Large-scale implementation of biorefineries

New value chains, products and efficient biomass feedstock utilisation

Briefing notes

Additional material and results can be found on:
www.ltu.se/biorefineries

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New value chains, products and efficient biomass feedstock utilisation

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Highlights of research results

The synopsis of the project can be summarised in seven highlights based on both results from individual models and on model integration. The highlights also outline published results as well as meta-conclusions based on combined insights.

1. **An increased biofuel production will not affect the production of wood products.** While on the aggregated level it is seen that the total production of wood for material use is not largely impacted by increasing bioenergy consumption, there are large sectorial differences. Some material-producing industries are projected to increase their profitability, driven by increased demand for their by-products. The results also indicate that without the additional biomass produced from fast-growing plantations, the pressure to use roundwood directly for energy purposes will increase.

2. **Increased biofuel targets will introduce fringe feedstocks to the fuel mix.** An opportunity that the forest industry, including sawmills and pulp mills, provides is the availability of by-products that could be used for biofuel production. Three types of by-products are of interest: forest residues, bark and sawdust. The use of falling bark from pulp mills or bark and sawdust from sawmills, is interesting from an economic point of view because the first transportation step can be avoided and no additional investment for biomass handling at the mill will be required. However, for bark there are uncertainties regarding how much that is technically possible to use in e.g., gasification-based SNG production, and if there are additional O&M costs related to the usage.

3. **Increased biofuel targets will, in general, have limited price effects on woody feedstocks.** Prices for forest feedstocks in Sweden will tend to increase in the face of increased demand, where the highest price impact is observed for harvesting residues. However, feedstocks markets, on average, will not experience large price spikes in the medium term. Woody biomass markets can handle the additional demand pressure from biofuel production. Even when considering a tightening of competition.

4. **We can reach biofuel targets using many technologies and localisation options with reasonable costs.** There are many different ways to reach high levels of biofuel production in Sweden, at reasonable costs, and the dependency on specific locations or technologies is not particularly strong. Economy-of-scale and high biomass-to-biofuel conversion efficiencies provide the largest potentials for decreased production costs, which benefits large-scale gasification-based biofuel production, which in turn would require substantial investments in capital intensive production concepts.

5. **Projected price effects will not affect the profitability of investments in large-scale biorefineries.** Generally, the projected increase in demand for forest feedstocks stemming from production targets of 2nd generation biorefineries have little impact on average prices in the short to medium term. The plant costs (capital cost and O&M) have the largest impact on the economic performance, followed by the total feedstock cost (internal or external, depending on case, plus feedstock transportation). The impact of plant costs is most significant for smaller plants while feedstock related costs dominate for larger plants. High transportation cost for the feedstock clearly limits the performance of the large-scale investments.

6. **Geography matters.** Spatial issues are important determinates for the implementation of large-scale biorefineries. Not predominantly because of transportation costs but because of the spatially rigid industrial structure. The geographic locations of biofuel production facilities should be strategically chosen in order to minimise the total cost of using biofuels. Proximity to biomass resources, possibilities for integration, and distance to biofuel users are aspects that need to be considered.

7. **Centralised supply chains are preferable compared to distributed supply chains.** Supply chain configurations with high biomass efficiency show a clear economic advantage, as the advantages of economy-of-scale outweigh the cost of longer transportation. Decentralised supply chain configurations can play a role in particular at very high biofuel production levels or under very high biomass competition. Under lower biomass competition conditions, site specific conditions have a strong influence on the preference for either centralised or decentralised configurations.

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Project synopsis

Background

The development of commercial biorefinery concepts is of strategic importance for Sweden's development into a biobased economy. Biorefineries help to replace fossil with bio-based raw materials. Additionally, they contribute to a smarter use of biomass, increased added value and development potential of new bio-products. Technical potentials and industrial applications are linked with raw material supply, marketing, innovation and policy aspects.

The project is interdisciplinary and covers the integration of models that can account for the interplay between the various sectors, which include spatial variations in supply and demand of forest biomass, and that can capture the impact of changing market conditions and policy instruments. For the model integration, tools are developed to facilitate communication and feedback between the models. The project expands previous research by:

- Combing woody feedstock consideration with biorefinery concepts and new value chains
- Applying a multidisciplinary spatial approach
- Integrating localisation, technology choice and price determination aspects into a coherent framework

The project purpose is to generate new knowledge and a model framework for advanced systems analysis related to:

(i) Swedish biomass and its role in a sustainable energy system
(ii) Industrial transformation of the process industry towards a future biorefinery industry

This is done by evaluating large-scale implementation of biorefineries in order to:

- Achieving a spatial efficient use of woody feedstock
- Addressing the need for a spatial understanding of policy and competition effects on feedstock markets
- Understanding spatial cost structures and availability
- Evaluating biorefinery concepts and their value-chains

Aim and objectives

We apply a holistic multidisciplinary approach to study the importance of and possibilities and potentials for large-scale implementation of biorefineries in Sweden. The aim is to generate new knowledge and a model framework for advanced system analyses related to the Swedish woody biomass and its role in a sustainable energy system and to the industrial transformation of the process industry towards a future biorefinery industry. We also aim to optimise the spatial utilisation and production of woody biomass, including new and improved value chain and advanced biomass conversion technologies with focus on biorefineries.

Implementation

A model-based integration approach is used for advanced system analyses related to Swedish woody biomass resources and the implementation of large-scale biorefineries.

- BeWhere Sweden is a techno-economic, geographically explicit optimisation model that is used to analyse localisation of energy conversion facilities in Sweden.
- SpPDM is an economic spatial price determination model developed in the

project, which is used to analyse price effect from changing demand or supply patterns.

- GLOBIOM is a global bio-physical land use model covering the forest and agricultural sector and G4M is a global forest model that analyses forest related biophysical processes under various management options.

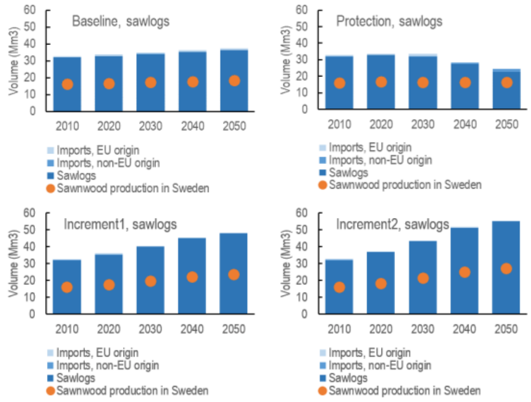
Integration of the models is based on shared variables and parameters. The model integration provides a holistic perspective towards the conducted analyses and produces consistent and transparent results of the interaction between economic and technology issues.

An increased biofuel production will not affect the production of wood products

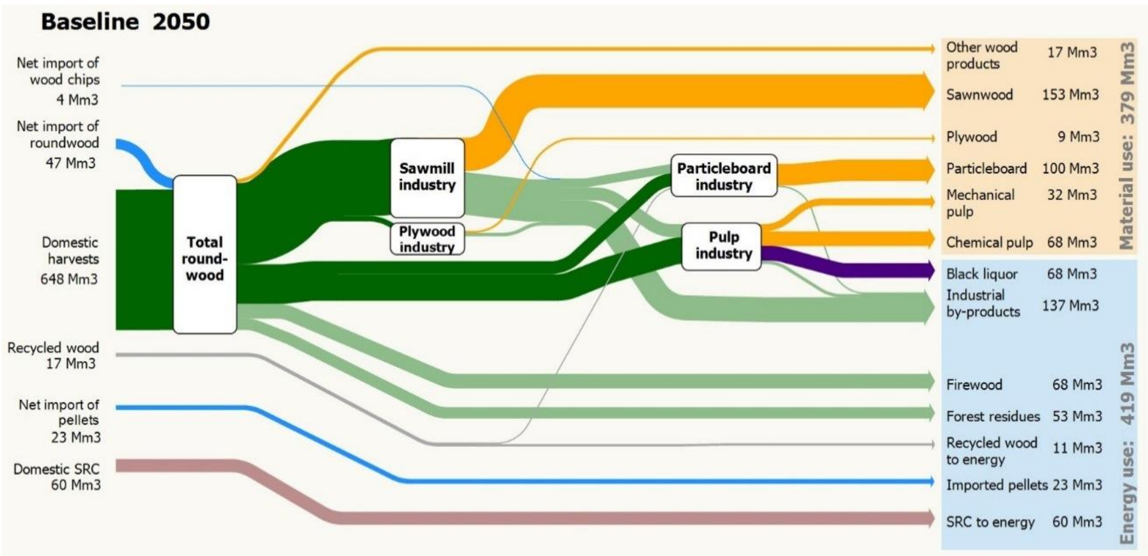
Impact assessment

The implication of three policy scenarios was assessed for each individual EU28 member state and for Sweden in particular. The scenarios include one with enhanced forest protection schemes and two with incremental increases in roundwood product. The chosen approach of integrating the modelling of trade, biomass harvest, material production, and competition for biomass resources between sectors was found essential in examining the complex question of wood use for increased bioenergy demand, within the EU and Sweden.

The estimates are particularly created so that they could be used as exogenous input to the models being used in the project to describe the development in Sweden, thereby allowing them to incorporate a consideration to not only Swedish developments, but also international market developments.

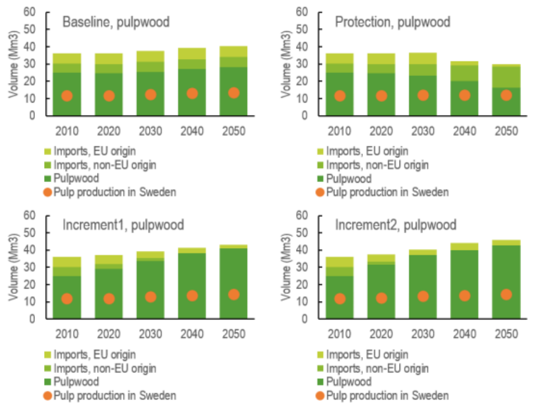


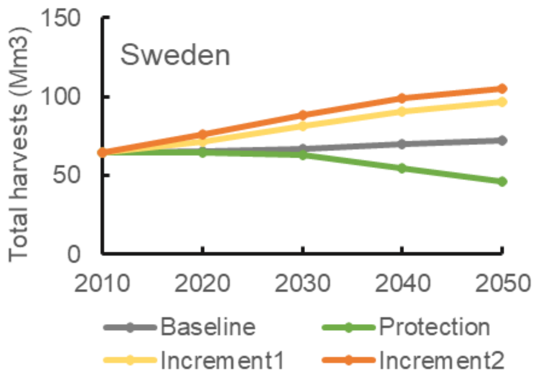
Generally, the results highlight that increased bioenergy demand leads to a stronger pressure on the forests in the EU, i.e. higher harvest levels and more intensive use of forests throughout the EU. In addition, the results show that high future bioenergy demand levels are likely to lead to increased EU biomass imports, especially wood pellets. High bioenergy demand levels are also seen to counteract cascading use of wood, and even lead to increased combustion of roundwood to energy.

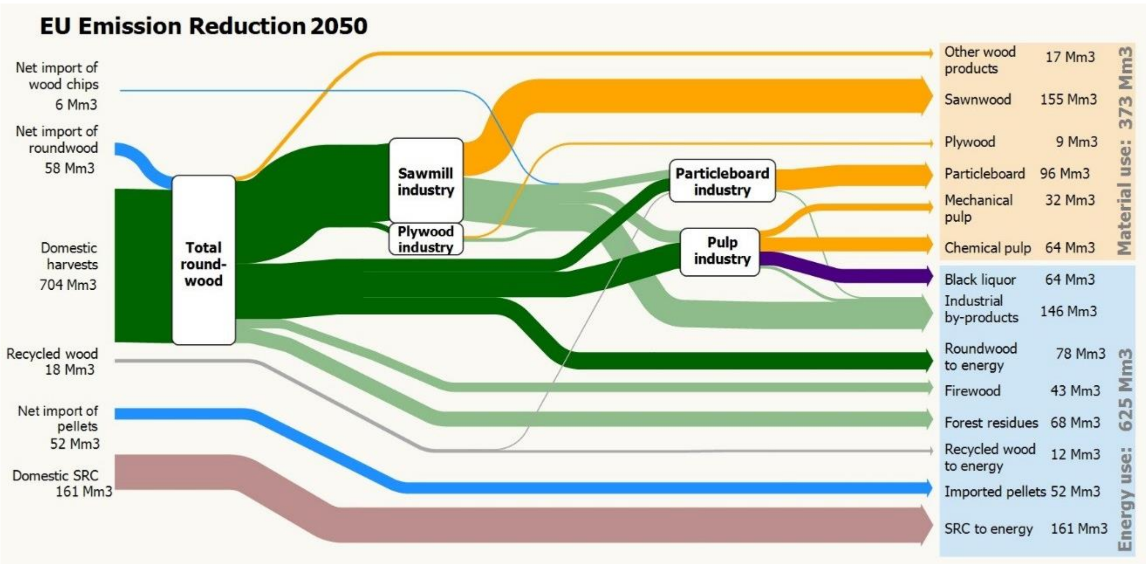


While on the aggregate level it is seen that the total production of wood for material use is not largely impacted by increasing bioenergy consumption, there are large sectorial differences. Some material-producing industries (especially sawmill industries) are projected to increase their profitability, driven by increased demand for their by-products to be used for energy, some industries will face increased competition for feedstocks (especially particleboard production). The estimates also show that without the additional biomass produced from fast-growing plantations such as short rotation coppice (SRC), the pressure to use roundwood directly for energy purposes and EU biomass imports will heavily increase.

In terms of the estimates for Sweden, the results show that the short-term demand for wood is close to the full harvesting potential in Sweden. In the period from 2020 to 2040, all demand scenarios display similar levels of high demand that are close to the potential supply. Under high bioenergy demand, harvest levels are projected to stay high over a longer time and particularly impact the harvest levels of pulpwood.







Increased biofuel targets will introduce fringe biomass feedstocks to the fuel mix

Biofuel targets and biomass

The demand for biofuels produced from lignocellulosic feedstock is projected to increase significantly in the future, as part of reaching the targets for renewable energy in the transport sector, especially in forest endowed countries like Sweden. However, the potential for increased sustainable biomass usage is still limited, making it important to use the resource efficiently.

An opportunity that the forest industry, including sawmills and pulp mills, provides is the availability of by-products that could be used for biofuel production. Three types of by-products are of interest: forest residues, bark and sawdust.

Resource potential

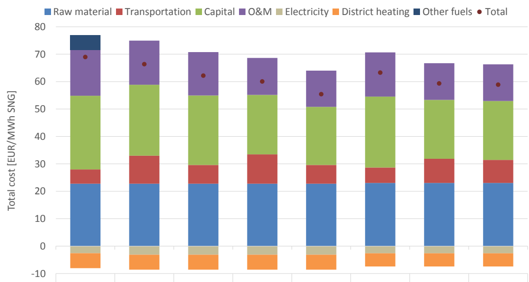
Estimations of the future potential for forest biomass indicate significant prospects for increased biomass supply, compared to the just over 10 TWh per year currently used. The potential for logging residues in 2030 is estimated to 25 to 31 TWh per year. In addition, 13-16 TWh stumps could potentially be harvested, giving a total potential of over four times the current use. The deployment of stumps as biorefinery feedstock is however highly uncertain, due primarily to environmental concerns, but also to technical reasons.

At pulp mills, the bark is removed from the pulpwood before the further processing. Most market kraft pulp mills do not need the bark to satisfy the internal process steam demand. The steam production from the recovery boiler is enough to satisfy the mill process steam demand. At a large Swedish kraft pulp mill, producing 2000 ADt of pulp per day, approximately 70 MW is available.

Sawdust, woodchips and bark are by-products from sawmills. Approximately 15 MW of bark, 20 MW of sawdust and 50 MW of woodchips are produced at sawmills with an annual capacity of 250,000 m^3 sawn wood. Part of the by-products (just over 10%), primarily bark, are used to satisfy the internal heat demand.

Synthetic natural gas

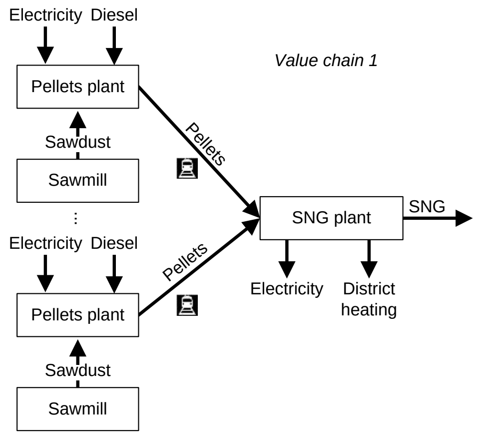
Different value chains based on domestic forest biomass for the production of bio-SNG were evaluated. The results show that the total cost for SNG is dominated by capital cost and the cost for raw materials and is therefore found to be sensitive to the investment cost, as well as the price of raw materials.



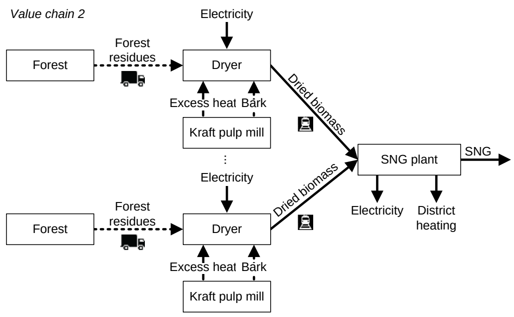
Value chain	1	2	2	2	2	Ref	Ref	Ref
SNG prod. [MW]	100	100	100	300	300	100	300	300
Raw material	SD	FR	Bark	FR	Bark	FR	FR	Bark
Number of mills	8	2	2	4	6	-	-	6
Dryer temp. [°C]	-	60	60	60	60	-	-	-

A higher SNG production rate will result in significantly lower total cost because the decrease in specific capital cost is greater than the increase in transportation costs.

The lowest total cost was found for value chains in which falling bark was dried at pulp mills and transported to the SNG plant. Similar total costs are found for value chains in which forest residues were transported directly to the SNG plant and for value chains in which forest residues were first transported to a pulp mill for drying.

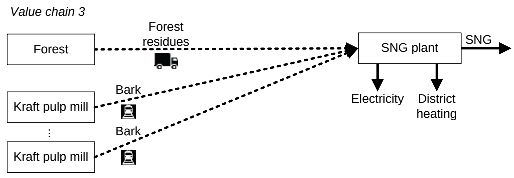


The use of falling bark from kraft pulp mills is interesting from an economic point of view because the first transportation step can be avoided and no additional investment for biomass handling at the mill will be required.

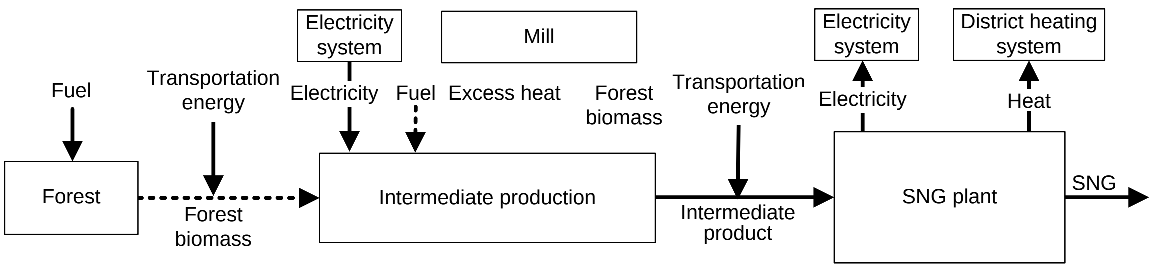


However, there is uncertainty about how much bark can be used in the SNG process. No additional costs related to the O&M of an SNG plant were included when bark was used, which could be the case in reality.

The value chain using pellets indicated lower transportation costs, but the total costs were the highest for this value chain due to the relatively high energy use for pellet production, i.e., more pre-treatment than was required for the SNG process to lower transport costs was found unprofitable.



Value chains with intermediate products based on forest residues had higher total transportation costs than direct transport of forest residues to the biofuel plant. However, if bark were used the transportation costs became lower. Using the available pulp mill excess heat for drying bark or forest residues is a way to "move" excess heat to another site (the SNG plant) where it could be used for district heating, which increases the revenue for the integrated SNG plant.



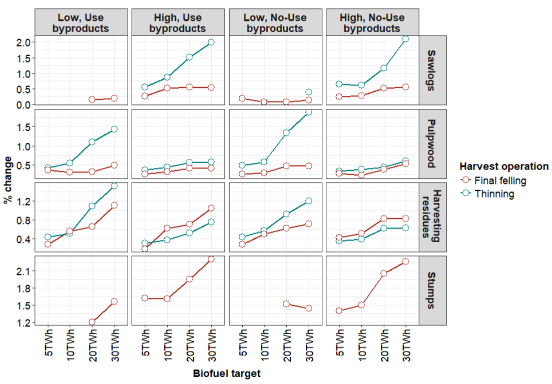
Increased biofuel targets will, in general, have limited price effects on woody feedstocks

Biofuel targets and scenarios

Scenarios were constructed with biofuel targets ranging from 5 to 30 TWh, under different assumptions on the competitive situation and use of by-products. The price effects of the scenarios is analysed using the spatial price determination model SpPDM.

Aggregate price effects

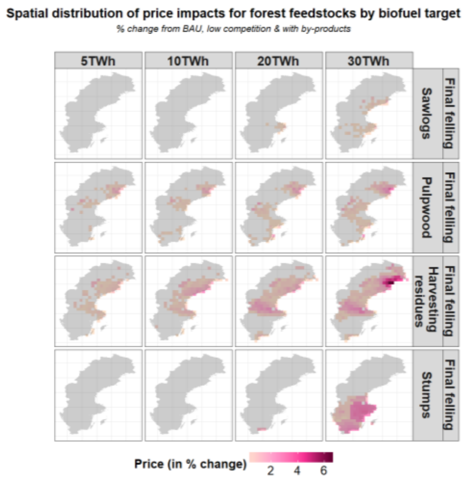
The results suggest marginal impacts on the prices of forest biomass. The average across spatial-explicit prices varies from 0 to 2.8% across feedstocks and scenario types. However, the distribution of the spatial-explicit price impacts display large variation, with price impacts reaching as high as 8.5%.



We find that the pattern of spatial distribution of price impacts follows relatively well the spatial distribution of demand pressure. However, locations with the highest price impacts show a tendency of mismatch with the locations of the highest demand pressure (e.g. sawlogs). This is an important conclusion that stems from the spatial-explicit structure of the framework developed, and which is missing in other methods that do not use and/or use coarse spatial scales. Hence, from a policy-making perspective, careful analysis should be devoted to the locational linkages for forestry markets of increased biofuel production in Sweden.

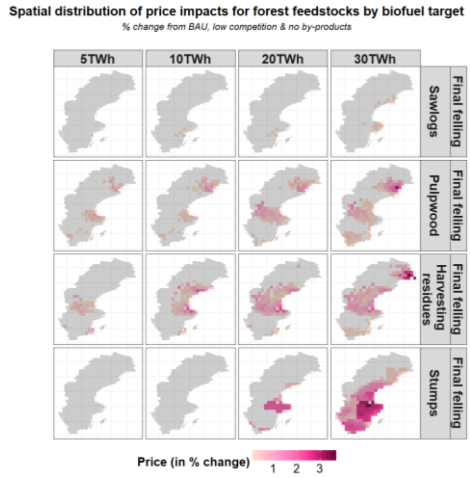
Spatial price effects

The results indicate a relatively good match between the spatial location of price impacts and changing demand.



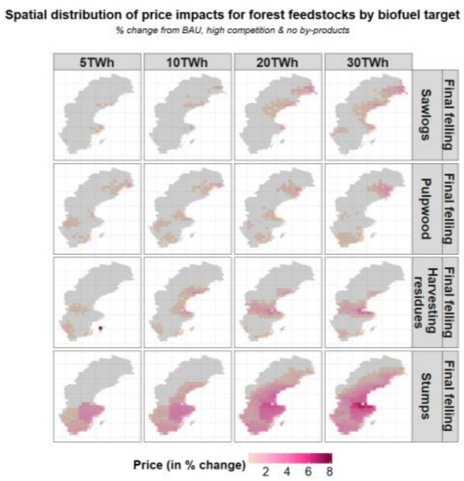
Reflecting the dynamics of demand changes, the spatial distribution of the price effect is increasing with the biofuel target. This effect is more pronounced for pulpwood and harvesting residues.

Under high competition, the price effect on sawlogs and stumps are showing a wider spatial distribution. By-products inclusion does not affect the matching of the spatial distribution of price impacts and demand changes.



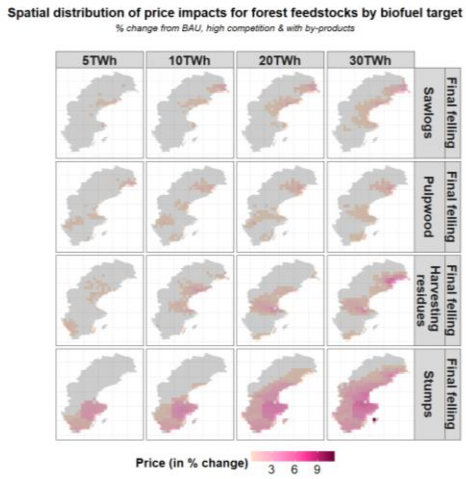
Price effect on specific wood assortments

For pulpwood and harvesting residues, the price impact is higher under the low competition scenario. For sawlogs and stumps, the price impacts are negligible at low biofuel targets. Under high competition scenario, the price effect on sawlogs and stumps are more spatially distributed, especially for stumps. Non-inclusion of by-products puts more pressure on prices for stumps. The results do not differ substantially when industrial by-products are allowed in the biomass mix.



Key insights

Prices for forest feedstocks in Sweden will tend to increase in the face of increased demand, where the highest price impact is observed for harvesting residues. However, feedstocks markets, on average, will not experience large price spikes in the medium term. Woody biomass markets can handle the additional demand pressure from biofuel production. Even when considering a tightening of competition.



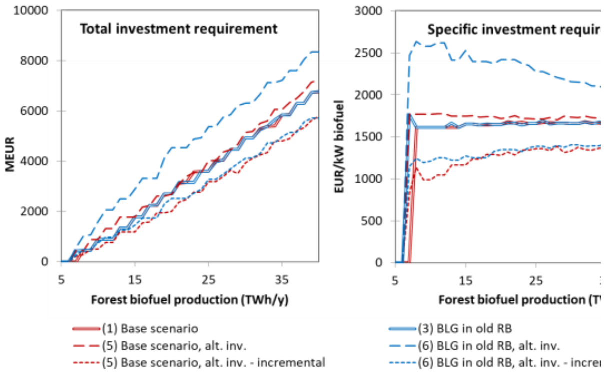
From a policy-making perspective, intervention in the woody biomass markets is not necessary, at least not in the medium term. However, special attention must be given to the locational linkages with respect to forestry markets in Sweden.

Generally, the results highlight that increased bioenergy demand leads to a stronger pressure on the forests, i.e. higher harvest levels and more intensive use of forests. In addition, the results show that high future bioenergy demand levels are likely to lead to increased biomass imports. High bioenergy demand levels are also seen to counteract cascading use of wood, and even lead to increased combustion of roundwood to energy.

We can reach biofuel targets using many technologies and localisation options with reasonable costs

The role of the industry

Integration of biofuel production with existing industry was studied, as well as how different parameters affect biofuel production costs, the choice of technologies and biofuels, and the localisation of new biofuel plants. A methodology was developed considering inclusion of detailed, site-specific conditions for potential host industries in the spatially explicit BeWhere Sweden model.



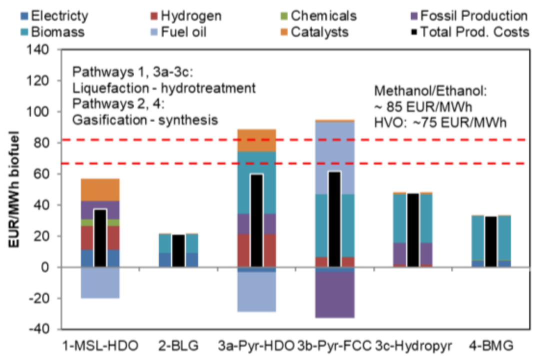
Investment needs

Total and specific investment requirements to meet different biofuel production targets, with and without alternative investments considered, as well as with and without the possibility for alternative investments are analysed. Incremental investment requirement indicates additional cost compared to alternative investment in conventional technology.

The results show a general benefit from integration with forest industries compared with stand-alone localisations. This is especially true when biorefinery investments are done in conjunction with, or as alternative to, other investments on site (e.g. boilers), as the alternative investment credit reduces the biorefinery investment cost. Additional benefits can be gained when the biorefinery investment can replace capital intensive equipment at the host industry, which can significantly improve the economic performance. This demonstrates that the Swedish industry could play a vital role in reaching a cost efficient large-scale implementation of lignocellulosic biorefineries.

Biofuel production costs

Biofuel production pathways that are seen as commercially relevant in the near future were evaluated. The pathways belong to either the liquefaction-hydrotreatment conversion route or to the gasification-synthesis route. A particular focus was put on integration with existing pulp mills and crude oil refineries. The results suggest that the income from biofuel sales is enough to cover the expenditure on commodities, thus all the pathways has a positive specific investment margin.

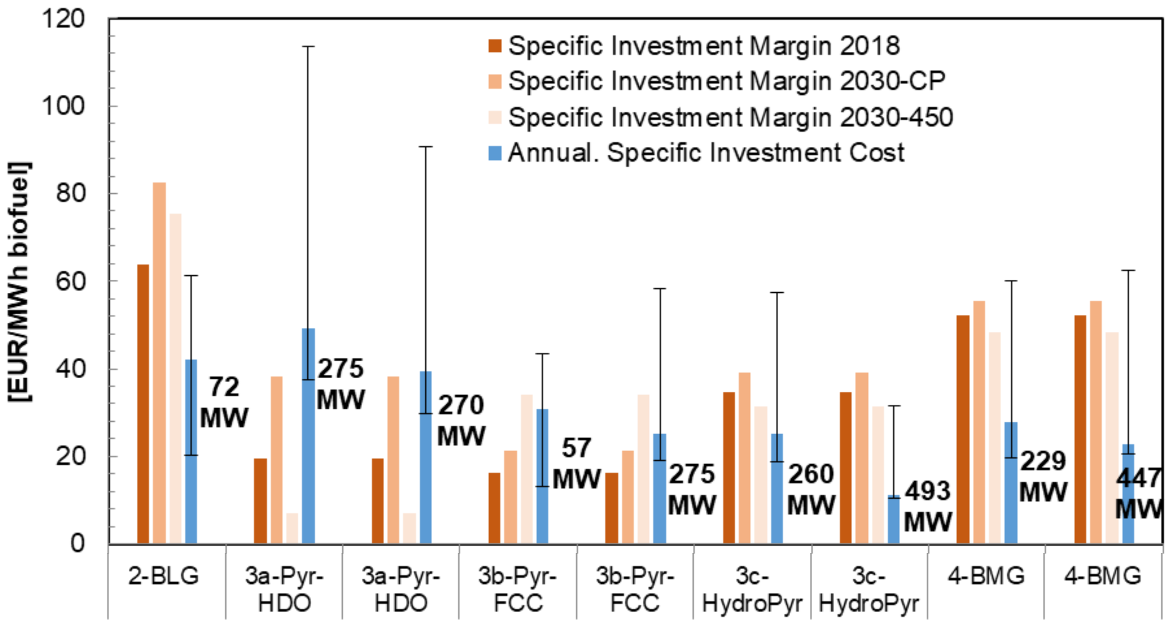


When comparing with investment cost estimates, both gasification-based and liquefaction-based pathways demonstrate relatively robust profitability for both current and future energy market scenarios and for different production scales.

Key insights

The results indicate significant potential in Sweden for biofuel production from woody biomass by investing in new integrated production plants. However, competing biomass users risk increasing biomass costs at ambitious biofuel production targets. There are many different ways to reach high levels of biofuel production in Sweden, at reasonable costs, and the dependency on specific locations or technologies is not particularly strong.

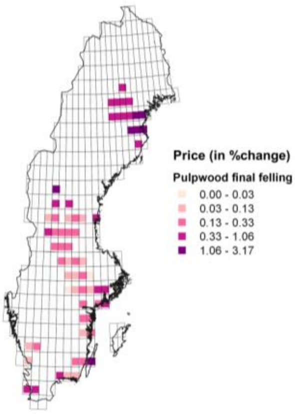
Substantial total capital requirement for new biofuel production investments is needed, but alternative required industrial investments at the host sites can dampen the effects. The cost of biomass and the biofuel plant capital cost generally dominate the biofuel cost, but the cost for biomass transportation and biofuel distribution can also have a significant impact. Economy-of-scale and high biomass-to-biofuel conversion efficiencies provide the largest potentials for decreased production costs, which benefits large-scale gasification based biofuel production. This stands in 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.



Projected price effects will not affect the profitability of investments in large-scale biorefineries

Feedstock prices

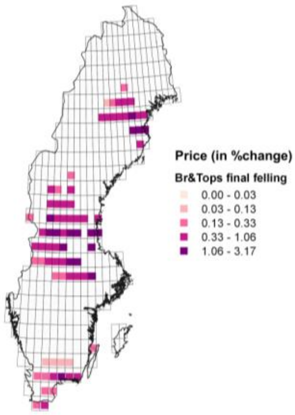
The project has improved our understanding of the spatial price impact on forest markets from the introduction of new high-volume user of forest biomass, such as large-scale biorefineries. Generally, increases in demand for forest feedstocks for production targets of 2nd generation biorefineries have little impact on average prices, in the short to medium term.



For the spatial assessment, a set of plausible future scenarios is outlined for an introduction of large-scale production of transportation biofuel. The assessment is based on price impacts and changing allocation patterns on forest feedstocks. The scenarios included in the analysis represent the projected demand schedule for forest feedstocks in Sweden for incremental biofuel production targets by 2030.

We observe that the highest price impacts do not always match up with locations where demand pressure is highest. This implies that the severity of the competition effect will tend to be more localised, and is affected by local conditions in terms of availability of woody materials and costs.

The results show that feedstock prices will not, in general, increase that much from an increased biofuel production. This implies that the production of considerable volumes of forest-based biofuel is possible, without significantly increasing the competition for the feedstock within the Swedish context. This reduces the uncertainty of feedstock prices for investments in large-scale biorefineries.



From a policy perspective, there is no need for market intervention to secure woody feedstock availability for any particular use or to even-out the argued price effect on the feedstocks from implemented energy policies. Instead, the results suggest that policy-making should focus on the locational linkages of price impacts.

Investment aspects

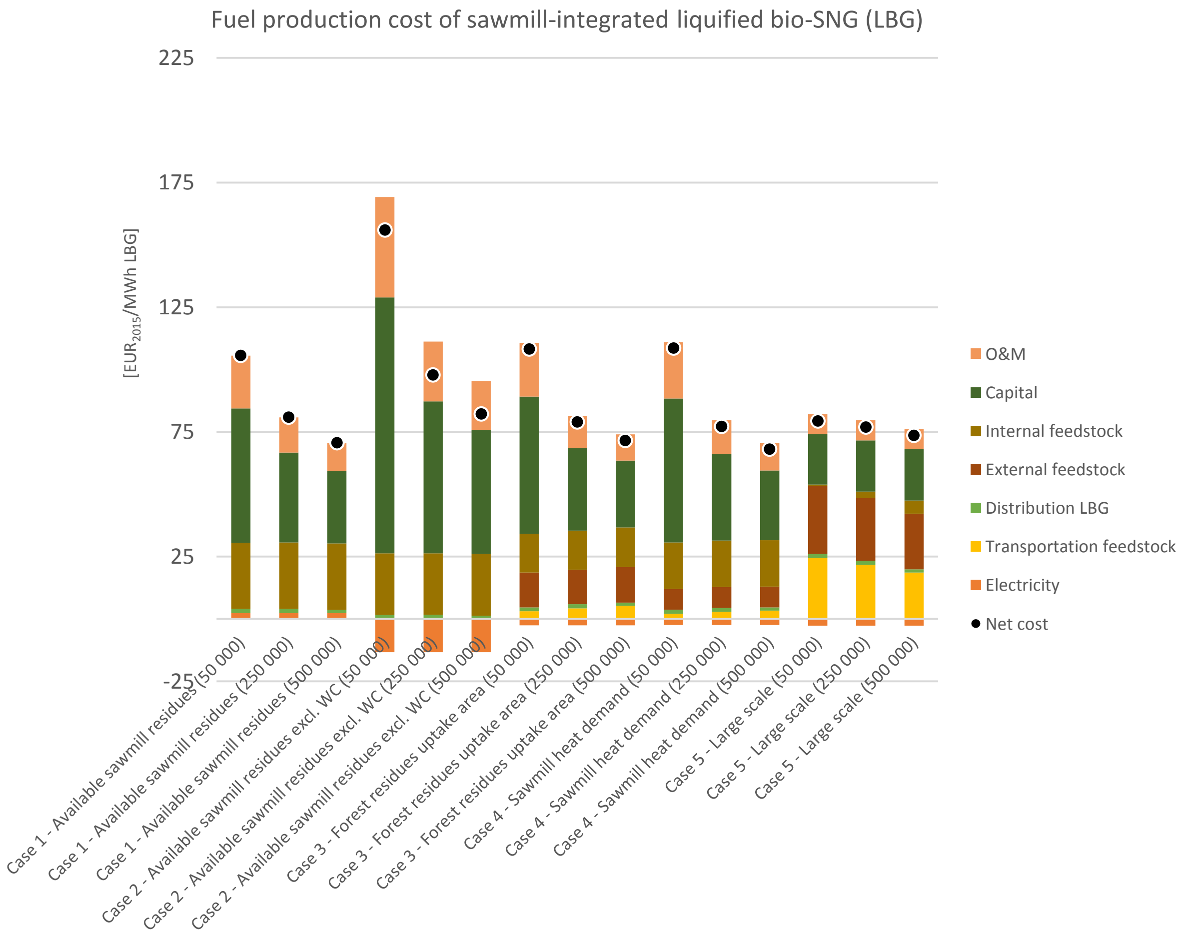
In general, plant costs (capital cost and O & M) have the largest impact on the economic performance, followed by the total feedstock cost (internal or external, depending on case, plus feedstock transportation). The impact of plant costs is most significant for smaller plants while feedstock related costs dominate for larger plants. High transportation cost for the feedstock clearly limits the performance of the large-scale investments.

The energy performance of the production process has the largest impact on the value chain performance in terms of carbon footprint, while the size of the production plant has the largest impact on the fuel production cost, followed by feedstock transportation costs for larger plants.

Size matters

Our results suggest that, in economic terms, size matters. This is because the specific capital cost decreases with scale of production. Capital cost is not a linear function, contrary to all energy related flows, but decreases non-exponentially per produced unit with increased production (economy-of-scale).

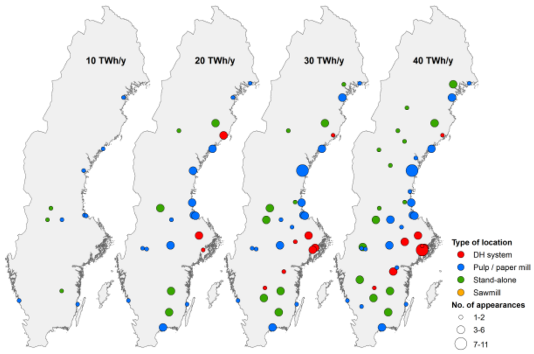
Regarding fuel production cost, the results indicate a significant variation due to scale effects, with smaller plants or integration with smaller mills suffering from high specific capital and O & M costs, thus leading to higher fuel production costs.



Geography matters

Spatial issues

Spatial issues are important determinates for the implementation of large-scale biorefineries. Not predominantly because of transportation costs but because of the spatially rigid industrial structure and spatial distribution of current biomass demand.



The geographic locations of biofuel production facilities should be strategically chosen in order to minimise the total cost of using biofuels. Proximity to biomass resources, possibilities for integration, and distance to biofuel users are aspects that need to be considered.

The geographically explicit optimisation model BeWhere Sweden was used to investigate the future production of next-generation biofuels from forest biomass in Sweden. Different biofuel routes and technologies were considered, with a special focus on integration with existing industry. Generally, plants with low specific investment costs, i.e., large biofuel production, and/or plants with low specific net biomass transportation costs, due to elimination of the need to transport biomass by-products from industrial plants, occur most frequently in simulations. Because these properties often vary significantly among different individual host industry sites, the results show the advantage and importance of including site-specific data in this type of model.

Industry structure

The biofuel cost consists of the cost for biomass, biomass transportation, investment, operation and maintenance, electricity, fossil fuels and biofuel distribution. Different combinations of biofuel technology and host industry differ significantly regarding the absolute and relative levels of these costs per unit of biofuel produced.

For a given combination of biofuel technology and host industry, the main differences between different individual host industry sites are the specific net biomass transportation and investment cost. The cost for biomass and the capital cost generally dominate the biofuel cost, but the cost for biomass transportation and biofuel distribution can also have a significant impact. These costs are in various ways all dependent on geographical location.

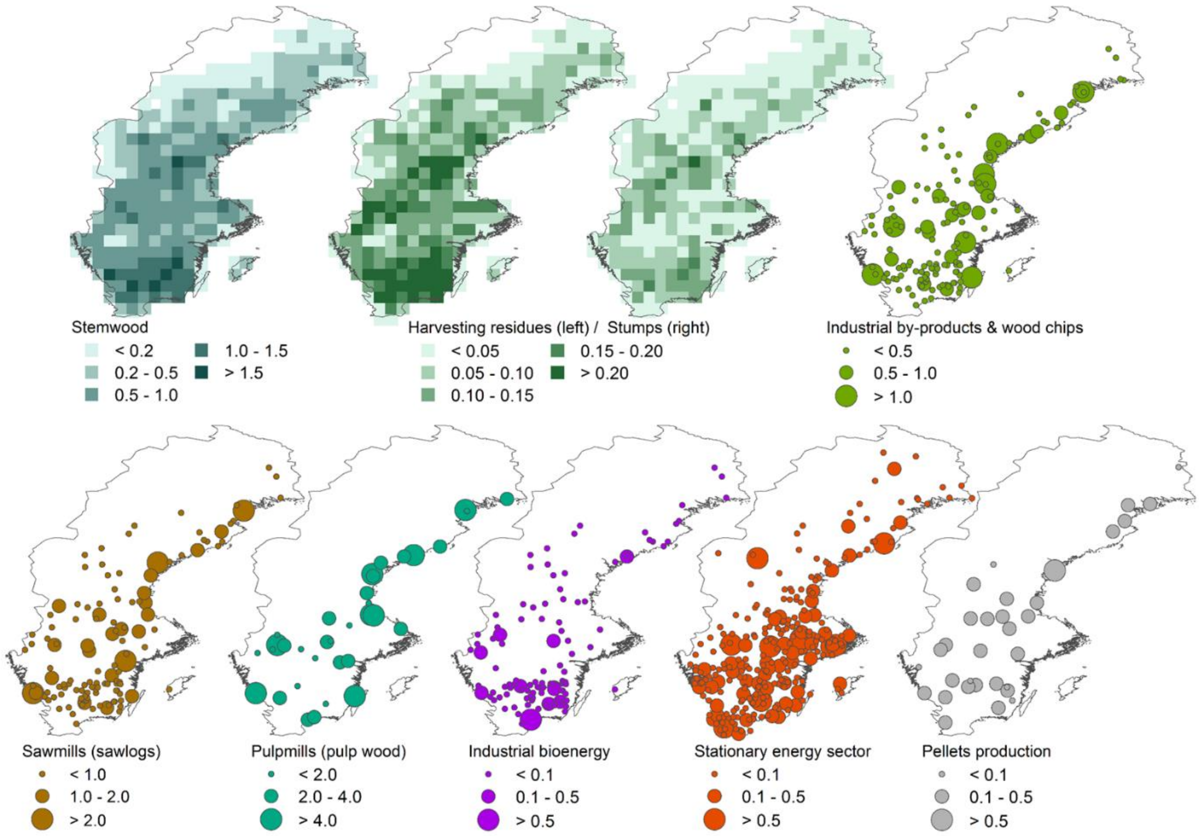
Chemical pulp mills dominate as host industries, due to proximity to feedstock, heat integration benefits, high conversion efficiency and large credits for alternative investments. However, complex integration requires major changes to pulp mill operations. District heating networks offer less complex integration and can also be of interest as hosts, but waste and bio-CHP compete for the heat load.

Key insights

Bioenergy demand is expected to potentially lead to large changes in the composition of bioenergy feedstocks. The results highlight increasing future connectivity between the import of wood pellets, production of SRC, and use of forest-based industrial by-products. The development of the forest-based industry and the bioenergy sector is expected to lead to a strong intensification in the use of EU forests and conversion of other natural vegetation areas.

Site-specific integration opportunities which can be applied on a large-scale may yield significant cost reductions for biofuel production which can outweigh the potential increased cost of feedstock mobilisation at that site. Conversely, site-specific safety issues, site layouts or strategic interests of the host might impede integration. Integration benefits have a particularly profound impact in the early stages of biofuel deployment.

Existing industry thus plays an important but complex role in the implementation of forest-based biorefineries. On the one hand, existing forest industry may face increased competition for feedstock. On the other hand, existing industry can play a role in mitigating future biofuel production costs. This potential synergy benefit must then be shared between the host industry operation and the biofuel production, an aspect which is lacking in current policy.



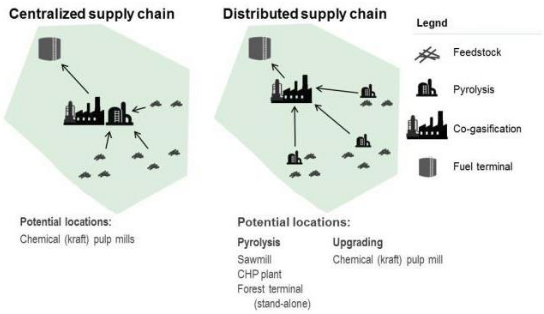
Centralised supply chains are preferable compared to distributed supply chains

Centralised vs. distributed supply chains

Biorefineries for the production of fuels, chemicals, or materials can be an important contributor to reduce the dependence of fossil fuels. The economic performance of biorefinery supply chains can be improved by different strategies, such as industrial integration in order to e.g. utilise excess heat and products, economy-of-scale benefits from increased plant sizes, and intermediate upgrading to reduce feedstock transport cost. The identification of cost-efficient supply chain configurations is crucial in order to enable large-scale introduction of biorefineries. Two different case studies are outlined to investigate industrially integrated lignocellulosic biorefinery concepts regarding the impact of different economic conditions on the preferred supply chain configurations.

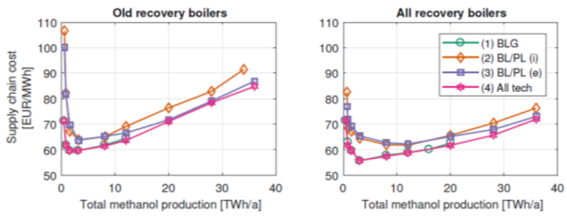
Case 1: Pyrolysis and catalytic co-gasification with black liquor

Case 1 considered methanol production via black liquor gasification, with the option to also add pyrolysis liquids as a secondary feedstock in order to increase the production capacity (however leading to decreased overall biomass conversion efficiency). The analysis focused on trade-offs between high biomass conversion efficiency and economy-of-scale effects, as well as the selection of centralised vs. decentralised supply chain configurations.



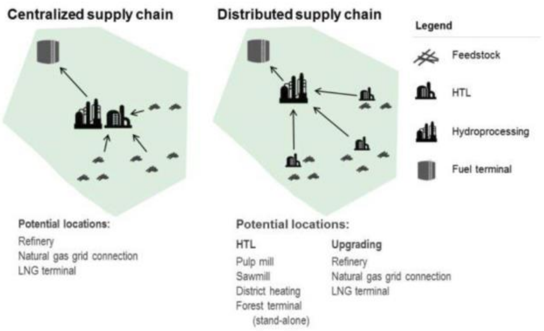
The centralised supply chain was assessed using chemical (kraft) pulp mills as potential production locations. Distributed supply chain was assessed along two paths: pyrolysis at sawmills, CHP plants and stand-alone forest terminals and; upgrading for gasification at chemical pulp mills.

Larger sites are available when allowing all sites than when only considering mills with old recovery boilers. Therefore the total supply chain cost was lower when allowing all sites. This implies that economy-of-scale is favourable, as long as it does not influence the biomass resource efficiency. Co-gasification significantly increases production capacity when the black liquor is limited.

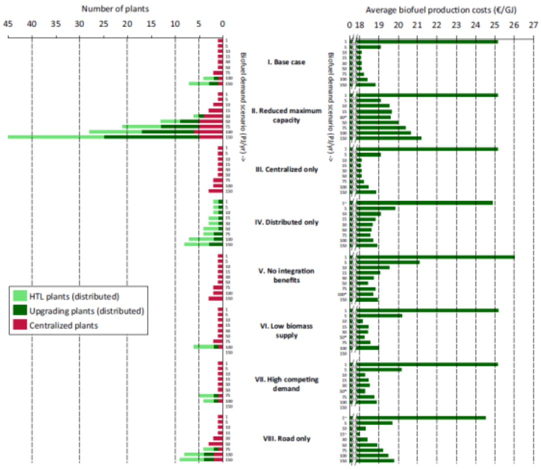


Case 2: HTL and hydro-processing

Case 2 considered biofuel production from forest biomass via conversion to biocrude through hydrothermal liquefaction (HTL). The biocrude was subsequently hydroprocessed to drop-in biofuels at refineries, LNG terminals or natural gas grid connections. The analysis focused on the impact of and interrelation between four cost reduction strategies for biofuel production: economies-of-scale, intermodal transport, integration with existing industries, and distributed supply chain configurations.

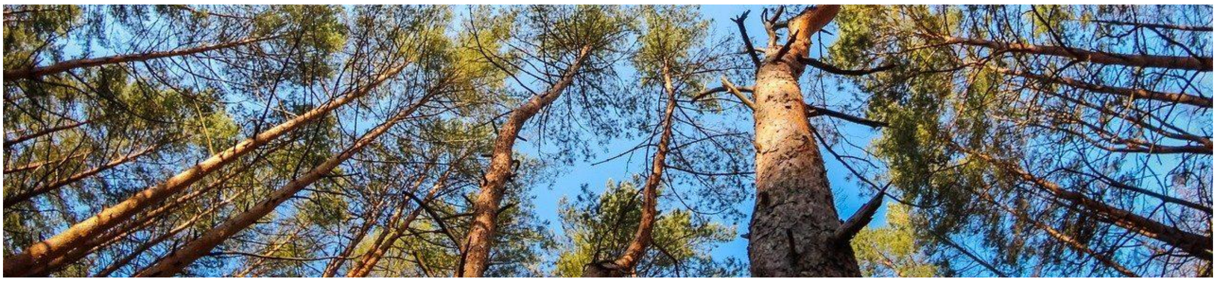


Simultaneous implementation of all cost reduction strategies yielded minimum biofuel production costs of 18.1–18.2 € per GJ at biofuel production levels between 10 and 75 PJ per year. Limiting the economies-of-scale was shown to cause the largest cost increase, followed by disabling integration benefits and allowing unimodal truck transport only. Distributed supply chain configurations were introduced once biomass supply became increasingly dispersed, but did not provide a significant cost benefit (<1%). Disabling the benefits of integration favours large-scale centralised production, while intermodal transport networks positively affect the benefits of economies-of-scale.



Overall conclusions

The results show a clear economic advantage for the supply chain configurations with high biomass efficiency, for the cases when the biorefinery was assumed to benefit from an alternative investment credit due to replacement of current capital intensive equipment at the host industry. Decentralised supply chain configurations were only favourable at very high biofuel production levels or under very high biomass competition. Under lower biomass competition conditions, site specific conditions were found to have a strong influence on the preference for either centralised or decentralised configurations. As biofuel production costs still exceed the price of fossil transport fuels in Sweden after implementation of the investigated cost reduction strategies, policy support and stimulation of further technological learning remains essential to achieve cost parity with fossil fuels for the studied feedstock/technology combinations in this spatial-temporal context.



Acknowledgments

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BeWhere model description

Model outline

BeWhere is a family of techno-economic, geographically explicit, bottom-up optimisation models that are used to analyse localisations and properties of different energy conversion plants, in order to, for example, investigate different policy instruments and to provide decision support for the development of strategies and policies. The model has been applied at local, national and supranational levels. Initially the scope of application was limited to bioenergy plants, but has been expanded to also include e.g. solar, wind, hydropower, public transport, and algae-based plants.

BeWhere Sweden

BeWhere Sweden is focused particularly on forest biomass, biofuel production and design of forest-based value chains, with a high degree of detail regarding the biomass supply and industrially integrated biofuel production, where potential plant hosts are largely modelled individually. The model is primarily used to analyse how future bio-based value chains can be implemented cost-effectively from a system perspective, what role the existing energy infrastructure (industry and energy facilities) can play, and how different parameters affect, for example, 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 model minimises the cost of the entire studied system to simultaneously meet a certain defined biofuel production demand, as well as the demand for biomass from other sectors. The system cost includes costs and revenues for production and transportation of biomass, production facilities, transportation and delivery of biofuels, by-products sales, and economic policy instruments. The cost is minimised under a number of constraints that describe and limit, for example, supply and demand for biomass, possible import and export of biomass, plant operation and demand for end products. The model will thus choose the least costly combinations of feedstocks, production facilities and biofuel distribution. The resulting model output includes a set of new biofuel production facilities in order to meet the defined production target, the resulting supply chain configurations, the origin of used biomass, and costs related to the different parts of the supply chain.

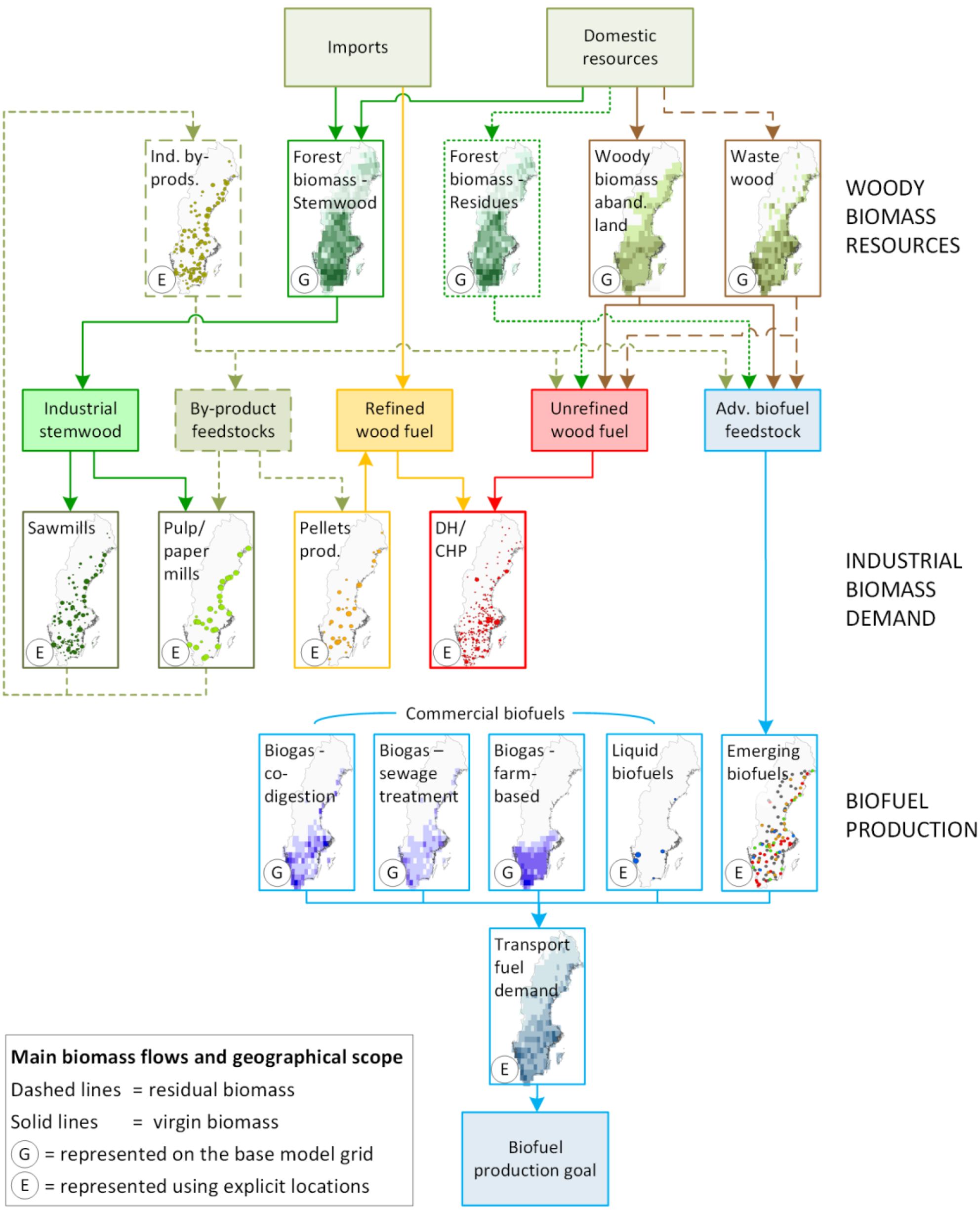
Forest biomass supply and demand

Focus is on woody biomass resources: virgin forest biomass from forestry operations (sawlogs, pulp wood, harvesting residues, stumps), by-products from forest industry (chips, bark, sawdust), farmed wood from abandoned arable land, waste wood, and refined wood pellets. In addition to demand as feedstock for biofuel production, competing demand from the forest industry (pulp mills, sawmills and pellets industries) as well as the stationary energy sector (heat and electricity) are also considered explicitly.

For biofuel production, the main focus is on forest-based biofuels produced via thermochemical (gasification, HTL, pyrolysis) or biochemical (fermentation, anaerobic digestion) conversion. Also commercial biofuel production technologies that are currently in operation in Sweden are included in the model (biogas from anaerobic digestion, grain-based ethanol, RME, and tall oil based HVO).

Spatial structure

BeWhere Sweden is geographically explicit regarding woody biomass cost-supply, competing biomass demand, existing and potential new biofuel production, transportation infrastructure, and biofuel demand. The figure below gives an overview of the main biomass flows and geographic scope of the BeWhere Sweden model. Two different geographic representations are used: a base model grid with 0.5 degree spatial resolution ("G" in the figure), and explicit locations ("E" in the figure).



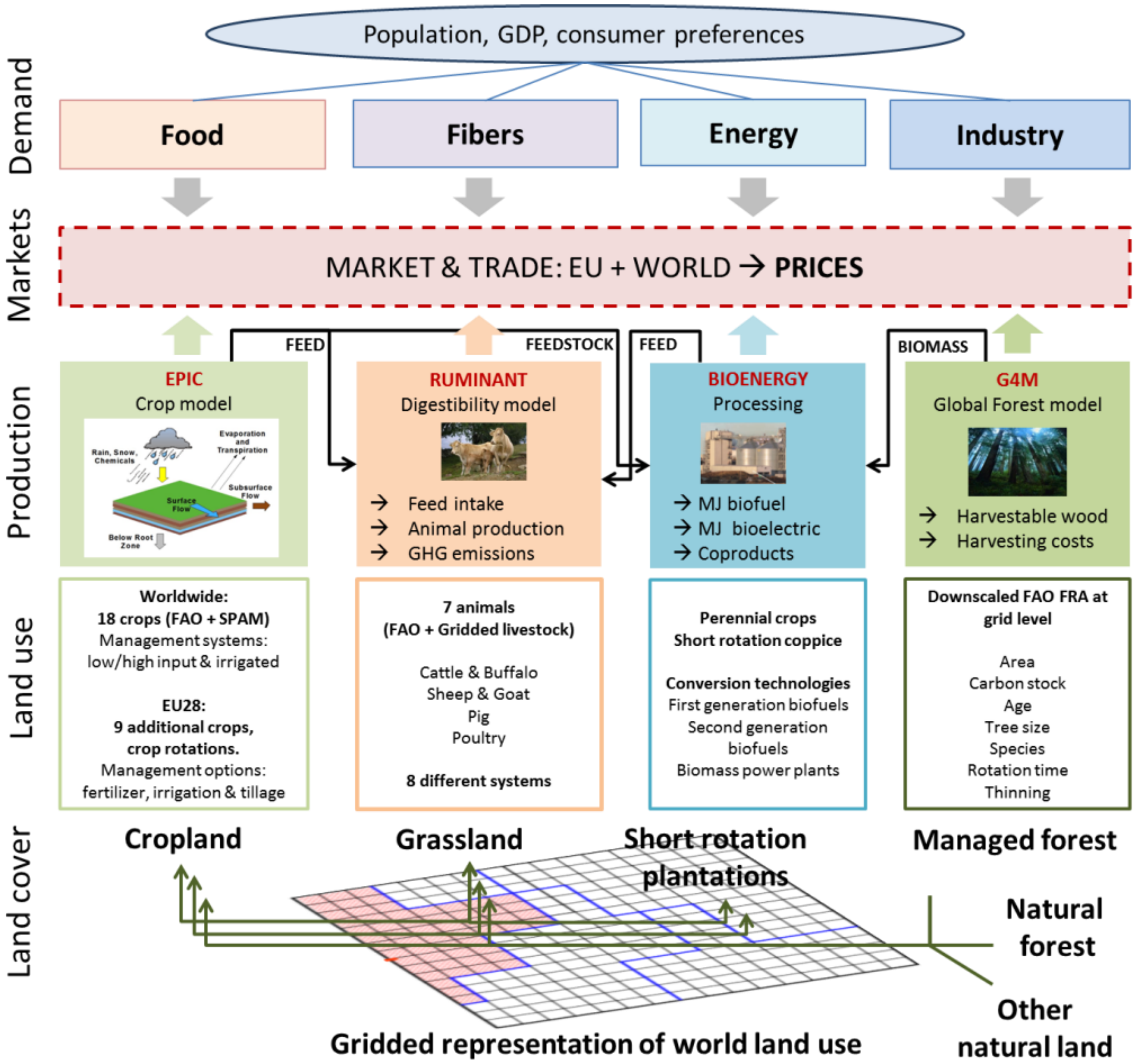
GLOBIOM model description

The Global Biosphere Management Model (GLOBIOM) is a global recursive dynamic partial equilibrium model of the forest and agricultural sectors, where economic optimisation is based on the spatial equilibrium modelling approach. The model is based on a bottom-up approach where the supply side of the model is built-up from the bottom (land cover, land use, management systems) to the top (production/markets). The agricultural and forest productivity is modelled at the level of gridcells of 5 x 5 to 30 x 30 minutes of arc, using biophysical models, while the demand and international trade occur at regional level (30 to 53 regions covering the world, depending on the model version and research question). Besides primary products, the model has several final products and by-products, for which the processing activities are defined.

The model computes market equilibrium for agricultural and forest products by allocating land use among production activities to maximise the sum of producer and consumer surplus, subject to resource, technological and policy constraints. The level of production in a given area is determined by the agricultural or forestry productivity in that area (dependent on suitability and management), by market prices (reflecting the level of demand), and by the conditions and cost associated to conversion of the land, to expansion of the production and, when relevant, to international market access. Trade is modelled following the spatial equilibrium approach, which means that the trade flows are balanced out between different specific geographical regions. Trade is furthermore based purely on cost competitiveness as goods are assumed to be homogenous. This allows tracing of bilateral trade flows between individual regions.

Woody biomass demand and forest industry technologies

The forest sector is modelled to have seven final products (chemical pulp, mechanical pulp, sawn wood, plywood, fibreboard, other industrial roundwood, and household fuelwood). Demand for the various final products is modelled using regional level constant elasticity demand functions. Forest industrial products (chemical pulp, mechanical pulp, sawn wood, plywood and fibreboard) are produced by Leontief production technologies, with input-output coefficients based on the engineering literature. By-products of these technologies (bark, black liquor, sawdust, and woodchips) can be used for energy production or as raw material for pulp and fibreboard. Production capacities for the base year 2000 of forest industry final products are based on production quantities from FAOSTAT. After the base year the capacities evolve according to investment dynamics, which depend on depreciation rate and investment costs. This implies that further investments can be done to increase production capacities or allow industries to reduce their production capacities or be closed.


Population, GDP, consumer preferences
Demand
Food
Fibers
Energy
Industry
Markets
MARKET & TRADE: EU + WORLD → PRICES
FEED
FEEDSTOCK
FEED
BIOMASS
Production
EPIC
Crop model
RUMINANT
Digestibility model
→ Feed intake
→ Animal production
→ GHG emissions
BIOENERGY
Processing
→ MJ biofuel
→ MJ bioelectric
→ Coproducts
G4M
Global Forest model
→ Harvestable wood
→ Harvesting costs
Land use
Worldwide:
18 crops (FAO + SPAM)
Management systems:
low/high input & irrigated
EU28:
9 additional crops,
crop rotations.
Management options:
fertilizer, irrigation & tillage
7 animals
(FAO + Gridded livestock)
Cattle & Buffalo
Sheep & Goat
Pig
Poultry
8 different systems
Perennial crops
Short rotation coppice
Conversion technologies
First generation biofuels
Second generation biofuels
Biomass power plants
Downscaled FAO FRA at grid level
Area
Carbon stock
Age
Tree size
Species
Rotation time
Thinning
Land cover
Cropland
Grassland
Short rotation plantations
Managed forest
Natural forest
Other natural land
Gridded representation of world land use

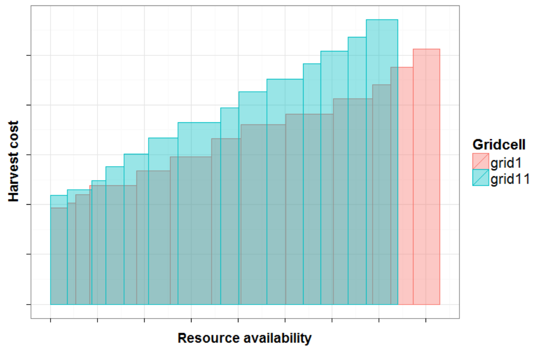
SpPDM model description

The spatial price determination model (SpPDM) is developed for spatial pricing of multi-market heterogeneously distributed resources. The theoretical spatial pricing mechanism is similar to non-spatial pricing, where the interaction of demand and supply determines the market price. However, in spatial pricing both the demand and supply need be spatial in their character and the markets need to be product as well as geographically delineated. The product delineation is based on resource categorisations, while the geographical delineation is based on a system of two-dimensional quadratic shaped gridcells. That is, each gridcell represents a separate market, where transactions between the resource suppliers and users can occur, thus generating spatial price equilibrium for each categorised resource.

Spatial structure of the supply

The on-site supply, i.e., the supply in each gridcell, is derived based on a bottom-up approach using gridcell-specific resource availability and extraction costs for each type of resource. Each gridcell has a single observed availability per type of resource and a unique extraction cost associated with that availability. The gridcell-specific availability and extraction cost is the fundamental building block for the quantity-cost relationship of the spatial supply.

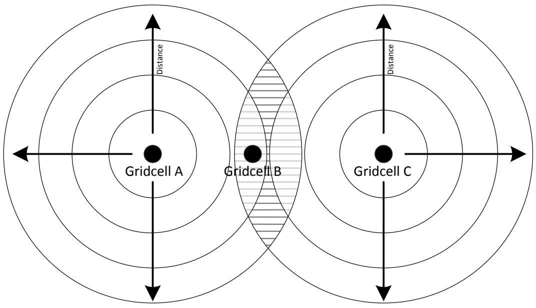
The spatial structure of the supply is captured by aggregating the on-site availability with that of n adjacent gridcells, creating a supply area for each gridcell. The number of adjacent gridcells to include is based on assumptions on transportation distance. Aggregated, regional supply curves are constructed for each gridcell and resource, using a merit-order framework.

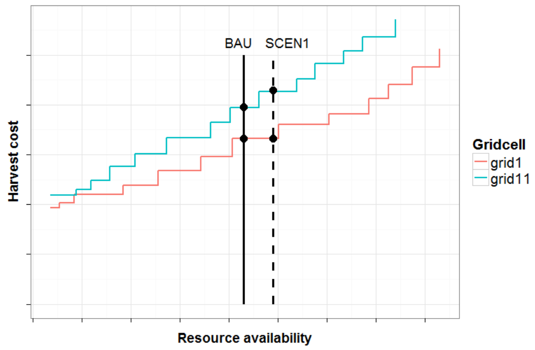


The main rationale for using a merit-order approach for constructing the supply curves is twofold. First, the need to make strict theoretical assumption on the quantity-cost relationship is eliminated. Second, it allows the use of empirical data that often are availability for heterogeneously distributed resources, such as forestry and agricultural resources.

Spatial structure of the demand

The spatial demand structure is represented by two demand concepts: Site demand and demand pressure. They are aggregated in each gridcell and for each resource to create an aggregate demand per resource in each gridcell. The site demand is representing the demanded quantity of a resource by all the users in a specific gridcell. The demand pressure is measuring the spatial interaction across gridcell with a site demand. The estimation of the demand pressure is based on a distance-decay framework. The demand pressure is monotonically decreasing with distance until it eventually disappears. The only reason a gridcell might not have an aggregated demand is if it is located too far away from a site demand so that the demand pressure drops to zero.





Market equilibrium

The market price determination is given by the intersection of the aggregate demand and the regional supply curve. Equilibrium is established for each market, but no general equilibrium is solved. Instead, the equilibrium should be interpreted as partial since no price equalising condition is imposed between markets. The spatial price equilibrium is stable if no user can decrease its cost by changing procurement markets, i.e., buying the resource from another gridcell. In this framework, resource owners can make excess profits due to locational cost advantages.

The method can be used for a wide range of applications assessing spatial heterogeneously distributed resources, e.g., forest and agricultural resources. Based on the application, the method can also be used to assess direct policy options and their implications on market conditions. It allows the modelling of a wide range of pricing behaviours, especially when considering the interaction of competitive policies. By also including conjectural variation into the demand structure, it is possible to identify interdependencies between spatial markets.