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

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HIGHLIGHTS

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

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ABSTRACT

This study uses a geographically-explicit cost optimization model to analyze the impact of and interrelation between four cost reduction strategies for biofuel production: economies of scale, intermodal transport, integration with existing industries, and distributed supply chain configurations (i.e. supply chains with an intermediate pre-treatment step to reduce biomass transport cost). The model assessed biofuel production levels ranging from 1 to 150 PJ a^{-1} in the context of the existing Swedish forest industry. Biofuel was produced from forestry biomass using hydrothermal liquefaction and hydroprocessing. Simultaneous implementation of all cost reduction strategies yielded minimum biofuel production costs of 18.1–18.2 € GJ^{-1} at biofuel production levels between 10 and 75 PJ a^{-1}. Limiting the economies of scale was shown to cause the largest cost increase (+0–12%, increasing with biofuel production level), followed by disabling integration benefits (+1–10%, decreasing with biofuel production level) and allowing unimodal truck transport only (+0–6%, increasing with biofuel production level). Distributed supply chain configurations were introduced once biomass supply became increasingly dispersed, but did not provide a significant cost benefit (<1%). Disabling the benefits of integration favors large-scale centralized production, while intermodal transport networks positively affect the benefits of economies of scale. As biofuel production costs still exceeds the price of fossil transport fuels in Sweden after implementation of all cost reduction strategies, policy support and stimulation of further technological learning remains essential to achieve cost parity with fossil fuels for this feedstock/technology combination in this spatiotemporal context.

1. Introduction

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

Abbreviations: CAPEX, capital expenditures; ESRI, Environmental Systems Research Institute; GAMS, general algebraic modeling system; GIS, geographic information system; HTL, hydrothermal liquefaction; IBP, industrial by-products from pulp mills; IBS, industrial by-products from sawmills; LNG, liquefied natural gas; MILP, mixed integer linear programming; OD matrix, origin-destination matrix; OPEX, operational expenditures; SCENT, Standardized Cost Estimation for New Technologies; SMR, steam methane reformer.

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

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

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

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

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

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

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

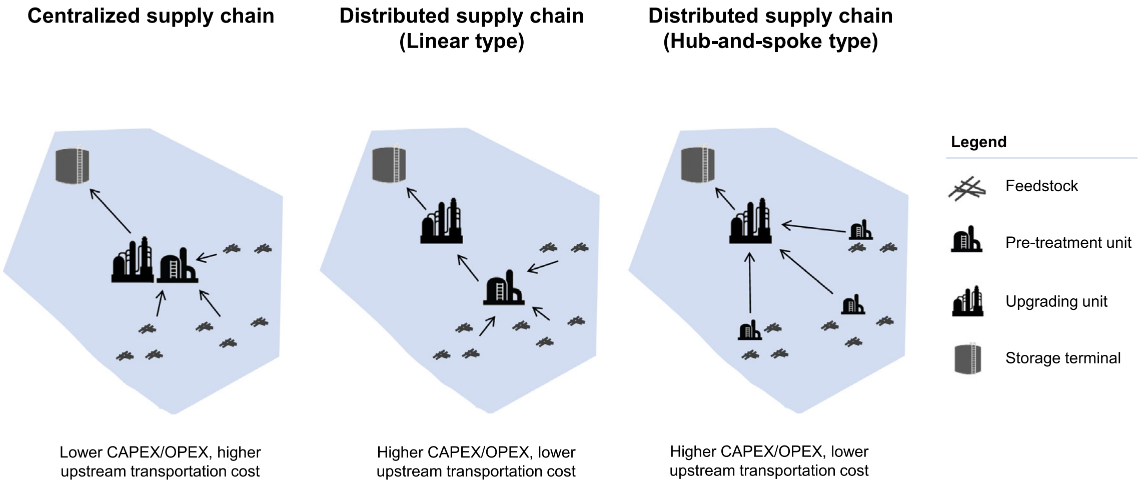

Fig. 1. A schematic image of centralized and distributed supply chain configurations.