were considered (biogas from anaerobic digestion, grain- or brown liquor-based ethanol, RME, and tall oil based HVO). Existing production (2015 as base year) as well as modelled capacity expansion potentials were considered, based largely on scenarios developed by Martin et al. [4].

For ethanol, current production in three different plants was considered: Lantmännen Agroetanol in Norrköping, St1 in Gothenburg, and Domsjö Fabriker/SEKAB in Örnsköldsvik. A small expansion potential was considered for Agroetanol's facility, while the other two were assumed to operate at maximum the current capacity.

For RME (rape methyl ester, or biodiesel), Perstorp's facilities in Stenungsund and Fredrikstad[9], as well as Ecobränsle in Karlshamn were considered. The production in 2015 for all facilities was lower than the max capacity, for which reason the max capacity for each facility were considered in addition to the current production.

For HVO (hydrotreated vegetable oil)[10], only the domestically produced HVO from Preem's facility in Gothenburg is considered. Of this, the main part originates from crude tall diesel, produced from crude tall oil. Today most of the HVO used in Sweden is imported and only a relatively small part (16%) originates from tall oil [41]. Here, the production in 2015 was used as base and the maximum production capacity in Preem's facility (increased from 90,000 to 220,000 m^3 per year in late 2015) is used as max potential. Higher capacity would require substantially increased imports, which has not been considered here.

For biogas, the production was modelled spatially explicitly on an aggregated level (individual plants not modelled explicitly) divided into three production categories: sewage treatment plants, farm-based biogas plants and co-digestion plants. The farm-based biogas production potential from crop residues and manure was adapted from the base scenario from Einarsson and Persson [15,23]. For sewage treatment and co-digestion, the current production on county level [42] was downscaled on grid population for inclusion in BeWhere Sweden. For the expansion potential, the "Scenario 2, min" developed by Dahlgren et al. [3] was modified (reduction of co-digestion potential in order to take the farm-based production into account) and implemented in BeWhere Sweden.

Production costs for biofuels from the commercial production technologies were calculated using continuous variables only. The costs for each type of fuel were adapted from Börjesson et al. [43, fig. 7], with additions for biogas upgrading, compression and distribution (see also below) [16] and some modifications to take different biogas substrates into account [44]. The modelled biofuel costs are summarised in Table A-3.

Table A-3. Modelled production costs for commercial biofuel production technologies.

Biofuel	Production cost (EUR/MWh)
Biogas, co-digestion	80
Biogas, sewage treatment	60
Biogas, farm-based	70
Ethanol, grain-based	88
Biodiesel (RME)	80
HVO, tall oil based	80

[9] Even though this facility is located in Norway, it produces RME for the Swedish market, and was included in this study, after input from Perstorp.
[10] Even though the term HVO strictly only applies to fuel originating in oils of vegetable origin, such as crude tall oil, palm oil or rapeseed oil, it is in this paper applied also to fuels from non-vegetable origin (e.g. slaughterhouse waste and tallow).

Emerging biofuel production technologies

Four different emerging biofuel production technology concepts were considered, for localisation either as stand-alone plants or integrated with existing industrial or energy plants. Only integration benefits from reduced need for fuel use in boilers and reduced need for transportation of by-products from e.g. sawmills were considered. Other co-location benefits (e.g. shared work force, buildings and service facilities, feedstock handling systems) were not included, but can be assumed to contribute to reduced biofuel production costs for integrated production plants.

Table A-4 presents the modelled energy balances for the considered biofuel production technologies and Table A-5 presents the investment cost functions used. Annual operation and maintenance (O&M) costs were set to 4% of the investments costs. For the EtOH/BG-ssf plant, an additional cost for chemicals and enzymes was added, corresponding to 2.3% of the investment cost.

Table A-4. Energy balances for the considered biofuel technologies integrated with different hosts (see Table A-2), based on one unit of fuel input.

Biofuel production technologies	Biofuel 1	Biofuel 2	Steam/ heat	Purge gas	Electricity production	Electricity use
MeOH-blg-cPoP [a]	0.54	-	0.16 [b]	0.04	-	0.11
MeOH-bmg-cPoP	0.51	-	0.20	-	0.05	0.09
MeOH-bmg-mPoP	0.51	-	0.14	-	0.06	0.09
MeOH-bmg-SM	0.51	-	0.14	-	0.07	0.09
MeOH-bmg-DH	0.51	-	0.14	-	0.07	0.09
MeOH-bmg-SA	0.51	-	-	-	0.09	0.09
SNG-bmg-cPoP	0.70	-	0.14	-	0.08	0.07
SNG-bmg-mPoP	0.70	-	0.08	-	0.09	0.07
SNG-bmg-SM	0.70	-	0.08	-	0.09	0.07
SNG-bmg-DH	0.70	-	0.08	-	0.10	0.07
SNG-bmg-SA	0.70	-	-	-	0.11	0.07
EtOH/BG-ssf-cPoP	0.42	0.14	0.17	-	0.09	0.04
EtOH/BG-ssf-mPoP	0.42	0.14	0.17	-	0.09	0.04
EtOH/BG-ssf-SM	0.42	0.14	0.17	-	0.10	0.04
EtOH/BG-ssf-DH	0.42	0.14	0.22	-	0.11	0.04
EtOH/BG-ssf-SA	0.42	0.14	-	-	0.13	0.04

[a] This is the balance of only the MeOH-blg plant based on a certain amount of black liquor. The bark boiler plant has different sizes in relation to the MeOH-blg plant depending on the specific mill.

[b] Total effect on low pressure (LP) and medium pressure (MP) steam, as the biofuel plant has a need for MP steam and an excess of LP steam.

Table A-5. Investment cost functions. C is the capacity in MW. All investment costs were recalculated to a 2015 monetary value using the Chemical Engineering's Plant Cost Index (CEPCI).

Biofuel production technologies	Inv. cost function $a \cdot C^b$ ($MEUR_{2015}$)			Data based on
	a	*b*	*C (MW)*	
MeOH-blg	20.3	0.49	Input black liquor	[45]
MeOH-bmg	5.4	0.7	Input wood fuel	[38]
SNG-bmg	6.4	0.7	Input wood fuel	[38]
EtOH/BG-ssf	4.6	0.7	Input wood fuel	[16,46]
Steam boiler (wood fuel) [a]	2.3	0.7	Input wood fuel	[47] [b]
Hot water boiler (wood fuel) [b, c]	2.1	0.7	Input wood fuel	[47]
Recovery boiler [d]	2.5	0.7	Input black liquor	[20]
Steam cycle [e]	2.2	0.7	Produced electricity	[38]
Integrated drying [f]	1.9	0.7	Drying capacity	[38]
Biomass handling system [g]	0.20	0.7	Input wood fuel	[38]
Biogas upgrading [h]	0.26	1.0	Input raw biogas	[16]

Included in investments in:

[a] MeOH-blg, EtOH/BG-ssf, and alternative investments in DH systems, some chemical pulp mills and mechanical pulp/paper mills.

[b] Investment cost assumed to be 10% higher than for a heat only boiler (HOB).

[c] Alternative investments in sawmills.

[d] Alternative investments in chemical pulp mills.

[e] All biofuel technologies and alternative investments in DH systems, chemical pulp mills and mechanical pulp/paper mills.

[f] MeOH-bmg and BG-bmg.

[g] Biofuel technologies integrated with DH systems, chemical pulp mills, mechanical pulp/paper mills and alternative investment in DH.

[h] EtOH/BG-ssf.

Gasification based biofuels

Solid biomass gasification (BMG) was considered with two different fuels as end products: methanol and SNG (synthetic natural gas/methane). The considered MeOH-bmg process is based on direct circulating fluidised bed gasification [38]. There are significant amounts of high temperature heat from the process, enabling integration of a heat recovery steam generator (HRSG) connected to a steam turbine producing electricity, steam for internal process heat demands as well as steam for heat demands at a host plant. The considered SNG-bmg process is based on indirect dual fluidised bed gasification [38]. As for the MeOH-bmg process, a HRSG connected to a steam turbine is considered.

Black liquor gasification (BLG) was considered in certain scenarios, with methanol as fuel output (MeOH-blg). The MeOH-blg process considered here is based on high-temperature entrained-flow gasification [45]. There are significant amounts of excess steam from the MeOH-blg process that are considered for use in the mill processes.

Cellulosic ethanol

The EtOH/BG-ssf process starts with a steam pre-treatment step, followed by simultaneous hydrolysis and fermentation and anaerobic digestion, for production of ethanol and biogas [46]. Residues from the process are used in a boiler to generate high-pressure steam, expanding through a steam turbine to generate electricity, steam for internal process heat demands as well as steam for heat demands at a host plant. The produced biogas is upgraded to transport fuel quality [16].

Integration

Integration was considered on two main levels; (1) utilisation of industrial by-products as feedstock for biofuel production, and (2) heat integration with surplus heat from the biofuel production process being utilised to meet heat demands in industrial processes/DH systems. All four advanced biofuel technologies were considered on individual plant level, for which reason the host industries were also considered on individual site level.

When integrated in industries, an annual operating time of 7,838 hours (full load) was applied for the biofuel plants and industrial hosts. Due to heat load competition from e.g. waste incineration or existing industrial excess heat, which typically operates as base load, the annual full load operation with heat deliveries when integrated in a DH system was limited to 4,800 hours. It was assumed that the biofuel plants in DH systems can however operate the full 7,838 h/y, but with additional electricity production (condensing mode) instead of heat deliveries, during the excess 3,038 hours.

In the model, all technologies are flexible and can be integrated with all hosts or operated as stand-alone facilities, except for black liquor gasification (MeOH-blg), which can for natural reasons only be located at chemical pulp mills.

When modelling integration of advanced biofuel production at chemical pulp mills, technologies with a heat surplus (MeOH-bmg, BG-bmg, EtOH/BG-ssf) were considered for integration with chemical mills with a deficit of steam. The biofuel plants were sized so that the excess steam from the plant would cover the mill's steam deficit (here defined as the extra steam needed in addition to the steam from the recovery boiler), thereby replacing the bark boiler that would otherwise be required. Falling bark from the mill was considered available for usage in the biofuel plants. Excess low temperature heat at the chemical pulp mills was assumed to be used for biomass drying prior to gasification (BMG). MeOH-blg plants were sized according to the flow of black liquor. The steam deficit originating in replacing the recovery boiler with a biofuel plant was assumed to be covered by firing wood fuel (and purge gas from the BLG plant) in a bark boiler connected to a steam turbine.

Biofuel production integrated in mechanical pulp mills and large paper mills was considered for biofuel production technologies with a heat surplus (MeOH-bmg, BG-bmg, EtOH/BG-ssf). The biofuel plants were sized according to the mills' steam demand, thereby replacing the boiler otherwise used. As for chemical mills, falling bark was assumed available for usage in the biofuel plants.

Also for sawmills, integrated biofuel production was considered for biofuel production technologies with a heat surplus (MeOH-bmg, BG-bmg, EtOH/BG-ssf). Here the amount of by-products (sawdust, bark, wood chips) was used to dimension the biofuel plants. Excess steam from the plants was assumed to be used to satisfy the internal heat demand at the sawmill, which would otherwise be met by using a share of the by-products in a hot water boiler. In cases with additional excess steam available, it was assumed that additional electricity (condensing mode) is produced.

In district heating (DH) systems, the biofuel plants (MeOH-bmg, BG-bmg, EtOH/BG-ssf) were dimensioned to cover the same heat demand as an assumed alternative investment in the form of a biomass fired CHP (combined heat and power) plant.

For stand-alone facilities, a fixed size of 400 MW feedstock was selected for all locations. This size is comparable to the largest biomass fired CHP plant in Sweden currently in operation (Fortum, Värtan). When considered for operation in stand-alone mode, the modelled MeOH-bmg, BG-bmg, and EtOH/BG-ssf plants all produce electricity (condensing mode) from excess steam.

BIOMASS FEEDSTOCKS

Focus in this study was mainly on woody biomass resources for which competition situations in a geographical context were identified that needs to be considered: virgin forest biomass from forestry operations, by-products from forest industry, farmed wood from abandoned arable land, waste wood, and refined wood pellets. The production of agricultural biomass feedstocks for crop-based biofuel, as well as of tall oil for HVO, was not considered explicitly. The reason is that these biomass assortments are not subject to resource competition (e.g. land) on the geographical scale and within the scope considered here. Table A-6 summarises the modelled biomass supply.

For virgin forest biomass resources, feedstocks from forestry operation (sawlogs, pulpwood, harvesting residues and stumps) were included. The supply potential was estimated based on modelled scenarios from the Swedish Forest Agency's forest impacts assessment (SKA 15) [25] ("Today's forestry" scenario), where theoretical potential outcomes from future harvesting operations (final fellings and thinnings) were calculated. A bottom-up approach was used to estimate the spatial variation in forest biomass harvesting and extraction costs, by applying time and productivity functions for forestry machinery, on the geographically explicit forest data. The disaggregated forest biomass cost-supply data was aggregated on the model grid. The approach has been described more in detail in [20,21].

For forest industry by-products, two different assortments were included: sawmill wood chips and low-grade industrial by-products (mainly bark, sawdust). The modelled quantities were based on modelled production volumes (site specific) and generic yield relations [48–50].

The potential for farmed wood from abandoned arable land in Sweden was estimated using a bottom-up GIS-based approach, as described in [22]. First, abandoned arable land areas were identified using various GIS databases. Abandoned arable land was here defined as land that has been cultivated before but is not currently occupied, but that could be cultivated again. Abandoned pasture land was excluded from the analysis, in order to reduce the risks for negative effects on biodiversity. Next, the potential production capacity for fast-growing growing broadleaf trees, such as poplar and hybrid aspen, was estimated based on land productivity data. Finally, the production costs were estimated based on cost estimations for short rotation forestry from [51].

Waste wood quantities were estimated based on [26], and disaggregated on the model grid based on population. Refined wood pellets was considered both from domestic production and from import (unlimited import potential assumed). The costs for waste wood and wood pellets were derived from wood fuel price statistics [27].

Table A-6. Aggregated modelled biomass supply and average modelled prices [17,21,27,52].

Biomass assortment	Supply potential [TWh/y]	Average price [EUR/MWh]
Forest virgin biomass		
Sawlogs	89	23
Pulpwood	69	15
Harvesting residues	31	15
Stumps	16	22
Forest industry residues		
Sawmill chips	24	11
Low-grade by-products	23	10
Other woody biomasses		
Waste wood	5.1	10
Farmed wood from abandoned arable land	2.3	16
Wood pellets	Unrestricted [a]	30

[a] The modelled domestic production amounts to 8.1 TWh, and in addition to this, pellets can be imported with no restriction.

TRANSPORT AND DISTRIBUTION

Transport of biomass feedstocks and produced liquid biofuels was considered using road, rail and short sea shipping. The transportation costs between all possible origins and destinations were calculated with a geographically explicit intermodal transport model (pre-optimisation), as described in [17].

For SNG and biogas, grid injection (including compression) was considered for locations with gas grid connections (local grids or the national gas grid in the south-western parts of Sweden). For locations without grid connection, road transportation as CBG (compressed biogas) was instead assumed. Another option, that has not yet been implemented in the model, would be transport of SNG/biogas as liquefied gas (LBG). As shown in the MetDriv project [16], this could reduce the transport costs for large off-grid plants.

Table A-7 presents the modelled transport cost parameters.

Table A-7. Transport costs (EUR/GWh) for feedstocks and biofuels. d is the transport distance in km. Based on [16,17].

Energy carrier	Road	Rail	Short sea	Grid
Roundwood	326 + 26.4*d*	1316 + 2.14*d*	1060 + 0.983*d*	–
Harvesting residues, stumps (chipped)	1103 + 34.8*d*	1924 + 2.82*d*	1046 + 1.29*d*	–
Industrial by-products	554 + 33.0*d*	1826 + 2.68d	1325 + 1.23d	–
Liquid biofuels	117 + 14.4*d*	275 + 0.721d	972 + 0.654d	–
SNG / biogas	7375 + 31.1*d*	–	–	10271

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