



Optimal locations for second generation Fischer Tropsch biodiesel production in Finland



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ABSTRACT

A country level spatially explicit mixed integer linear programming model has been applied to identify the optimal Fischer Tropsch biodiesel production plants locations in Finland. The optimal plant locations with least cost options are identified by minimizing the complete costs of the supply chain with respect to feedstock supply (energywood, pulpwood, sawmill residuals, wood imports), industrial competition (pulp mill, sawmill, combined heat and power plants, pellet industries) and energy demand (biodiesel, heat, biofuel import). Model results show that five biodiesel production plants of 390 MW_{feedstock} are needed to be built to meet the 2020 renewable energy target in transport (25.2 PJ). Given current market conditions, the Fischer Tropsch biodiesel can be produced at a cost around 18 €/GJ including by-products income. Furthermore, the parameter sensitivity analysis shows that the production plant parameters such as investment costs and conversion efficiency are found to have profound influence on the biodiesel cost, and then followed by feedstock cost and plant size. In addition, the variations in feedstock costs and industrial competition determine the proportion of feedstock resource allocation to the production plants. The results of this study could help decision makers to strategically locate the FT-biodiesel production plants in Finland.

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1. Introduction

Finland plays a leading role as a member state of the European Union in implementing EU's integrated climate and energy package by adopting mandatory 20/20/20 targets in order to build a sustainable energy efficient Europe [1]. In November 2008, the nation's long-term climate and energy strategy approved by the Finnish Parliament set binding targets to achieve a 38% share of renewable energy on the final energy consumption, and 10% renewable energy share in transport fuel consumption by 2020 [2]. Recently, the Finnish government enacted an act on biofuel minimum distribution requirement based on double-counting method that sets a year wise obligatory use of biofuels in traffic should be at least 6%(2011–2014), 8%(2015), 10%(2016), 12%(2017), 15%(2018), 18%(2019) and 20%(2020) [3]. In addition, the National Renewable

Action Plan 2010 strives to increase the present consumption of forest chips from 6 million m³ to 13.5 million m³ (97 PJ) by 2020, mainly for combined heat and power (CHP) production and separate heat production [4]. One way to reach these ambitious targets is to promote the use of lignocelluloses i.e., wood-based raw material, in liquid biofuel production which would eventually transform the existing fossil fuel based economy into a low carbon economy, which in turn also boosts bio-economy as a whole. As a forest resource rich country (73% of total land area) and a pioneer in forest technology, Finland has a long standing tradition of utilizing forest biomass for bioenergy production, mainly CHPs. In 2009, wood fuels accounted about 21% of primary energy production [5]. To achieve 10% (25.2 PJ from 2005 base year) biofuel share in traffic substituted with wood-based biodiesel production would require around 4.6 million m³ (82 PJ) of wet forest biomass to be harvested annually.

Meanwhile, the Finnish forest industry is undergoing a rapid structural changes, particularly pulp and paper industries, and pellet industries are being closing down which would provide an opportunity for energy industries to tap the unutilized biomass

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resources. Heinimö et al. [6] have estimated that an additional 15 million m³ of forest biomass could be available for bioenergy production by 2020 based on the projections conducted on outlook of Finnish forest industry production and consumption [7]. However, in practice, the availability of biomass for energy production is restricted by several factors like land ownership, harvesting operations/conditions/seasons, industrial competition, annual growing stock increment, market price, and raw wood import.

Domestic second generation biodiesel production offers an excellent opportunity to use locally available biomass as an alternative to fossil fuel import reducing dependency on imports and achieving energy security. Fossil fuel imports cover nearly half of country's total energy requirements where gasoline consumption continued to follow a downward trend while diesel consumption has been increasing steadily [8]. Although significant proportion of biofuel (renewable diesel, ethyl tert-butyl ether and bioethanol) is produced and blended with gasoline and diesel, the origin of the feedstock is animal fat, imported vegetable oils, imported palm oil, imported ethanol, and food industry waste. Therefore, biodiesel production from forest biomass could not only provide environmental benefits like carbon dioxide (CO₂) emission reductions [9] but also offers new economic opportunities like employment to the society [10]. Moreover, biodiesel is sulfur free having higher cetane number of around 75 which can be directly used in the conventional diesel engines without requiring any further engine modifications [11].

As it stands on today, the Finnish second generation Fischer Tropsch (FT) biodiesel production technology is at its pinnacle in the world to demonstrate the conversion of woody biomass into biodiesel. Since 2006, several consortiums have been formed to develop, demonstrate and commercialize the second generation FT-biodiesel production technology. Companies like UPM, Neste oil–Stora Enso, and Metsäliitto–Vapo possess biomass to liquids (BTL) technological know-how and one example was the Neste–Stora's small scale demonstration plant (12 MW gasifier) at Stora Enso Varkaus mill [12]. However, commercial FT-biodiesel plants have not yet been constructed and recently, Metsäliitto–Vapo's FT-biodiesel concept was approved for investment grant under the European Union's NER 300 subsidy to begin their commercial operation at Kemi [13]. Most importantly, such large-scale commercial production of FT-biodiesel would face great number of challenges such as cost-optimal plant locations, high investment costs, secure biomass supply, industrial competition, transportation logistics, mature production technology, market demand, and social acceptance.

The overarching objective of this paper is to investigate the potential expansion of the second generation FT-biodiesel industry in Finland. However, the commercial FT-biodiesel production should take place in a large-scale in order to be economically competitive, and also achieve improved efficiency and economy of scale [14]. On the other hand, the commercial-scale plant would require huge amount of biomass to be procured and transported to the plant. Similarly, produced biodiesel should be delivered to the potential customers as well. Therefore, a well-designed supply chain with respect to biomass supply and energy demand is essential to allocate the limited biomass resources to the production plant both by cost efficiently and environment sustainably.

2. Materials and methods

2.1. Optimization modeling

Previously, several methods have been developed to solve the wide range of facility location problems; GIS based [15–18], LP [19], MILP [20–25] and MINLP [26]. In this paper, a robust country level

MILP optimization model (BeWhere) [27] is used to solve the formulated facility location problem (FLP). The model minimizes the complete costs of FT-biodiesel supply chain from feedstock supply to biodiesel delivery at the gas stations to determine the number, optimal location, size and configurations of FT-biodiesel production plants in Finland as given in the equation (1);

$$C_{\text{total}} = C_{\text{supply chain}} + E_{\text{supply chain}} \cdot C_{\text{CO}_2} \quad (1)$$

where C_{total} is the total supply chain cost, $C_{\text{supplychain}}$ the costs of the supply chain, $E_{\text{supplychain}}$ the emissions of the supply chain and C_{CO_2} the carbon tax for CO₂ emissions. The supply chain economics $C_{\text{supplychain}}$ include:

- Feedstock harvesting, communiton and collection costs
- Long distance transportation cost of feedstock from supply site to production plant (truck and train)
- FT-biodiesel plant installation and production costs
- FT-biodiesel transportation and distribution costs at the gas stations
- Income from by-products (heat and electricity)

The supply chain emissions $E_{\text{supplychain}}$ include:

- Fossil fuel CO₂ emissions of feedstock and FT-biodiesel transportation (truck and train)
- Offset emissions from displaced fossil diesel, heat and electricity

The total cost of the supply chain C_{total} is minimized subjected to constraints such as feedstock supply capacity, production plant and energy demand. The model selects the least costly pathways from one set of feedstock sourcing points to a specific FT-production plant location, and further to a set of energy demand points. The structure of the model is presented in Fig. 1. A continuous variable is associated to each arc, representing delivery of feedstock, FT-biodiesel and heat energy. Binary variables are associated to the plant nodes, modeling when the current plant is in operation.

The model has previously been applied for different countries like Austria [28,29], Sweden [30] or India [31]. A complete description of the model with mathematical formulations can be found in Refs. [32] or [33]. The main difference of this work from earlier studies [15–26] is that the proposed model includes a national level database on forest resources (saw wood, pulpwood, energywood), existing industrial supply and demand, complete supply chain, detailed transport network, state of the art technology and energy demand (dwelling heat, transport fuel, biofuel import). A complete flow of feedstock and energy between different end users used in the model is presented in Fig. 2. The model calculates which type of feedstock is cost-optimal to be used for biodiesel production, and also from where and how much it shall procure. Moreover, the model allocates feedstock resources to the FT-biodiesel production plants only after meeting the existing feedstock demand from the wood based industries. In addition, a transport fuel demand constraint which considers the competition between FT-biodiesel and fossil fuels is defined for each city. Furthermore, spatial distribution of heat demand is modeled to distribute the residual heat produced at the plant. In total, 120 possible production plant locations (grid points close to high feedstock supply, high energy demand, ports, industries) covering the entire country were then used in the model analysis.

2.2. Feedstock supply

The information on the spatial availability of feedstock resources and its potential route flow is crucial to realistically model the

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