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Resource efficiency or economy of scale: Biorefinery supply chain configurations for co-gasification of black liquor and pyrolysis liquids

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HIGHLIGHTS

- Biomass conversion efficiency presents economic advantages over economy of scale.
- Industrial integration is beneficial to reach cost-efficient biorefineries.
- Replacing capital-intensive equipment at the host industry is beneficial.
- No benefit for centralised or decentralised supply chain configurations.

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ABSTRACT

Biorefineries for the production of fuels, chemicals, or materials can be an important contributor to reducing dependence on fossil fuels. The economic performance of the biorefinery supply chain can be increased by, for example, industrial integration to utilise excess heat and products, increasing size to improve economy of scale, and using intermediate upgrading to reduce feedstock transport cost. To enable a large-scale introduction of biorefineries it is important to identify cost efficient supply chain configurations.

This work investigates a lignocellulosic biorefinery concept integrated with forest industry, focusing on how different economic conditions affect the preferred supply chain configurations. The technology investigated is black liquor gasification, with and without the addition of pyrolysis liquids to increase production capacity. Primarily, it analyses trade-offs between high biomass conversion efficiency and economy of scale effects, as well as the selection of centralised vs. decentralised supply chain configurations.

The results show the economic advantage for biomass efficient configurations, when the biorefinery investment is benefited from an alternative investment credit due to the replacement of current capital-intensive equipment at the host industry. However, the investment credit received heavily influenced the cost of the biorefinery and clearly illustrates the benefit for industrial integration to reduce the cost of biorefineries. There is a benefit for a decentralised supply chain configuration under very high biomass competition. However, for lower biomass competition, site-specific conditions will impact the favourability of either centralised or decentralised supply chain configurations.

1. Introduction

Biorefineries for the production of hydrocarbons in the form of fuels, chemicals, or materials, can make an important contribution to reaching a fossil-free economy. Several factors influence the performance of biorefinery supply chains, for example, biomass conversion efficiency, economy of scale, transportation cost, and commodity prices, as well as the choice of transport modes, and location of facilities [1,2].

A number of previous studies have shown that the integration of biorefineries with other industries, for example, utilisation of excess heat and by-products, can be beneficial (e.g., [3,4]). Integration with traditional forest industries can also be beneficial in terms of logistics, due to the industries' experience in operating large-scale biomass

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Nomenclature

BL	black liquor
BLG	black liquor gasification
CAPEX	capital expenditures
CEPCI	chemical engineering plant cost index
CHP	combined heat and power
HP	high pressure
LP	low pressure
MP	medium pressure
O&M	operation and maintenance
OPEX	operational expenditures
PL	pyrolysis liquids
RB	recovery boiler

supply chains. For biorefinery concepts relying on industrial by-products as feedstock, the production capacity will be limited by the feedstock availability. To increase the production capacity an additional feedstock is required, but depending on the by-product, the additional feedstock might require pre-processing.

The use of a pre-processing technology enables a decentralised upgrading of the additional feedstock to increase the energy density before transport. Decentralised supply chain configurations have been suggested to improve economic performance by reducing the cost of transportation [5,6]. However, this is not necessarily favourable for all biorefinery supply chains, where, for instance, forest-based biorefinery supply chains in regions with a highly developed forestry sector, favour centralised supply chains [7–9]. With dispersed biomass availability however, the distributed supply chains can become competitive [7].

Black liquor (BL) is a liquid by-product from the chemical kraft pulping process that is currently combusted in a recovery boiler (RB) at the pulp mill to produce electricity and steam, and to recycle the pulping chemicals back to the mill. Black liquor gasification (BLG) has been successfully demonstrated as an alternative chemical recovery route [10]. The implementation of BLG has the potential to create an additional revenue stream for pulp mills as it offers a potential for higher value utilisation of this liquid by-product through high efficiency conversion to biofuels or biochemicals, when compared to combustion for heat production. BLG with downstream biofuel production has been shown to provide high resource and economic efficiency [11,12]. The BL has a high alkaline content, resulting in a catalytic effect during gasification that allows for lower temperatures, yielding a high carbon conversion efficiency, and lowering the specific biomass usage [13].

The integration of black liquor gasification (BLG) instead of investing in a new RB can increase both the process economics and energy efficiency of the mill [14]. The BL availability is closely related to pulp production, which in turn sets an upper limit on the total gasification-based production capacity. The RB represents a major investment and is unlikely to be replaced before the end of service life, either by a new RB or by a BLG plant. Since there are a limited number of RBs near their end of service life, the number of sites where it might be of interest to replace the RB with BLG in the short to medium-term future, are reduced.

The production capacity of a specific site, given the available BL, can be increased by blending the BL with an additional liquid feedstock [15]. By using a fast pyrolysis process to produce pyrolysis liquids (PL), several types of biomass could be converted into a suitable form to blend in with the BL for gasification. This enables the PL to piggy-back on the catalytic effect from the BL, yielding higher conversion efficiency compared to gasification of only PL. Additionally, due to the significantly higher energy density of PL, a blend-in of 50 wt% results in a tripled energy input for a specific BL availability, thus increasing the economy of scale effects for the gasification facility [16].

Co-gasification of BL and PL has been proven both in lab- and pilot-scale facilities [17,10], and has been shown to be economically favourable for small pulp mills [12]. Compared with the BLG, it enables a more flexible supply chain design, either as a centralised supply chain, with the PL produced on site, or as a decentralised supply chain, where PL is produced elsewhere. The PL, in turn, can either be produced in a stand-alone facility, or in a facility integrated with other industries.

The economic viability of the co-gasification concept is highly influenced by the cost for PL compared to BLG [12], which in turn depends mainly on the cost of feedstock (including transport related costs), but that is also significantly influenced by plant configuration (e.g., integration) and conversion efficiency. PL is produced from the fast pyrolysis process and can be produced from various types of biomass with yields up to 75 wt% [18]. Increased efficiency and a reduced production cost can be reached with integration [19,20].

Previous studies of the co-gasification of BL and PL have applied system boundaries around the plant only. The PL production has not been considered explicitly, as PL has been considered to be imported over the fence. When applying plant level system boundaries, key geographical aspects are thus omitted, where, for example, the location of biomass and competing biomass users, as well as the location of potential host industries for integration, could significantly influence the performance of the concept. To address this, the system boundaries need to be expanded to include relevant aspects of the entire supply chain, including location and supply chain configuration for both the fast pyrolysis and the gasification facilities. This will additionally enable explicit evaluation of the choice between centralised or decentralised supply chain configurations, in terms of potential to improve the overall performance of the technology.

Mathematical supply chain optimisation has been used in a large number of previous studies to identify low-cost biorefinery supply chain configurations, commonly implemented as mixed integer linear programming (MILP) (see [21,22] for an overview). This type of modelling approach can be used to address several types of problems including regional [23] to trans-national problems [24], and long- [25] and medium term problems [26].

The geographically explicit approaches are suitable for the investigation of biorefinery supply chains, since they can consider local characteristics such as feedstock availability, local or regional feedstock competition, and the location of industrial infrastructure that can provide integration opportunities, but which may also constitute competition for biomass feedstock.

This paper investigates the full supply chain performance of a technology for the valorisation of black liquor relying on the co-gasification of black liquor together with pyrolysis liquids. The overall aim is to investigate an industrially integrated forest biorefinery concept, focusing on how different economic conditions affect the preferred types of supply chain configurations.

The investigated biorefinery concept is based on the gasification of BL, or BL and PL with downstream production of methanol for use as transport fuel. Three basic types of supply chain configurations are considered: (1) pure BLG, (2) co-gasification of BL/PL with a centralised supply chain (on-site production of the PL), and (3) co-gasification of PL/BL with a decentralised supply chain (off-site PL production). Of particular interest are potential trade-offs between high biomass conversion efficiency and economy of scale effects in terms of biomass usage, economic performance, and CO_2-emissions, and the selection of centralised vs. decentralised supply chain configurations. The analysis is done with respect to supply chain costs, biomass usage, and carbon footprint.

A geographically explicit cost minimisation model is used for the analysis. Explicit location options are considered for both gasification/biofuel production plants, and fast pyrolysis facilities, as well as competing biomass demand. The results from the analysis will provide general insights into factors that makes either centralised or decentralised supply chain configurations favourable, while further increasing the knowledge basis regarding biorefinery concepts based on the gasification of BL.

2. Case study

This study concerns industrially integrated forest biorefinery supply chains for methanol production based on the gasification of BL with and without the addition of PL see [16,12] for a more detailed description of the technology. The technologies were configured to produce methanol for use in the road transport sector. Methanol was chosen due to the high well-to-wheel efficiency, the possibility of using it as a blend-in fuel, and its suitability as a platform chemical for the synthesis of other fuels and chemicals [27].

The geographical scope was limited to the national borders of Sweden, due to the well-developed forestry sector and high utilisation of forest biomass. The focus was on nationally available resources in terms of biomass and industrial facilities. The location of the methanol production was limited to chemical pulp mills due to the nature of the considered core biorefinery technology (BLG), which enables recycling of the necessary chemicals to the pulp mill. The PL production locations considered were chemical pulp mills (for on-site production of PL), sawmills, CHP plants in DH systems, and stand-alone facilities.

Four different supply chain configuration scenarios were evaluated:

(1) BLG: Black liquor gasification, representing a value chain configuration with maximised biomass conversion efficiency [12]).
(2) BL/PL-(centralised): Co-gasification of BL and PL with a centralised supply chain, that is, production of PL at the gasification plant representing a value chain with a possibility to significantly increase economy of scale (compared to BLG), but with a higher biomass transport cost.
(3) BL/PL-(decentralised): Co-gasification of BL and PL with decentralised supply chain, that is, off-site production of PL, representing a value chain with the possibility to significantly increase economy of scale (compared to BLG), but with lower biomass transport cost and increased capital cost due to the intermediate upgrading of biomass to PL compared to (2) BL/PL-(centralised).
(4) All technologies considered simultaneously. This scenario represents an overall value chain configuration that allows for a mix of separate configurations from options (1–3).

The supply chain configuration scenarios (1)–(2) are illustrated in Fig. 1.

2.1. Alternative investment

It was assumed that the host industries are facing major energy investment where boilers and/or steam turbine(s) are at the end of their lifetime. They have a choice of investing in either (a) a conventional investment, that is, new boilers, and if applicable, steam turbines, or (b) methanol production and, if necessary, additional boilers and turbines to satisfy base utility requirements of the host industry. This reasoning is motivated by the fact that gasification of BL constitutes an alternative recovery route for the chemicals and energy in the BL. Investment in BLG (or in BL/PL co-gasification) can thus be expected to take place when the recovery boiler is due for replacement or refurbishment. To be consistent, this reasoning is extended to the other required new investments (PL production).

The CAPEX and OPEX of the investment in methanol production were thus determined from the additional cost compared to the conventional investment for each specific host site. This assumes that all host industries face an investment at the same time, which is unrealistic. However, this was assumed in order to not exclude any location from the analysis.

2.2. Input data

2.2.1. Host industries and location assumptions

There are 21 chemical pulp mills in Sweden, which were all included as potential biorefinery host sites. All pulp mills were considered for all types of supply chain configurations, that is, BLG as well as BL/PL co-gasification with either on-site (centralised), or off-site (decentralised) PL production.

The data required for the pulp mills were pulpwood demand, BL availability, process steam demand, and electricity demand and generation, estimated based on [28,29]. The internal demand for medium- and low-pressure steam at the different pulp and paper mills was estimated based on generalised data for different types of standard mills, depending on the production as presented in [30]. The individual mills were, depending on their respective production, classified as integrated fine paper mills, bleached kraft market pulp mill, kraftliner mill, or a combination of the three mill types.

For the decentralised supply chain configuration, (3) BL/PL-(decentralised), 35 CHP plants in district heating (DH) networks, 21 sawmills, and 41 forest terminals (representing stand-alone locations) were considered as potential locations for PL production.

Sawmill data were based on data from the Swedish Forest Industries Federation (SFIF) [31], and general correlations between sawn goods and by-products were used, based on [32]. All heat demand at a sawmill was assumed to be possible to cover with DH-level heat (97 °C, 0.9 bar(a)), and the investment in PL production included investment in a biomass boiler to cover the heat demand of both the sawmill and the fast pyrolysis-process. The sawmill location was dimensioned to utilise all available wood chips on site. Additionally, the investment covered an investment in a steam turbine. For the alternative investment, without PL production, the study assumed that the investment would only be in a new heat only boiler (HOB).

For integration in CHP plants a base criteria was set that the heat demand of the DH network must be satisfied, also with the inclusion of a new PL plant. The size of the fast pyrolysis unit was limited to one single reactor, and the boiler size was adjusted to satisfy the heat demand of the fast pyrolysis process, as has been described in [20]. As an alternative to investment in fast pyrolysis, investment in a new high-efficiency replacement CHP plant (boiler and turbine) was considered.

The size of the stand-alone PL production was limited to one or two fast pyrolysis reactors (see Section 2.2.2). This corresponds to a maximum PL production capacity of 104 and 86 $\mathrm{MW_{th}}$.

Annual operating time was assumed to be 7884 h/a (representing an annual availability factor of 90%) for all locations except the CHP plants. For the CHP plant, the integration of fast pyrolysis was assumed to enable an increased annual operating time, due to a heat load being available during a longer period of the year [33,34]. An annual operating time of 6000 h/a was thus considered for fast pyrolysis integrated CHP, while the operating time for alternative investment CHP plants

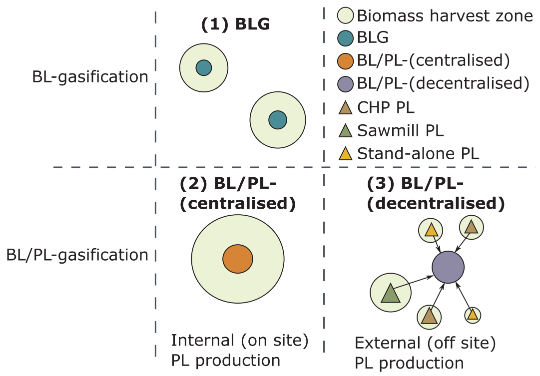

Fig. 1. Supply chain configuration scenarios for methanol production in this study.

was limited to 4800 h/a.

2.2.2. Techno-economic input data

The techno-economic performance parameters for BLG and co-gasification were taken from [12]. Two different options were considered for the co-gasification technologies: 20 wt% or 50 wt% PL blend in the BL. The gasification based biofuel plant produces steam from the cooling of, for instance, the syngas and the synthesis reactor, which is used to cover steam demand in the biofuel production, as well as in the pulp mill.

The considered configuration for the methanol production has a deficit of medium pressure (MP) steam and a surplus of low pressure (LP) steam. To satisfy the steam demand of the pulp mill and the integrated methanol production facility, investment into an additional boiler is thus considered, when necessary. Moreover, when an RB is replaced with a BLG, the recovery route of the pulping chemicals is altered and the composition of the recycled alkali stream (green liquor) is diluted, resulting in a higher energy demand in the lime kiln [12]. The changed lime kiln fuel balance was also considered. The increased lime kiln demand was assumed to be satisfied with off-gases (gas by-products, see below), and if necessary, with additional biomass fuel.

The fast pyrolysis performance considered different process efficiencies for low ash (e.g., wood chips) and high ash (e.g., forest residues) feedstock [35,36]. For the supply chain configuration (2) BL/PL-(centralised), with on-site production of PL, the fast pyrolysis unit was modelled as integrated with the biomass boiler on site, and dimensioned to produce all PL required for either a 20 or 50 wt% blend-in of PL with BL. For a decentralised production of PL, either as integrated with sawmills or CHP plants, or as stand-alone facilities (forest terminals), the dimensioning of the PL was done according to host industry characteristics, as described in Section 2.2.1.

The size of one fast pyrolysis reactor was limited to 15 t-dry feed/h [37] for all location options, corresponding to 72 $\mathrm{MW_{th}}$ of biomass input, and 54, and 45 $\mathrm{MW_{th}}$ of PL production for low and high ash feedstock, respectively. In the case of a site needing a larger PL production, several reactors were used in parallel. Any surplus char and gas from the process was used internally to provide heat for the internal processes. In cases of surplus by-products, they were sold to market as industrial by-products (see Section 2.2.5).

The energetic yields and demands of the major equipment considered are shown on LHV basis in Table 1.

The parameters for calculating the investment cost in major equipment are presented in Table 2. The investment was discounted over the assumed economic lifetime assuming an annuity factor of 0.13, corresponding to e.g., an 11.5% discount rate and 20 years lifetime. The O&M cost was assumed to be 4% of the CAPEX. nth plant investment costs were used and the investments were converted to EUR with the monetary value year of 2015 using the chemical engineering plant cost index (CEPCI) [38].

Table 2
Investment cost function for major equipment considered in this study. C is the capacity of the flow the cost is scaled against in MW.

	$Investment \quad Cost = a \cdot C^{b}$ [MEUR$_{2015}$]			
	a	b	C [MW]	Source
BLG	6.15	0.7	BL	[12]
BL/PL 20 wt%	7.11	0.7	BL	[12]
BL/PL 50 wt%	10.9	0.7	BL	[12]
Fast pyrolysis w comb.chamber[b]	2.08	0.81	prod. PL	[37]
Fast pyrolysis w/o comb.chamber[b]	1.61	0.76	prod. PL	[37]
Heat only boiler	2.56	0.7	Biomass feed	[39]
Steam boiler	2.82	0.7	Biomass feed	–[a]
Recovery boiler	2.52	0.7	BL	[40]
Steam cycle	2.21	0.67	prod. el	[41]

[a] Assumed 10% higher than heat only boiler.

[b] For low ash feed, valid for PL production < 289 MW.

Benefits from integration were only gained from the avoided cost of the alternative investment and from heat integration with the host industry. No additional benefits from integration were taken, for instance, benefits from feedstock handling and reduced O&M cost, which could be lower for the integration cases compared to stand-alone operation.

2.2.3. Forest biomass supply and demand

For the supply of biomass, both primary resources from forestry operation (sawlogs, pulpwood, harvesting residues, and stumps) and secondary resources (forest industry by-products) were considered. The spatially explicit supply potential for primary forest biomass was estimated based on scenarios from the Swedish Forest Agencys forest impacts assessment (SKA 15) [42] (Todays forestry scenario), where future harvesting operations (final felling and commercial thinning) have been modelled. For more details, see [43,40,7]. For forest industry by-products, two different assortments were included: sawmill wood chips and low-grade industrial by-products, such as bark and sawdust. The modelled quantities were based on modelled production volumes (site specific), and generic yield relations [31,44,32]. The focus in this study was on the utilisation of domestic resources and biomass imports were restricted to current levels. A cap on the import was set to 5 and 15 TWh

Table 1
Normalised energetic yields and demands of major equipment shown on LHV basis. Positive values are outputs and negative values are inputs.

	Methanol	Pyrolysis liquids	Biomass	Black liquor	High temperature heat[a]	Meduim pressure steam[b,h]	Low pressure steam[c,h]	District heating[d]	Char/gas by-product[e]	Electricity	Source
Fast pyrolysis (low ash)		0.75	−1					−0.25	0.48	−0.04	[35,36]
Fast pyrolysis (high ash)		0.62	−1		−0.23			−0.32	0.85	−0.06	[35,36]
BLG[f]	0.54			−1		−0.04	0.21		0.04	−0.11	[12]
BL/PL 20 wt[f]	0.90	−0.51		−1		−0.08	0.25		0.06	−0.16	[12]
BL/PL 50 wt[g]	1.93	−2.05		−1		−0.19	0.40		0.13	−0.30	[12]

[a] Heat provided directly from the boiler (as sand from the fluidised bed).

[b] Steam 10 bar(a), 200 °C.

[c] Steam 4.5 bar(a), 150 °C.

[d] District heat, 0.9 bar(a), 97 °C.

[e] By-product including what is internally combusted to produce heat.

[f] Increased lime kiln load by 30%.

[g] Increased lime kiln load by 78%.

[h] If negative: The heat must be satisfied from another heat source on site (e.g. steam boiler). If positive: The heat is used to satisfy heat demand on site. The steam passes through steam turbines if the heat demand is at a lower pressure than what is available.

for sawlogs and pulpwood, respectively, which can be compared to current net import volumes of 2.5 and 12 TWh SDC2017.

Competing demand from the forest industry (pulp mills, sawmills, and pellet industries) and the stationary energy sector (heat and electricity production) was considered spatially explicitly. The demands were described statically on an annual basis in the model, based on current production and demand (2015) [31,44,28,45–47].

Fig. 2 shows the modelled spatial distribution of biomass supply (top) and competing demand (bottom). Table 3 summarises the total modelled supply potential for each feedstock, and Table 4 the demand sectors, the modelled demand levels, and the respective biomass assortments each sector can use.

2.2.4. Transpor and distribution

Transport of biomass feedstock, PL, and produced methanol was considered using road and rail. The transportation costs between all possible origins and destinations were calculated with a geographically explicit intermodal transport model (pre-optimisation) using ArcGIS, as described in [7]. Transport capacity limits were not considered. Methanol was assumed to be transported from the biorefinery to blending terminals [48,49] for distribution to final consumers.

Costs for transportation was based on [7] and CO_2 emissions are based on [50]. Transportation cost and emissions are shown in Table 5.

2.2.5. Energy carriers

All flows of biomass and other energy carriers were converted to energy units on a LHV basis, also including biomass demand not used for energy purposes, that is, sawlogs and pulpwood demand from the forestry industry. For conversion between units, conversion factors of 0.42 odt/m^3 (oven dry tonnes of wood) and 4.9 MWh/odt (energy content of woody biomass) were applied.

Table 3
Aggregated modelled biomass supply.

Biomass assortment	Supply potential [TWh/a]
Sawlogs	89
Pulpwood	66
Harvesting residues	37
Stumps	16
Sawmill chips	25
Low-grade by-products	23

In order to estimate the spatial variation in forest biomass costs, a bottom-up approach was used, where time and productivity functions for forestry machinery were applied on the geographically explicit forest data (described above). The forest biomass cost-supply data was aggregated on the model grid. The approach has been described in more detail in [40,7,43]. Table 6 summarises the energy and feedstock prices used in this study. Table 6 also includes the emissions from the average Swedish electricity mix, used for calculating the CO_2 impact from changes in electricity production and the emissions for fossil-based methanol use, for calculating the avoided fossil emissions.

The electricity market was treated exogenously. Any increase or decrease in the production or demand of electricity in the modelled system was assumed to be met by either an increase or decrease in the production of electricity from the market.

3. Method

3.1. Model description

This study used the geographically explicit mixed linear programming (MILP) model BeWhere Sweden, written in GAMS and using CPLEX as the solver [59,40]. The model is a biorefinery localisation

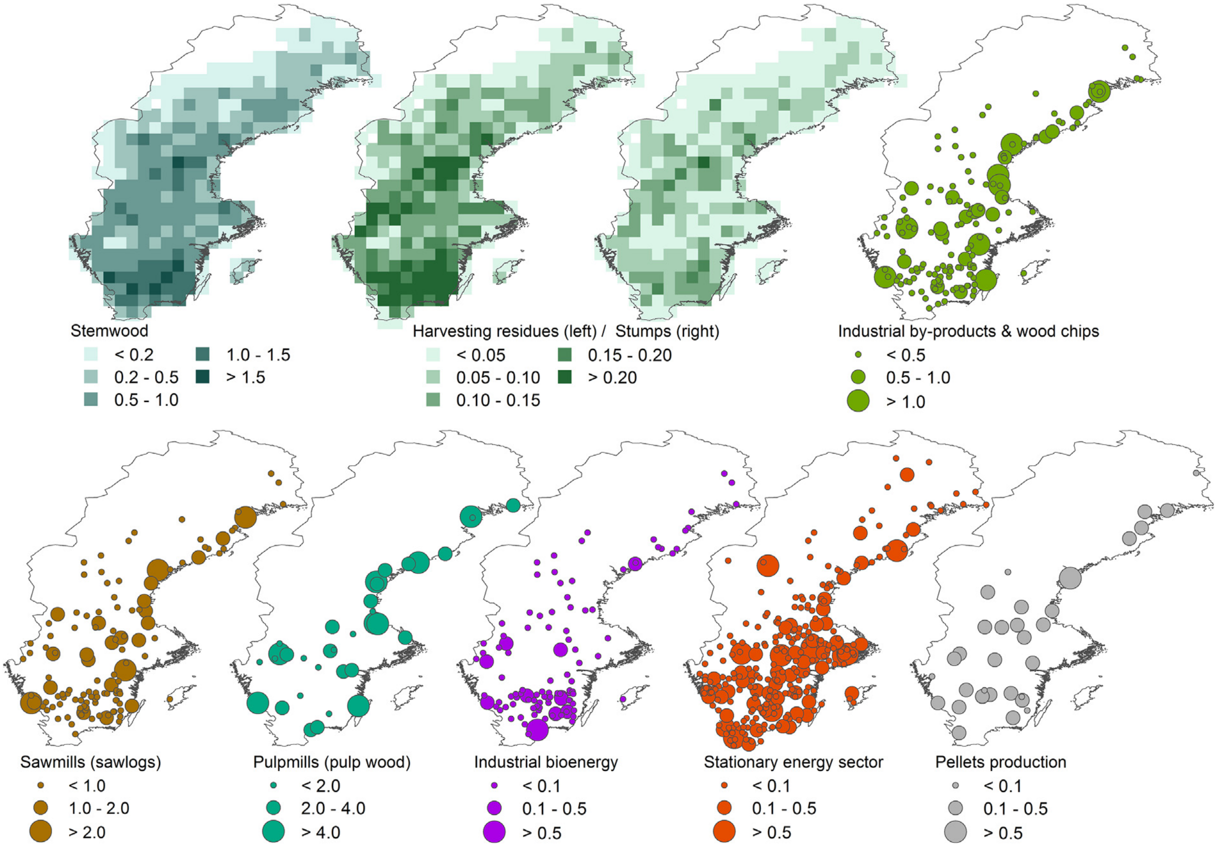

Fig. 2. Modelled spatial distribution of biomass supply (top) and competing demand (bottom). All values are TWh/a. Stemwood includes both sawlogs and pulp wood.

Table 4
Aggregated woody biomass demand for biofuel production, forest industries and the stationary energy sector, and the corresponding biomass assortments that can be used in each sector in the model.

		Biomass assortments						
	Aggregated demand [TWh/y]	Sawlogs	Pulp wood	Harv. residues	Stumps	Sawmill chips	Low-grade by-prods.	Wood pellets[a]
Sawmills (sawn products)	75	x						
Sawmills (heat demand)	4.1					x	x	
Pulp and paper mills (pulp)	93	x	x			x		
Pulp and paper mills (heat demand)	25[b]		x	x	x	x	x	
Pellets production plants	8.1					x	x	
Stationary energy (DH and CHP)	28		x	x	x	x	x	x
Fast pyrolysis (low ash)	Variable		x			x		
Fast pyrolysis (high ash)	Variable			x	x	x	x	
BLG, BL/PL[c]	Variable		x	x	x	x	x	

[a] The modelled domestic production amounts to 8.1 TWh, and in addition to this, pellets can be imported with no restriction.
[b] Including use of internal fuels, excluding black liquor.
[c] For use in the bark boiler to meet the mills steam demand.

Table 5
Cost and CO_2 emissions for transporting different energy carriers - *d* is the transport distance in km.

	Transport cost [MEUR/TWh] [7]		CO_2 emissions [tCO_2/TWh,km]	
	Truck	Rail	Truck [50]	Rail [51]
Pulpwood and sawlogs	0.33 + 0.026*d	1.32 + 0.0021*d	20.2	0.15
Harvesting residues	1.10 + 0.035*d	1.92 + 0.0028*d	25.1	0.18
Pyrolysis liquids	0.15 + 0.018*d	0.36 + 0.0009*d	11.05	0.08
Methanol	0.12 + 0.014*d	0.28 + 0.0007*d	6.5	0.05

Table 6
Energy prices and CO_2 emissions

	Base price (2016) [EUR/MWh]	CO_2 emissions [tCO_2/GWh]	Source
Electricity	21.0	95	[52,53,8]
Sawlogs	22.9[a]	1.5[b]	[54,55,8]
Pulpwood	15.2[a]	1.5[b]	[54,55,8]
Tops and branches	15.3[a]	1.5[b]	[55,8]
Stumps	22.1[a]	1.5[b]	[56,55,8]
Sawmill chips	11.4		[56,57]
Industrial by-products	10.4[a]		[55]
Wood pellets	26[a]		[55]
Imported biomass	10% higher than domestic		Assumed
Fossil fuel based methanol		264	[58]

[a] Average prices in Sweden.
[b] Biomass harvest emissions.

model that minimises the total supply chain cost and includes a large number of sites of importance for biomass supply and demand. Competing industries and potential biorefinery sites are considered individually, with site-specific data on energy, and biomass use and production. The model uses a grid of 334 cells with a half-degree spatial resolution, which is used for the representation of, for instance, biomass demand and supply, and product demand.

The model objective was to minimise the supply chain configuration cost to satisfy a determined methanol demand for usage in the road transport sector, while simultaneously satisfying biomass demand from other sectors (forest industry, stationary energy sector). The investigated biorefinery technologies (fast pyrolysis and gasification) have been investigated with a future perspective, i.e. they have not been demonstrated at the scales assumed here, and their performance has been investigated with current energy prices as the base case. The total supply chain cost included costs for biomass (both imported and domestic), transport and distribution, electricity, and operational and capital expenditures (OPEX, and CAPEX) for new plants.

Decision variables in the model were the choice of biorefinery technologies and localisations (binary), flow of biomass from harvesting to biomass to demand sites (continuous), flow of methanol from production sites to fuel distribution centres (continuous), and flow of PL from production sites to co-gasification facilities (continuous, only for the BL/PL-(decentralised) technology configuration). Since the sizes of the facilities were dependent on the specific characteristics of the host industry (e.g., BL availability), the non-linearity of the capital investment were addressed outside of the optimisation.

3.2. Model runs

The model objective was set to satisfy a given methanol demand and minimise the total system cost, while still satisfying the competing industries biomass demand. Each value chain configuration, (1) BLG, (2) BL/PL-(centralised), (3) BL/PL-(decentralised), and (4) all technologies, were investigated for methanol production scenarios in the range of 0–36 TWh/a, provided that the scenarios were not constrained by either biomass availability or the number of facilities available for conversion prior to reaching the 36 TWh/a target. The co-gasification cases were limited to a blend-in of PL of 20 wt% or 50 wt%.

The core biorefinery technology considered in this study (BLG) has been assumed to utilise all BL on site, and thus fully replace the current RB. The base assumption has been that all 21 chemical pulp mills are available as biorefinery hosts. In order to acknowledge the age of existing capital-intensive equipment, a second host availability scenario was assessed, where only pulp mills with RBs near the end of their economic lifetime (older than 25 years) were assumed available as hosts.

As described in Section 2.1, this study has applied an alternative investment perspective where an investment credit is received. To quantify the economic benefit from integration, a scenario was evaluated without considering a credit for the alternative investment for the four supply chain configuration scenarios.

The scenarios were evaluated for biomass usage in the system, total supply chain cost, and carbon footprint depending on CO_2 emissions from transport, and electricity generation and mitigated fossil emissions. This was done in comparison with the reference scenario without methanol production, see Section 3.2.2.

3.2.1. Sensitivity analysis

A sensitivity analysis representing significant changes to the prices of energy carriers, and transportation costs were conducted. Additionally, it was investigated how a significant increase in the annuity factor would influence the results, see Table 7.

All combinations of electricity price, biomass price, and biomass transportation costs were investigated. The analysis included base (derived from current costs and prices), low, and high prices for biomass feedstock and biomass transportation, as well as base, and high prices for electricity. Low electricity price was not investigated due to the current prices on the spot market being low.

In addition to these parameters, the impact of a higher annuity factor of 0.20 was investigated (corresponding to e.g., 19% discount rate and 20 years lifetime). This was made for a few methanol demand scenarios for the (4) all technologies value chain configuration to evaluate the impact on the number of facilities converted to each specific value chain configuration.

3.2.2. Supply chain performance evaluation

The performance of each of the four considered supply chain configuration scenarios was evaluated in terms of total biomass usage, total supply chain cost, and total supply chain CO_2 emissions. Each modelled scenario was compared to a reference scenario without methanol production. In this scenario, the model objective was set to no methanol production, and the costs of the reference system includes the biomass transportation and the alternative investment. Any changes compared to the reference system was attributed to methanol production, which includes, for example, changes in biomass transport for other facilities not converted to biorefineries. This supply chain methanol production performance represents the system performance and can differ from the site-specific performance.

In summary, the methanol supply chain biomass usage thus covers all changes in biomass usage of the system, including not only biomass directly used for the biorefineries, but also potential changes for other users regarding the type of biomass used. Similarly, the calculated methanol supply chain cost includes the system changes in biomass transportation, biomass usage, electricity usage, CAPEX, and OPEX.

CO_2 emissions were calculated from emissions from biomass harvest, transport of biomass from harvesting sites to industrial facilities, electricity production, transport of methanol to gas stations, and fossil fuels.

4. Results

In the following sections, the major results from the model runs are presented. In total, including sensitivity analysis and base scenarios, the model was run 1549 times.

4.1. Supply chain performance: base scenario

As previously described, the four biorefinery supply chain configuration scenarios were evaluated in terms of supply chain cost, CO_2 mitigation, and total biomass use, in relation to a reference scenario with no methanol production. This section presents the results for the base scenario, where current energy prices and the base transport costs were applied.

Fig. 3 shows the resulting total supply chain methanol for the evaluated methanol production scenarios for the two considered host availability scenarios (only pulp mills with old RBs, and all pulp mills, respectively). Fig. 4 shows the resulting number of biorefinery plants created to meet the modelled methanol production scenario.

As Figs. 3 and 4 show, the maximum methanol production in the BLG only supply chain configuration scenario (1) is limited to about 12 TWh/a in the “Old RB” host availability scenario, and to 20 TWh/a in the “All RB” scenario. Accordingly, methanol capacity targets above 20 TWh/a would necessarily require feedstock blending.

From a supply chain cost perspective, the results show that the supply chain configuration scenario (1) BLG is economically favourable compared to the co-gasification cases, indicating that high biomass conversion efficiency is favoured over larger facilities. This is also confirmed when examining the blend-in options favoured by the model, which show that the model heavily favours a 20 wt% blend-in of PL (Fig. 4, unfilled markers). The very large-scale facilities, with a 50 wt% blend-in of PL (Fig. 4, filled markers) only appear in the solution when the number of facilities are limiting the production capacity, as happens in the 36 TWh/a methanol production scenario for the “all RB”, and earlier for the “old RB” host availability scenario. These results can be explained by the lower overall biomass conversion efficiency from the increased usage of PL, and the increased transportation cost with large facilities.

Fig. 3 indicates that at high methanol production scenarios, the decentralised (3) supply chain configuration results in slightly lower supply chain costs, compared with the centralised configuration (2), confirming previous research findings [7]. However, for lower production scenarios, there is little difference in the supply chain cost for the centralised and decentralised supply chain. This is further confirmed by Fig. 4 for the (4) all technologies supply chain configuration scenario, where there is no clear advantage for centralised or decentralised configurations. This would indicate that the cost advantage for centralised or decentralised configurations is highly dependent on the specific site location and biorefinery technology.

The host availability scenario also had a major impact on the supply chain cost. When allowing all chemical pulp mills as potential locations for conversion for methanol production (as opposed to restricting this to only sites with old RB) the supply chain cost is on average reduced by 6, 9.9, 8.6, and 10.3% for the (1) BLG, (2) BL/PL-(centralised), (3) BL/PL-(decentralised), and (4) all technologies scenarios, respectively. The main contributor here is that larger pulp mills are available as locations, which gives a lower specific investment cost for each specific technology configuration, which further confirms the result that suitable host locations can suppress biofuel production costs.

The potential trade-off between supply chain cost, CO_2 mitigation, and biomass usage are displayed in Fig. 5. The figure shows that the BLG supply chain configuration (1) is favourable not only regarding supply chain cost, but also regarding total CO_2 mitigation potential, and total biomass usage. However, as already discussed, the total methanol production potential is limited when considering BLG only, which in turn limits the CO_2 mitigation potential correspondingly. With co-gasification allowed (supply chain configuration scenarios (2–4), higher CO_2 mitigation can be achieved. This, however, comes at the cost of a significant increase in total, as well as specific biomass usage, and consequently a lower CO_2 mitigation potential per unit of biomass used.

Fig. 5 shows that there is little difference in CO_2 mitigation for the different supply chain configurations. Here, the mitigated fossil methanol emissions are the main component, and the differences in emission levels for the supply chains are comparatively small and depend on emissions related to transport within the supply chain.

Sustainable biomass can be considered a limited resource and it is of interest to evaluate the CO_2 per unit of biomass. In Fig. 6 the specific CO_2 per unit of biomass is displayed.

As expected, there is in general a significantly higher specific CO_2 mitigation for the (1) BLG value chain configuration. What can also be observed, is a reduction in the specific CO_2 mitigation for the co-gasification value chain configurations for higher methanol production scenarios resulting from both higher transport emissions, but also that locations with lower biomass efficiency is included in the solution,

Table 7
Range of the values for the parameters studied for the sensitivity analysis.

	Low	Base	High
Biomass price	−50%	Current	+50%
Biomass transport cost	−50%	Current	+50%
Electricity price		Current	+50%
Annuity factor		0.13	0.20

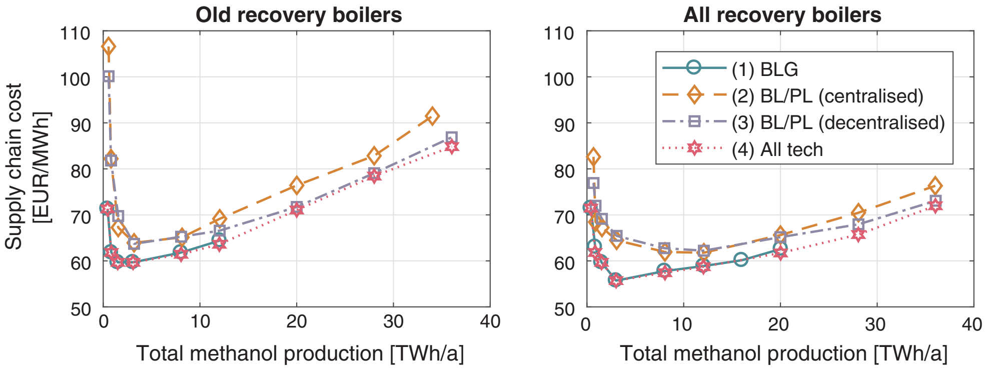

Fig. 3. Supply chain methanol production cost.

which is more apparent in the "Old RB" host availability scenario.

4.2. Alternative investment benefit

As described in Section 2.1, a fundamental assumption for the biorefinery configurations investigated was that all BL on site would be used for gasification (un-blended or blended), which would entail that the existing RB would need to be replaced. In the base scenario, an investment credit for the alternative investment in a new RB was consequently awarded for methanol production. This has a large impact on the supply chain methanol production cost, as is illustrated in Fig. 7, where the supply chain methanol cost is shown with and without the alternative investment accounted for.

Fig. 7 illustrates the benefit from industrial integration when the biorefinery investment can replace equipment currently in use at the facility. Moreover, Fig. 7 shows a significant reduction in the supply chain methanol cost, attributed to the alternative investment credit for the RB, ranging from 30 to 40 EUR/MWh for BLG (1), and about 20 EUR/MWh for the co-gasification cases (2–3).

Fig. 7 clearly shows that a large part of the advantage in terms of supply chain cost of BLG (1) over co-gasification (2–3) originates from the RB investment credit. Without this credit, co-gasification is always beneficial for methanol production scenarios over 3 TWh/a, and can be preferable over (1) BLG at lower production scenarios.

The supply chain cost can be compared with a fossil methanol price of 40–81 EUR/MWh [60], showing that the configurations are competitive at the higher range of fossil methanol prices when the alternative investment credit is considered. However, if not, the fossil methanol has a significantly lower cost. This highlights the importance of utilising current industrial infrastructure to reach a cost efficient large-scale introduction of biorefineries.

From an implementability perspective, the investment credit is more reasonable to include for the pure BLG, as the configuration included here considered gasification of all BL on site. For the co-gasification concepts, an alternative configuration could be to only utilise part of the BL on site, and still reach economies of scale. For this type of configuration, it would be incorrect to include the investment credit. It should be noted that the chosen configuration for the BLG requires replacement of the RB since it will utilise all BL on site. Therefore, it is reasonable to consider the alternative investment credit. However, for configurations utilising a part of the BL on site, the co-gasification cases could be more favourable due to the lack of this investment credit.

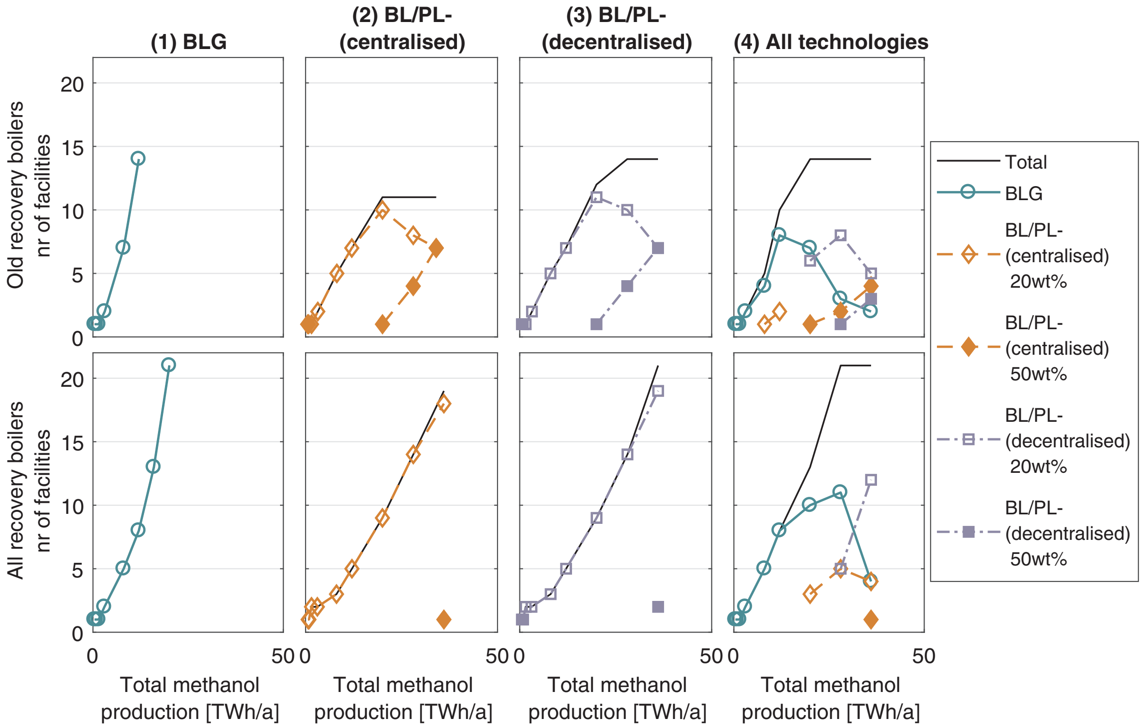

Fig. 4. Number of facilities converted to methanol production. Top: "Old RB" host availability scenario, Bottom: "All RB" host availability scenario.

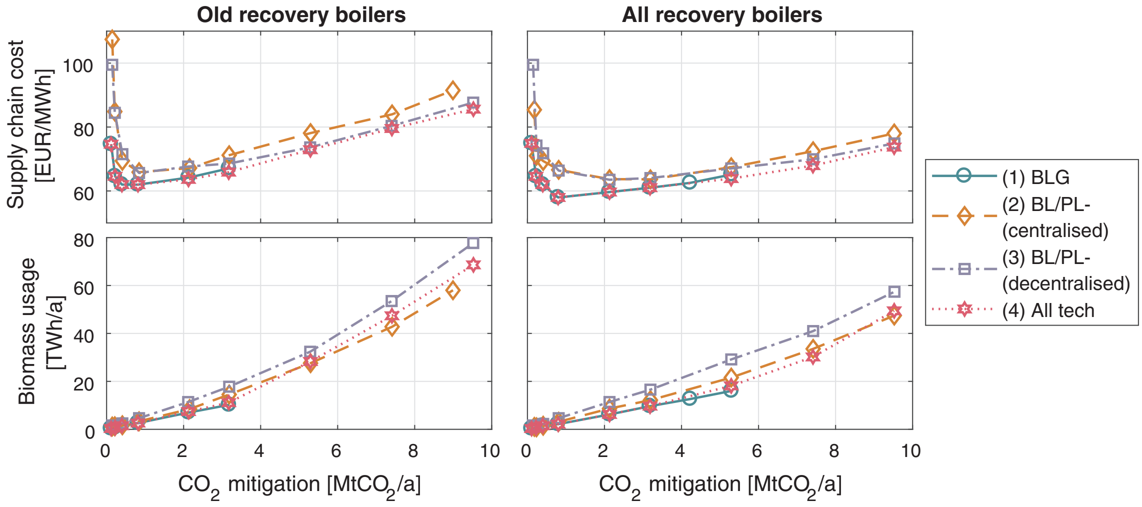

Fig. 5. Top: Supply chain cost and CO_2 mitigation. Bottom: Biomass usage and CO_2 mitigation.

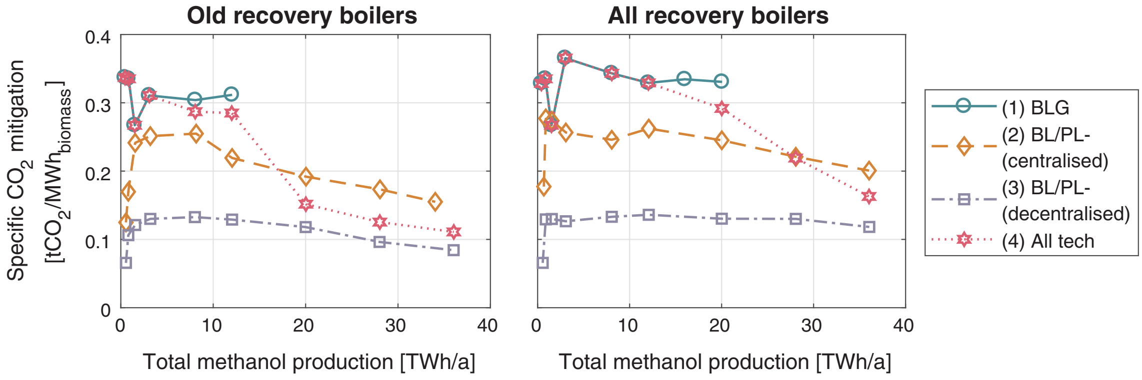

Fig. 6. Specific CO_2 mitigation.

4.3. Price and cost sensitivity

Given the uncertainty for future price development, it is of particular importance to identify biorefinery technologies that are robust to changing market conditions. For the technology configurations considered, changes in the electricity price turned out to have only a minor impact on the total supply chain cost. However, there is a major impact on the supply chains from changes in the biomass price, and to a lesser extent the biomass transportation cost. Fig. 8 shows the high (+50%), and low (−50%) sensitivity analysis for respective parameter.

As expected, with increased biomass price there is a greater cost advantage for the BLG compared to co-gasification, due to lower biomass usage. However, even with a 50% decrease in the biomass price, the BLG still has a lower supply chain cost. This shows that the biomass conversion efficiency has a larger impact on the total supply chain cost than economy of scale, when the economy of scale comes with the drawback of reduced overall biomass efficiency (as is done when introducing fast pyrolysis as an intermediate step).

Changes in biomass transportation have a significantly lower impact on the supply chain costs, compared to biomass price. As could be expected, an increase or decrease in the transportation cost will either favour the decentralised or centralised supply chain configuration. However, the changes do not create a significant difference between the BL/PL-(centralised) (2) and BL/PL-(decentralised) (3) configurations.

All economic conditions tested in the sensitivity analysis, generally showed the lowest supply chain costs for the (1) BLG configuration. The combinations that resulted in the lowest supply chain cost difference (on average) between the (1) BLG and (2) BL/PL-(centralised), and (1) BLG and (3) BL/PL-(decentralised) are shown in Fig. 9. Both of these scenarios have a low biomass price and current electricity prices. The scenarios favouring the centralised or decentralised supply chain has a low or high biomass transport cost, respectively.

Fig. 9 shows that BLG generally has a lower supply chain cost compared to the co-gasification cases when restricting the choices to only one technology. However, the all technologies scenario introduces co-gasification for significantly lower methanol production scenarios compared to the base case with current energy prices and biomass transportation cost (see Fig. 4).

Fig. 10 shows how the interaction of changes in biomass price, electricity price, and biomass transport cost influences the supply chain methanol production cost, and total biomass usage for the (4) all technologies scenario.

The magenta[1] coloured line in Fig. 10 represents the cost for the base case, with current costs and prices. The multi-coloured arrowheads point in the direction of a reduction of the cost or price for the respective parameter, that is, biomass price, biomass transport cost, and electricity price. For example, starting at the "base case" and following the green arrow downward in the figure, identifies the biomass usage and supply chain methanol cost, for the scenario with a 50% reduction in the biomass price. Likewise, starting at the base case and following an arrow in the opposite direction of the arrowhead identifies the

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[1] For interpretation of color in Fig. 10, the reader is referred to the web version of this article.

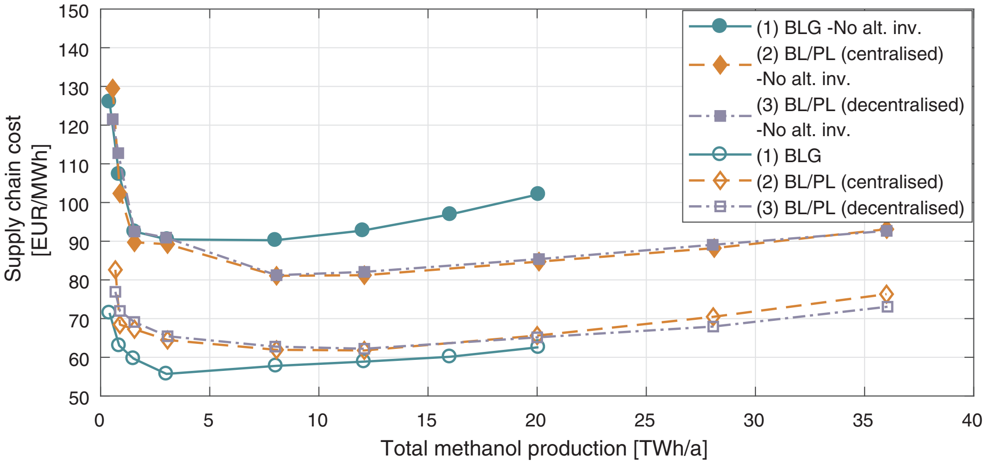

Fig. 7. Supply chain cost with (un-filled markers) and without (filled markers) alternative investment credit, respectively. The figure shows the results for the “All RB” host availability scenario.

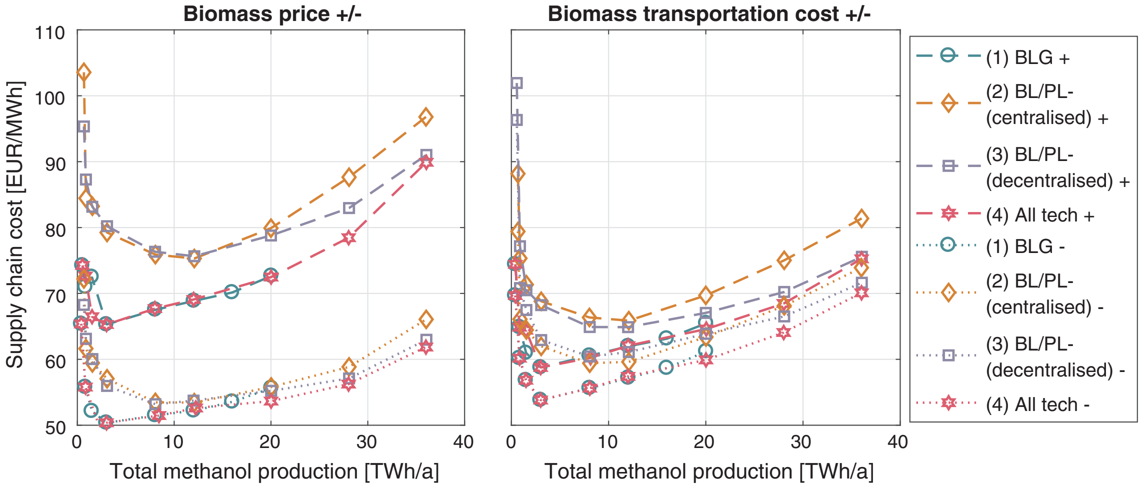

Fig. 8. Impact of biomass price and biomass transportation cost on the supply chain cost. The supply chain cost curves are shown for the ± 50% sensitivity analysis.Results are shown for the “All RB” host availability scenario.

biomass usage and supply chain methanol cost for a scenario with a 50% increase in either biomass price, biomass transport cost, or electricity price. By following the different arrows in different directions it is possible to identify the performance of all possible combinations of biomass price, biomass transport cost, and electricity price.

Fig. 10 shows that the prices assumed for the high methanol production scenarios heavily impact both the supply chain cost and biomass usage. A decrease in biomass price has a very high impact on the total system cost. It is however not apparent how a reduction in the biomass price will influence the biomass usage by the system. It could be expected that a decrease in biomass price would lead to either no difference, or an increase in the biomass usage of the system. This behaviour is however not always observed, and the impact on biomass usage will be influenced by the interaction with other costs in the system.

For high methanol production targets, the decrease in biomass transport cost also leads to lower biomass usage by the system for most cases. Since the biomass transport cost is decreased, the model chooses to transport the biomass over longer distances to facilities with higher biomass conversion efficiency, rather than using facilities closer to the biomass resource (lower transport cost), but with lower biomass conversion efficiency.

A sensitivity analysis investigating the impact of choice of annuity factors on the lowest cost technology mix is displayed in Fig. 11, displaying the base annuity factor of 0.13, together with the annuity factor of 0.2 in the sensitivity analysis.

Fig. 11 shows a significant increase in the annuity factor, representing an increase in the discount rate from 11.5% to 19%. While this increase results in a significant increase in the supply chain methanol production cost, from 66 to 80 EUR/MWh for the 12 TWh/a methanol production scenario with the “old RB” host availability constraint, there is in general only a minor impact on the chosen technology mix. The only scenario showing a significant impact on the technology mix is the 36 TWh/a methanol production scenario that allows for all chemical pulp mills as possible locations where the model favours a larger share of BLG installations.

5. Discussion

Previous research has shown an economic benefit of co-gasifying BL with PL, compared to BLG only [12,16]. Compared to previous studies which evaluated the performance of co-gasification of BL with PL, this study expanded the system boundaries to the national level, in order to consider the full supply chain performance of the concept. The results show that there is a benefit for gasification of pure BL, compared to using a blend of BL and PL to increase the production capacity and reaching higher economy of scale effects. This shows that the benefits from economy of scale effects do not outweigh the disadvantage of

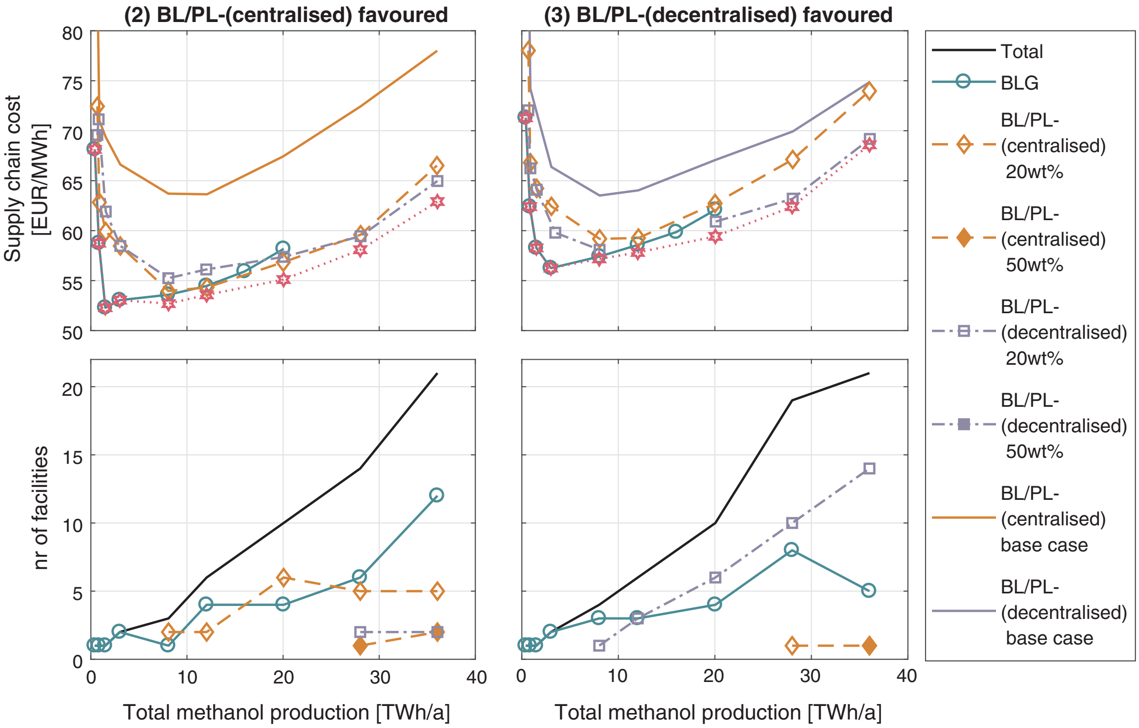

Fig. 9. Supply chain cost for the four supply chain configuration scenarios (upper half), and technology mix for the (4) all technologies scenario for selected price and cost combinations favouring (2) BL/PL-(centralised) (biomass price −50%, and biomass transportation cost −50%, and electricity price −50%) (left) and (3) BL/PL-(decentralised) (biomass price −50%, and biomass transportation cost +50%, and electricity price −50%) (right).

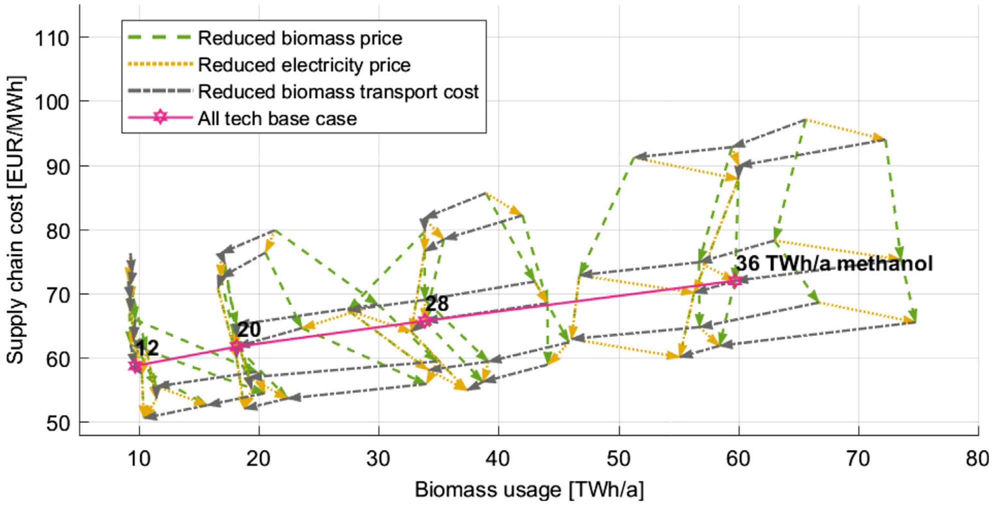

Fig. 10. Influence on biomass usage and supply chain cost depending on system prices and cost for the all technologies supply chain configuration scenario (4), for the “All RB” host availability scenario.

lower resource efficiency from the added processing step of producing PL.

However, the economic advantage of BLG is highly sensitive to the inclusion of a credit for the avoided investment in a new recovery boiler. When the investment credit for the RB is removed, the co-gasification cases becomes favourable compared to the BLG. However, this concept heavily relies on the replacement of the RB, and excluding the alternative investment credit also excludes the fact that this configuration will replace major equipment on site. This shows the large benefit for the industrial integration of biorefineries with a possibility of replacing very capital intensive industrial equipment on site, and highlights the large part the current industry can play in reaching a cost efficient large-scale introduction of biorefineries.

There is still relevance for the co-gasification of PL with BL when considering the alternative investment. This would make it possible to convert underutilised, low-grade biomass to high energy PL for further upgrading. It also presents a path for a mill to use a partial stream of BL, and blend in PL to reach larger production capacities. Additionally, both co-gasification and BLG could be of interest for pulp mills where the RB is a bottleneck for increasing the pulp production.

Both BLG and co-gasification represent pathways of interest for pulp mills where the pulp production is currently limited by the capacity of the current RB. Gasification could in those cases be used to debottleneck the RB to reach higher production capacities. Using co-gasification in this instance could be a way to significantly increase the economy of scale effects for this type of installation, as the BLG facility would be

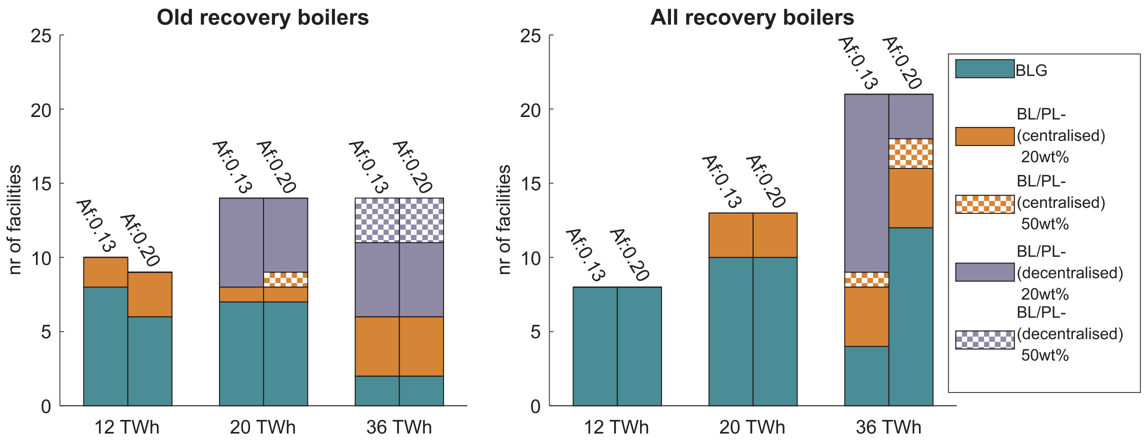

Fig. 11. Sensitivity analysis for the annuity factor. Af = Annuity factor.

significantly smaller compared to utilising all BL available on site.

The technology concept investigated here requires replacement of major process equipment as well as heavy process integration at the mill, resulting in high uncertainties for the investment cost. These high uncertainties should influence the willingness to invest and it is recommended that the way in which uncertainties influence willingness to invest is investigated.

This work shows that there is no conclusive evidence that there is a favourability for decentralised over centralised supply chain configurations. Rather the model results show that under current economic conditions a mixture of both configurations is the most favourable configuration. With dramatic changes to the biomass transportation cost, either configuration will be favourable, but there is not a significant economic advantage for either of them. That indicates that under current projected efficiencies and costs, site specific conditions have a high impact on the favourability of centralised or decentralised configurations. It is recommended that technology and site-specific investigations are instituted for determining the most favourable supply chain configuration.

This study investigated uncertainties for the biomass price and represented this with a 50% price increase or decrease. The increase could represent biomass price under high biomass utilisation scenarios, or the prices can represent other markets with higher biomass prices. The low biomass prices are not realistic, but are used to provoke the model to opt for supply chain configurations with higher biomass usage. However, these significant reductions still don't offset the increased supply chain cost from the intermediate processing step introduced for the production of PL.

6. Conclusions

This work investigated a forest industry integrated biorefinery concept based on black liquor gasification with, and without the addition of pyrolysis liquids. It shows that biorefinery supply chains with a trade-off between economy of scale and biomass efficiency should prioritise biomass efficiency, if the biorefinery investment can replace capital intensive equipment on site and an alternative investment credit is considered. This was shown to be true for both current prices and significant market changes for the technology scenario tested. If the alternative investment credit was not considered, the results showed a significant benefit for the configurations reaching higher economy of scale effects. Given the specific technology configurations tested, it is reasonable to include the alternative investment credit as the biorefinery performs crucial services to the host industry in the form of chemical recycling. Given the significant benefit in replacing capital-intensive equipment at the host industry, this work shows the important role that the current industry can play in enabling the large-scale introduction of biorefineries.

Confirming previous findings, there is a benefit for a decentralised supply chain configuration under high biomass competition. However, it also highlights that benefits from centralised or decentralised supply chains are more dependent on the specific location and other economic factors in the system under lower biomass demand, rather than a fundamental advantage of either configuration for current cost projections for fast pyrolysis. It is recommended that site and technology-specific investigations are used to identify the lowest cost supply chain configuration.

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