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Modeling the impact of competing utilization paths on biomass-to-liquid (BtL) supply chains

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HIGHLIGHTS

- Optimization model for BtL production considering competing utilization paths.
- Supply chain with decentralized pre-treatment via torrefaction and fast pyrolysis.
- Local supply curves are used to model diseconomies of scale in biomass supply.
- Synthetic gasoline can be produced at a cost of 0.8–0.9 € per liter.
- BtL feedstock costs are 20–50% higher compared with established consumers.

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ABSTRACT

Second generation biofuels offer the opportunity to mitigate emissions from the growing transportation sector while respecting the scarcity of arable land in agriculture. Biomass-to-liquid (BtL) concepts based on large-scale gasification are capable of using low-quality residual feedstock, such as wheat straw or forest residues, for the production of transportation fuels. However, large amounts of biomass feedstock are required to achieve the economic capacity of a synthesis plant. Depending on the steepness of the terrain and the role of feedstock owners, biomass potentials can only be utilized to a large extent at increasing costs per ton. Such diseconomies of scale are particularly problematic in the presence of already established value chains consuming the easily accessible and low-cost feedstock. As a result, second-generation biofuel supply chains face steep supply curves with sharply increasing unit costs. This article investigates the impact of established utilization paths on a large-scale biofuel production value chain. To do so, a mixed-integer linear model is presented which first determines the allocation of biomass resources to CHP plants and domestic consumers. Based on the resulting costs and supply curves, the model then determines the optimum configuration of the synfuel supply chain including locations and capacities of conversion plants, feedstock procurement and transportation. The model is applied to a case study covering six regions in south-central Chile. The total supply chain cost for the production of synthetic gasoline is estimated to amount to 0.8–0.9 € per liter. Feedstock costs of the synfuel supply chain are 20–50% higher in comparison to the price paid by CHP plants and households. The results indicate that both torrefaction and fast pyrolysis can be applied beneficially to utilize remote biomass resources which are less in demand by established consumers.

1. Introduction

1.1. Production of synfuel via thermo-chemical conversion

Liquid biofuels are considered a potential solution to mitigate emissions from the transportation sector and to reduce the global dependency on fossil fuels. However, the production of first-generation biofuels based on energy crops has also led to environmental and social concerns regarding the utilization of arable land [1]. It has therefore been proposed to utilize agricultural and forest residues to produce second-generation biofuels. Biomass-to-liquid (BtL) concepts based on large-scale gasification have been investigated as a pathway to produce high-quality transportation fuels from low-quality residual feedstock, such as wheat straw or forest residues [2]. In comparison to first-generation feedstock, residues are often characterized by contamination and lower quality in terms of chemical composition and energy content.

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Utilization of straw is complicated by the higher ash content in comparison to other lignocelluloses, such as wood. Biomass-to-liquid (BtL) concepts based on large-scale gasification can be used to produce biofuels from low-quality residual feedstock [3]. During gasification, the biomass feedstock is converted into synthesis gas (or syngas), a mixture of carbon monoxide, hydrogen and carbon dioxide. The syngas can be burnt directly in a gas engine or used to produce synthetic fuel (synfuel) or chemicals such as methanol [2,4].

The production of synthetic biofuels can be based on different gasification technologies, including fixed-bed, fluidized bed and entrained flow gasifiers. According to [5], mainly fluidized bed and entrained flow gasifiers are considered for synfuel production as these reactor designs offer the best scale-up potential. Fluidized bed gasifiers are characterized by simple construction, low capital investment and high cold gas efficiency [6]. Moreover, fluidized bed gasification is a well-established technology for the conversion of biomass. In contrast, entrained flow gasification of biomass is still at a research stage. However, entrained flow gasifiers have been widely used for coal gasification [5,7]. They have been considered a promising alternative for large-scale biomass gasification as they produce a synthesis gas with a very low tar and methane content and achieve nearly complete carbon conversion [7,8]. Disadvantages of entrained flow gasification include higher capital costs, more complex construction and more intensive pre-treatment of the feedstock as smaller particle sizes are required [6,9]. Fluidized bed and entrained flow gasification were compared in detail in [6,9,10].

Many concepts for synfuel production assume that the biomass feedstock undergoes thermal pre-treatment (pyrolysis, torrefaction) before gasification [8,11–14]. In the case of entrained flow gasification, pre-treatment is necessary to achieve the required particle size of the feedstock [8]. However, thermo-chemical conversion has also been proposed in combination with fluidized bed gasification to increase the efficiency of the gasification step [11,12]. Fast pyrolysis is a thermal process that takes place at a temperature of 300–650 °C and in an inert atmosphere [7]. Pyrolysis of biomass yields three different fractions: The liquid main product, called bio-oil, char and non-condensable gases. Bio-slurry is a highly viscous suspension of bio-oil and milled char. As char has a higher LHV than bio-oil, slurry production leads to further densification in terms of energy content and reduces the transportation cost per GJ delivered [2,15].

As an alternative to pyrolysis, torrefaction was proposed for the pre-treatment of biomass before gasification [16–20]. Torrefaction is a thermal process that decomposes biomass at temperatures between 200 and 300 °C and moderate heating rates [7,21,22]. The solid product is a dark and brittle substance of low moisture content and increased heating value, which has to be pelletized for storage, handling and transportation. Torrefaction reduces the O/C ratio of the feedstock and increases the efficiency of a subsequent gasification step [19,20,23,24].

1.2. Assessment of synfuel supply chains

The costs of synthetic biofuel production via gasification were investigated in a number of studies and estimated at 1.0–1.5 € per liter [14,25–27]. In order to take advantage of economies of scale, large-scale entrained flow gasification with capacities of 1000–1500 MW_{th} input to the gasifier was proposed in [27–29]. To supply a synthesis plant of this size with input, large amounts of biomass feedstock are needed which requires transports over long distances. Many BtL concepts, hence, include a decentralized pre-treatment step where feedstock is densified via fast pyrolysis or torrefaction and transported to a centralized large-scale gasification and synthesis plant. The supply chain cost of decentralized pre-treatment was investigated in [27,28,30]. These studies compare the economies of scale of the pre-treatment plants to the transportation costs in order to determine the total cost of decentralized pre-treatment. Braimakis et al. analyzed the transportation of bio-oil by truck and pipeline to a large gasification plant and found that the cost of the pyrolysis process generally is not compensated by reduced transportation costs [30]. In contrast, Henrich et al. concluded that fast pyrolysis enables cost-efficient transport to a centralized gasification facility, but also assumed that bio-oil and char are transported as bio-slurry and that train transportation is available for slurry transport [27]. Magalhães et al. compared fast pyrolysis and torrefaction as pre-treatment before gasification and found that torrefaction was economically preferable for the pre-treatment of wood [28]. Moreover, densification of biomass via pyrolysis and torrefaction was generally evaluated positively in international supply chains where densified pre-treatment products are shipped overseas to a large gasification plant from countries with low-cost biomass resources [31–34].

Other studies presented optimization models to determine the optimum configuration of the supply chain. Models specifically designed for a BtL supply chain are developed in [35–38]. The production of BtL fuels is also modelled in [39] together with a large set of other utilization paths. Optimization models for decentralized pyrolysis, including mobile pyrolysis plants, with subsequent upgrading are presented in [40,41]. The choice of different transportation modes including train and barge was modelled in [38,39,42–44]. Stochastic optimization models were developed in [35,41,45–47] to consider uncertainties of synfuel production and to obtain more robust supply chain configurations. Other articles have applied multi-criteria optimization to include ecological or social impacts in the evaluation [40,44,48–50]. Different products including gasoline, diesel and jet fuel can be produced from syngas. Thus, strategic production decisions under different market scenarios were modelled in [38,51]. The literature discussed above refers to synfuel supply chains based on thermo-chemical conversion processes and does not include heat and power or first-generation biofuels. Comprehensive reviews of optimization models for biomass-based supply chains in general were conducted in [52–55].

1.3. Motivation and scope of the study

Previous studies have estimated that feedstock costs account for approximately half of the cost per liter of gasoline. These existing assessments, however, do not consider the cost elasticity of feedstock supply. Depending on the steepness of the terrain and the willingness of feedstock owners to sell, increasing unit costs can be observed if biomass potentials are utilized to a large extent. This relationship between feedstock cost and supply is particularly relevant for biomass-to-liquid concepts based on large-scale gasification. Due to the need for large quantities of low-cost feedstock, the profitability of such concepts is very sensitive to any increase in feedstock costs. Such diseconomies of scale are especially critical if biomass potentials are already utilized by established value chains which consume the easily obtainable and low-cost biomass resources. Existing models for synfuel supply chains are based on the assumption that biomass potentials can be allocated to utilization paths without any preference. However, it can be observed in practice that existing value chains take precedence over potential new concepts. For instance, forest residues are frequently utilized by the company owning the respective plantation or sawmill and therefore do not enter the market. This has two implications for the production of BtL fuels: First, a potential synfuel production must be based on feedstock which is not already used as an energy source by CHP plants or households. Second, BtL supply might face very steep cost-supply curves as only biomass resources with limited accessibility are left.

In this article, an optimization model is developed which takes into account the impact of competing utilization paths. The model first determines the allocation of biomass resources to existing value chains using local supply curves of the biomass potentials. Based on the resulting costs and supply levels, the model then determines the optimum configuration of the synfuel supply chain including locations and capacities of conversion plants, feedstock procurement and transportation.