REPORT

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CENTRALIZED VS. DISTRIBUTED BIOFUEL SUPPLY CHAINS BASED ON LIQUEFACTION TECHNOLOGY – THE CASE OF SWEDEN

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 is a networking organization, which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

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

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

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

The report is the result of work carried out within the f3 project "Optimization of biofuel supply chains based on liquefaction technologies", which has been carried out in collaboration with researchers at University of Utrecht, the Netherlands, within the EIT Climate-KIC funded RENJET project (Renewable Jet Fuel Supply Chain Development and Flight Operations).

This report is based on a scientific paper:

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SUMMARY

Traditional bioenergy supply chains design considers a centralized facility around which the biomass is collected. In the centralized supply chain design the benefits from economies of scale are counterbalanced by rising upstream transport costs as a higher scale requires a larger feedstock collection radius. Distributed supply chains configurations (i.e. including a pre-treatment step in which the biomass is densified) are often proposed to reduce the upstream transportation costs. It is hypothesized that such configuration allows for further upscaling and can hence decrease bioenergy production costs, particularly when using liquefaction technologies which are able to convert biomass into a transportable biocrude with a much high energy and bulk density compared to biomass.

In this analysis we explore the preconditions under which distributed supply chain configurations (based on hydrothermal liquefaction) are preferred over centralized supply chains. A spatially explicit optimization model based on Swedish data on biomass supply and price, intermodal transport infrastructure, competing demand, and potential conversion sites (including integration benefits) was evaluated at different biofuel demands. It was found that distributed supply chains may reduce upstream transport cost. Nonetheless, the additional costs for conversion and intermediate transportation associated with distributed supply chains generally leads to a preference for centralized supply chains at biofuel demands below 75 PJ_{out}/yr (21 TWh/yr). Distributed supply chains were shown to be useful in cases in which the feedstock cost-supply curves are steep, biofuel production beyond 75 PJ_{out}/yr is targeted, or the available biomass resource base is almost fully utilized.

SAMMANFATTNING

Utformning av försörjningskedjor för bioenergi innebär vanligtvis en central anläggning kring vilken biomassan samlas in. I en sådan centraliserad försörjningskedja uppvägs ekonomiska skalfördelar av högre transportkostnader uppströms i kedjan, då ökande produktionsskala medför ökande radie för uppsamlingsområdet för biomassa. Distribuerade försörjningskedjekonfigurationer, som alltså inkluderar ett förbehandlingssteg där biomassans energidensitet ökas, föreslås ofta som en metod att minska transportkostnaderna uppströms. Hypotesen som ofta förs fram är att denna typ av konfiguration medger vidare uppskalning, med minskade totalproduktionskostnader som följd. Detta gäller särskilt för försörjningskedjor där intermediärsteget innehåller förvätskningsteknik där biomassa omvandlas till bioolja (biocrude), med väsentligt mycket högre energi- och volymdensitet jämfört med råbiomassan.

I denna rapport analyserar vi under vilka förutsättningar distribuerade konfigurationer för försörjningskedjor (baserade på hydrotermisk förvätskning, HTL) är att föredra framför centraliserade konfigurationer, för fallet Sverige. Det övergripande syftet med studien är att identifiera kostnadseffektiva försörjningskedjekonfigurationer för produktion av drop-in-biodrivmedel från skogsbiomassa med hjälp av förvätskningsteknik. En spatialt explicit optimeringsmodell baserad på data för tillgångar på och kostnader för biomassa, intermodal transportinfrastruktur, konkurrerande efterfrågan på biomassa från andra sektorer, samt potentiella lokaliseringar för produktionsanläggningar, där integrationsfördelar beaktas explicit, användes för att utvärdera försörjningskedjorna vid olika nivåer av biodrivmedelsproduktion. Resultaten visade att även om distribuerade försörjningskedjor har möjlighet att minska transportkostnaderna uppströms, leder de ökade kostnaderna för konvertering till och transport av intermediärprodukten generellt till en preferens för centraliserade försörjningskedjor, för en total årlig biodrivmedelsproduktion under 75 PJ (21 TWh). I fall där utbudskurvan för biomassatillgångarna är brant eller där biomassaresurserna redan är nästan fullutnyttjade, visade sig distribuerade försörjningskedjor ha en roll, liksom då årsproduktionen av biodrivmedel översteg 75 PJ.

CONTENTS

1 INTRODUCTION

Unlike traditional uses of biomass for energy purposes (bioenergy) for local heating and cooking, modern bioenergy demand in urban and industrial areas is often remote from regions that are rich in biomass supply. Whereas fossil energy carriers typically have a high energy density, biomass in its raw form generally has a high moisture content, low energy and bulk density, and poor transferability characteristics.[1] Consequently, biomass transportation and handling can be a significant contributor to the overall cost of the production system, especially compared to energy carriers produced in fossil supply chains.[2] Whereas higher production scales allow for cost reductions due to economies of scale effects, it increases the need to mobilize biomass over larger distances and thus upstream transport cost.

Distributed supply chain configurations including pre-treatment options early in the supply chain based on drying or densification (e.g. chipping, pelletization, torrefaction, liquefaction) are often proposed to decrease the transportation cost and allow for further upscaling, especially when transport distances are high.[3–8] Although an intermediate conversion step adds capital expenditures (CAPEX) and operational expenditures (OPEX) to the overall costs, it may reduce transportation costs because the intermediate product, such as chips, (torrefied) pellets or a biocrude, has a higher energy and bulk density than biomass (see Figure 1).

The merit of distributed supply chains has been assessed using techno-economic analysis based on predefined pre-treatment technologies (e.g. chipping, pelletization, torrefaction, ammonia fiber expansion or pyrolysis).[3,5,7,9–12] Whereas techno-economic analyses can identify promising supply chain configurations based on case studies, the approach is unsuitable to find the optimal solution while simultaneously varying supply chain configuration, number of production units and plants, production location or production scale. Although optimization models are apt to do this, they are often used to optimize for number, location and scale[13–18]; only a few studies explicitly include the trade-off between centralized and distributed supply chain configurations[19,20].

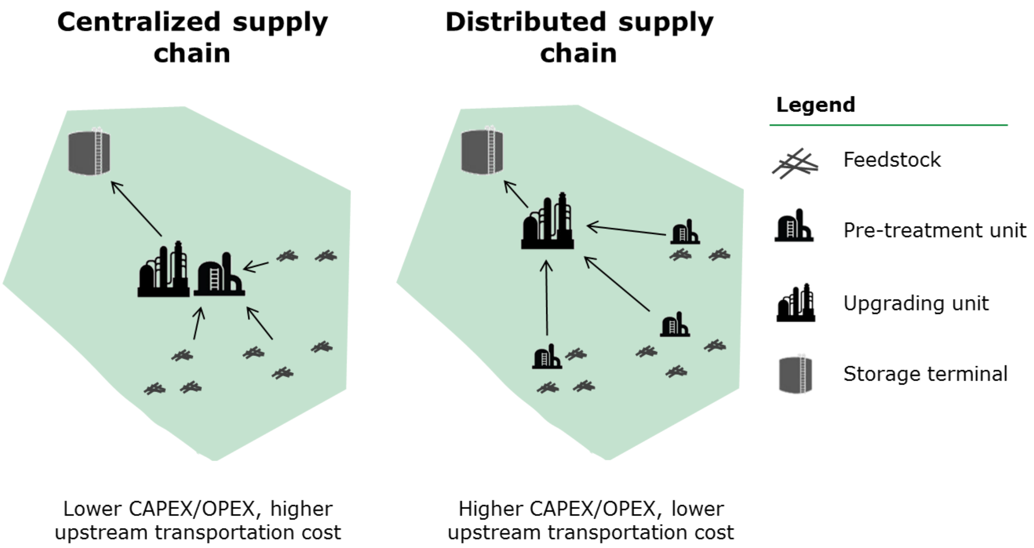


Figure 1. Centralized versus distributed supply chain.

As the merits of a distributed supply chain configuration are proposedly more profound in areas with high transportation costs and/or low biomass supply density, it seems essential to take into account the geospatial character of biomass supply, intermodality in transport networks, competing demand for biomass, and integration benefits with existing industries, all of which affect the biomass supply and/or transport costs. Whereas the first factor is generally included in optimization models, the influence of the latter three aspects on supply chain configuration is still poorly understood.

In this analysis we explore the preconditions under which distributed supply chain configurations are preferred over centralized supply chains, for the case of Sweden. The overall aim of the study is to identify cost efficient supply chain configurations for the production of drop-in biofuels from forest biomass using liquefaction technologies. We apply a spatially explicit modeling approach attempting to reflect local circumstances by including aforementioned factors, supplemented with detailed CAPEX scaling curves for biomass pre-treatment and upgrading to biofuels.

2 METHODS

2.1 GEOGRAPHICAL SCOPE

The case study is based on the introduction of additional forest-based biofuel production in Sweden. The Swedish forestry sector is a highly developed sector in which a large part of the biomass supply is already utilized. Sawlogs and pulpwood is 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).[21] Although there is considerable competing demand over biomass, the presence of industrial sites close to biomass supply and longstanding experience with biomass transport and conversion may offer distinct integration benefits which could stimulate the development of a biofuel sector in Sweden. As such, Sweden presents a suitable case study to explore the merits of distributed supply chain configurations.

2.2 SUPPLY CHAIN DESCRIPTION

The scope includes centralized and distributed biofuel supply chains from feedstock to blending terminal (

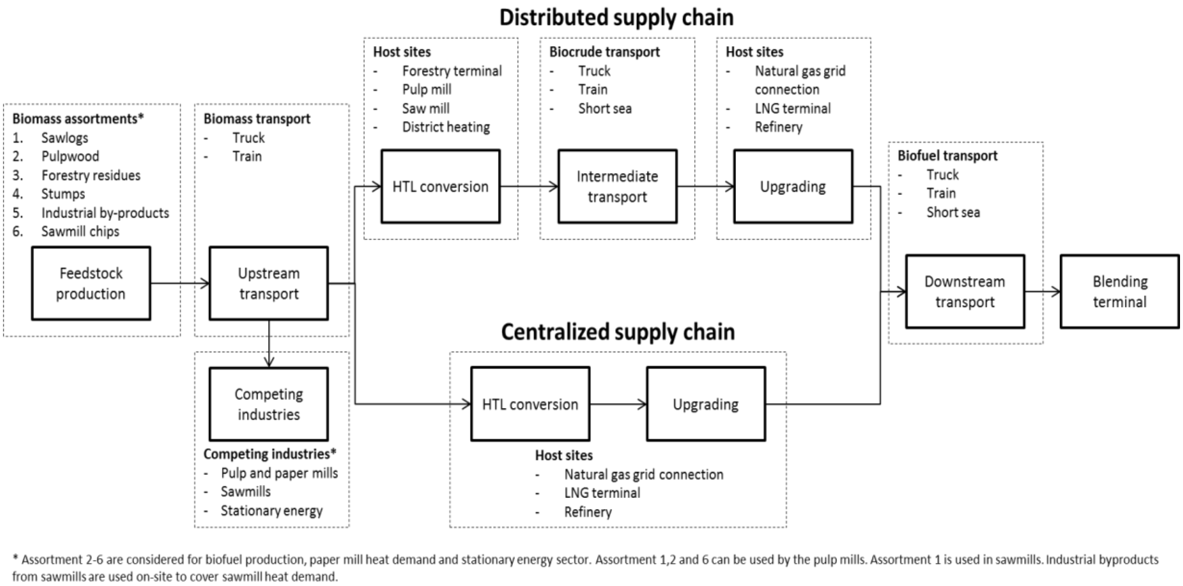
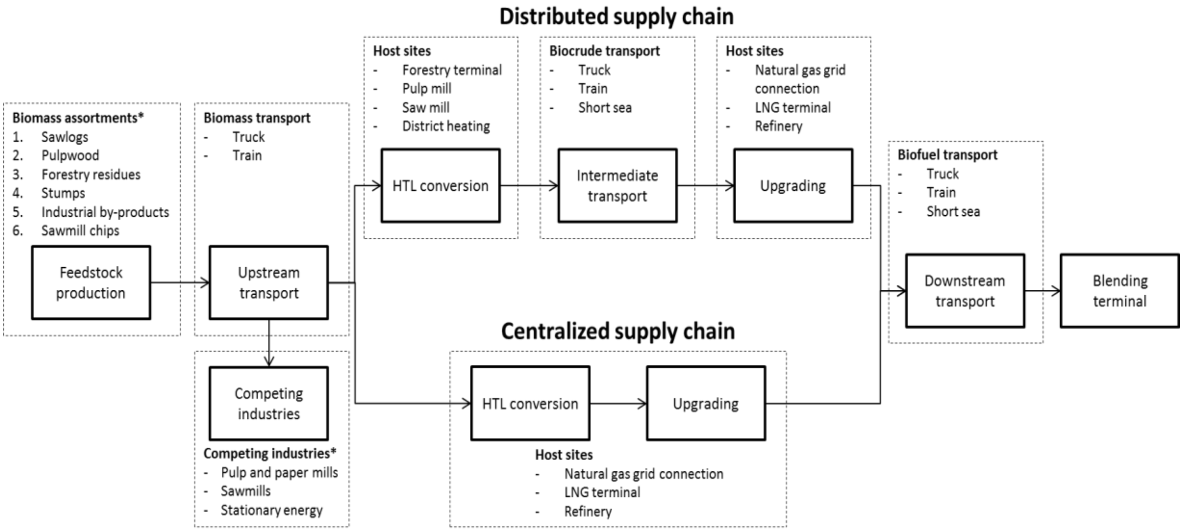


Figure 2). Feedstocks encompass both virgin feedstocks (sawlogs, pulpwood, primary forestry residues, stumps) and by-products from the forestry industry (sawmill chips and industrial by-products from sawmills (IBS) and pulp mills (IBP)). Biomass was assumed to be converted to biofuel using Hydrothermal Liquefaction (HTL). HTL produces a biocrude from biomass of higher quality than pyrolysis in terms of heating value, moisture content, oxygen content, and stability.[22, 23] The biocrude is consequently upgraded to gasoline, diesel, heavy oil and light ends by hydrotreating and hydrocracking. HTL was selected based on its ability to be used in a distributed supply chain configuration (the biocrude can be transported), promising techno-economic performance and integration opportunities with existing industries.[22–27] Spatially explicit biomass demand from sawmills, pulp and paper mills and the stationary energy sector (heat and power) are taken into account. Sawmills, pulp and paper mills, district heating systems, and forestry terminals constitute possible host sites for the HTL plants in the distributed supply chains. Possible host sites for

the biocrude upgrading include the natural gas grid, liquefied natural gas (LNG) terminals and refineries. In case of centralized supply chains HTL conversion also takes place at these sites. Potential integration benefits with host sites (e.g. heat sales, shared equipment or work force) were quantified and constrained based on production statistics of the host site. Truck, train and short sea transport were included for the transportation of biomass, biocrude and biofuel.



* Assortment 2-6 are considered for biofuel production, paper mill heat demand and stationary energy sector. Assortment 1,2 and 6 can be used by the pulp mills. Assortment 1 is used in sawmills. Industrial byproducts from sawmills are used on-site to cover sawmill heat demand.

Figure 2. Scope of the analysis.

2.3 MODELLING FRAMEWORK

A mixed integer linear programming (MILP) optimization model was adapted from Lin et al.[13] The model was written in the commercial modeling software GAMS using the solver CPLEX by ILOG. For a certain biofuel demand, the model optimized total system cost for one production year for a certain set of constraints. The total system costs were defined as the total 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 portion, and cost of conversion (CAPEX and OPEX). The current demand for biomass from competing industries was expressed explicitly in the model, instead of being subtracted from the total biomass supply. This means that the feedstock mix for e.g. competing industries may change, even though the total demand is still met. Constraints were imposed on biomass supply, maximum production capacity, and integration benefits. Model variables included number of production units, production capacity and location, material flows, supply chain configuration (centralized or distributed) and amount of heat transferred at integrated sites.

2.4 INPUT DATA

2.4.1 General assumptions

In general the units J or J/yr (with relevant prefixes) are used throughout this report to express energy amounts and flows, based on lower heating value (LHV). In certain places the corresponding values have also been given using Wh or W (with relevant prefixes).

A load factor of 90% was assumed, corresponding to an annual operating time of 7884 hours.

Monetary values were normalized to $€_{2015}$ using the yearly EU harmonized index of consumer prices.[28] Values in US$ were converted to € using the euro-dollar exchange rate for the respective year.[29] A similar approach was followed for the conversion of SEK to €.

2.4.2 Feedstock supply and price distribution

The total feedstock supply and cost distribution is shown in **Fel! Hittar inte referenskälla.**. A spatially explicit bottom-up approach was applied to define the harvesting costs and theoretical supply potential for sawlogs, pulpwood and forestry residues from final felling and thinning, as well as stumps from final felling.[16,30] 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.[30] The potentials for 'Current forestry management' reported by the Swedish Forestry Agency were used as a basis, with the potentials for harvesting residues and stumps adjusted for techno-economic restrictions.[31–33] The roadside biomass price was calibrated against bioenergy and stemwood price statistics.[34,35] Available by-product quantities are directly correlated to the forest industry production and were estimated based on production capacities of individual industries and generic relations for by-product yields.[36–41] No spatial variations have been assumed for the production cost of industrial by-products. Instead, generic costs have been assigned to the different by-product assortments.[42,43]

Table 1. Available quantities and price distribution of biomass assortments.

Biomass assortments	**Total supply**		**Price**			
	PJ/yr	TWh/yr	€/GJ		€/MWh	
			Average	Standard deviation	Average	Standard deviation
Sawlogs	321	89	5.96	0.44	21	1.6
Pulpwood	248	69	4.23	0.30	15	1.1
Forestry residues	111	31	4.18	0.45	15	1.6
Stumps	58	16	5.94	1.13	21	4.1
Sawmill chips	87	24	3.06	0	11	0
Industrial by-products from sawmills (IBS)	63	18	2.78	0	10	0
Industrial by-products from pulp mills (IBP)	5	1.4	2.78	0	10	0
Total	**893**	**248**				

2.4.3 Competing industrial biomass demand

Competing biomass demand from the pulp and paper mills, sawmills and stationary energy sector were considered spatially explicitly in the model (Table 2). The demands are described statically on an annual basis, based on current production and demand[39–41,44,45] Internal industrial heat demand was compiled from various sources[39,41,46], and can be met in the model by integration with an HTL plant or by using all or a share of the available industrial by-products in a combined heat and power plant or heat-only boiler station (Figure 3). Deficits are met by biomass imported to the industrial site.

Table 2. Biomass demand for competing industries and biofuel production. IBS = industrial by-products from sawmills, IBP = industrial by-products from pulp mills.

	Aggregated demand		**Biomass assortments**						
	PJ/yr	TWh/yr	Sawlogs	Pulpwood	Forestry residues	Stumps	Sawmill chips	IBS	IBP
Competing industry									
Sawmills (sawn products)	247	69	x						
Pulp mills (pulp)	304	84	x	x			x		
Stationary energy sector	103	29		x	x	x	x	x	x
Saw mills (heat demand)[0]	14	3.9						x	
Pulp mills (heat demand)[0]	28	7.8		x	x	x	x	x	x
Total	**696**	**193**							
Biofuel production	Variable			x	x	x	x	x	x

i) For sawmills and pulp mills, a boiler conversion efficiency of 80% and 90% (on energy basis) are used, respectively.

2.4.4 Host sites

It is assumed that HTL conversion can take place at the location of forestry terminals, pulp and paper mills, sawmills, and district heating networks, data for which were obtained from various sources.[39–41,44,46–48] Upgrading plants were assumed to be located near natural gas networks, LNG terminals and refineries.[49–51] Biofuel production using centralized supply chain configurations occurs strictly at upgrading locations. Petroleum storage and blending terminals were considered the end point of the supply chain.[51,52] Site-specific data on the location and integration possibilities (based on e.g. heat demand) of host sites are included in the model. Integration benefits include reduced CAPEX due to shared equipment, reduced OPEX (e.g. shared workforce) as well as availability of on-site feedstocks (i.e. sawmill chips, IBS and IBP) and steam sales[I] (Figure 3). At pulp and paper mills, sawmills, district heating networks and refineries (only in the centralized case) sales of excess steam are allowed until the steam demand of the host is satisfied. Purchase of natural gas or hydrogen from the natural gas grid, LNG terminals or refineries is included. The quantity of purchased gas at the latter two locations is constrained by the host's capacity.

[I] Heat sales and by-product purchases at pulp and paper mills and sawmills are considered an internal cash flow to the model. Whereas it impacts the biofuel production costs and costs for competing industries, it does not affect the total system costs as the internal cash flows cancel each other out. It does, however, impact the overall system cost indirectly since it liberates on-site low-cost IBP for biofuel production, and decreases biomass purchases or increases byproduct sales for sawmills and pulp and paper mills. At refineries, steam sales reduce the use of natural gas for steam production at the refinery. As such, they provide a cash flow from the refinery to the HTL plant, which results in cost reductions.

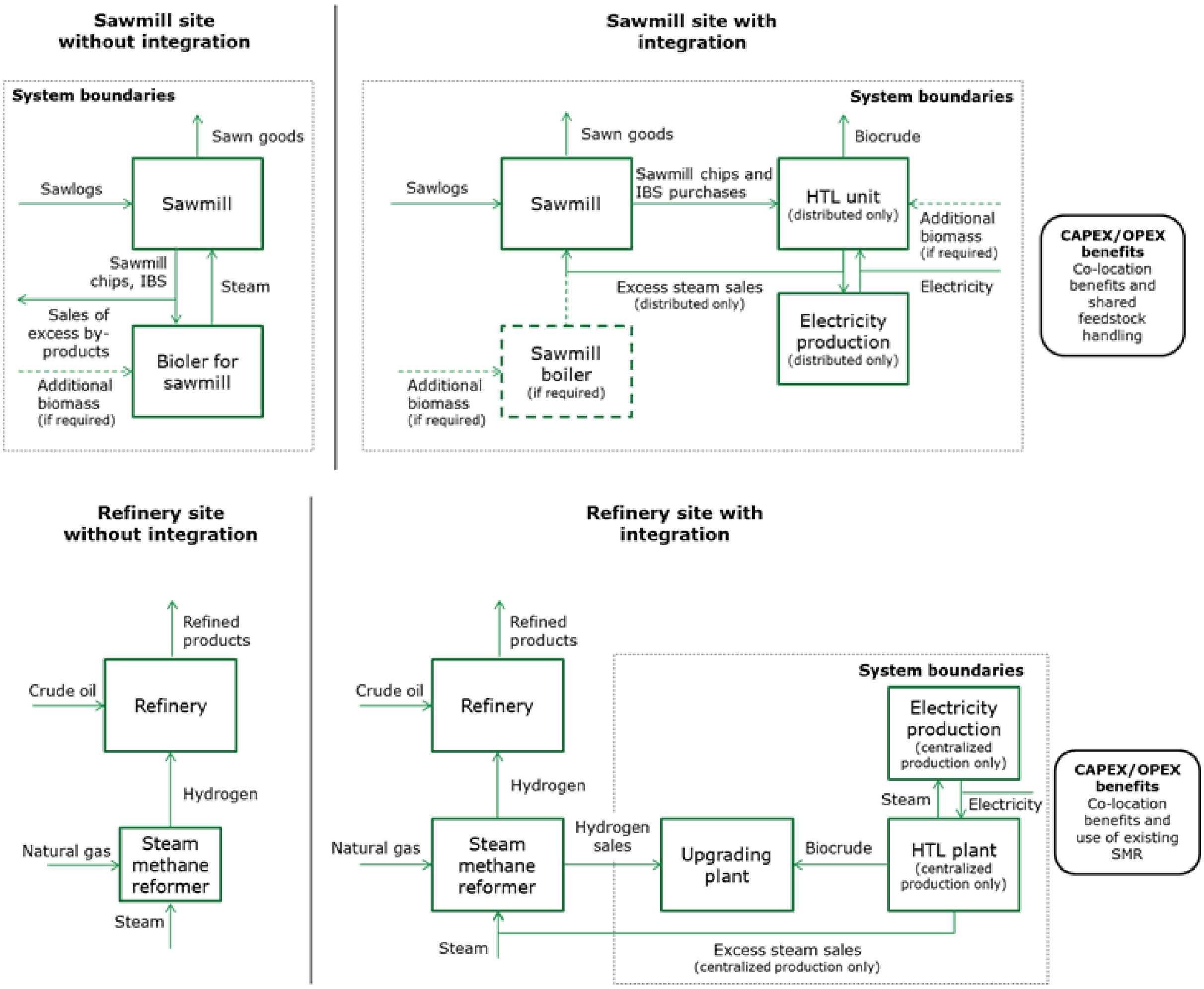


Figure 3. Example site layouts for a sawmill (top) and refinery (bottom) with and without integration with biofuel production. Integration with a pulp mill is similar to the example of a sawmill.

2.4.5 Techno-economic input data

Data for biofuel production through hydrothermal liquefaction (HTL) is based on a process design, mass and energy balances, and equipment costs provided by Zhu et al.[26] (goal case). The Standardized Cost Estimation (SCENT) method was used to calculate the production costs.[53] The general benefits of co-location (i.e. shared work force, buildings and service facilities) at a host site were calculated using the approach by De Jong et al.[24] The production costs for each production location are shown in Table 3. Due to the high degree of integration between the HTL and upgrading unit (i.e. exchange of offgases and shared utilities), the sum of the costs for a separate units (in case of a distributed supply chain) is larger than the total cost of a centralized facility, even when considering integration opportunities at host sites for HTL units such as shared equipment and workforce. However, the total costs in Table 3 do not include feedstock costs, upstream transport and potential steam sales. Furthermore, data is presented for a specific capacity; upscaling reduces the difference between distributed and centralized production, as the scale-dependent costs decrease with size.

The liquefaction process and the waste water treatment produce offgases which can be used to produce electricity and (excess) steam (distributed case and centralized refinery case) or to partially fuel the steam methane reformer (SMR) which produces hydrogen for the upgrading process (centralized natural gas and LNG terminal case). The excess steam can be exported to host industries.

Upgrading in the distributed supply chain thus requires additional natural gas input for hydrogen production, compared to the centralized cases which use HTL offgases. For co-location with refineries hydrogen is assumed to be bought from the refinery, hence eliminating the need for an SMR.

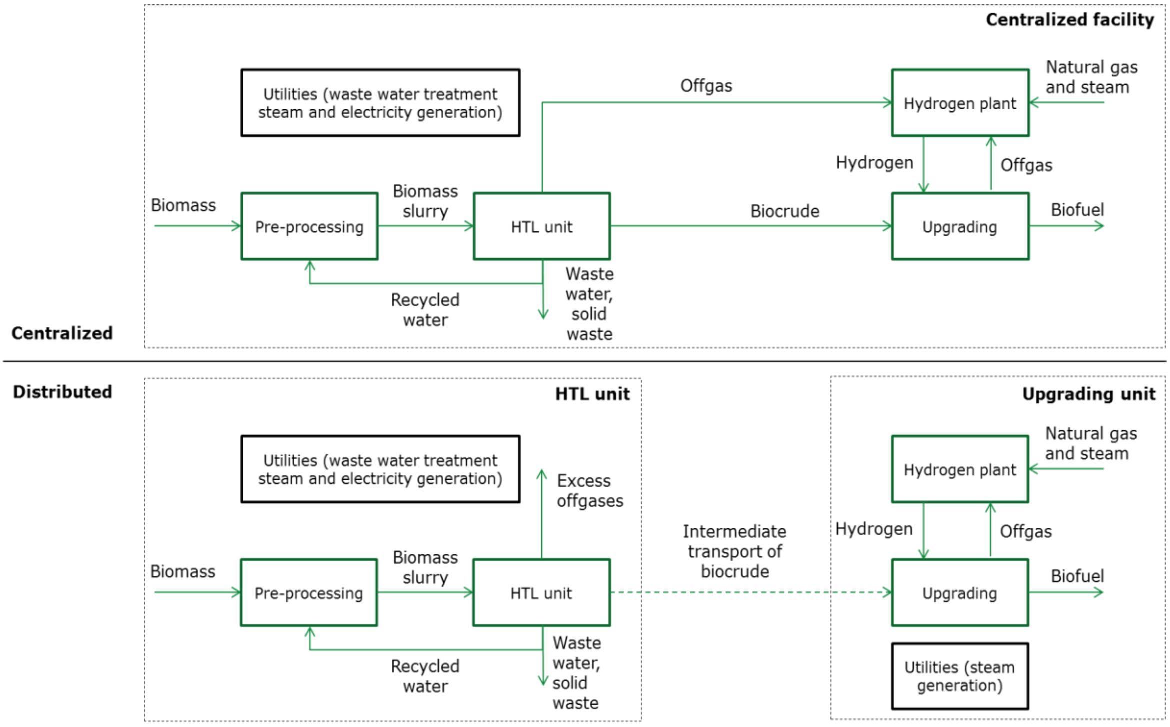


Figure 4. Process configuration for centralized and distributed production, adapted from Zhu et al.[26]

The scale-dependent behavior of conversion costs was approximated using the power law.[54] Scaling factors were employed on a process unit level (see Appendix A)[26,54,55], applying a maximum scale for the HTL reactor, SMR and hydrotreater. In practice this means that when the maximum scale for a particular unit is reached, the scaling curve for the units breaks down and multiple units will need to be built at a specific site. The maximum scales were based on previously mentioned limits for liquefaction units and reported scaling curves for SMRs and hydrotreaters.[22,54] Since MILP models can utilize linear equations only, the non-linear power law was approximated by a piecewise linear function[13], with the power function divided into three linear functions with breaks at the maximum capacity of a HTL reactor (2.75 PJ_{in}/yr or 97 MW) and SMR (39.3 PJ_{in}/yr or 1.4 GW) respectively. The maximum scale of production at one site was aligned with the maximum scale of a hydrotreater (73.1 PJ_{in}/yr, 61.2 PJ_{out}/yr or 2.6 GW_{in}, 2.2 GW_{out}), which is less than halve the size of a small refinery, such as the ST1 refinery in Gothenburg (174 PJ_{in}/yr or 6.1 GW).

Table 3. Biofuel production costs.

Cost item	**Unit**	**Distributed supply chain**							**Centralized supply chain**		
		HTL conversion Reference capacity: 2.3 PJ_{in} (81 MW_{in})				Upgrading Reference capacity: 1.8 PJ_{in} (63 MW_{in})			Conversion and upgrading Reference capacity: 2.3 PJ_{in} (81 MW_{in})		
Host site		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}	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}		0.10	0.10	0.10						0.09
Net electricity requirement	GJ/GJ_{out}	0.007	0.007	0.007	0.007	0.014	0.014	0.007	0.049	0.049	0.021
Natural gas requirement	kg/ GJ_{out}					3.33	3.33		1.22	1.22	
Hydrogen requirement	kg/ GJ_{out}							1.27			1.27
Total Purchased Equipment	M€	16.53	16.53	16.53	16.85	18.05	18.05	13.35	32.52	32.52	28.62
Total Capital Investment	M€	82.3	76.4	76.4	83.9	89.8	89.8	61.7	161.9	161.9	132.3
Annualized total Capital investment (CAPEX)	€/GJ_{out}	4.44	4.12	4.12	4.53	4.58	4.58	3.15	8.26	8.26	6.75
Operational expenditures (OPEX)[0]	€/GJ_{out}	6.31	5.83	5.83	6.39	6.23	6.23	6.37	11.24	11.24	11.68
Total production cost (OPEX + CAPEX)[0]	**€/GJ_{out}**	**10.7**	**10.0**	**10.0**	**10.9**	**10.8**	**10.8**	**9.5**	**19.5**	**19.5**	**18.4**
Scale-independent conversion costs	€/GJ_{out}	2.2	2.0	2.0	2.2	2.0	2.0	3.5	3.6	3.6	5.5
Scale-dependent conversion costs	€/GJ_{out}	8.5	7.9	7.9	8.7	8.8	8.8	6.0	15.9	15.9	13.0

i) Excluding feedstock costs, upstream transport cost and potential steam sales, but including hydrogen and natural gas costs.

2.4.6 *Transport cost*

Transport costs of solids (biomass) and liquids (biocrude and biofuel) were calculated with a geographically explicit intermodal transport model that runs in the Network Analyst extension of the commercial geographic information system (GIS) software ArcGIS by ESRI. The geodatabase of the transport model consisted of transport network layers for road[56], rail[57] and short sea shipping[58]. Swedish forest biomass terminals were used as intermodal terminals.[59,60] 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 (origins) and demand nodes (destinations), based on mode-specific parameters shown in Table 4 (based on e.g. fuel consumption and prices, variable cost, fixed cost, see Appendix A).

Table 4. Transport cost parameters (see Appendix A for additional information).

Parameter	**Unit**	**Road[0]**	**Rail[0]**	**Short Sea Shipping[0,0]**
Transport cost				
Chips	€/GJkm (€/tkm)	0.0097 (0.162)	0.0008 (0.013)	0.0004 (0.006)
IBP	€/GJkm (€/tkm)	0.0097 (0.162)	0.0008 (0.013)	0.0004 (0.006)
Sawlogs and pulpwood	€/GJkm (€/tkm)	0.0097 (0.162)	0.0008 (0.013)	0.0004 (0.006)
Biocrude	€/GJkm (€/tkm)	0.005 (0.162)	0.0002 (0.008)	0.0002 (0.007)
Biofuels	€/GJkm (€/tkm)	0.004 (0.162)	0.0002 (0.008)	0.0002 (0.007)
Loading/unloading[0]				
Chips	€/GJ (€/t)	0.31 (5.11)	0.53 (8.93)	0.29 (4.85)
IBP	€/GJ (€/t)	0.16 (2.71)	0.53 (8.93)	0.39 (6.48)
Sawlogs and pulpwood	€/GJ (€/t)	0.12 (1.99)	0.48 (8.04)	0.39 (6.48)
Biocrude	€/GJ (€/t)	0.04 (1.39)	0.1 (3.26)	0.35 (11.53)
Biofuels	€/GJ (€/t)	0.03 (1.31)	0.08 (3.08)	0.27 (10.89)

i) Based on Athanassiadis et al. (2009) [60], transport of wood chips. Corrected for inflation and converted to € (SEK_{2015}/SEK_{2008} = 1.08, $SEK_{2015}/€_{2015}$ = 0.11). Liquid bulk assumed similar to dry bulk. Diesel cost: 0.7 €/L, excise duty: 0.46 €/L, VAT: 25%.

ii) Dry bulk rail freight rates and load based on the Heuristics Intermodal Transport Model Calculation System (Floden 2011) [61], Medium case, electric engine. Corrected for inflation and converted to € (SEK_{2015}/SEK_{2011} = 1.04, SEK2015/€2015 = 0.11) Liquid bulk calculated from dry bulk and NEA (2004) [62]. Electricity price: 0.075 €/kWh.

iii) Short sea shipping > 7500 dwt dry and wet bulk international/continental. Based on NEA (2004) [62], corrected for inflation (€2015/€2004 = 1.24). Price fuel oil 694 €/t.

iv) Loading and unloading cost are assumed to be similar.

2.5 BASE CASE AND ALTERNATIVE CASES

The model is evaluated for a range of total biofuel demand scenarios for the case of Sweden (1, 5, 10, 15, 30, 50, 75, 100, and 150 PJ/y)[II] to evaluate the resulting supply chain configurations at various scales. The Base case solution for each biofuel scenario is compared to alternative cases to identify key determinants regarding supply chain design decisions:

- **Base case**. The Base case run includes competing demand, both supply chain configurations, integration with host industries, and intermodal transport.
- **Road transport only**. In this case only road transportation (by truck) was allowed for solid biomass and biocrude. Downstream logistics of refined biofuels could still occur through train or short sea shipping.
- **No integration benefits.** In this case integration benefits (steam sales, hydrogen exchange, OPEX/CAPEX reductions) were disabled. OPEX and CAPEX profiles from district heating sites (HTL conversion), LNG terminals (upgrading) and LNG terminals (centralized facilities) were adopted for other host sites. Exchange of industrial by-products and sawmill chips was still allowed.
- **Low biomass supply.** Total biomass supply of virgin feedstocks (i.e. stumps, forestry residues, sawlogs, and pulpwood) was diminished by 10%.
- **High competing demand.** Competing demand as well as the production of industrial by-products was increased by 10%.
- **Centralized supply chain configurations only.** Only centralized supply chain configurations were allowed in the model solution.
- **Reduced maximum capacity.** The maximum production capacity per site was set to one-tenth of the initial value (i.e. 7.31 PJ_{in}/yr).

[II] 0.28-42 TWh/yr. This can be compared to current total fuel consumption for road transport in Sweden, which amounts to approximately 320 PJ/yr (90 TWh/yr).

3 RESULTS

Figure 5 gives an overview of the results for each case considered. Each run will be discussed in the following sections. Although the model optimizes total system costs, we mainly focus on the average biofuel production costs, which are computed by dividing the total biofuel production costs (total system cost minus the costs of competing industries) by the total biofuel production. The costs of competing industries was monitored to check whether decreases in biofuel production costs did not instigate an anomalous rise in feedstock procurement costs for competing industries due to feedstock reallocation.

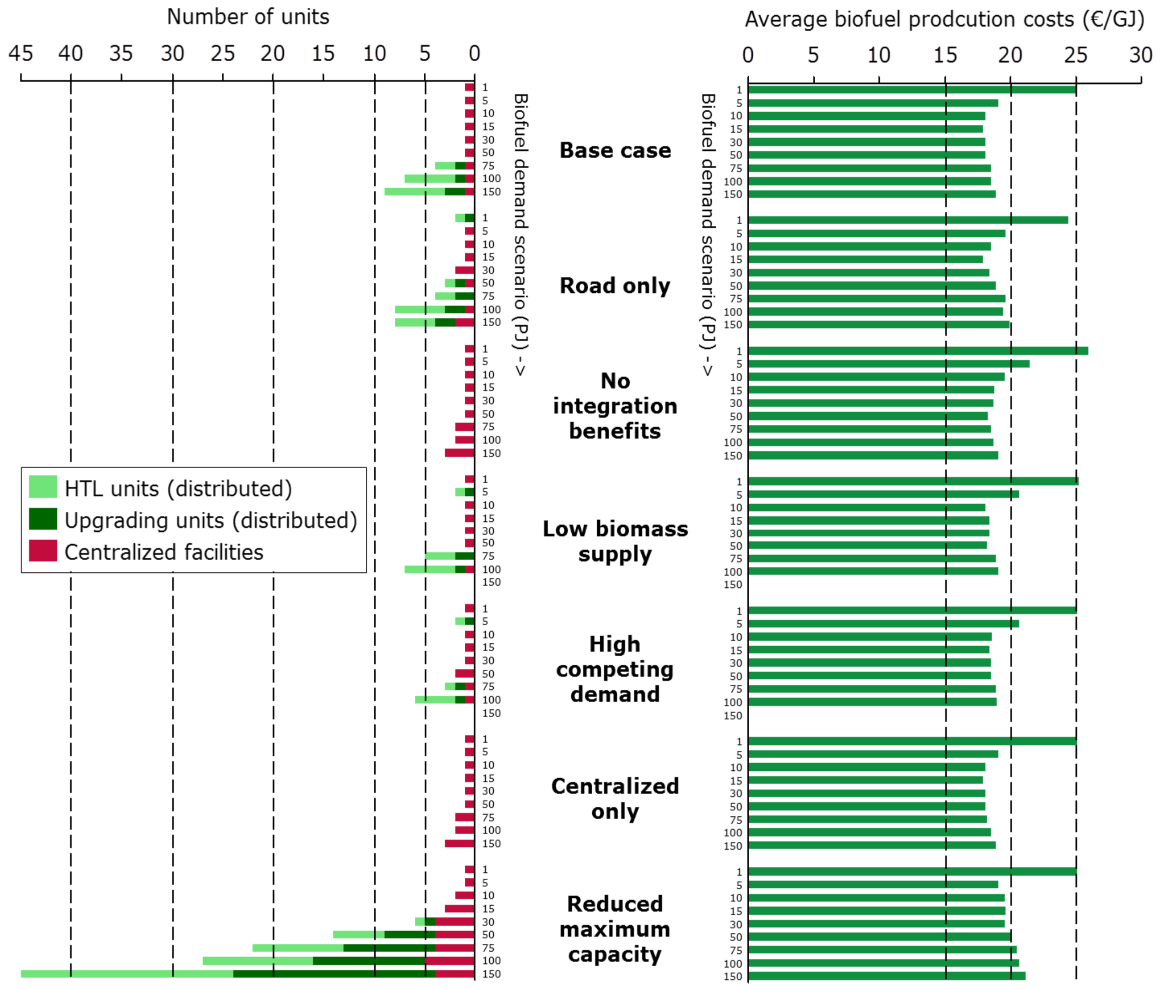


Figure 5. An overview of number of plants and average biofuel production costs for different biofuel demand scenarios. The biofuel production costs can be compared to current (2015) fossil fuel pump prices in Sweden of 14-15 €/GJ (taxes excluded).[63]

3.1 BASE CASE

Figure 6 shows the cost breakdown for the Base case. The figure describes a sharp downward cost trend at first which is counteracted by a slight upward tail after 15 PJ (4 TWh). The initial cost decrease is mainly due to a decline in CAPEX; the upward trend in the tail is caused by increased feedstock costs and upstream transportation costs. The contribution of downstream transport costs is marginal and is roughly similar in all biofuel demand scenarios. Even though the lowest production cost can be observed at 15 PJ, increasing the biofuel demand by one order of magnitude increases the cost by 0.9 €/GJ. The contribution of upstream transport costs never exceeds 10%. Intermediate transport is only added in solutions containing distributed supply chain configurations and contributes less than 2% to the total biofuel production costs. The cost of feedstock procurement for sawmills and pulp mills are hardly affected in the Base case; they witness a cost rise of 2% and 8% in the highest demand scenario relative to a reference scenario with zero biofuel demand. On the other hand, feedstock procurement costs for pulp mills (to cover heat demand) and district heating, which use the same low-value feedstocks as biofuel production, rise by 33% and 10%, respectively, in the highest demand scenario due to feedstock reallocation.

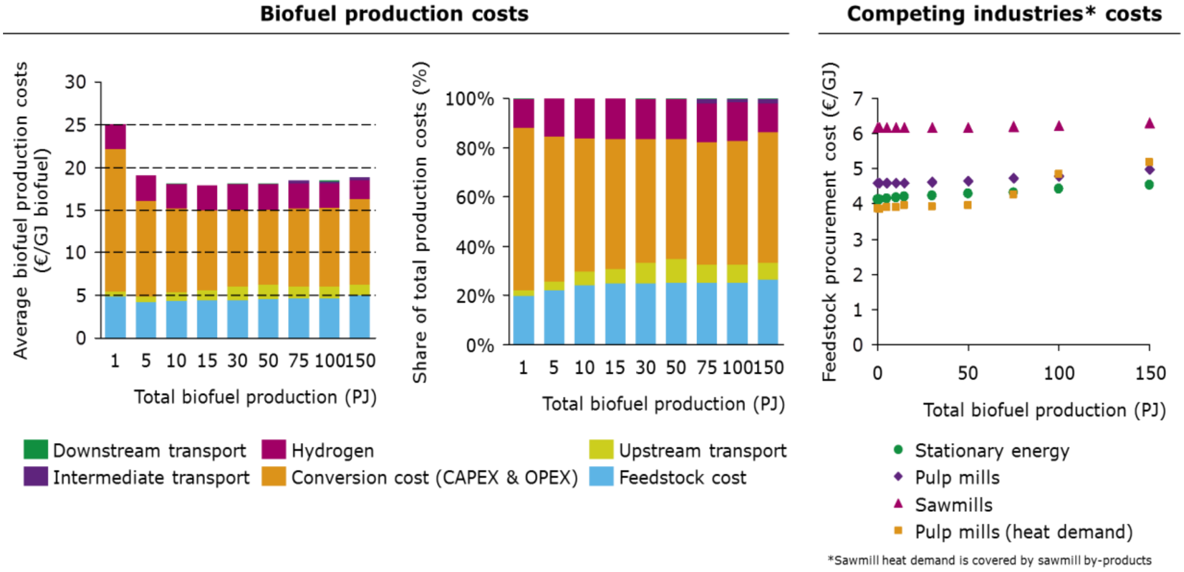


Figure 6. The biofuel production costs and procurement cost (i.e. feedstock and upstream transport costs) for competing industries for the Base case.

The Base case shows minimum costs (17.9 €/GJ) at around 15 PJ, indicating a cost floor for biofuel production through HTL which cannot be lowered any further through integration benefits, upscaling or alternative supply chain configurations. Whereas scaling benefits are significant at smaller scales, the production costs remain relatively stable after 5 PJ. Between 5 and 50 PJ the benefits of economies of scale and the rise in transport cost and feedstock cost are in balance. After 50 PJ (14 TWh) additional rather than bigger plants are built. As a result, the CAPEX rises slightly while transport costs decrease. However, the upward tail is mainly caused by higher feedstock costs, which is explained by the fact that less suitable sites are available as the biofuel demand increases. When comparing the lowest and highest biofuel demand scenario only modest increases in feedstock cost (0.06 €/GJ) and upstream transport cost (0.7 €/GJ) are observed.

At scales below 75 PJ (21 TWh) a centralized supply chain configuration prevails, since it offers the lowest production costs. After 100 PJ (28 TWh) distributed supply chains are introduced in the model solution, even though a distributed supply chain entails higher conversion costs than centralized production at similar scale. In the highest biofuel demand scenario, almost 80% of the biofuel volumes are supplied through distributed supply chains. Distributed supply chains are hence used to unlock more widely dispersed biomass supply locations and flatten the upward tail in the curve. HTL conversion plants are generally built integrated with sawmills or pulp mills as they provide the greatest integration benefits.

The number of production plants increases gradually with biofuel demand; from one centralized facility in the range 1-50 PJ, to nine production plants at 150 PJ (one centralized facility, two upgrading facilities, and six HTL plants). All demand scenarios show one centralized facility, reaching a maximum size in the 50 PJ/yr scenario. Almost all of the production facilities are built integrated with a refinery, as this host site shows the lowest production costs (see Table 3). The six HTL plants in the highest demand scenario vary greatly in size; the smallest has a size of 0.83 PJ_{in}/yr (29 MW), the largest is of the maximum capacity (73 PJ_{in}/yr, 2.6 GW). The input capacity of the upgrading plants in the highest demand scenario is of the same order (33 and 58 PJ_{in}/yr, 1.2 and 2.0 GW).

3.2 ROAD ONLY CASE

Relative to the Base case, the Road only case is characterized by higher overall production costs (up to 6%) due to higher feedstock and intermediate transport cost, but roughly similar upstream transport costs. The higher cost of transport in the Road only case, especially over long distance, causes a switch to close by, but more expensive feedstocks (e.g. stumps). On the one hand the increase of intermediate transport cost favors the construction of centralized facilities. On the other hand distributed supply chain configurations can be used to access lower-cost feedstocks. As the latter effect has a higher impact, the model results show that the distributed supply chains are introduced at lower biofuel demands (at 1 PJ and at >30 PJ) than in the Base case. Also, the introduction of distributed supply chains is marked by a drop in upstream transport costs.

Remarkably, the lowest biofuel scenario favors a distributed supply chain configuration. As upgrading at refinery sites provides a significant cost drop relative to other upgrading sites due to integration benefits (especially at small scales), refinery sites are chosen in the majority of the investigated cases at small scale. The preference for distributed supply chains can be explained by the fact that Swedish refineries are not well situated in terms of biomass availability (partially due to high competing demand nearby), so they need intermodal transport to flatten the cost-supply curve. Furthermore, pulp mills and sawmills provide attractive integration benefits (particularly on-site feedstock availability and steam sales opportunity), but only for small scale conversion units: sawmills or pulp mills provide 5.8 and 1.4 PJ/yr (1.6 and 0.39 TWh/yr) of by-products, respectively, at maximum. At higher scales these effects are smoothened out due to economies of scale and the limited impact of integration with sawmills and pulp mills.

3.3 NO INTEGRATION CASE

The No integration case shows higher production costs than the Base case, predominantly due to higher conversion costs. The difference compared to the Base case is more profound at smaller scales, as the conversion costs make up a higher share of the total production cost. Due to the high contribution of conversion costs to the total cost, this case demonstrates a preference for large scale centralized production for all biofuel demands. In the highest demand scenario three large scale facilities (40-60 PJ_{out}/yr or 1.4-2.1 GW) are built. As integration benefits are particularly applicable for locations utilized by distributed supply chain locations (e.g. pulp mills, sawmills), the benefits of distributed supply chains at higher biofuel demands (i.e. lower feedstock cost and upstream transport cost) that were observed in the Base case, are thus negated by the higher conversion costs in the No integration case. Whereas the Base case showed a preference for refinery locations, the results for this case strictly include locations with a connection to the natural gas grid or LNG terminals. This shows that the integration benefits for refineries (see Table 3) are sufficiently high to shift the preference from locations which may be better situated in terms of biomass supply, like locations with a natural gas grid connection or LNG terminals.

3.4 LOW BIOMASS AND HIGH COMPETING DEMAND CASE

These cases are discussed together as they both decrease the remaining biomass potential after the demand from competing industries is satisfied. In the Low biomass supply case the remaining biomass supply is more diluted than in the High competing demand case. In the High competing demand case, however, biomass supply becomes more dispersed. Both cases lead to a larger collection radius for competing industries, smaller areas of underutilized biomass supply and higher upstream transport costs. The latter case, however, also leads to a larger accumulation of by-products at the potential host sites. Both effects proposedly would increase the preference for distributed supply chain configuration. The cases were run up to 100 PJ only, as there was no feasible solution for 150 PJ due to biomass supply constraints.

Both cases show a preference for distributed supply chain configurations at 5 PJ, which is due to the same reason as the occurrence of such configurations in the Road only case (albeit at a different biofuel demand): Swedish refineries are not situated well in terms of biomass availability, but provide great integration benefits. Unlike what the abovementioned dynamics suggest, distributed supply chains are introduced at the same biofuel demand as in the Base case. Furthermore, neither the feedstock procurement costs nor the amount and type of plants built vary significantly between these cases and the Base case. The only difference is related to feedstock and upstream costs which increase in these cases because more expensive feedstocks are used (particularly stumps) and feedstock is transported over larger distances. As biomass supply is particularly under additional stress near clusters of competing demand in these cases, host sites for distributed supply chain configurations are also associated with increased transport costs and/or feedstock costs. Hence, decreasing the biomass supply or increasing the competing demand was not found to give rise to a stronger preference for distributed supply chain configurations.

3.5 CENTRALIZED ONLY CASE

The Centralized only case shows a slightly more rapid increase in the upstream transport costs compared to the Base case. However, as the increase is till only marginal (1.2 €/GJ between 1 and 50 PJ_{out}/yr), economies of scale dominate the production costs. This is illustrated by the fact that the model introduces multiple facilities at a biofuel demand only beyond the maximum allowed production capacity at one site (61.2 PJ_{out}/yr). At the highest biofuel demand scenario only three facilities are built, compared to nine in the Base case. The preference for centralized supply chain relies heavily on the dominance of economies of scale. Distributed supply chains are associated with smaller conversion plants (Base case), and although a smaller scale decreases upstream transport cost, it also increases the conversion costs. The total production costs at higher scales are almost similar to the costs found in the Base case, which indicate that there is no strong preference for distributed supply chains, even at higher biofuel demands.

3.6 REDUCED MAXIMUM CAPACITY CASE

When maximum capacity is confined, the model results show more plants being built, a stronger preference for distributed supply chain configurations and higher average production costs (about 1.4-2.3 €/GJ). The increase in average production costs is a direct result of the construction of more (and thus smaller) plants. Although conversion costs remain constant in higher biofuel demand scenarios, upstream transport cost decline as a result of small-scale production. The upward tail at higher biofuel demand scenarios is mainly caused by increasing feedstock costs; upstream transport costs show a decreasing trend as distributed supply chain configurations are introduced.

This case illustrates that when the benefits of economies of scale are constrained, the dominance of centralized supply chains already fades at 30 PJ/yr (8 TWh/yr). In the highest biofuel demand scenario 83% of the biofuel is supplied through distributed supply chains. Although centralized facilities are still part of the solution at higher biofuel demand, there are limited centralized locations which are situated well enough to be able to compete with distributed supply chains, which may be situated closer to cheaper feedstock supply areas.

4 DISCUSSION

The Base case results show a preference for distributed supply chain configurations only after 75 PJ_{out}/yr (21 TWh_{out}/yr). Other studies comparing centralized and distributed supply chain configurations, albeit using techno-economic analysis, found a similar transition point between roughly 30-60 PJ_{out}/yr (8-17 TWh_{out}/yr) .[10,12] Relative to centralized supply chain configurations, distributed supply chains are associated with lower upstream transport costs, but higher conversion costs and (negligible) additional costs due to intermediate transport. As the cost of feedstock and upstream transport grows only gradually with rising biofuel demand, the benefits of distributed production are generally offset by its higher conversion costs, especially at lower biofuel demands. The preference for centralized supply chains relies heavily on economies of scale; when the maximum capacity is constrained a trend towards distributed production becomes visible.

The impact of economies of scale is highly dependent on the scaling factor and assumed maximum capacity. While production scales beyond 20 PJ_{in}/yr (630 MW_{in}) dominate model solutions at higher biofuel production scales, the technical feasibility and the economic benefits of upscaling have yet to be confirmed. As comparison, the capacity of the largest Swedish pulp mill corresponds to roughly 20 PJ_{in}/yr (630 MW_{in}); the largest existing lignocellulosic ethanol plants are even smaller (~5 PJ_{in}/yr, 160 MW_{in}).[64] HTL is still in the early demonstration phase.[23,65] The Reduced maximum capacity case (constraining capacity to 7.31 PJ_{in}/yr or 232 MW_{in}) shows that limits on the benefits of economies of scale may particularly increase the value of distributed configurations.

The additional conversion costs of distributed supply chains are partly due to the lost synergies (mainly offgas integration and shared utilities) between the pre-treatment process and the upgrading process, thus specific to the study scope. However, as other pre-treatment processes such as pelletization, torrefaction also incur additional cost 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 marginally with scale. Furthermore, the other part of the cost increase is caused by the fact that distributed supply chains are often associated with smaller facilities. While this causes decreased upstream transport costs, it increases the capital intensity of the supply chain.

In the literature, the merits of distributed supply chains have mainly been identified for supply chains in which the location of biomass supply and end use are fixed and far apart. For example in the case of electricity generation in Europe using US (torrefied/pelletized) biomass[3,5,7] it has been shown that distributed supply chains may unlock areas further away which have significantly lower feedstock costs, as long as the lower feedstock costs and decrease in transportation costs justify the additional investments of a pre-processing unit. When cost-supply curves are too shallow (like in this case study, especially with intermodal transport included), distributed configurations start to become interesting only when the most suitable production locations are taken, when the additional conversion costs in distributed relative to centralized supply chains are marginal, or when very high total biofuel scales are targeted.

The performance of distributed supply chains may improve for host sites at which additional benefits may be achieved through site-specific integration (bolt-on solutions) or geographies without intermodal transport infrastructure. Nonetheless, the results show that centralized supply chain configurations always prevail at lower biofuel demands for all studied cases (with some exceptions due to site-specific circumstances). As the development of biofuel capacity generally sprouts from bottom-up action of single actors, it is unlikely that distributed supply chain configurations will be preferred by early movers, especially because the biofuel production capacities at which distributed supply chains are introduced (>50 PJ_{out}/yr or 14 TWh_{out}/yr) are currently unprecedented for single production facilities. However, solutions at higher biofuel demand scenarios (which may represent more mature biofuel systems) do include distributed supply chain configurations. Hence, the introduction of distributed supply chains may provide benefits as the biomass resource base becomes fully utilized.

Project developers should not discard distributed supply chains altogether as they provide distinct benefits in some cases. A more profound preference for a distributed configuration may emerge for supply chains whose cost profile shows a lower share of conversion cost (and hence less benefits of economies of scale), lower additional conversion costs for distributed relative to centralized configurations, a steeper feedstock cost-supply curve or a greater differential between the cost of transportation of biomass and the intermediate product. In addition, 'soft' benefits at host sites, such as experience with biomass handling, safety aspects, strategic interest to produce bioenergy or existing feedstock contracts may justify the cost premium for a distributed supply chain design. For instance, for demonstration units an incubator environment may be more important than optimal cost performance. Additionally, some host sites, e.g. refineries, may not be willing to take in untreated biomass directly from the forest to co-produce biofuels, due to lack of experience in handling biomass or to safety issues. Then distributed supply chains, where the biomass is pre-treated at host sites with experience and infrastructure for biomass handling (pulp mills or sawmills) to a feedstock more similar to crude oil (biocrude), or another actor taking responsibility for the pre-treatment of biomass but located adjacent to the refinery, could be preferred.[11]

The model contains a relatively high degree of geospatially 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, 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 favoring large-scale conversion especially near ports. As the additional conversion cost of distributed relative to centralized configurations due to loss of synergies between the HTL and upgrading plant is decisive for the trade-off between both configurations, more detailed quantification is recommended. Whereas integration benefits between biofuel production and existing industries were constrained on a site-specific level, the type and quantification of integration benefits was generalized for each type of production location. 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. On the other hand, the site layout, strategic interests or safety issues might impede integration.

5 CONCLUSIONS

Distributed supply chain configurations may decrease upstream transport cost and unlock areas of cheaper feedstock supplies. However, in a region with shallow feedstock cost-supply curves (like the current study area), the benefits are generally outweighed by additional costs for conversion and intermediate transportation, especially at smaller plant scales (<75 PJ_{out}/yr). Below this scale centralized supply chain configurations yield lower biofuel production costs.

Distributed supply chains may show better performance in specific circumstances in which demand and supply are far apart, additional conversion costs can be mitigated (by e.g. bolt-on solutions), feedstock cost-supply curves are steep or high production scales are targeted. In addition, distributed supply chains provide a cost-effective solution when approaching the maximum utilization of the biomass resource base. As such, multi-step optimization could be used in future research to explore different growth strategies and identify lock-in effects, taking into account time-dependent variability in, for example, competing demand and feedstock availability.

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7 APPENDIX A - SUPPLEMENTARY MATERIAL

BIOFUEL PRODUCTION COSTS INPUT DATA

Cost item	**Unit**	**Distributed supply chain**							**Centralized supply chain**			**Scaling factor**	**Source**
		HTL conversion Reference capacity: 2.3 PJ_{in} (81 MW_{in})				Upgrading Reference capacity: 1.8 PJ_{in} (63 MW_{in})			Conversion and upgrading Reference capacity: 2.3 PJ_{in} (81 MW_{in})				
Host site		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		
Production data													
Yield	GJ_{out}/GJ_{in}	0.79	0.79	0.79	0.79	1.06	1.06	1.06	0.84	0.84	0.84		[26]
Electricity production[i]	GJ/GJ_o	0.065	0.065	0.065	0.065				0.034	0.034	0.061		[22,26]
Electricity consumption[i]	GJ/GJ_{in}	0.072	0.072	0.072	0.072	0.014	0.014	0.007	0.083	0.083	0.083		[22,26]
Net electricity requirement	GJ/GJ_{in}	0.007	0.007	0.007	0.007	0.014	0.014	0.007	0.049	0.049	0.021		
Natural gas requirement	kg/ GJ_{out}					3.33	3.33		1.22	1.22			
Hydrogen requirement	kg/ GJ_{out}							1.27			1.27		
Steam production[i]	GJ/GJ_{put}		0.10	0.10	0.10						0.09		[22,26]
CAPEX													
Feedstock handling	M€	0.29	0.29	0.29	0.59				0.59	0.59	0.59	0.77	[55]
Biomass conditioning	M€	3.59	3.59	3.59	3.59				3.59	3.59	3.59	0.70	[26]
HTL reactor	M€	6.82	6.82	6.82	6.82				6.82	6.82	6.82	0.70	
Hydrotreater	M€					8.86	8.86	8.86	8.86	8.86	8.86	0.60	
Hydrocracker	M€					3.28	3.28	3.28	3.28	3.28	3.28	0.60	
Hydrogen plant	M€					3.55	3.55		3.55	3.55		0.79	
Utilities[i, v]	M€	4.32	4.32	4.32	4.32	0.72	0.72		2.88	2.88	2.88	0.70	
Missing equipment (10%)	M€	1.50	1.50	1.50	1.53	1.64	1.64	1.21	2.96	2.96	2.60		
Total purchased equipment cost (TPEC)	M€	16.53	16.53	16.53	16.85	18.05	18.05	13.35	32.52	32.52	28.62		
Lang factor[ii]		4.98	4.62	4.62	4.98	4.98	4.98	4.62	4.98	4.98	4.62		[24]
Total capital investment (TCI)	M€	82.3	76.4	76.4	83.9	89.8	89.8	61.7	161.9	161.9	132.3		

Total CAPEX[iv]	€/GJ$_{out}$	4.44	4.12	4.12	4.53	4.58	4.58	3.15	8.26	8.26	6.75		
Cost item	**Unit**	**Distributed supply chain**							**Centralized supply chain**			**Scaling factor**	**Source**
		HTL conversion Reference capacity: 2.3 PJ$_{in}$ (81 MW$_{in}$)				Upgrading Reference capacity: 1.8 PJ$_{in}$ (63 MW$_{in}$)			Conversion and upgrading Reference capacity: 2.3 PJ$_{in}$ (81 MW$_{in}$)				
Host site		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		
OPEX													
Electricity[i,v]	€/GJ$_{out}$	0.09	0.09	0.09	0.09	0.17	0.17	0.09	0.59	0.59	0.26		26,66
Catalyst and chemicals[v]	€/GJ$_{out}$	0.25	0.25	0.25	0.25	0.28	0.28	0.28	0.51	0.51	0.51		26
Waste disposal[v]	€/GJ$_{out}$	1.34	1.34	1.34	1.34				1.26	1.26	1.26		26
Labor cost[vii]	€/GJ$_{out}$	0.43	0.25	0.25	0.43	0.26	0.26	0.15	0.65	0.65	0.38		24,53
Other[ix]	€/GJ$_{out}$	0.12	0.11	0.11	0.12	0.04	0.04	0.03	0.17	0.17	0.13		24,53
Hydrogen[vi]	€/GJ$_{out}$							2.92			2.92		
Natural gas[vi]	€/GJ$_{out}$					1.26	1.26		0.46	0.46			
CAPEX-dependent OPEX[viii]	€/GJ$_{out}$	4.09	3.80	3.80	4.17	4.22	4.22	2.90	7.61	7.61	6.22		24,53
Total OPEX	€/GJ$_{out}$	6.31	5.83	5.83	6.39	6.23	6.23	6.37	11.24	11.24	11.68		
Total production cost (OPEX + CAPEX)	€/GJ$_{out}$	10.7	10.0	10.0	10.9	10.8	10.8	9.5	19.5	19.5	18.4		
Scale-independent production costs	€/GJ$_{out}$	2.2	2.0	2.0	2.2	2.0	2.0	3.5	3.6	3.6	5.5		26
Scale-dependent production costs	€/GJ$_{out}$	8.5	7.9	7.9	8.7	8.8	8.8	6.0	15.9	15.9	13.0		

i. In the reference study, which is based on a centralized supply chain, offgases from the HTL process are used as a feed for hydrogen production and anaerobic digestion (AD) is used to produce steam for electricity production (11 MW @ 2000 t biomass input/day) and heating the HTL unit, reformer and upgrading areas.[26] When the HTL conversion and upgrading are disconnected, HTL and AD offgases can be fully utilized to produce electricity and heat, which is both used to heat the process and export to host industries. Similar to the reference study, it is assumed for forestry terminals, PPM, sawmills, district heating (all distributed) and refineries (centralized only) that the AD offgas can be utilized to heat the HTL process and generate 11 MW of electricity. Based on the HTL offgas composition reported in Zhu et al.[26] and an assumed conversion rate to electricity of 30%, electricity generation from HTL offgases was approximated to be 8.9 MW. Furthermore, it was assumed that 1.5 units of exportable heat are produced per unit of electricity. Hence, for a reference HTL plant of 2000 t biomass input/day we assume 19.9 MW of electricity generation and 29.9 MW of exportable heat. As the offgases are also not used at the refinery sites (centralized supply chain design), increased electricity generation (19.9 MW) is also assumed here. Electricity consumption is distributed over the HTL conversion (22.2 MW) and upgrading (4.6 MW) according to the OPEX split reported in Tews et al.[22] (see also note v). Electricity consumption is assumed to be similar to the reference study. We assume the electricity consumption for the upgrading plant remains the same

ii. The CAPEX for utilities for distributed supply chains (which include waste water treatment, electricity generation and steam production) was adapted from Zhu et al.[26] For HTL conversion, CAPEX was inflated by a factor 1.5 to account for the increased electricity and steam production. For natural gas sites and LNG terminals 25% of the costs was used to cover the steam generation unit. For refineries no utility costs were allocated as only the hydrotreatment occurs on site.

iii. The Lang factor was adjusted for sites where co-location synergies exist (i.e. pulp mills, sawmills and refineries).[24]

iv. The capital recovery factor (0.118) was calculated assuming a 10% discount rate, 20 years plant lifetime and 90% load factor.

v. Allocation factors for Electricity use (83%, 9%, 8%), Waste disposal cost (100%,0%,0%) and Catalyst and chemicals (46%, 54%, 0%) cost are used to distribute the total OPEX over HTL conversion, upgrading and hydrogen plant. The allocation factors are calculated based on the OPEX distribution in Tews et al.[22]

vi. Hydrogen requirement for refinery sites (1.35 kg H_2/GJ biocrude) and natural gas requirement for natural gas and LNG terminal sites in centralized supply chains were taken from Zhu et al.[26] For natural gas and LNG terminal sites in distributed supply chains, the amount of natural gas (0.15625 MMBtu natural gas/kg H_2) required to satisfy the hydrogen consumption for upgrading was determined using the NREL H2A study (Central Natural Gas design).[67] In centralized supply chains part of the hydrogen is generated from offgases from HTL conversion, explaining the lower natural gas consumption relative to distributed supply chains.

vii. Labor costs were determined according to Wessel's method at a capacity of 388 MW biomass input or 307 MW biocrude input. Labor costs were reduced for sites where co-location synergies exist (i.e. pulp mills, sawmills and refineries).[24] Swedish hourly wages were taken from Eurostat.[68]

viii. The CAPEX-dependent OPEX cost items include maintenance and repairs, operating supplies, local taxes, and insurance.[24,53] This cost is calculated in the model as a factor (0.102) of TCI and thus scales with capacity.

ix. Other includes distribution and marketing and patents and royalties fees, which amount 5.5% of total OPEX.

TRANSPORT INPUT DATA

Parameter	**Unit**	**Road[0]**		**Rail[0]**		**Short Sea Shipping[0,0]**	
		Solids	**Liquids**	**Solids**	**Liquids**	**Solids**	**Liquids**
Load capacity	t	22	22	465	864	9600	9600
Net load capacity roundtrip	%	50%	50%	75%	75%	94%	94%
Time cost	€/vkm	0.63	0.63			9.39	12.36
Labor cost	€/vkm	1.19	1.19				
Variable cost	€/vkm	0.36	0.36	3.83	4.06	14.73	24.46
Fuel cost	€/vkm	1.37	1.37	2.26	2.91	33.54	33.54
Total cost	**€/vkm**	**3.55**	**3.55**	**6.09**	**6.98**	**57.66**	**70.37**
	€/tkm	**0.162**	**0.162**	**0.013**	**0.008**	**0.006**	**0.007**
Loading/unloading[0]							
Chips	€/t	5.11		8.93		4.85	
IBP	€/t	2.71		8.93		6.48	
Sawlogs and pulpwood	€/t	1.99		8.04		6.48	
Biocrude			1.39		3.26		11.53
Biofuels			1.31		3.08		10.89

UNIT CONVERSION

	Unit	Biomass	Biocrude	Biofuel
Energy density (volume)[16]	GJ/m^3	7.41	-	-
Energy density (mass)[22]	GJ/t dry	16.7	32.7	40.3