# Cost optimization of biofuel production – The impact of scale, integration, transport and supply chain configurations

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## HIGHLIGHTS

- An optimization model was used to assess 4 cost reduction strategies simultaneously.
- Spatially-explicit data on biomass cost-supply and competing demand was included.
- Upscaling showed highest cost reductions, followed by integration and intermodality.
- Distributed supply chain configurations showed only marginal cost reductions.
- Simultaneous assessment is recommended as the strategies are interrelated.

## ARTICLE INFO

## ABSTRACT

This study uses a geographically-explicit cost optimization model to analyze 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 (i.e. supply chains with an intermediate pre-treatment step to reduce biomass transport cost). The model assessed biofuel production levels ranging from 1 to 150 PJ $a^{-1}$ in the context of the existing Swedish forest industry. Biofuel was produced from forestry biomass using hydrothermal liquefaction and hydroprocessing. Simultaneous implementation of all cost reduction strategies yielded minimum biofuel production costs of 18.1–18.2 € $GJ^{-1}$ at biofuel production levels between 10 and 75 PJ $a^{-1}$. Limiting the economies of scale was shown to cause the largest cost increase (+0–12%, increasing with biofuel production level), followed by disabling integration benefits (+1–10%, decreasing with biofuel production level) and allowing unimodal truck transport only (+0–6%, increasing with biofuel production level). 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 favors large-scale centralized production, while intermodal transport networks positively affect the benefits of economies of scale. As biofuel production costs still exceeds the price of fossil transport fuels in Sweden after implementation of all cost reduction strategies, policy support and stimulation of further technological learning remains essential to achieve cost parity with fossil fuels for this feedstock/technology combination in this spatiotemporal context.

## 1. Introduction

Bioenergy is expected to have a significant contribution in climate change mitigation strategies, especially for electricity, liquid fuel and biochemical purposes [1]. Whereas traditional bioenergy use mainly occurs locally, modern bioenergy use (for example large-scale power, heat, chemicals and transport fuels production)

requires more complex supply chains. Besides feedstock availability and sustainability, cost-effective mobilization and conversion of biomass is a prerequisite for the large-scale deployment of bioenergy.

On a supply chain level, the economic performance of a bioenergy supply chain can be optimized by strategic choices regarding production capacity, supply chain configuration, transport modes and conversion location [2]. A key factor in cost-effective supply chain design is the trade-off between economies of scale and transport cost: whereas higher production scales allow for cost reductions due to economies of scale, it increases the need to mobilize biomass over larger distances and thus the upstream transport cost [2–12]. Distributed supply chain configurations (as opposed to centralized configurations) have also been proposed to decrease the transportation cost of biomass and allow for further upscaling [2–10]. As illustrated in Fig. 1, distributed configurations use an intermediate densification step early in the supply chain (e.g. chipping, pelletization or liquefaction) to decrease transport cost, even though this may increase the capital or operational expenditures (CAPEX or OPEX). Additionally, intermodal transport networks based on multiple transport modes (i.e. road, rail and river/sea transport) have been examined as a means to decrease transport cost and unlock distant biomass supplies [13–18]. Furthermore, co-location of production at existing industrial sites may decrease production cost when integration benefits can be leveraged [19,20]. As all of these four cost reduction strategies (i.e. economies of scale, integration, intermodal transport and distributed supply chain configurations) are interrelated, it is important to evaluate them simultaneously to analyze the impact of and interrelations between the different options.

Mathematical optimization models are often used to find the optimal (e.g. least-cost) supply chain design. Unlike techno-economic analyses, optimization models can determine the optimal supply chain design while simultaneously considering a large array of possible supply chain configurations, production locations, biomass supply locations, production scales, transport modes or production locations [2]. Moreover, optimization models can include geographical heterogeneity in feedstock cost, demand and supply.

Various recent studies have used mathematical optimization models to determine the optimal design of bioenergy supply chains, addressing one or more of the aforementioned cost reduction strategies. A large number of optimization studies have looked at the optimal network structure and the number, location and size of the conversion plants in a certain geographical context [10,19,21–29]. Most of these studies include spatially-explicit data of feedstock supply and, to a lesser extent, feedstock cost and (intermodal) transport networks (see Yue et al. [2] for an extensive review) [10,19,21–26]. Only few models, however, incorporate the option of integration with existing industries [19] or different supply chain configurations [25,26], even though both could have a large impact on supply chain design. Moreover, although competition for feedstock and land resources has been discussed at length at a general level regarding crop-based biofuels [30–32] and forest-based biofuels [33,34], competing biomass demand from other industries has only been considered explicitly in a few optimization studies [19,27,28].

The aim of this study is to examine the impact of and interrelation between the four aforementioned cost reduction strategies in one optimization model. These strategies were applied to a case study in Sweden. Sweden was chosen because of its well-developed forest industry (creating competing biomass demand as well as integration opportunities), forestry feedstock potential and the ambitious vision to be one of the first nations to completely phase out fossil fuels for transport [35,36]. Moreover, the availability of detailed spatially-explicit data in Sweden allows for relatively detailed analysis. Although this study includes a high level of regional specificity and provides strategic insights for the development of a biofuel sector in Sweden, it was also attempted to generalize the findings within the boundaries of a case study.

A mixed-integer linear programming (MILP) model was developed to minimize the sum of biofuel production costs and feedstock procurement cost for forest industries (i.e. sawmills, stationary energy and pulp mills). Hence, unlike most other studies, this study does not minimize biofuel costs, but optimizes for the forestry system as a whole. For biofuel production, forest biomass is converted to biocrude through hydrothermal liquefaction (HTL). The biocrude is subsequently hydroprocessed to drop-in (i.e. hydrocarbon fuels which are chemically similar to their fossil counterpart) biofuels at sites with access to natural gas (natural gas grid or LNG terminal) or hydrogen (refinery). These high-quality 'advanced' biofuels can provide high greenhouse gas emission reductions [37,38] and can be used in transport sectors for which no low-carbon alternatives other than biomass-derived fuels are readily available, such as marine, aviation and heavy trucking [39].

Similar to pelletization or pyrolysis, HTL densifies biomass into a transportable intermediate and can hence be used in a distributed supply chain design. HTL was selected in this study based on its promising techno-economic performance and integration



| Centralized supply chain | Distributed supply chain (Linear type) | Distributed supply chain (Hub-and-spoke type) |
|---|---|---|

Legend

Feedstock

Pre-treatment unit

Upgrading unit

Storage terminal

Lower CAPEX/OPEX, higher upstream transportation cost

Higher CAPEX/OPEX, lower upstream transportation cost

Higher CAPEX/OPEX, lower upstream transportation cost
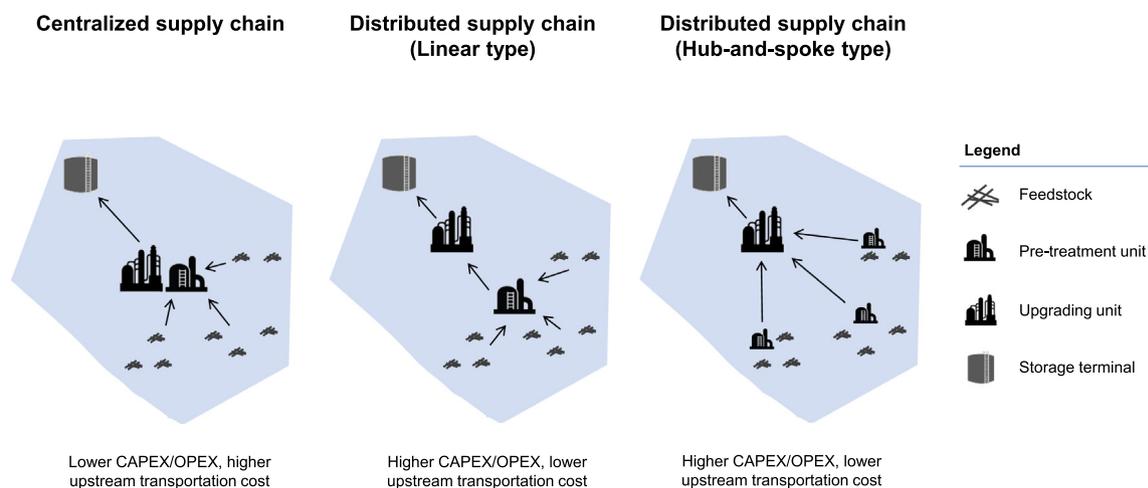
**Fig. 1.** A schematic image of centralized and distributed supply chain configurations.

opportunities with existing industries due to the possibility of excess steam production [20,37,40–43]. Furthermore, it produces a biocrude of higher quality than pyrolysis in terms of energy content, moisture content, oxygen content, and stability [37,43].

The optimization model is spatially explicit in competing biomass demand, transportation infrastructure, feedstock cost-supply data and production locations. The optimization parameters comprised production scale, supply chain configuration, feedstock source and type, transport mode, and production location. Furthermore, the benefits of co-location with existing assets (i.e. sawmills, pulp and paper mills, district heating, forestry terminals, refineries, LNG terminals and the natural gas grid) were quantified and included in the model calculations.

## 2. Methods

### 2.1. Geographical scope

This study focuses on feedstock supply and demand within the national boundaries of Sweden, hence excluding border effects. The Swedish forestry sector is a highly developed sector in which a large part of the biomass supply is already utilized. Sawlogs and pulpwood are almost completely utilized for materials (paper and sawn goods). By-products such as stumps and forestry residues are available, but may be restricted by mobilization constraints (e.g. by price or sustainability requirements) [34,44]. In 2013, biomass contributed to almost 34% (470 PJ a$^{-1}$ or 130 TW h a$^{-1}$) of final domestic energy use [34,45]. Liquid or gaseous biofuels in transport have grown significant in the last decade to 12% (40 PJ a$^{-1}$ or 11 TW h a$^{-1}$) of final energy use in the road transport sector. Although roughly 3.6 PJ (1 TW h) of forest biomass (mainly tall oil) is currently used for biofuel production, the demand for forest biomass for biofuel production was estimated to grow by 50–97 PJ a$^{-1}$ (14–27 TW h a$^{-1}$) in 2030 [34]. A description of Swedish feedstock cost-supply, competing biomass demand, potential conversion locations and transport costs can be found in Sections 2.4.1–2.4.3 and 2.4.6, respectively.

### 2.2. Supply chain scope

The scope encompasses the biofuel supply chains from feedstock production site to blending terminal (Fig. 2). Forestry feedstocks are converted to biocrude through HTL. The biocrude is consequently upgraded to diesel, gasoline and light ends using hydroprocessing [41]. In centralized supply chains, HTL conversion and upgrading occur at the same location. In distributed supply chains HTL conversion and upgrading occurs at different locations, thus requiring intermediate transport. Feedstocks include both virgin feedstocks (sawlogs, pulpwood, primary forestry residues and stumps) and by-products from the forest industry (sawmill chips and industrial by-products from sawmills (IBS) and pulp mills (IBP)). Other by-products from the forest industry (e.g. black liquor or tall oil) were excluded from this analysis (see for example Pettersson et al. [19]). Feedstocks may be used for biofuel production or competing forest industries, i.e. sawmills, pulp mills and the stationary energy sector, to produce heat and power (Section 2.4.2). HTL conversion may occur at sawmills, pulp and paper mills, forestry terminals or sites with access to district heating systems. Upgrading or centralized production is located at LNG terminals, refineries and sites connected to the natural gas grid. Integration benefits from for example steam sales, by-product sales, shared equipment or shared workforce were translated into a reduction in feedstock cost, OPEX and/or CAPEX (Section 2.4.3). Biomass, biocrude and biofuel were transported over lowest-cost intermodal routes (including road, rail and short sea transport). Petroleum

storage and blending terminals were considered the end point of the supply chain [46,47].

### 2.3. Modelling framework

A MILP optimization model was adapted from Lin et al. [21]. The model was written in GAMS using a CPLEX solver. For a defined demand for biofuels, the model optimized total system cost for one production year within a certain set of constraints. The total system costs were defined as the sum of the feedstock procurement cost for competing industries (i.e. feedstock and upstream transport cost) and biofuel production costs, which includes feedstock cost, transport cost for the upstream, intermediate and downstream portions, and cost of conversion (CAPEX and OPEX). Modelling parameters and constraints are given in Table 1. The employed model resolutions are listed in the Supplementary material.

### 2.4. Input data

This section discusses key input data. Additional input data can be found in the Supplementary material. All energy quantities were based on lower heating value. Plant capacities indicate actual capacity, not nameplate capacity. A load factor of 90% was used to relate nameplate capacity and actual capacity [41]. All costs are given in €$_{2015}$. Employed conversion factors can be found in the Supplementary material.

#### 2.4.1. Feedstock supply and price distribution
The aggregated feedstock supply and price distribution is shown in Table 2. A spatially-explicit bottom-up approach was applied to define the harvesting costs and theoretical supply potential for sawlogs from final felling and thinning, pulpwood from final felling and thinning, forestry residues from final felling and thinning and stumps from final felling. For harvesting residues and stumps a number of restrictions were implemented on the theoretical potentials to give the ecological potential, as described in Lundmark et al. [48]. The results from Lundmark et al. were updated to 2015 using more recent scenarios [49,50], which particularly decreased the potential for stumps. The feedstock supply potential was aggregated at a half-degree spatial resolution (Fig. 3). Available quantities of sawmill chips, IBS and IBP were correlated to the production capacities of pulp mills and sawmills using generic yield factors [51–56]. Imports and exports of biomass were not explicitly considered in the model. Instead, the industrial wood demand was calibrated using trade statistics from the Swedish Forest Agency [57]. As the imports (of which the main part consists of pulp wood) exceed the exports, the net imports of biomass were deducted from the total wood demand, i.e. all pulp mills and sawmills were assumed to use an equal share of imported wood. The costs of virgin biomass was converted into roadside prices using a calibration factor which was determined from bioenergy and stemwood price statistics [58,59]. Prices for sawmill chips, IBS and IBP were kept constant across Sweden [60,61]. The Supplementary material contains a geographical distribution of the feedstock price.

#### 2.4.2. Competing industrial biomass demand
Competing demand for biomass from pulp mills, sawmills and stationary energy sector was considered spatially explicitly in the model (Fig. 4). Sawmills and pulp mills use forestry feedstocks for material and process heat purposes. The stationary energy sector utilizes forestry feedstocks to produce heat and power. The demand sectors with the respective biomass assortments they use are listed in Table 3. From Figs. 3 and 4 it can be observed that biomass supply and competing demand is particularly high in the
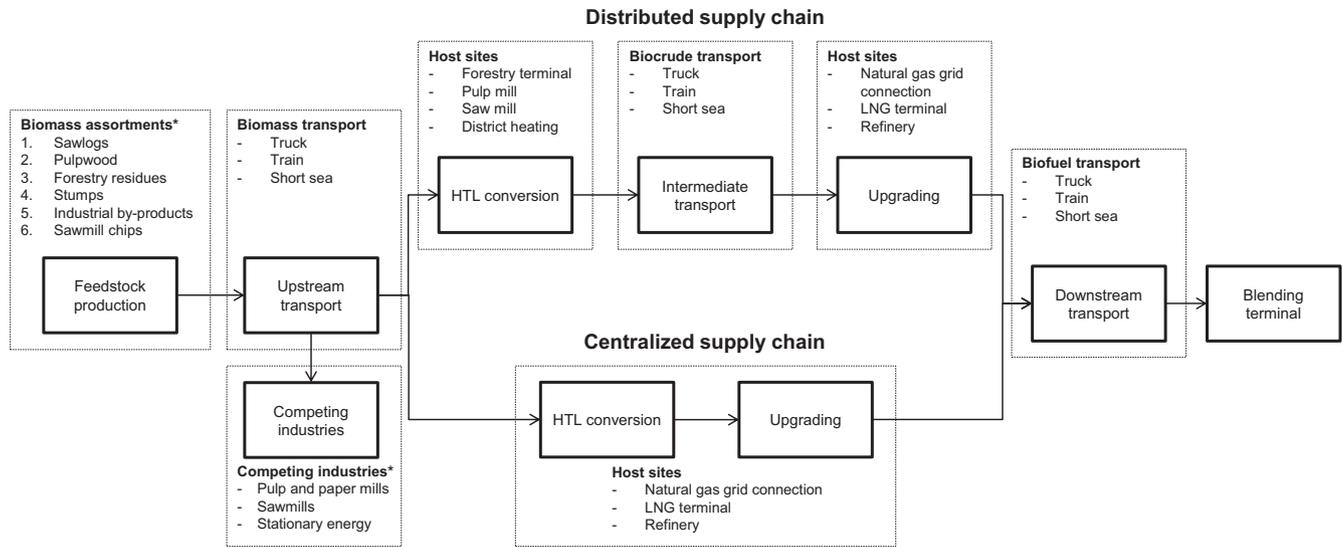
**Fig. 2.** Scope of the analysis.

**Table 1**
Modelling parameters and constraints.

| Modelling parameters | Modelling constraints |
|---|---|
| • Number, location and capacity of biofuel/biocrude production plants<br>• Supply chain configuration (centralized and distributed)<br>• Material flows (forestry feedstock, biocrude and biofuel) to biofuel/biocrude production plants and competing industries<br>• Steam and/or material transfer at a production site<br>• Transport mode | • Biomass supply<br>• Maximum production scale at a production site<br>• Amount of material and steam transfer at a production site |

southern part of Sweden and along the coastline. The demand is described statically on an annual basis (seasonal differences in demand were not taken into account here), based on production and demand in the reference year 2015 [54–57,62,63]. Heat demand from sawmills and pulp mills could be met in the model by integration with an HTL plant, by using (a share of) the industrial by-products available on-site or by transporting biomass to the industrial site. For sawmills and pulp mills, boiler conversion efficiencies of 80% and 90% (on energy basis) were used, respectively.

### 2.4.3. Production locations and blending terminals

Fig. 5 visualizes the potential production locations for HTL, upgrading and centralized plants as well as blending terminals. The production locations were selected based on the availability of essential utilities (natural gas or hydrogen) and/or integration opportunities, which may include a reduction of feedstock cost, OPEX and/or CAPEX depending on the host type (Table 4). Only refineries with a steam methane or catalytic reformer were included, as these are able to produce (excess) hydrogen. Production locations near a natural gas grid were localized at the center of those municipalities connected to the natural gas grid. Fig. 5 shows HTL plants may be located throughout the country, while upgrading locations and blending terminals are confined to the southern part of the country and some sites along the coastline. Moreover, the number of included HTL conversion locations (366) considerably exceeds the number of upgrading sites (37).

Sites with storage facilities for petroleum products were used as a proxy for sites with blending and storage capacity [46,47]. The size of the terminal was taken to be a measure of fuel demand in the region and was used as a constraint on the maximum supply to this terminal. Based on the oil handling capacity of the terminal, the maximum biofuel blending and storage capacity of the terminal was categorized into four groups: 0.2 PJ a$^{-1}$ (7), 1 PJ a$^{-1}$ (14), 50 PJ a$^{-1}$ (3) and 400 PJ a$^{-1}$ (2). It was assumed that 50% of the

**Table 2**
Aggregated supply and price distribution of biomass assortments.

| Biomass assortments | Total supply (PJ a$^{-1}$) | Roadside price (€ GJ$^{-1}$) | | Calibration factor to convert roadside cost to price |
|---|---|---|---|---|
| | | Average | Standard deviation | |
| Sawlogs | 321 | 5.96 | 0.44 | 2.23 |
| Pulpwood | 248 | 4.23 | 0.30 | 1.48 |
| Forestry residues | 111 | 4.18 | 0.45 | 1.39 |
| Stumps | 58 | 5.94 | 1.13 | 1.39 |
| Sawmill chips | 87[a] | 3.06 | 0 | – |
| Industrial by-products from sawmills (IBS) | 63[a] | 2.78 | 0 | – |
| Industrial by-products from pulp mills (IBP) | 5[a] | 2.78 | 0 | – |
| Total | 893 | | | |

[a] Yield factors of 5.41 GJ sawmill chips per m$^3$ sawn wood and 3.93 GJ IBS per m$^3$ sawn wood were used [51]. The production of IBP was estimated based on information from the environmental database of the Swedish Forest Industries Federation (SFIF) [55].

**Fig. 3.** Supply of forest biomass, industrial by-products and sawmill chips.

storage capacity could be used for biofuel blending and storage operations.

### 2.4.4. Integration benefits

Cost benefits from integration were determined on a high-level basis and generalized for each type of production location (Table 4). Steam sales and by-product purchases are cash flows between biofuel production and host industries. Whereas these transfers do not directly affect the total system costs (as the cash flows cancel each other out), they have an indirect impact since they liberate on-site low-cost by-products for biofuel production, and decrease biomass purchases or increase by-product sales for sawmills and pulp mills. Steam sales to refineries and district heating systems were deducted from the biofuel production costs. Co-location benefits (e.g. shared work force, buildings and service facilities) were calcu-

lated using the approach proposed by de Jong et al. [20]. At conversion locations with feedstock handling infrastructure in place, the CAPEX for handling infrastructure was reduced by 50%. For co-location with refineries, hydrogen is assumed to be bought from the refinery, hence eliminating the need for a steam methane reformer (SMR). Offgases from upgrading were assumed not to be recycled in this case, contrary to other upgrading locations. Example site layouts for integration with a sawmill and a refinery are provided in the Supplementary material.

Material and steam integration benefits were constrained based on the capacity of individual production locations. Steam demand was capped at the heat demand at individual production locations (Fig. 4). Heat transfer to district heating systems was limited to a site-specific heat demand (capped at 10 MW) and load factor [62]. Refinery steam demand was estimated using the average ratio

**Biomass demand for energy purposes**   **Biomass demand for material purposes**
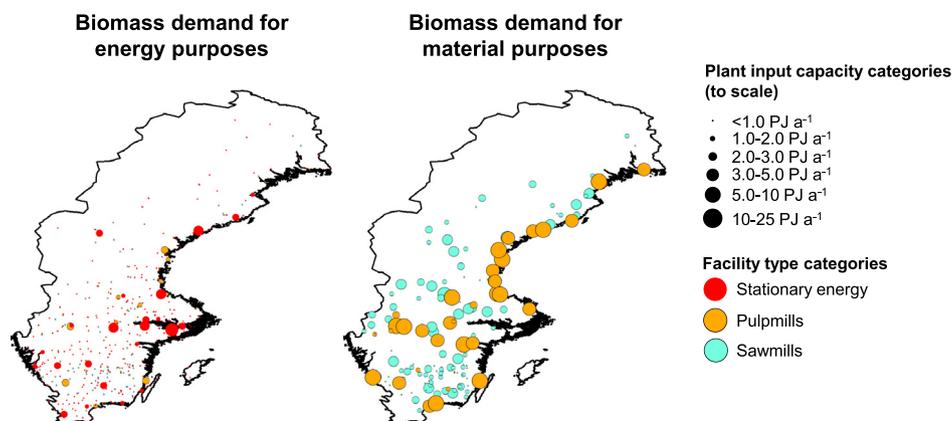


**Fig. 4.** Biomass demand for (process) energy purposes and material purposes (pulp and sawn products) in stationary energy plants, pulp mills and sawmills.

**Table 3**
Aggregated biomass demand for biofuel production, sawmills, pulp mills and the stationary energy sector in Sweden and the corresponding biomass assortments that are used in these sectors.

| Competing industry | Aggregated biomass demand (PJ a$^{-1}$) | Biomass assortments | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Sawlogs | Pulpwood | Forestry residues | Stumps | Sawmill chips | IBS | IBP |
| Sawmills (sawn products) | 247 | x | | | | | | |
| Pulp mills (pulp) | 304 | x | x | | | x | | |
| Stationary energy sector | 103 | | x | x | x | x | x | x |
| Saw mills (heat demand) | 14 | | | | | | x | |
| Pulp mills (heat demand) | 28 | | x | x | x | x | x | x |
| Total | 696 | | | | | | | |
| Biofuel production | Variable | | x | x | x | x | x | x |
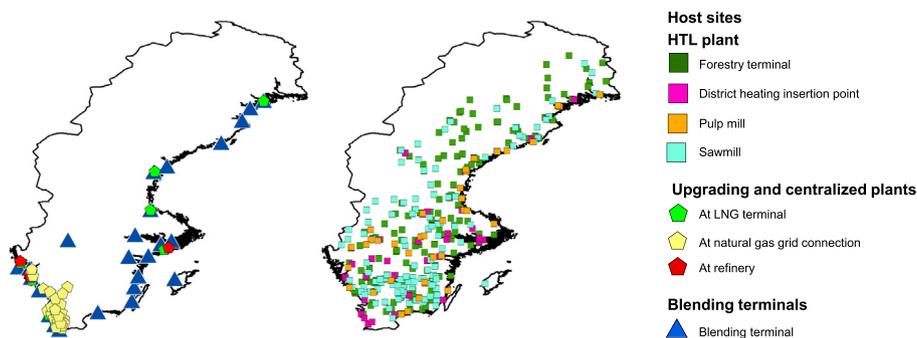


**Fig. 5.** Production locations for upgrading (left), centralized plants (left), blending terminals (left) and HTL conversion (right).

of steam use to crude oil processing capacity of US refineries over the last decade (2006–2015) [70,71]. It was assumed that steam could not be valorized at forestry terminals, LNG terminals or locations connected to the natural gas grid. The transfer of by-products at sawmills and pulp mills was constrained by its availability (Section 2.4.2 and Fig. 3). The maximum amount of hydrogen transferred at refineries was assumed to be 10% of the available hydrogen on-site [65]. The availability of natural gas at LNG terminals was assumed to be constrained at ten times the nominal LNG storage capacity [64]. No cap was placed on the availability of natural gas at sites connected to the natural gas grid.

*2.4.5. Techno-economic input data and economies of scale*

Data for biofuel production through HTL is based on the process design, mass and energy balances, and equipment costs provided by Zhu et al. [41] (goal case). The Standardized Cost Estimation for New Technologies (SCENT) [72] method was used to calculate

the production costs from the data provided by Zhu et al. The production costs vary for each type of production location due to integration benefits (Table 5). The total costs in Table 5 are given for selected production capacities and do not include feedstock costs, transport costs and potential steam sales. A more detailed breakdown of production costs is available in the Supplementary material.

Due to synergies between the HTL and upgrading plants (i.e. exchange of offgases and shared utilities, Fig. 6), the sum of the costs for separate plants (in case of a distributed supply chain) is larger than the total cost of a centralized facility, even when considering integration benefits. The liquefaction process and the waste water treatment produce offgases which can be used to produce electricity and (excess) steam (distributed case or centralized refinery case) or to partially fuel the SMR which produces hydrogen for the upgrading process (centralized natural gas or LNG terminal case). The excess steam produced in the former cases can be

**Table 4**
Material/steam exchange and CAPEX/OPEX benefits per type of production location.

| | Type of production location | Ref | Integration type | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | | Material/steam exchange | | | CAPEX/OPEX benefits[a] |
| | | | Flow | Price[b] | Maximum transfer quantity[c] | |
| **Unit** | | | | € GJ$^{-1}$ | PJ a$^{-1}$ | |
| **Centralized** | | | | | | |
| HTL & upgrading | Natural gas grid | | Natural gas | 8.02 | Not capped | – |
| | LNG terminal | [64] | LNG | 8.02 | 1.0–6.0 | – |
| | Refinery | [46,65][c] | Hydrogen | 19.2 | 2.2–16 | Use of existing SMR, Co-location benefits[e] |
| **Distributed** | | | | | | |
| HTL | Forestry terminal | [66,67] | – | | | Shared feed handling infrastructure |
| | Pulp and paper mill | [54,56] | IBP | 2.78 | 0–1.4 | Shared feed handling infrastructure, |
| | | | Steam | 3.48 | 0–2.6 | Co-location benefits[e] |
| | Sawmill | [55,63] | IBS | 2.78 | 0.01–2.4 | Shared feed handling infrastructure, |
| | | | Sawmill chips | 2.78 | 0.02–3.3 | Co-location benefits[e] |
| | | | Steam | 3.48 | 0–0.56 | |
| | District heating | [62][d] | Steam | 3.48 | 0.16–0.29 | – |
| Upgrading | Natural gas | | Natural gas | 8.02 | Not capped | – |
| | LNG terminal | [64] | LNG | 8.02 | 1.0–6.0 | – |
| | Refinery | [46,65][c] | Hydrogen | 19.2 | 2.2–16 | Use of existing SMR, Co-location benefits[f] |
| | | | Steam | 10.0 | 0.7–1.9 | |

[a] Quantification of the CAPEX/OPEX benefits is discussed in Section 2.4.5 and Table 5.
[b] The price for steam was approximated by assuming the current value is represented by the feedstock price of industrial by-products (2.78 € GJ$^{-1}$) or, in case of refineries, natural gas (8.02 € GJ$^{-1}$) and a boiler efficiency of 0.8 GJ steam per GJ biomass. The Swedish natural gas price was taken from Eurostat [68]. The hydrogen price was calculated based on a fixed (3.37 € GJ$^{-1}$ hydrogen) and a variable portion (1.97 € GJ$^{-1}$J hydrogen per € GJ$^{-1}$ natural gas), taken from the NREL H2A study (Central Natural Gas design) [69]. The LNG price is set similar to the natural gas price, as calculations of the LNG price based on either Norwegian or Henry Hub natural gas prices yielded lower prices than Swedish natural gas prices.
[c] The ranges are due to site-specific capacities.
[d] Hydrogen production at the Gothenburg (ST1) and Nynäshamn refinery was estimated using the Gothenburg (Preem) hydrogen per barrel oil input ratio [65].
[e] Only district heating systems with a substantial load factor (>4500 h a$^{-1}$) and base heat load (>10 MW) were considered. Exchange of heat was capped at 10 MW.
[f] These include benefits of a plant co-located with a processing plant (i.e. sawmill, pulp and paper mill or refinery) relative to a greenfield plant, such as reduced cost for buildings, service facilities, operating labor (shared workforce), and local taxes. These benefits reduce the CAPEX by 7.2% and labor cost by 41%, see also de Jong et al. [20] and the Supplementary material.

**Table 5**
Techno-economic data at selected capacities.

| | Unit | Distributed supply chain | | | | | | | Centralized supply chain | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | HTL conversion | | | | Upgrading | | | HTL conversion and upgrading | | |
| Reference capacity | | Biomass input: 2.75 PJ a$^{-1}$ (87 MW, 19 Mg h$^{-1}$) | | | | Biocrude input: 2.18 PJ a$^{-1}$ (69 MW, 7.6 Mg h$^{-1}$) | | | Biomass input: 2.75 PJ a$^{-1}$ (87 MW, 19 Mg h$^{-1}$) | | |
| Production location | | Forestry terminal | Pulp mill | Sawmill | District heating | Natural gas grid | LNG terminal | Refinery | Natural gas grid | LNG terminal | Refinery |
| Input | | Biomass | Biomass | Biomass | Biomass | Biocrude | Biocrude | Biocrude | Biomass | Biomass | Biomass |
| Output | | Biocrude | Biocrude | Biocrude | Biocrude | Biofuel | Biofuel | Biofuel | Biofuel | Biofuel | Biofuel |
| Process data | | | | | | | | | | | |
| Yield | GJ$_{out}$ GJ$_{in}^{-1}$ | 0.79 | 0.79 | 0.79 | 0.79 | 1.06 | 1.06 | 1.06 | 0.84 | 0.84 | 0.84 |
| Steam production | GJ GJ$_{out}^{-1}$ | | 0.10 | 0.10 | 0.10 | | | | | | 0.09 |
| Net electricity requirement | GJ GJ$_{out}^{-1}$ | 0.007 | 0.007 | 0.007 | 0.007 | 0.014 | 0.014 | 0.007 | 0.049 | 0.049 | 0.021 |
| Natural gas requirement | GJ GJ$_{out}^{-1}$ | | | | | 0.16 | 0.16 | | 0.06 | 0.06 | |
| Hydrogen requirement | GJ GJ$_{out}^{-1}$ | | | | | | | 0.15 | | | 0.15 |
| Total purchased equipment | M€ | 16.5 | 16.5 | 16.5 | 16.9 | 18.0 | 18.0 | 13.4 | 32.5 | 32.5 | 28.6 |
| Total capital investment | M€ | 82.3 | 76.4 | 76.4 | 83.9 | 89.8 | 89.8 | 61.7 | 162 | 162 | 132 |
| Annualized total capital investment (CAPEX) | € GJ$_{out}^{-1}$ | 4.44 | 4.12 | 4.12 | 4.53 | 4.58 | 4.58 | 3.15 | 8.26 | 8.26 | 6.75 |
| Operational expenditures (OPEX)[a] | € GJ$_{out}^{-1}$ | 6.31 | 5.83 | 5.83 | 6.39 | 6.23 | 6.23 | 6.37 | 11.2 | 11.2 | 11.7 |
| Total production cost (OPEX + CAPEX)[a] | € GJ$_{out}^{-1}$ | 10.7 | 10.0 | 10.0 | 10.9 | 10.8 | 10.8 | 9.51 | 19.5 | 19.5 | 18.4 |
| Scale-independent conversion costs | € GJ$_{out}^{-1}$ | 2.21 | 2.03 | 2.03 | 2.21 | 2.00 | 2.00 | 3.47 | 3.64 | 3.64 | 5.46 |
| Scale-dependent conversion costs | € GJ$_{out}^{-1}$ | 8.53 | 7.92 | 7.92 | 8.70 | 8.80 | 8.80 | 6.05 | 15.9 | 15.9 | 13.0 |

[a] Excluding feedstock costs, upstream transport cost and potential steam sales, but including hydrogen and natural gas costs.
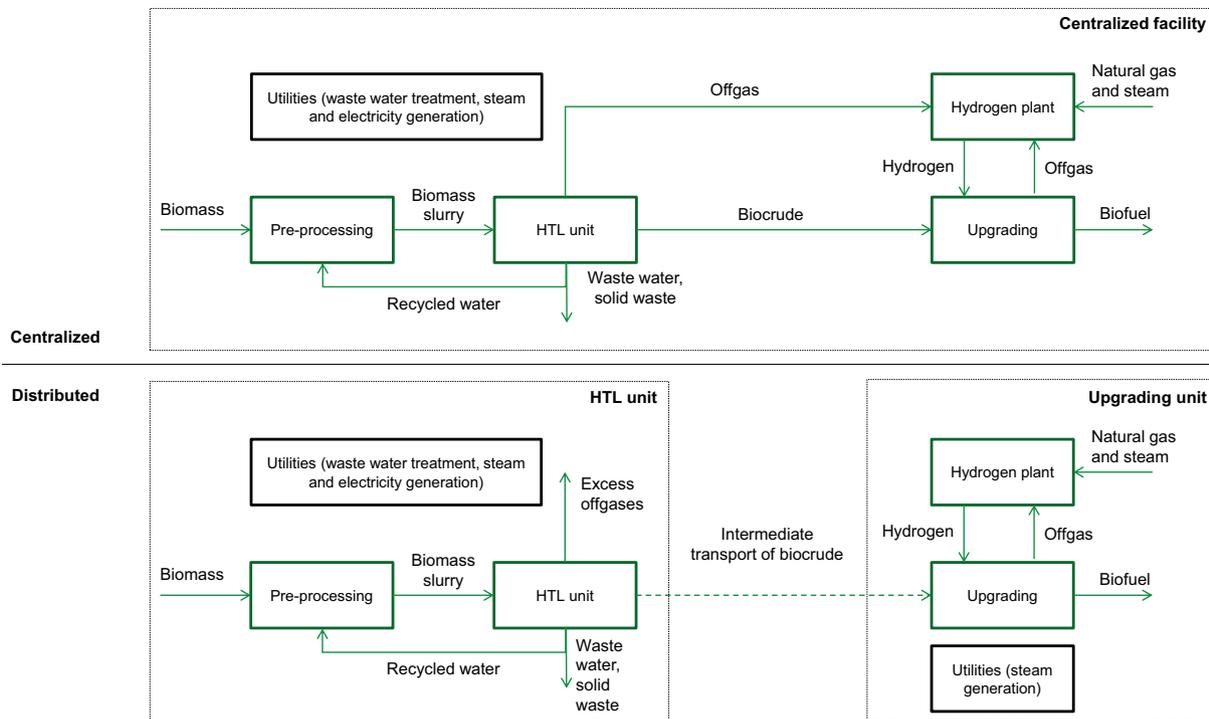
**Fig. 6.** Process configurations for centralized and distributed production, adapted from Zhu et al. [41].

exported to host industries. Upgrading in the distributed supply chain thus requires additional natural gas input for hydrogen production, compared to the centralized scenarios which partly use HTL offgases.

The scale-dependent behavior of conversion costs was approximated using the power law [73]. Scaling factors for process units range between 0.60 and 0.79 (Supplementary material) [41,73,74]. A maximum scale was applied to the HTL reactor, SMR and hydrotreater. Multiple units were built in parallel once the maximum scale for a particular unit is reached. The maximum scales were based on previously reported limits for liquefaction units and scaling curves for SMRs and hydrotreaters [37,73,75]. For implementation in the MILP model, the non-linear power law was approximated by a piecewise linear function [21]. The power function was divided into three linear functions with breaks at the maximum input capacity of a HTL reactor (2.75 PJ a$^{-1}$, 87 MW) and an SMR (39.3 PJ a$^{-1}$, 1246 MW). Remaining equipment (i.e. utilities, hydrotreater, hydrocracker, biomass conditioning and feedstock handling equipment) was scaled up to the maximum scale of production at one site, which was aligned with the maximum input scale of a hydrotreater (73.1 PJ a$^{-1}$, 2318 MW). This scale is less than half the input capacity of a small oil refinery, such as the ST1 refinery in Gothenburg (174 PJ a$^{-1}$), but much larger than a large Swedish pulp mill (∼21 PJ a$^{-1}$). Please note that the data in Table 5 is presented for a specific capacity; upscaling reduces the difference between distributed and centralized production, as the scale-dependent costs decrease with size. An example scaling curve is provided in the Supplementary material.

*2.4.6. Transport costs*

Transport costs of solids (biomass) and liquids (biocrude and biofuel) were pre-optimized using geographically explicit intermodal transport model that runs in the Network Analyst extension of ESRI's ArcGIS. The geodatabase of the transport model consisted of transport network layers for road [76], rail [77] and short sea shipping [78] (Supplementary material). Swedish forest biomass

terminals and sea ports were used as intermodal terminals [66,78,79]. For each commodity, the Network Analyst tool constructs origin–destination (OD) cost matrices for least-cost paths along the intermodal transport network between all possible supply nodes and demand nodes, based on mode- and feedstock-specific parameters shown in Table 6. The Supplementary material contains the underlying assumption regarding fuel consumption and prices, variable costs and fixed costs.

*2.5. Base scenario and alternative scenarios*

The model was evaluated for a range of total biofuel production levels (1, 5, 10, 15, 30, 50, 75, 100, and 150 PJ a$^{-1}$). This can be compared to current total fuel consumption for road transport in Sweden, which amounts to approximately 320 PJ a$^{-1}$. Scenario VI and VII were run up to 100 PJ a$^{-1}$ only, as there was no feasible solution for 150 PJ a$^{-1}$ due to biomass supply constraints. The Base scenario run includes competing demand, centralized and distributed supply chain configurations, all integration benefits, and intermodal transport. Alternative scenarios were run to isolate the role of different cost reduction strategies and examine the impact of competing demand and biomass supply:

I. **Base scenario**.
II. **Reduced maximum capacity.** The maximum input capacity per site was set to 7.31 PJ a$^{-1}$ (232 MW), i.e. 10% of the initial value, to explore the impact of limiting economies of scale. This scale is roughly the size of an average Swedish pulp mill, but relatively large compared to current cellulosic ethanol plants [80].
III. **Centralized only.** Only centralized supply chain configurations were allowed in the model solution.
IV. **Distributed only.** Only distributed supply chain configurations were allowed in the model solution.
V. **No integration benefits.** In this scenario all integration benefits listed in Table 4 were disabled, except the exchange of

**Table 6**
Transport cost parameters.

| Parameter | Unit | Road | Rail | Short sea shipping |
|---|---|---|---|---|
| **Transport cost** | | | | |
| Forestry residues and stumps (chipped) | € GJ$^{-1}$ km$^{-1}$ | 0.0097 | 0.0008 | 0.0004 |
| Industrial by-products (IBS, IBP and sawmill chips) | € GJ$^{-1}$ km$^{-1}$ | 0.0097 | 0.0008 | 0.0004 |
| Sawlogs and pulpwood | € GJ$^{-1}$ km$^{-1}$ | 0.0097 | 0.0008 | 0.0004 |
| Biocrude | € GJ$^{-1}$ km$^{-1}$ | 0.0050 | 0.0002 | 0.0002 |
| Biofuels | € GJ$^{-1}$ km$^{-1}$ | 0.0040 | 0.0002 | 0.0002 |
| **Loading or unloading cost**[a] | | | | |
| Forestry residues and stumps (chipped) | € GJ$^{-1}$ | 0.31 | 0.53 | 0.29 |
| Industrial by-products (IBS, IBP and sawmill chips) | € GJ$^{-1}$ | 0.16 | 0.53 | 0.39 |
| Sawlogs and pulpwood | € GJ$^{-1}$ | 0.12 | 0.48 | 0.39 |
| Biocrude | € GJ$^{-1}$ | 0.04 | 0.10 | 0.35 |
| Biofuels | € GJ$^{-1}$ | 0.03 | 0.08 | 0.27 |

[a] Loading and unloading cost are assumed to be similar.
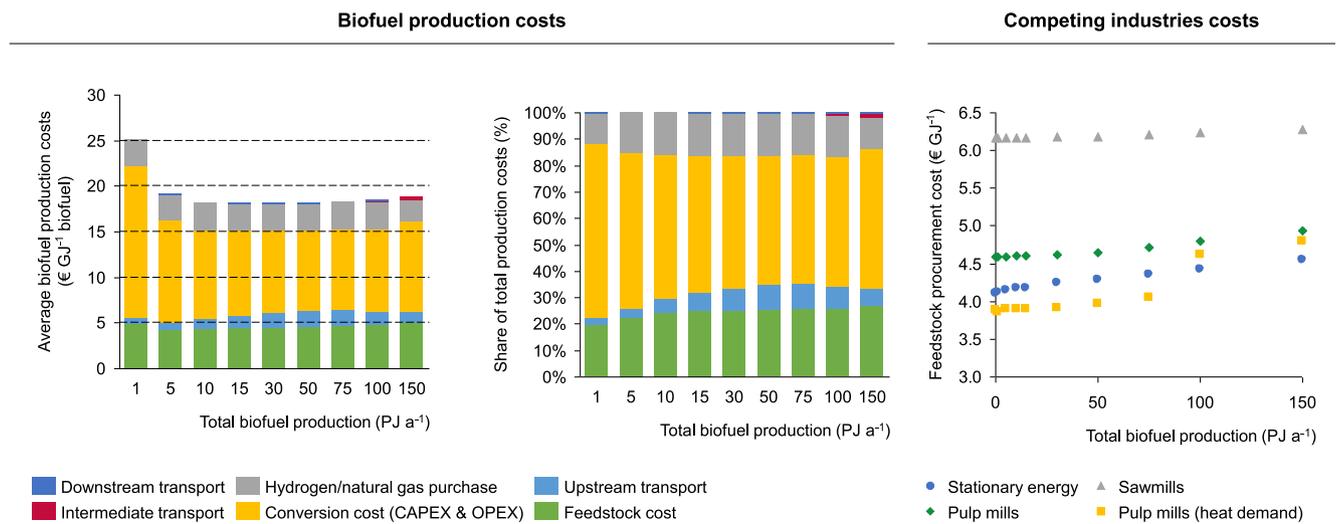


Fig. 7. The biofuel production costs and feedstock procurement costs (i.e. feedstock and upstream transport costs) for competing industries for the Base scenario.

industrial by-products. OPEX and CAPEX profiles from district heating sites (HTL conversion), LNG terminals (upgrading) and LNG terminals (centralized facilities) were adopted for other production locations.

VI. **Low biomass supply.** Total biomass supply of virgin feedstocks (i.e. stumps, forestry residues, sawlogs, and pulpwood) was diminished by 10% to analyze a scenario in which biomass supply decreases. Supply of industrial by-products and sawmill chips remained unaltered.

VII. **High competing demand.** Competing demand and the production of industrial by-products was increased by 10% to analyze a scenario in which competing demand increases.

VIII. **Road only.** Only road transportation (by truck) was allowed for solid biomass and biocrude. Downstream logistics of biofuels could still occur through road, rail or short sea transport. This scenario was used to explore the impact of introducing intermodal transport.

## 3. Results

### 3.1. Base scenario results

Fig. 7 shows the cost breakdown for the Base scenario. The figure describes a sharp downward cost trend at first, which is counteracted by an upward tail after 15 PJ a$^{-1}$ at which the cost are lowest (18.1 € GJ$^{-1}$). The initial cost decrease is mainly due to a decline in CAPEX; the upward tail is mainly caused by increased feedstock costs and upstream transport cost. The upward tail is shallow; the cost difference between 15 and 150 PJ a$^{-1}$ is only 0.8 € GJ$^{-1}$. The share of upstream cost never exceeds 10% and declines after distributed supply chain designs are introduced beyond 100 PJ a$^{-1}$ (Fig. 8). The contribution of downstream distribution or intermediate transport cost is negligible. Whereas feedstock procurement cost for sawmills are moderately affected in the Base scenario (+2%), procurement cost for pulp mills (+7% for pulpwood demand and +24% for heat demand) and stationary energy plants (+11%) increase significantly at 150 PJ a$^{-1}$ relative to the reference level with no biofuel demand, because they use the same (inexpensive) feedstocks as biofuel production. Sawmill heat demand is exclusively met by on-site sawmill by-products and does not incur a cost to the sawmill.

Fig. 8 visualizes the production locations in the Base scenario for six different biofuel production levels. It shows that centralized production at the southwestern refineries is preferred at all levels due to high feedstock availability and significant integration benefits. The Base scenario solution does not include HTL conversion at district heating sites or forestry terminals due to lower integration benefits compared to sawmills and pulp and paper mills. The location of the HTL plants, however, varies with the biofuel production level and cannot be explained by exceptional site-specific benefits, indicating there is no robust preference for particular HTL locations. Even though LNG terminals might be closer to HTL locations, natural gas upgrading plants are preferred over LNG terminals as the former allow for higher production scales since the supply of
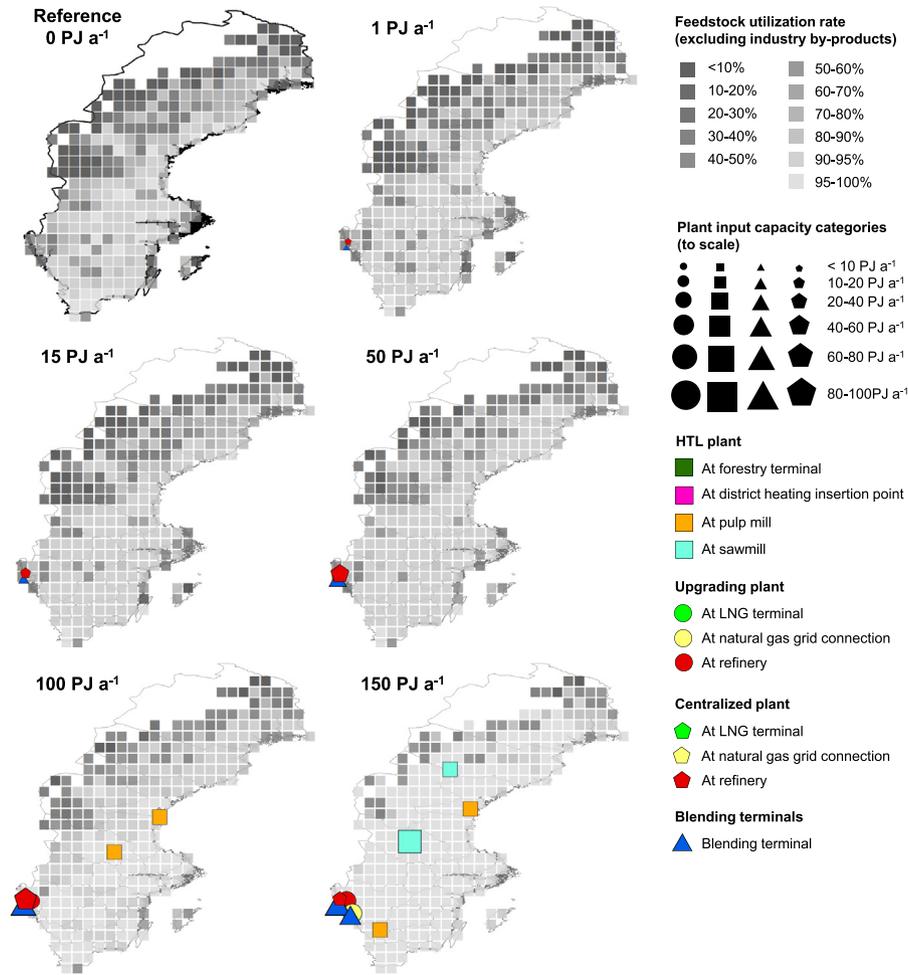
**Fig. 8.** Production locations and feedstock use in the base scenario at different biofuel production levels.

natural gas is constrained at LNG terminals (at 6–39 PJ a$^{-1}$ biofuel for upgrading plants and 17–101 PJ a$^{-1}$ biofuel for centralized plants). With the inclusion of a natural gas upgrading plant instead of a refinery upgrading plant at 150 PJ a$^{-1}$, conversion cost increase (due to the need for an SMR), while the average cost for hydrogen/-natural gas purchases decrease.

Fig. 8 also shows a gradual expansion with rising biofuel production levels to the north of the country because of lower feedstock utilization rates. Industrial by-products and sawmill chips (not shown in Fig. 8) are used first due to their low roadside price. From 15 PJ a$^{-1}$ onwards, pulpwood, forestry residues and sawmill chips are increasingly used for biofuel production because of relatively low roadside prices and moderate loading/unloading costs. This instigates a shift towards the use of more sawlogs and pulpwood in pulp mills. From 75 PJ a$^{-1}$ onwards, stumps are increasingly utilized, particularly for stationary energy and biofuel production. Even though the majority of unutilized feedstock supply is located in the north, it is only used at higher biofuel production levels, as the feedstock is also more expensive to mobilize and further away from locations where large-scale upgrading is possible.

### 3.2. Alternative scenarios

Fig. 9 gives an overview of the number and type of plants and the average biofuel production costs for each scenario considered.

#### 3.2.1. Large scale versus small scale

All scenarios show the expected cost profile with increasing biofuel production levels; a rapid cost decline at small biofuel production levels due to economies of scale followed by an upward tail beyond the optimum. Between the optimum and the maximum plant output capacity (61.2 PJ a$^{-1}$, 1941 MW), the upward tail is typically caused by increasing feedstock cost and/or upstream transport cost. Despite the upward tail, no additional plants are built before the maximum capacity is reached in the Base scenario, indicating that an optimum scale is a local optimum instead of a general optimum, depending on feedstock price, feedstock availability and integration benefits. Beyond the maximum capacity, additional (distributed) plants are built at less suitable locations which increase the CAPEX and feedstock cost while decreasing transport costs. Similar dynamics are visible in the Centralized only and No integration benefits scenarios. In these scenarios medium-sized plants (input capacity >30 PJ a$^{-1}$, 951 MW) also dominate the model solutions at higher biofuel production levels.

Scenarios in which economies of scale are restricted (Reduced maximum capacity), transport is more expensive (Road only) or distributed supply chain configurations are adopted (Distributed only) show a similar dominance of economies of scale at low production scales, but deviate from the aforementioned dynamics thereafter. Compared to the base scenario, the Reduced maximum capacity scenario shows a rise in biofuel production cost of 0–12% with an increasing trend towards higher biofuel production levels.

**Fig. 9.** An overview of number of plants and average biofuel production costs for different biofuel production levels.

The upward tail in the Reduced maximum capacity scenario is mainly caused by rising feedstock cost and higher conversion cost, because less suitable sites need to be introduced as the biofuel production level increases. The Road only scenario shows a much steeper upward tail and the introduction of multiple plants at a lower biofuel production level (30 PJ a$^{-1}$) due to increased transport cost. The Distributed only scenario shows a cost optimum at higher biofuel production levels (75 PJ a$^{-1}$) because distributed designs temper the effect of increasing upstream transport cost; the upward tail is mainly caused by increasing feedstock cost.

### 3.2.2. Distributed versus centralized supply chains

In the Base scenario, centralized supply chain configurations prevail at biofuel production levels below 75 PJ a$^{-1}$. The introduction of distributed supply chains at 100 PJ a$^{-1}$ is marked by lower feedstock and transport cost, but higher conversion cost. At the highest biofuel production level, almost 80% of the biofuel volumes are supplied through distributed supply chains. Centralized supply chains are preferred over distributed configurations, mainly because the latter show higher conversion cost due to the loss of synergies between the HTL plant and the upgrading plant (i.e. off-gas integration and shared utilities), even when including integration benefits. These additional costs outweigh the benefits of distributed configurations (i.e. lower upstream transport cost or access to lower-priced feedstocks). Distributed supply chains emerge at higher biofuel production levels, as upscaling reduces the difference between distributed and centralized production,

while the share of upstream transport costs increases. Furthermore, at higher production levels well-sited locations are already taken and the biomass supply becomes increasingly dispersed and expensive. Consequently, the value of distributed configurations becomes more pronounced. Limiting economies of scale (Reduced maximum capacity) and higher transport cost (Road only scenario) leads to the introduction of distributed configurations from 30 PJ a$^{-1}$ and 75 PJ a$^{-1}$ onwards, respectively.

By allowing distributed supply chain configurations in the model solution, the Base case yields insignificant cost reductions (<1%) relative the Centralized only scenario. The Distributed only scenario shows 5% higher production costs compared to the Base scenario at a low biofuel production level, which fades at higher biofuel production levels. Fig. 10 shows that upgrading remains centered in the southwest of Sweden in the Base scenario and Distributed only scenario. It is, however, only cost-effective to have multiple upgrading plants in one area (e.g. a refining cluster) if additional biomass is efficiently transported from elsewhere (e.g. by distributed supply chains). No significant variation was found in feedstock utilization rates.

Fig. 1 shows distributed supply chains may be linear-type (i.e. one pre-treatment plant supplying one upgrading plant) or hub-and-spoke-type (i.e. multiple pre-treatment plants supplying one or more upgrading plants). Both types aim to decrease the upstream transport cost. Whereas both types incur additional cost due to the loss of synergies between the HTL and upgrading plant, the hub-and-spoke-type also experiences a loss of economies of
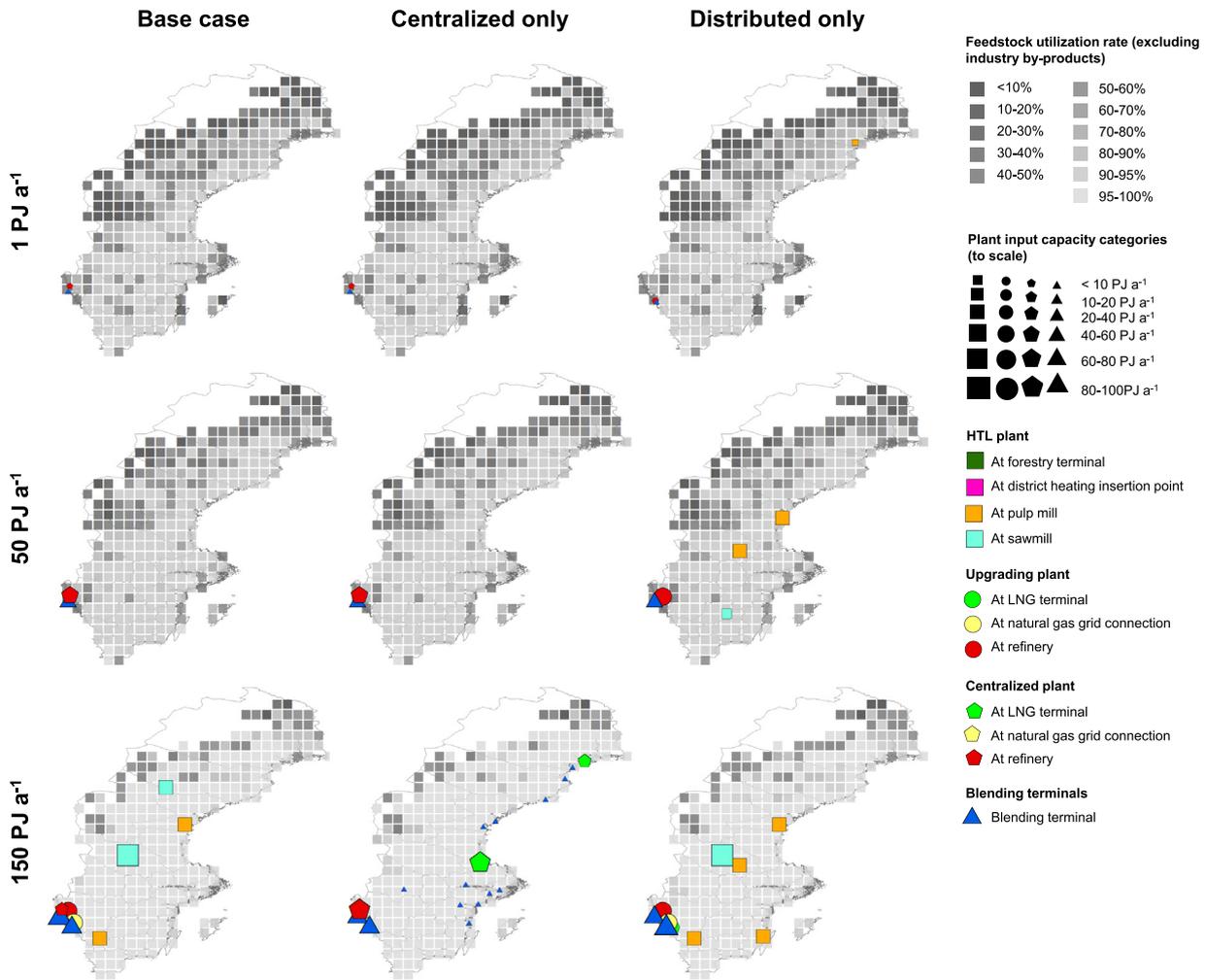
**Fig. 10.** Production locations and feedstock utilization rate for the Base scenario, Centralized only scenario and Distributed only scenario at 1, 50 and 150 PJ a$^{-1}$.

scale. For this reason, linear-type distributed supply chains emerge at lower biofuel production levels while hub-and-spoke-type supply chains are introduced once the biofuel production level allows multiple medium-sized HTL plants (input capacity >10 PJ a$^{-1}$, 317 MW) to be built.

### 3.2.3. Competing demand and the merits of integration

Biofuel production may be impeded by competition over biomass with existing forest industries, but may also profit from integration benefits with the same forest industries. The No integration benefits scenario shows higher production costs than the Base scenario (+1–10%, decreasing with biofuel production level). As conversion costs have a higher share in the total production cost at small scales, CAPEX/OPEX benefits are particularly pronounced at smaller scales. Moreover, eliminating the integration benefits increases the additional cost for distributed relative to centralized configurations, causing centralized plants to dominate the No integration benefits scenario. The material and energy integration benefits included in this study are valid on a small to medium scale. Cost reductions due to integrations benefits are, however, modest compared to the overall production costs and benefits of economies of scale. The production of by-products at pulp mills and sawmills provides 5.8 and 1.4 PJ a$^{-1}$ of by-products, respectively, at maximum. Similarly, steam integration at sawmills, district heating and pulp mills can be utilized at biomass input capacities of 7.2, 3.8 and 34 PJ a$^{-1}$ at maximum, but provide a marginal cost reduction (0.36 € GJ$^{-1}$ biofuel). For refineries, steam integration

can be utilized at input capacities up to 9–25 PJ a$^{-1}$ and provides a slightly higher cost reduction due to a higher heat transfer price (0.92 € GJ$^{-1}$ biofuel).

Integration benefits, if sufficiently large, may outweigh increased feedstock procurement cost at particular locations. For example, whereas the Base scenario mainly showed refinery locations, the No integration benefits scenario strictly includes locations with a connection to the natural gas grid or LNG terminals, indicating the latter locations are better sited in terms of biomass supply.

The impact of increased competition over feedstock was tested in the High competing demand and Low biomass supply scenarios. These scenarios show marginally higher biofuel production costs (+0–6%, increasing with biofuel production level) relative to the Base scenario, because more expensive feedstocks are used and feedstocks are transported over larger distances. Feedstock procurement cost for competing industries for these two scenarios also rise by 0–18% relative to a similar biofuel production level in the Base scenario. Stationary energy plants and pulp mills (heat demand) were most affected. It is shown that the amount, type or size of plants built in both scenarios roughly represents the dynamics of the Base scenario.

### 3.2.4. Intermodal transportation networks

Intermodal transport allows for lower transportation costs over large distances, thereby providing access to cheaper feedstocks. Relative to the Base scenario, the Road only scenario is character-
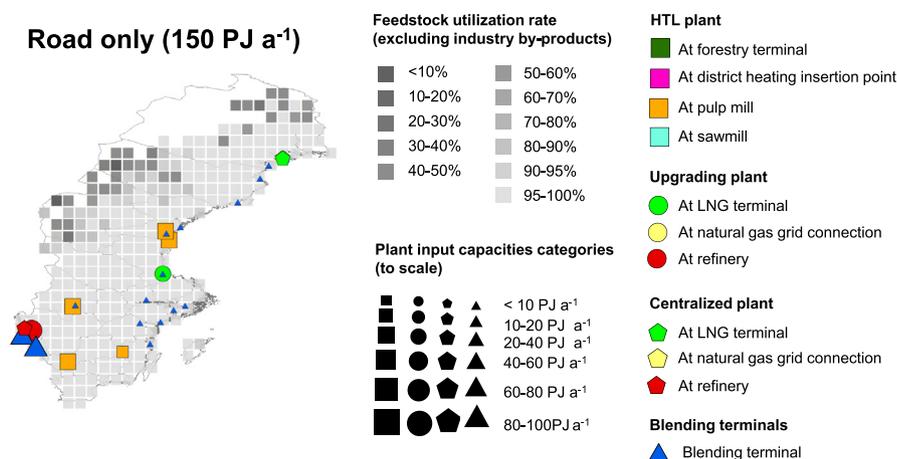
**Fig. 11.** Production locations and feedstock utilization rate for the Road only scenario at a biofuel production level of 150 PJ a$^{-1}$.

ized by higher overall production costs (+0–6%, increasing with biofuel production level) due to higher feedstock and intermediate transport cost, but roughly similar upstream transport costs. The Road only scenario increases the cost of feedstock mobilization, which causes a switch to nearby but more expensive feedstocks (e.g. stumps). Figs. 9 and 11 also show that the Road only scenario leads to a more decentralized system with more, smaller and more dispersedly located production plants.

## 4. Discussion

### 4.1. The impact of cost reduction strategies

This study explored the impact of economies of scale, integration, intermodal transport and distributed supply chain configurations on the cost performance of biofuel production. In the Base scenario, in which all cost reduction strategies were included, minimum biofuel production cost of 18.1–18.2 € GJ$^{-1}$ were obtained for biofuel production levels between 10 and 75 PJ a$^{-1}$. Production cost increase both at lower and higher biofuel production levels. Below 10 PJ a$^{-1}$ smaller units are built which increase conversion cost significantly. Beyond 75 PJ a$^{-1}$ increased feedstock and upstream transport cost are the main cause of rising cost. However, biofuel production costs rise only modestly between biofuel production levels of 10–150 PJ a$^{-1}$. Similar cost profiles were obtained in previous studies. Least-cost output capacities for various conversion technologies were found in a broad range between 4 and 67 PJ a$^{-1}$ (127–2125 MW), with an average at 21 PJ a$^{-1}$ (666 MW) [8,81–85].[1]

The minimum cost are still higher than current (2015) fossil fuel pump prices in Sweden of 14–15 € GJ$^{-1}$ (taxes excluded) [86]. Hence, besides implementing all four cost reduction strategies, policy support and further technological learning is still required for biofuels produced from HTL to achieve cost parity with fossil fuels in this spatiotemporal context.

The impact of individual cost strategies was analyzed in alternative scenarios. Limiting the economies of scale (Reduced maximum capacity scenario) was shown to cause the largest cost

increase relative to the Base scenario (+0–12%, increasing with biofuel production level), followed by disabling integration benefits (+1–10%, decreasing with biofuel production level) and allowing unimodal truck transport only (+0–6%, increasing with biofuel production level). Please note that the cost reductions cannot be added as the strategies are interrelated: disabling integration benefits favors large-scale centralized production, while intermodal transport networks positively affect the benefits of economies of scale.

Distributed supply chain configurations were introduced in the Base scenario once biomass supply became increasingly dispersed (at biofuel production levels beyond 100 PJ a$^{-1}$), but did not provide a significant cost benefit (<1%) over the production costs found in the Base scenario or Centralized only scenario. Reducing the maximum production capacity (Reduced maximum capacity scenario) and increasing the cost of transport (Road only scenario) instigated a preference for distributed supply chains at biofuel production levels of 30 and 75 PJ a$^{-1}$, respectively. Two previous analyses using techno-economic analyses found a similar transition point at output capacities between roughly 30–60 PJ a$^{-1}$ [9,10]. Hub-and-spoke-type distributed supply chains require large benefits from upstream transport cost reductions, economies of numbers, or site-specific integration benefits to offset the loss of economies of scale. Linear-type distributed supply chains may be preferred over centralized supply chains in cases where a high distance between the location of biomass supply and end use justifies additional CAPEX and/or OPEX (e.g. electricity generation in Europe using overseas (pelletized) biomass [3,5,7]).

### 4.2. Key uncertainties

The relative differences between cost reduction strategies are small and the impact of individual strategies on the overall production costs is modest. As such, it is important to discuss the impact of key uncertainties.

The impact of economies of scale is highly dependent on the scaling factor and assumed maximum capacity. While production input scales beyond 30 PJ a$^{-1}$ (951 MW) dominate model solutions at higher biofuel production scales, the technical feasibility and the economic benefits of upscaling have yet to be confirmed. The input capacity of the largest Swedish pulp mill is roughly 21 PJ a$^{-1}$ (666 MW); the largest lignocellulosic biofuel (ethanol) plants are even smaller (~5 PJ a$^{-1}$, 159 MW) [80]. HTL is still in the early demonstration phase [43,87]. Given the commercialization status and the associated risk profile of HTL, investor appetite to build large-scale plants in the near future will likely be low, especially if the overall fuel costs are not substantially lower than fossil fuels.

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[1] This range was obtained from six studies. Most of these studies assume a homogeneous feedstock density. Generally, a generic participation rate was assumed to represent competing demand for land and feedstock. A large variety in assumed feedstock densities (4–673 Mg km$^{-2}$) was found to be a main contributor to the broad range in least-cost capacities. The feedstock density used in this study ranges from 2 to 396 Mg km$^{-2}$ (average 120 Mg km$^{-2}$). This density was calculated before competing demand was deducted (only 22% of the total feedstock was available for biofuel production).

Hence, it is more likely that small-scale plants will be built in the near future before larger scales can be targeted. The Reduced maximum capacity scenario (constraining input capacity to 7.31 PJ a$^{-1}$ or 232 MW) shows that limits on the benefits of economies of scale may particularly increase the value of distributed configurations. Also, it is expected that integration benefits will have a large impact in the first phase. Depending on the development of biomass supply and competing demand, (policy/industry) strategies focused on further upscaling (i.e. scale-dependent learning) and the development of an intermodal transport network will likely contribute to further cost reductions. As the biomass surplus fades, the merits of distributed supply chains become more profound and may be employed to gradually scale-up existing upgrading plants.

The model contains a relatively high degree of spatially-explicit detail regarding competing demand, transport network and production locations. The spatial resolution of biomass supply and price data (half-degree) is relatively coarse and can be improved. While adding detail may instigate a clearer preference for particular production locations, which may be of interest to industry stakeholders, it is not expected to alter the merit of the cost reduction strategies. The addition of international biomass trade, however, may alter domestic cost-supply curves, likely strengthening the trend towards large-scale conversion plants, especially near sea ports. As the additional conversion cost of distributed relative to centralized configurations is decisive for the trade-off between both configurations, more detailed quantification and optimization of the cost performance of different pre-treatment technologies is recommended. Whereas integration benefits between biofuel production and existing industries were constrained on a site-specific level, the character and monetary value of integration benefits was generalized for each type of production location. As a result, a robust preference was found for the type of host site (i.e. refineries), but a low convergence was observed for preferred production locations. Site-specific integration opportunities (e.g. bolt-on solutions, co-processing of biocrude at refineries) which can be applied at large scales may yield significant cost reductions and outweigh the potential increased cost of feedstock mobilization at that site. Conversely, site-specific safety issues, site layouts or strategic interests of the host might impede integration.

Whereas adding more detail may improve the robustness of the results, it is strongly advised to select only the most relevant modelling parameters on the basis of their expected impact (e.g. by doing a pre-analysis) to limit computation time and improve the transparency of the results. For example, eliminating conversion locations at district heating systems and forestry terminals from this study would not have an impact on the results.

### 4.3. Generalization of results

Temporal variability in competing demand, production locations, infrastructure, feedstock supply and feedstock prices was not captured in this study. In Sweden in particular, annual forestry biomass demand for energy and bio-chemicals may increase by 80–100 PJ in 2030 relative to current demand (excluding additional demand from biofuel production), mainly due to biochemical production [34]. Although the Swedish production of pulp, paper and sawn wood has stagnated or decreased during the last decade [57,88], the output of the Swedish forest industry is likely to grow alongside the increasing global demand for forest products [89]. Moreover, biomass demand from competing industries may become more clustered if the trend towards increasing plant scale and phase out of smaller plants continues [90]. The highest biofuel production levels examined in this study would require full utilization of all residues, including stumps. While the standing volume is projected to increase in the coming decades (hence increasing the potential supply of forest biomass for energy

purposes) [48,49,91], the actual sustainable harvesting rates are subject to discussion, especially for stumps [34,92]. A lower biomass surplus (as demonstrated in the Low biomass supply and High competing demand scenarios) shows a mildly higher preference for smaller distributed plants; an opposite trend will likely show larger centralized plants. Moreover, this study utilizes top-down optimization of biofuel production systems for a particular biofuel demand, neglecting the fact that production systems grow organically and originate from bottom-up action of single actors.

Multi-step optimization can be used to capture time-dependent variability in competing demand, feedstock availability, production scale and technology performance [29]. Such analysis enables the user to identify lock-in effects and explore of the role and robustness of different cost reduction strategies at various development stages, both of which are important components of regional biofuel deployment strategies. Multi-objective optimization can be used to simultaneously optimize conflicting objectives (e.g. economic and environmental indicators) [93,94].

Furthermore, the geographical characteristics of the study area and choice of feedstock-technology combination influence the results. Whereas a higher transport cost and lower feedstock density will limit the impact of economies of scale (see footnote 1), more capital intensive technologies or a higher scaling factor enlarge the role of economies of scale [8,81–85,95]. As other pre-treatment processes, such as pelletization, also incur additional OPEX/CAPEX relative to a supply chain without pre-treatment, it should be examined closely under what circumstances such additional costs are justified, especially because feedstock and transport cost tend to rise only marginally with scale.

### 5. Conclusions

This study evaluated the impact of four strategies to reduce the cost of biofuel production in a Swedish context: economies of scale, intermodal transport, integration, and distributed supply chain configurations. Simultaneous implementation of all cost reduction strategies yielded minimum biofuel production costs of 18.1–18.2 € GJ$^{-1}$ at production levels between 10 and 75 PJ a$^{-1}$. As the minimum biofuel production costs are still higher than the current fossil fuel prices, policy support and technological learning remains essential to achieve cost parity.

Limiting the economies of scale was shown to cause the largest cost increase (+0–12%), followed by disabling integration benefits (+1–10%) and allowing unimodal truck transport only (+0–6%). Distributed supply chain configurations were introduced once biomass supply became increasingly dispersed, but did not provide a significant cost benefit (<1%). The merits of the different cost reduction strategies depend on the maturity of the biofuel production system: whereas the benefits of economies of scale and intermodal transport grow with increasing biofuel production level, integration benefits have a more profound impact in the early stages of biofuel deployment. These strategies are interrelated and should therefore ideally be analyzed simultaneously in optimization models. Model results show that disabling integration benefits favors large-scale centralized production, while intermodal transport networks positively affect the benefits of economies of scale. Similarly, constraints on the benefits of economies of scale particularly increase the value of distributed configurations.

The analysis may be expanded by including more geographically-explicit detail to improve the robustness of results. Multi-step can be used to capture temporal variability, while multi-objective optimization allows for simultaneously optimization of conflicting objectives. At the same time, it is strongly

advised to pre-select only the most relevant modelling parameters to improve the transparency of the results.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.03.109.

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