OPTIMAL LOCATION FOR A BIOMASS BASED METHANOL PRODUCTION PLANT: CASE STUDY IN NORTHERN SWEDEN

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ABSTRACT: Methanol appears to be a new alternative fuel in the transport sector. Methanol can be produced through gasification of lignocellulosic biomass, which makes it a renewable fuel, and its utilization has therefore an impact on greenhouse gas emissions. The county of Norrbotten in northern Sweden has the characteristic to have great amount of woody biomass, and a sparsely inhabited area. Transportation distances of both biomass and methanol would then have a great impact on the final cost of methanol depending on where the methanol plant is located. This county was therefore studied as a case study with a twenty year perspective in order to validate an optimization model. The optimal locations of three different sizes of methanol plants were studied for four demographic scenarios. From this study it appears that methanol plants of 100 $MW_{biomass}$ and 200 $MW_{biomass}$ would be set up closer to the demand area than a 400 $MW_{biomass}$ that would optimally be set up more inlands close to the available biomass.
Keywords: bio-methanol, forestry, gasification, agriculture

1 INTRODUCTION

1.1 Background

An increased utilization of bioenergy constitutes one of the key alternatives to replace fossil fuels and mitigate green house gas emissions. At present, several different routes for biomass based heat and power production are established in a variety of markets, but only a small amount of liquid biofuels is produced.

Substituting fossil fuels in the transportation sector does not only serve the purpose to mitigate the climate impact, but also to decrease the oil dependency. The global transport sector is today highly dependant on fossil fuels and the introduction of biofuels is an important measure to reduce the CO_2 emissions in this sector. The European Commission has set a target that biofuels should constitute 5.75% of the sold volume of transport fuels in Europe by the year 2010 [1].

Considerably larger renewable fuel volumes would be necessary to give an increased supply security and decrease the CO_2 emissions. With today's price levels on biofuels, the costs for the society would be high. It is therefore of significant importance to promote measures to reduce the costs for the introduction of biofuels on the market.

Biomass based methanol appears to be a potential competitor to fossil fuel in the transportation sector. The total feedstock cost including transportation constitute more than 40% of the total production cost and the methanol transport around 5% if only truck transportation is considered [2]. These cost shares differ a lot depending on where the methanol plant is located relative to the feedstock and the gas stations. It is therefore of great importance to build the plants at proper locations and in appropriate sizes to minimize the transportation cost and thereby also reduce the production cost.

1.2 Objectives

The main objective of this study has been to find an appropriate geographic position of a methanol production plant of a certain size by the minimization of the transport costs. In this study, the county of Norrbotten in northern Sweden has served as a case study. It is however important to stress that this is only an illustrative study, since sale of the waste heat is not considered and the data on the forest fuel availability is not accurate enough. The found location must therefore be regarded as highly uncertain.

2 METHODOLOGY

To assess an appropriate plant location, it is crucial to know available amount and location of the feedstock as well as user demand and demand density in a future perspective. In this study, four different fuel demand scenarios have been created and the forest fuel resources have been assessed until the year 2025.

2.1 Automotive fuel demand

The future development of the automotive fuel demand is strongly depending on demographic changes, changes in car travel habits, infrastructure as well as the technological development of the cars, in particular the fuel efficiencies of the engines. The total transportation fuel demand (E_{fuel}) have been calculated according to equation (1):

$$E_{fuel} = P \cdot l_c \cdot c_p \cdot e_d \qquad (1)$$

where P represents the total population, l_c is the average driving distance per car and year, c_p is the number of cars per capita, and e_d is the specific average fuel consumption (kWh per km).

Two different population scenarios titled A and B (created by use of a population projection model (PDE – Population-Development-Environment developed by the International Institute of Applied System Analysis (IIASA)) constitute the base of four different fuel demand scenarios (A-BAU, B-BAU, A-Green and B-Green). The BAU scenarios illustrate how the demand would develop if present trends of all variables continue, while the Green scenarios aim to illustrate how the fuel demand would develop towards a more environmentally friendly future. A more detailed description of the methodology and the made assumptions can be found in Lundgren, 2007 [3].

2.2 Methanol production chain

Biomass supply

The estimation of the future potential biomass production is based on data from a forest inventory [4], which comprises about 12,000 forest plot measurements arranged in clusters of around nine circular plots (ca 0.007 ha each) that are evenly distributed over the study area. For each plot, biomass and biomass-growth per hectare of the three most abundant tree species (Norway spruce, Scots pine, and birch) and other deciduous trees are reported. Each plot is representative of a surrounding forest area, which varies in size between plots and is not geographically explicitly defined. These forest inventory data were converted to a geographically explicit grid using the following method: the whole study area was divided into equally sized grid-cells, 10x10 km. For each inventory plot and tree species, the representative forest area was assumed to be circular and centered in the location of the plot. The circular forest areas of the plots were then laid over the grid-cells and distributed to the grid cells covered according to the area covering each grid cell.

Biomass productivity was estimated for each grid-cell and tree species using the plot data assigned to each cell (2-50 plots per cell), where each data point (plot) was weighted by the forest area it covers in the grid-cell. By fitting the set of biomass, age and biomass-growth data points for each grid-cell to species specific biomass growth functions [5], site productivity and the mean biomass production over time was estimated. In this estimation it was assumed that the forest management (for example thinning intensity) is not changed, and that forest stands are harvested at an age that maximizes harvested biomass over time. The biomass growth functions used in the estimation relate biomass, growth, age, stand density and site productivity and have been parameterized for all included species using an extensive set of yield table data [5].

Biomass transportation

The biomass transportation cost (in €/TJ) is described by Börjesson et al., 1996 [6]. In the county of Norrbotten, only tractor-trailer and truck transportations are considered represented by equations (2) and (3) respectively.

$$\mathrm{C}_{\mathrm{Truck}} = 344 + 7.77d \qquad (2)$$

$$\mathrm{C}_{\mathrm{Tractor}} = 226 + 12.78d \qquad (3)$$

The actual distance (in km) to the methanol plant, d, is defined as the direct distance multiplied by the estimated ratio of actual road length to direct distance (this ratio has an average value of 1.34 for Norrbotten). These values correspond to the transportation costs if the biomass is extracted from the surrounding areas.

Methanol production

Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following steps: pre-treatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification [7]. A gas turbine or boiler is optional to employ the unconverted gas equipments for heat production (or a steam turbine for electricity co-production). In this paper an atmospheric indirectly fired gasifier is selected. This is a fast fluidized bed gasifier suitable for large-scale fuel gas production [7].

Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (such as boilers, turbines, etc.). This difference can be adjusted using the scaling function:

$$\frac{Cost_a}{Cost_b} = \left(\frac{Size_a}{Size_b}\right)^R \qquad (4)$$

where R is the scaling factor, $Cost_a$ and $Cost_b$ are the costs of equipments for the bio-fuel plant (a) and (b) respectively, and $Size_a$ and $Size_b$ are the sizes of the bio-fuel plant (a) and (b), respectively. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding investment costs from the separate units, the total investment cost for the new size is determined, and production cost for the current methanol plant size can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [8]. The uncertainty range of such estimates is up to ± 30% [7].

Methanol transportation

The transport infrastructure in Norrbotten is mainly suitable for trucks all over the county. The costs of methanol transportation by truck are calculated using figures from Börjesson et al., 1996 [6]. The transportation cost by truck (in €/$\mathrm{TJ}_{\mathrm{methanol}}$) is described in equation (5):

$$\mathrm{C}_{\mathrm{Truck}} = 138 + 3.05d \qquad (5)$$

where d is the direct distance (in km) from the methanol plant to the gas stations multiplied by the estimated ratio of actual road length to direct distance (this ratio is the same as the for the biomass transportation).

Methanol distribution

It is assumed that all the gas stations that are considered are able to distribute methanol. As methanol today is not widely used in the transportation sector, changes to gas stations would be required. The cost for handling methanol at a gas station with a capacity of 125,000 liters/month is between 0.2031 and 0.2412 €/$\mathrm{GJ}_{\mathrm{methanol}}$. The costs are assumed to be independent of the station size [9].

2.3 Model

This section formulates the problem as a Facility Location Problem (FLP). Solving the problem will result in the optimal locations and sizes of the plants and gas stations. The model is defined as a mixed integer linear optimization problem [10].

The parameter S is the number of biomass supply regions, P is the number of plants, G is the number of gas stations, D is the number of demand regions, Y is the number of years in the planning horizon. The corresponding sets are: $\tilde{S}=\{1,...,S\}$, $\tilde{P}=\{1,...,P\}$, $\tilde{G}=\{1,...,G\}$, $\tilde{D}=\{1,...,D\}$, $\tilde{Y}=\{1,...,Y\}$.

The following variables are defined: $b_{i,j,y}$, the amount of biomass delivered from supply region i to plant j in year y, $x^{biofuel}_{j,k,y}$, the amount of biofuel delivered from plant j to gas station k in year y, and $x^{biofuel}_{k,l,y}$, the amount of biofuel sold at gas station k to costumers from demand region l in year y. The variable $x^{fossil}_{l,y}$ is the amount of fossil fuel sold to costumers from demand region l year y. The binary variables are $u_{j,y}$ and $u_{k,y}$, respectively, indicating if the plant j and the gas station k is in operation year y. If $u_{j,y}$ ($u_{k,y}$) is equal to one, then the plant (station) is in operation, otherwise $u_{j,y}$ ($u_{k,y}$) is zero.

The cost for producing biomass in supply region i year y is $c_{i,y}$. The biomass delivered from region i is restricted by

$$\sum_{j=1}^{P} b_{i,j,y} \le \bar{b}_{i,y}, \qquad i\in\tilde{S}, y\in\tilde{Y} \tag{6}$$

where $\bar{b}_{i,y}$ is the available biomass. The cost for transporting biomass from supply region i to plant j is $t_{i,j,y}$.

Plant j is described by the following parameters and equations. The cost for building a plant with maximal biofuel capacity $\bar{x}^{biofuel}_{j}$ in year y is $e_{j,y}$, and the cost for producing biofuel in the plant is $c_{j,y}$. The biofuel production is thus restricted by

$$\sum_{k=1}^{G} x^{biofuel}_{j,k,y} \le \bar{x}^{biofuel}_{j} u_{j,y}, \qquad j\in\tilde{P}, y\in\tilde{Y} \tag{7}$$

The biofuel produced at a plant is limited by the capacity of the certain plant.

The efficiency producing methanol is $a^{biofuel}_{j}$, giving

$$a^{biofuel}_{j}\sum_{i=1}^{S} b_{i,j,y} = \sum_{k=1}^{G} x^{biofuel}_{j,k,y}, \qquad j\in\tilde{P}, y\in\tilde{Y} \tag{8}$$

The biomass received at the plant, i.e. harvested biomass, multiplied by the plant efficiency, is then the output of biofuel delivered to the gas stations.

The cost for setting up a gas station k year y with the capacity $\bar{x}^{biofuel}_{k}$ is $e_{k,y}$. The cost for handling biofuel at the station is $c_{k,y}$. Similar to the plant procedure, the gas station is also modeled using capacity and mass flow equations, i.e.

$$\sum_{l=1}^{D} x^{biofuel}_{k,l,y} \le \bar{x}^{biofuel}_{k} u_{k,y}, \qquad k\in\tilde{G}, y\in\tilde{Y} \tag{9}$$

and

$$\sum_{j=1}^{P} x^{biofuel}_{j,k,y} = \sum_{l=1}^{D} x^{biofuel}_{k,l,y}, \qquad k\in\tilde{G}, y\in\tilde{Y} \tag{10}$$

must hold.

The demand for car fuel in region l year y is modeled by

$$\sum_{k=1}^{G} x^{biofuel}_{k,l,y} + x^{fossil}_{l,y} = d_{l,y}, \qquad l\in\tilde{D}, y\in\tilde{Y} \tag{11}$$

where $d_{l,y}$ is the demand. The corresponding transportation cost is $t_{k,l,y}$, which is interpreted as the driving cost for people driving from region l to gas station k. The fossil fuel is assumed to be available for a price $p^{fossil}_{l,y}$.

Once a plant or a gas station is built, it is available the following years. This is modeled using

$$u_{j,y} \ge u_{j,y-1}, \qquad j\in\tilde{P}, y\in\tilde{Y} \tag{12}$$

and

$$u_{k,y} \ge u_{k,y-1}, \qquad k\in\tilde{G}, y\in\tilde{Y} \tag{13}$$

Given the costs and prices (exogenously), the objective function is defined as

$$\begin{cases} f(b,x,u) = \\ \sum_{y=1}^{Y}\sum_{i=1}^{S}\sum_{j=1}^{P}\left(c_{i,y}+t_{i,j,y}\right)b_{i,j,y} + \sum_{y=1}^{Y}\sum_{j=1}^{P} e_{j,y}\left(u_{j,y}-u_{j,y-1}\right) \\ +\sum_{y=1}^{Y}\sum_{j=1}^{P}\sum_{k=1}^{G}\left(c_{j,y}+t_{j,k,y}\right)x^{biofuel}_{j,k,y} + \sum_{y=1}^{Y}\sum_{k=1}^{G} e_{k,y}\left(u_{k,y}-u_{k,y-1}\right) \\ +\sum_{y=1}^{Y}\sum_{k=1}^{G}\sum_{l=1}^{D}\left(c_{k,y}+t_{k,l,y}\right)x^{biofuel}_{k,l,y} + \sum_{y=1}^{Y}\sum_{l=1}^{D} p^{fossil}_{y,l}\, x^{fossil}_{l,y} \end{cases} \tag{14}$$

The different summands are:

- Cost of biomass production (parameter) plus the transportation cost (parameter) times the amount of biomass which is actually taken (variable)
- Plant setup cost (parameter) times the “decision” (variable) of building a plant
- Plant production cost (parameter) plus transportation cost of biofuel from the plant to the gas stations (parameter) times the amount of methanol being produced at the plant (variable)
- Setup cost of gas stations (parameter) times the “decision” (variable) of setting up a gas station
- Gas station handling cost (parameter) plus transport cost from the gas station to the living area (parameter) times the amount of bio fuel taken from the gas station (variable)
- Price of fossil fuel (parameter) times the amount of fossil fuel taken (variable)

Finally, define the FLP problem as

$$\min_{b,x,u}\left[f(b,x,u)\right]$$
$$s.t.$$
$$(6)-(14) \qquad (15)$$
$$b_{i,j,y}, x^{biofuel}_{j,k,y}, x^{biofuel}_{k,l,y}, x^{fossil}_{l,y} \geq 0,$$
$$i \in \tilde{S}, j \in \tilde{P}, k \in \tilde{G}, l \in \tilde{D}, y \in \tilde{Y}$$
$$u_{j,y} \in \{0,1\}, u_{k,y} \in \{0,1\},$$
$$j \in \tilde{P}, k \in \tilde{G}, y \in \tilde{Y}.$$

3 CASE STUDY

Norrbotten is the largest county in Sweden covering around 25% or 98,911 km^2 of the country's total area. Norrbotten is sparsely populated with an average population density of around four inhabitants per square kilometer and is strongly characterized by its arctic climate. Norrbotten is also a county with abundant resources of biomass. At present, most of the resources are used in the paper- and pulp industries, sawmills, district heating plants and in domestic boilers. The actual supply of wood-fuels, reaching nearly 2.3 TWh per year, represents around 6% of the total primary energy supply in Norrbotten. The total biomass supply (including peat, municipal waste, black liquor, etc.) amounted to 8.1 TWh in the year 2004 [11] and the annual usage of wood-fuel amounts 1.8 TWh. No liquid biofuels are currently produced, even if the potential is considered as large. Norrbotten has the particularity that biomass shall be supplied from long distances over the county and methanol supplied to concentrated areas around the coastline.

Fourteen potential locations for the construction of the plants are studied. These are the positions of the main cities and towns in Norrbotten (Table I).

Table I: Potential locations of the methanol plants and coordinates

Location number	City name	Longitude (˚E)	Latitude (˚N)
1	Älvsbyn	21	65.65
2	Arjeplog	17.90	66.03
3	Arvidsjaur	19.15	65.58
4	Boden	21.63	65.83
5	Gällivare	20.67	67.18
6	Haparanda	24.05	65.80
7	Jokkmokk	19.85	66.58
8	Kalix	23.20	65.83
9	Kiruna	20.28	67.85
10	Luleå	22.08	65.62
11	Överkalix	22.83	66.32
12	Övertorneå	23.62	66.37
13	Pajala	22.77	67.29
14	Piteå	21.37	65.23

Three different methanol plant sizes have been considered. The scenarios S-I, S-II and S-III consider plant sizes of 400 $MW_{biomass}$, 200 $MW_{biomass}$ and 100 $MW_{biomass}$ respectively. Table II shows required fuel input per year for each plant size assuming an overall efficiency of 55%.

Table II: Sizes of the methanol plants studied

Plant scenario	Plant size $MW_{biomass}$	Required fuel input GWh/year
S-I	400	2,880
S-II	200	1,440
S-III	100	720

4 RESULTS AND DISCUSSION

4.1 Future automotive fuel demand

This paper studies four different scenarios of transportation fuel demand in Norrbotten until the year 2025. There is a national goal that biofuels should constitute 20% of the total transportation fuel demand by the year 2020. In the so-called 'business as usual' (BAU) scenarios it is assumed that the goal is reached. The 'green scenarios' (Green) are even more optimistic assuming a biofuel share of 75% until the year 2025. Figure 1 describes the total fuel demand as well as the assumed evolution of the fuel shares (gasoline, diesel and biofuel) for the years 2004 to 2025.

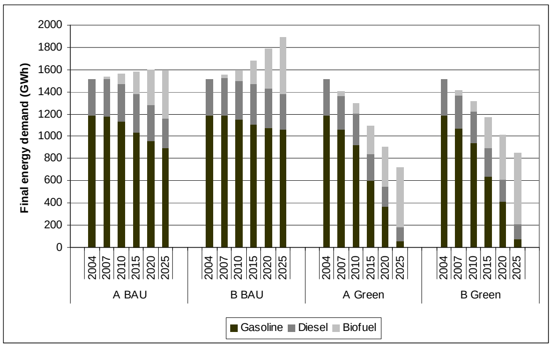

Figure 1: Total transportation fuel demand in Norrbotten until the year 2025 according to the four scenarios

As shown in the figure, the two reference (BAU) scenarios show on increasing motor fuel demand, while both of the alternative ones (Green) show on a significant reduction. Based on the assumed shares the biofuel demand will be in the range of 430-640 GWh per year in the year 2025.

4.2 Feedstock

Woody biomass from the forest is used as a feedstock. It includes pine, spruce, birch and other deciduous trees. According to the calculations, the theoretically potential woody biomass would be 8.4 TWh/year (Table III) until 2025.

Table III: Woody biomass potential in Norrbotten until 2030

Feedstock	Pine	Spruce	Birch	Deciduous trees
Potential (GWh/year)	3.66	1.73	2.76	0.26

4.3 Plant locations Perspective until 2025

For all four scenarios, each methanol plant selected would be set up from the first year. The results are similar for all the demographic scenarios. In Table IV the optimal positions of the three different sizes of plants are presented.

Table IV: Results for the different scenarios

	Unit	S-I	S-II	S-III
Location number		1	14	14
Size	$MW_{biomass}$	400	200	100
Area	10^3 ha	283	206	103
Supply	%	100	65	27
Max biomass Transports	km	251	274	274
Max methanol transports	km	444	197	103
Feedstock	€/GJ	4.35	4.35	4.35
Feedstock transport	€/GJ	4.12	4.49	4.49
Methanol transport	€/GJ	1.97	0.95	0.56
Plant costs	€/GJ	8.86	10.93	13.54
Total cost	€/GJ	19.53	20.95	23.17

Table IV shows that a 400 $MW_{biomass}$ would produce the cheapest methanol (19.53 €/GJ). This plant would cover the demand for the all county until 2025 for all demographical scenarios. There would moreover be excess production for some eventual exports. The methanol plants of 200 $MW_{biomass}$ and 100 $MW_{biomass}$ will not cover the demand in Norrbotten, even not in 2025, where a methanol plant of 215 $MW_{biomass}$ is needed for the scenario with less biofuel (BAU-A). Anyhow, they would supply respectively 65% and 27% of the demand. The maximum driven distance for biomass transportation is almost the same for the three plants: a higher share of the forest was set for the bigger plants. This interprets the consequences of the biomass availability in Norrbotten.

Concerning the optimal position of the methanol plants, the smaller plants are both located closer to the demand on the sea coast. The 400 $MW_{biomass}$ plant, which has a greater need of raw material, would be optimally set up more inlands, as close as possible to the biomass.

4.4 Competition with other fuels

A study from Faaij, 2000 [12], and Turkenburg, 2000 [13], predicts the evolution of different fuel production costs in the short- and long-term (Table V).

Table V: Short- and long-term production cost range for different fuels [12], [13]

Fuel type (feedstock)	Short-term (€/GJ)	Long-term (€/GJ)
Gasoline/diesel (fossil)	4-7	6-10
Hydrogen (cellulose)	9-12	4-8
Ethanol (sugar)	25-35	20-30
Ethanol (cellulose)	12-17	4-7
Methanol (cellulose)	10-15	6-8
Biodiesel (rape seeds)	25-40	20-30

In the long-term, ethanol can be produced at a cost in the range of 4-7 €/GJ and methanol at 6-8 €/GJ (Table V). These estimations are promising and fit with the results obtained (Table IV) where methanol production costs would vary from 8.86 €/GJ (400 $MW_{biomass}$) to 13.54 €/GJ (100 $MW_{biomass}$).

From a production cost point of view, ethanol or methanol seem to be the most interesting fuel types to produce from woody biomass to replace gasoline in Norrbotten.

5 CONCLUSIONS AND FUTURE WORK

The study was conducted on a twenty year perspective, for which methanol demand was assessed and biomass supply calculated. For the county of Norrbotten in northern Sweden, the optimal locations of three different sizes (400, 200 and 100 $MW_{biomass}$) of methanol plants were studied for four demographical scenarios. The two smaller methanol plants would optimally be set up closer to the demand areas close to the sea coast, whereas the 400 $MW_{biomass}$ methanol plant would optimally be set up more inlands, closer to the raw material. This article validates the use of an optimization model with regard to the time.

For more accurate results, one should take into account the location and quantity of biomass used from the pulp- and paper industry and other biomass based industries. Feedstock limitation sets an upper limit of the plant size, while production cost sets the lower limit. Taking care of the heat demand in the county would also have a bigger impact on both the location of the plant and the cost of methanol.

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