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Location of a biomass based methanol production plant: A dynamic problem in northern Sweden

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ABSTRACT

Concerning production and use of biofuels, mismatch between the locations of feedstock and the biofuel consumer may lead to high transportation costs and negative environmental impact. In order to minimize these consequences, it is important to locate the production plant at an appropriate location. In this paper, a case study of the county of Norrbotten in northern Sweden is presented with the purpose to illustrate how an optimization model could be used to assess a proper location for a biomass based methanol production plant. The production of lignocellulosic based methanol via gasification has been chosen, as methanol seems to be one promising alternative to replace fossil gasoline as an automotive fuel and Norrbotten has abundant resources of woody biomass. If methanol would be produced in a stand-alone production plant in the county, the cost for transportation of the feedstock as well as the produced methanol would have great impact on the final cost depending on where the methanol plant is located. Three different production plant sizes have been considered in the study, 100, 200 and 400 MW (biomass fuel input), respectively. When assessing a proper location for this kind of plant, it is important to also consider the future motor fuel demand as well as to identify a heat sink for the residual heat. In this study, four different automotive fuel- and district heating demand scenarios have been created until the year 2025. The results show that methanol can be produced at a maximum cost of 0.48 €/l without heat sales. By selling the residual heat as district heating, the methanol production cost per liter fuel may decrease by up to 10% when the plant is located close to an area with high annual heat demand.

1. Introduction

The greenhouse gas emissions from the transport sector represent a large share of the current total anthropogenic emissions, of which road transport is expected to be the largest by 2050 [1]. An increased utilization of bioenergy constitutes one of the key alternatives to replace fossil fuels and mitigate greenhouse gas emissions. At present, 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 and thereby increase the energy supply security. The global transport sector is today highly dependent 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 renewable energies should constitute 5.75% of the sold volume of transport fuels in Europe by the year 2010 [2] and 10% by the year 2020 [3].

Using wood as a primary resource in the transportation sector is a competitive alternative in terms of efficiency, CO_2 mitigation and land requirement [4]. Biomass based methanol appears to be a potential competitor to fossil fuel in the transportation sector, primarily to replace gasoline. Methanol burns at a lower temperature than gasoline, and is less volatile, reducing the risk of explosion or flash fire. Methanol is less flammable than usual gasoline, and methanol fires can be extinguished with water. It also has the advantage of having a greater octane number (107) than gasoline (98). It can also be safely transported by road, rail, barge, ocean tanker or in pipelines. Methanol is also a hydrogen carrier. The main drawbacks using methanol as transportation fuel is that it is a highly toxic substance and that there are concerns about emissions of formaldehyde from methanol-fueled vehicles. Additionally, methanol has lower volumetric energy content than gasoline.

The costs for the feedstock, the feedstock transportation, the methanol production and the methanol transportation represent approximately 26%, 16%, 46% and 12% of the total production cost

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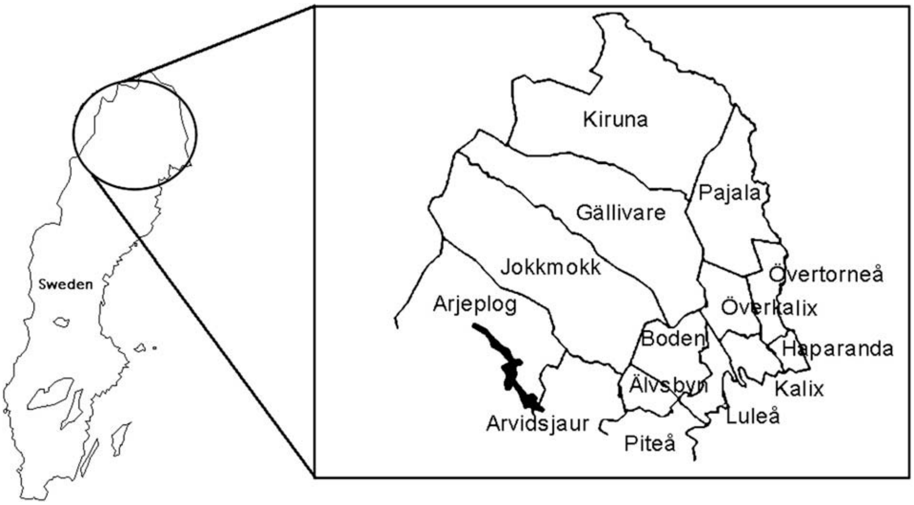

Fig. 1. Maps over the county of Norrbotten subdivided in different municipalities.

respectively; if only truck transportation is considered for a 100 $MW_{biomass}$ plant [5]. These cost shares may differ significantly 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 total production cost.

The main objective of this study has been to illustrate the use of a dynamic optimization model in order to find an appropriate geographic position of a methanol production plant to minimize the specific biofuel production cost. The county of Norrbotten in northern Sweden (Fig. 1), where distances between the major cities and the raw material play an important role, has been used as a case study.

2. Methodology

To be able to minimize the transportation cost of feedstock and the produced fuel, it is crucial to know the available amount and location of the feedstock as well as the local automotive fuel demand. To decrease the specific production cost further, it is also important to identify nearby heat sinks to make the residual heat possible to sell either as district heating to nearby societies or as process heat to other industries. The demands for district heating and automotive fuels change over time, which makes it necessary to also consider the possible future development.

In the case study, four different scenarios on how the demands for district heating and motor fuels may develop until the year 2025 have been created for the county of Norrbotten. Additionally, the future forest fuel resources have been assessed. Three different production plant sizes have been considered in the study, 100, 200 and 400 MW (biomass fuel input), respectively (100 MW fuel input means a methanol production of about 90,000 m^3 annually and a biomass supply of about 700 ton per day roughly corresponding to 100,000 ha of land on annual basis).

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}) has been assessed according to Eq. (1):

$$E_{fuel} = P \cdot l_c \cdot c_p \cdot e_d \tag{1}$$

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

As an approach to assess the future motor fuel demand, four plausible scenarios for fourteen municipalities in the county have been created. Two different population scenarios titled A and B (created by use of a population projection model, PDE – Population-Development-Environment) [6] constitute the base of the four demand scenarios titled A-BAU, B-BAU, A-Green and B-Green. In the A scenarios, the current demographic trends (fertility rate, mortality, net immigration) of Norrbotten continues, which leads to a declining population, from the current level of 251,000 to 215,000 in the year 2025. The B scenarios represents a brighter future, where the population number approximately stabilizes at the current level.

In the BAU (business-as-usual) scenarios, all the considered parameters (see Eq. (1)) that influence the fuel demand have been extrapolated until the year 2025. In the Green scenario, it is assumed that we work less and thereby also make less business trips. Better interactive communication options facilitate distance work meetings as well as the possibility to work from home which reduces the travelling needs for working purposes. As the spare time increases, there is however more time for leisure travelling. Therefore, it is assumed that the present annual driving distance per car remains at the same level until the year 2025.

The development of the influencing parameters have been assessed through literature studies in combination with own assumptions. Table 1 shows the current and future parameter values in each of the municipalities.

According to the European Commission, renewable sources are to account for 20% of the total energy consumption within the EU, of which biofuels should account for at least 10% of the motor fuel consumption by the year 2020 [7]. Partly due to the abundant resources of biomass in the county of Norrbotten, an even more challenging target of 20% biofuels was set in the BAU scenarios. Assuming that the same required growth rate to reach that target continues, the biofuel demand in the year 2025 becomes 27%. Regarding the development of the gasoline and diesel share, the BAU scenarios assume that the present trends continue, which leads to that the gasoline- and fossil diesel shares amount to 51% and 22%, respectively. The Green scenarios assume that biofuels constitutes as much as 75% of the total demand. Regarding gasoline

Table 1
Current and assumed future average values of the influencing parameters in Norrbotten.

	Current situation (2004)	BAU scenarios (2025)	Green scenarios (2025)
Driving distance (km per car and year)	14,800	17,490	14,800
Car ownership (cars per person)	0.53	0.62	0.50
Average gasoline/diesel consumption (litres per 100 km)[a]	8.6/6.8	7.5/5.5	4.2/3.4

[a] Specific biofuel consumption is assumed to be 30% higher on volume basis than gasoline.

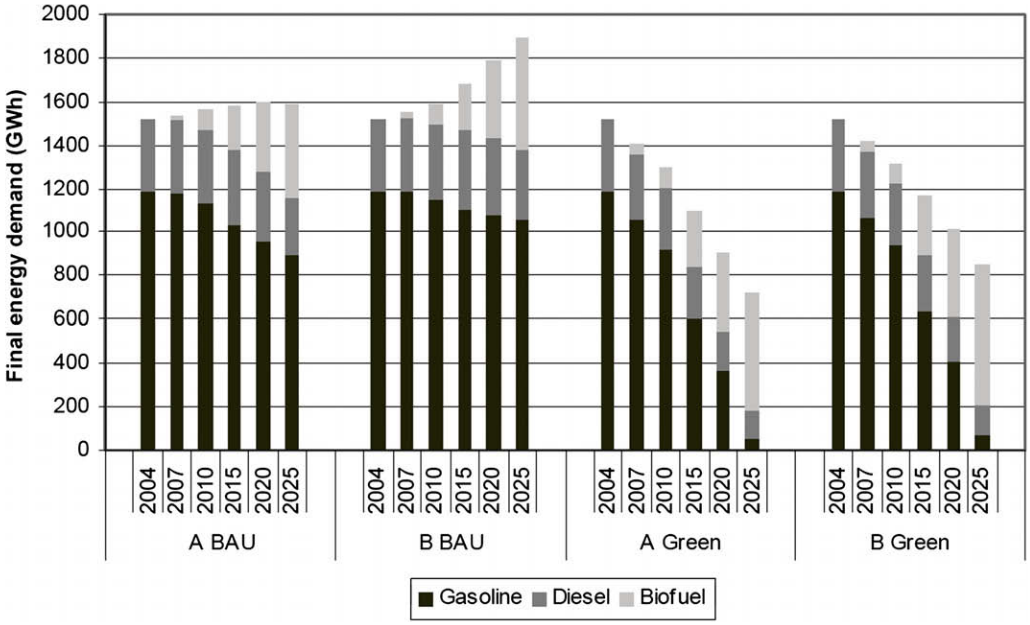

Fig. 2. Total fuel demand for private transport by car in Norrbotten until the year 2025 according to the four scenarios.

and diesel, the shares in the year 2025 is assumed to be 8% and 17%, respectively.

The biofuel may be blended with gasoline before delivery to the gas stations. This is taken into account when the demand levels for the different fuels are calculated. A more detailed description of the methodology and the made assumptions are described by Lundgren and Pettersson [6].

Fig. 2 describes the total fuel demand as well as the assumed evolution of the fuel shares (gasoline, diesel and biofuel) from the year 2004 to 2025. As seen in the figure, the two reference scenarios (BAU) show an increasing motor fuel demand, while the alternative ones (Green) show a significant reduction. Based on the assumed shares, the biofuel demand will be in the range of 430–640 GWh (1.55–2.30 PJ) per year in the year 2025 in the county of Norrbotten.

2.2. Methanol production chain

2.2.1. Potential biomass supply

The estimation of the future potential biomass production is based on data from a forest inventory [8], which comprises about 12,000 forest plot measurements arranged in clusters of around nine circular plots (about 0.007 ha each). 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, 10 × 10 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 [9], 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 growth to biomass, age, stand density and site productivity and have been parameterized for all included species using an extensive set of yield table data [9]. In this paper a regional biomass price of 35 €/m^3 (0.02 €/kWh) was assumed to be constant for the complete time period, (a sensitivity analysis on the price is performed in Section 4.3). This is the average value of the wood price in northern Sweden from 2002 to 2007 [10].

According to the calculations, the theoretical potential of woody biomass supply would be around 11.5 TWh (41.4 PJ) per year until 2025, which is around 15.7% more than the inventory from the year 2005 [16]. Table 2 shows the future theoretical potential of forest fuels divided into different tree species. Please note that this is the theoretical potential meaning that less will be available and exploited in practice due to economic or technical restrictions.

Table 2
Woody biomass potential 2025 in Norrbotten in TWh/year (PJ/year in parenthesis).

Feedstock	Pine	Spruce	Birch	Deciduous trees
Potential 2025	5.14 (18.50)	2.96 (10.66)	3.11 (11.20)	0.30 (1.08)

2.2.2. Biomass transportation

The biomass transportation cost (in €/TJ) is described by Börjesson and Gustavson [11]. In the county of Norrbotten, only tractor–trailer and truck transportations are considered represented by Eqs. (2) and (3), respectively.

$$C_{\text{Truck}} = 344 + 7.77d \tag{2}$$

$$C_{\text{Tractor}} = 226 + 12.78d \tag{3}$$

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 is estimated to an average value of 1.4 for Norrbotten). These values correspond to the transportation costs if the biomass is extracted from the surrounding areas.

2.2.3. Methanol production

Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following steps: fuel 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 [12]. A boiler is optional to employ the unconverted gas for heat production (or a turbine for electricity co-production). According to Hamelinck and Faaij [12], only circulating fluidized bed gasifiers are feasible for large-scale fuel gas production. This conclusion is based on an analysis of throughput, cost, complexity and efficiency issues. They have analyzed two types of circulating fluidized bed gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. The latter type is selected in this study. In this gasifier, ash, char and sand are entrained in the product gas, separated using a cyclone, and sent to a second bed where the char is burned in air to reheat the sand. The heat is transferred between the two beds by circulating the hot sand back to the gasification bed. This allows one to provide heat by burning a part of the fuel, but without oxygen supply as combustion and gasification occur in separate vessels. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production [12]. In this study, it is assumed that the blending of methanol with gasoline to suitable mixtures, e.g. M85 containing an 85% share of methanol, is performed on site immediately after the methanol production process.

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 by using the scaling function:

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

where R is the scaling factor, $Cost_a$ and $Cost_b$ are the costs of equipments for the biofuel plant (a) and (b), respectively, and $Size_a$ and $Size_b$ are the sizes of the biofuel 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 the costs of 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 [13]. The uncertainty range of such estimates is up to ±30% on investment costs [12].

2.2.4. 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 and Gustavson [11]. The transportation cost by truck (in €/$\text{TJ}_{\text{methanol}}$) is described in Eq. (5):

$$C_{\text{Truck}} = 138 + 3.05d \tag{5}$$

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 ratio for the biomass transportation).

2.2.5. Methanol distribution

It is assumed that all gas stations in the county are able to distribute methanol. As methanol today is not widely used in the transportation sector, adaption at the gas stations will be required. The cost for handling methanol at a gas station with a capacity of 125,000 l/month is between 0.20 and 0.24 €/$\text{GJ}_{\text{methanol}}$. The costs are assumed to be independent of the station size [14].

2.3. Model

This section formulates the problem as a Facility Location Problem. Solving the problem will result in the optimal locations and sizes of plants and gas stations under the given conditions.

First, let S be the number of biomass supply regions, let P be the number of plants, let G be the number of gas stations, let D the be the number of demand regions, and let Y be the number of years in the planning horizon. Also define the corresponding sets: $\widetilde{S}=\{1,\ldots,S\}$, $\widetilde{P}=\{1,\ldots,P\}$, $\widetilde{G}=\{1,\ldots,G\}$, $\widetilde{D}=\{1,\ldots,D\}$ and $\widetilde{Y}=\{1,\ldots,Y\}$. Besides biofuel, a plant may be constructed to produce one or several additional commodities, e.g. heat, power, pellets or pulp. Let C be the number of additional commodities and define $\widetilde{C}=\{1,\ldots,C\}$ as the corresponding set.

Define the following variables. Let $b_{i,j,y}$ be the amount of biomass delivered from supply region i to plant j in year y, let $x^{bio}_{j,k,y}$ be the amount of biofuel delivered from plant j to the gas station k in year y, and let $x^{bio}_{k,l,y}$ be the amount of biofuel sold at the gas station k to the customers from the demand region l in year y. Let the variable $x^{c}_{j,y}$ represent the amount of commodity c that is produced at the plant j during year y. The variable $x^{fossil}_{l,y}$ is the amount of fossil fuel sold to costumers from the demand region l year y. The variables $b_{i,j,y}$, $x^{bio}_{j,k,y}, x^{bio}_{k,l,y}, x^{c}_{j,y}$ and $x^{fossil}_{l,y}$ are non-negative. Let the binary variables $u_{j,y}$ and $u_{k,y}$, respectively, indicate 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

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

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 $\bar{x}^{bio}_{j}$ in year y is $e_{j,y}$, and the cost for producing in the plant is $c_{j,y}$. The biofuel production is thus restricted by

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

The plant is modeled using an energy balance equation,

$$\eta_j \sum_{i=1}^{S} b_{i,j,y} = \sum_{k=1}^{G} x^{bio}_{j,k,y} + \sum_{c=1}^{C} x^{c}_{j,y}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}, \tag{8}$$

where η_j is the plant efficiency. The relations between the biofuel and the commodities produced are modeled using parameters ρ^c_j, giving

$$x^{c}_{j,y} = \rho^{c}_{j} \sum_{k=1}^{G} x^{bio}_{j,k,y}, \qquad j \in \widetilde{P}, \quad c \in \widetilde{C}, \quad y \in \widetilde{Y}. \tag{9}$$

The produced biofuel in plant j is transported to gas station k for the cost $t_{j,k,y}$.

The cost for setting up a gas station k in year y with the capacity $\bar{x}^{bio}_k$ is $e_{k,y}$. The cost for handling biofuel at the station is $c_{k,y}$. Similar to the plant model, also the gas station is modeled using capacity and energy balance equations, i.e.

$$\sum_{l=1}^{D} x^{bio}_{k,l,y} \le \bar{x}^{bio}_{k} u_{k,y}, \qquad k \in \widetilde{G}, \quad y \in \widetilde{Y}, \tag{10}$$

and

$$\sum_{j=1}^{P} x^{bio}_{j,k,y} = \sum_{l=1}^{D} x^{bio}_{k,l,y}, \qquad k \in \widetilde{G}, \quad y \in \widetilde{Y}, \tag{11}$$

must hold.

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

$$\sum_{k=1}^{G} x^{bio}_{k,l,y} + x^{fossil}_{l,y} = d_{l,y}, \qquad l \in \widetilde{D}, \quad y \in \widetilde{Y}, \tag{12}$$

where $d_{l,y}$ is the demand calculated from Eq. (1). The corresponding transportation cost is $t_{k,l,y}$, which shall be 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 $p^{fossil}_{l,y}$.

In this paper, one additional commodity c, heat, is considered. Therefore, also define the variable $q_{j,y}$ as the heat from an alternative heat source located close to plant j. The heat demand equation is

$$x^{c}_{j,y} + q_{j,y} \ge q^{D}_{j,y}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}, \tag{13}$$

where the parameter $q^{D}_{j,y}$ is the corresponding heat demand. The alternative heat source, which typically is a heating boiler or a CHP plant, is associated with a production cost $c^{heat}_{j,y}$.

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

$$u_{j,y} \ge u_{j,y-1}, \qquad j \in \widetilde{P}, \quad y \in \widetilde{Y}, \tag{14}$$

and

$$u_{k,y} \ge u_{k,y-1}, \qquad k \in \widetilde{G}, \quad y \in \widetilde{Y}. \tag{15}$$

Given the costs and prices, the objective function is defined as

$$\begin{cases} f(b,x,q,u) = \sum_{y=1}^{Y} \sum_{i=1}^{S} \sum_{j=1}^{P} (c_{i,y} + t_{i,j,y}) b_{i,j,y} \\ \quad + \sum_{y=1}^{Y} \sum_{j=1}^{P} e_{j,y}(u_{j,y} - u_{j,y-1}) + \sum_{y=1}^{Y} \sum_{j=1}^{P} \sum_{k=1}^{G} (c_{j,y} + t_{j,k,y}) x^{bio}_{j,k,y} \\ \quad + \sum_{y=1}^{Y} \sum_{j=1}^{P} c^{heat}_{j,y} q_{j,y} + \sum_{y=1}^{Y} \sum_{k=1}^{G} e_{k,y}(u_{k,y} - u_{k,y-1}) \\ \quad + \sum_{y=1}^{Y} \sum_{k=1}^{G} \sum_{l=1}^{D} (c_{k,y} + t_{k,l,y}) x^{bio}_{k,l,y} + \sum_{y=1}^{Y} \sum_{l=1}^{D} p^{fossil}_{l,y} x^{fossil}_{l,y}. \end{cases} \tag{16}$$

Finally, define the Facility Location Problem as

$$\begin{cases} \min_{b,x,q,u} [f(b,x,q,u)] \\ s.t. \\ (6) - (16) \\ b_{i,j,y}, x^{bio}_{j,k,y}, x^{c}_{j,y}, x^{bio}_{k,l,y}, x^{fossil}_{l,y}, q_{j,y} \ge 0, \quad i \in \widetilde{S}, j \in \widetilde{P}, c \in \widetilde{C}, k \in \widetilde{G}, \\ \quad l \in \widetilde{D}, y \in \widetilde{Y} \\ u_{j,y} \in \{0,1\}, u_{k,y} \in \{0,1\}, \quad j \in \widetilde{P}, k \in \widetilde{G}, y \in \widetilde{Y}. \end{cases} \tag{17}$$

The problem is an ordinary Mixed Integer Program (MIP) and can thus be solved using standard MIP techniques [15].

3. Case study

Norrbotten is the largest county in Sweden covering around 25% of the country's total area. Norrbotten is sparsely populated with an average population density of around 2.5 inhabitants per square kilometer and is strongly characterized by its arctic climate. Norrbotten is also a county with abundant resources of biomass. Currently the total supply of combustible renewable and waste amounts to nearly 6.7 TWh/year (24.12 PJ/year). The annual supply is mainly dominated by black liquor in the paper- and pulp-industries corresponding to roughly 4.0 TWh (14.4 PJ/year). The present share of woody biomass is around 34% corresponding to 2.3 TWh/year (8.28 PJ/year) [16]. Municipal waste contributes with a minor part. At present, the biomass is mainly used in the paper- and pulp-industries, sawmills and district heating plants. No liquid biofuels are currently produced, even if the potential is considered as large. Norrbotten has the particularity that biomass must be supplied from long distances over the county and methanol supplied to concentrated areas around the coastline.

A grid over the county is considered where each grid point is located every third of a degree. The fourteen main cities are also considered in this grid. Each grid point represents a potential position of the plant.

It is assumed that when the local demand is fulfilled, the amount of excess methanol is sent by truck to the main harbor in the city of Luleå from where it can be exported either by train or ship. The study does not consider any export market, and limits the transport of methanol within the county only.

The district heating demand is also considered in the model. Table 3 shows the current heat demand of each municipality in the county with their different heat price. From Table 4 one can find the change in the heat demand for the four scenarios, within the whole county. It is further assumed that the heat demand and price are fluctuating at the same rate all over the county and that exist-

Table 3
Heat demand in GWh/year (PJ/year in parenthesis) from the district heating [19] and heat price [18] in €/kWh for different municipalities in Norrbotten.

Municipality	Heat demand	Heat price
Luleå	690 (2.48)	0.0393
Boden	259 (0.93)	0.0472
Kiruna	209 (0.75)	0.0646
Piteå	175 (0.63)	0.0504
Gällivare	136 (0.49)	0.0642
Kalix	97 (0.35)	0.0630
Haparanda	46 (0.17)	0.0588
Älvsbyn	40 (0.14)	0.0542
Jokkmokk	36 (0.13)	0.0748
Överkalix	26 (0.09)	0.0656
Övertorneå	26 (0.09)	0.0678
Pajala	22 (0.08)	0.0574

Table 4
Change in the heat demand and price in % from 2005 to 2025 for the county.

	2005	2010	2015	2020	2025	References
Heat demand, A-BAU	0	1.3	2.7	4.0	5.3	[6]
Heat demand, A-Green	0	−5.4	−10.9	−16.3	−21.8	[6]
Heat demand, B-BAU	0	5.7	11.5	17.2	23.0	[6]
Heat demand, B-Green	0	−2.2	−4.5	−6.7	−8.9	[6]
Heat price	0	5.5	11.1	11.1	11.1	[17]

Table 5
Results for the different scenarios (no district heat production considered), for the year 2025.

Size	$\text{MW}_{\text{biomass}}$	100	200	400
Position		Boden	Boden	Boden
Load hours	h	7200	7200	7200
Wood				
Amount	t/year	207,360	414,720	829,440
Share of potential	%	6.25	12.5	25
Area	ha	82,030	191,779	407,445
Methanol sold	m^3/year	90,340	180,680	361,350
Max distance				
Biomass transports	km	65	100	170
Fuel transports	km	180	320	340
Costs				
Biomass cost	€/GJ	10.75	10.75	10.75
Biomass transports	€/GJ	1.95	2.33	3.26
Plant cost	€/GJ	17.49	14.09	11.38
Fuel transports	€/GJ	0.38	0.35	0.22
Gas station cost	€/GJ	0.24	0.24	0.24
Total cost				
Mean	€/l	0.48	0.43	0.40

ing district heating network can be used without any restrictions. Moreover, it is assumed that 10% of the total fuel input to the plant becomes residual heat that can be sold as district heating within a 30 km radius from the plant.

4. Results and discussion

4.1. Results without district heat production

In all four scenarios described in Fig. 2, a methanol plant would be built in the first year, and all excess of methanol is considered for export. In these cases, no heat is sold to any district heating network. The cost of methanol produced from these plants is in the range of 0.40–0.48 €/l depending on the plant size. In Table 5 the most proper positions, the costs and other details for each plant size are presented for the year 2025.

4.2. Results with district heat production

The specific methanol production cost will change if the residual heat can be sold to an adjacent district heating network. If a 100 $\text{MW}_{\text{biomass}}$ or a 200 $\text{MW}_{\text{biomass}}$ plant is built, the optimal position becomes the town of Boden independent of the heat price and demand scenario. The methanol cost decreases by 0.009 €/l as the heat price increases by 0.01 €/kWh (Fig. 3).

If a 400 $\text{MW}_{\text{biomass}}$ plant is built, the plant location moves towards higher heat demand areas. In this case, the optimal position becomes the town of Luleå. As the 400 $\text{MW}_{\text{biomass}}$ plant can deliver a larger amount of heat than the two smaller plants, the location is more influenced by the heat price and the heat demand. This shall be set in relation to the costumer price for district heating, which in the county ranges from 0.039 to 0.083 €/kWh [18]. The heat price has the same influence in all scenarios and controls the position of the plant to move closer to the heat demand. However, in Luleå there is a lot of inexpensive excess heat already available from the local steel industry. This issue is analyzed in Section 4.3, as well as other factors that may affect the methanol cost and the plant position.

4.3. Sensitivity analysis

A sensitivity analysis is carried out with focus on the following parameters: biomass price, transportation costs, heat prices and heat demand. A change in both the heat price and the transport costs is also studied. Moreover, as Luleå has vast amounts of excess heat available at a low price [18] from the local steel mill, a change of the heat price is also studied by assuming a very low cost for the district heat in Luleå. A base heat price for Luleå in 2005 is assumed to be 0.01 €/kWh, and is presumed to increase until 2025 at the

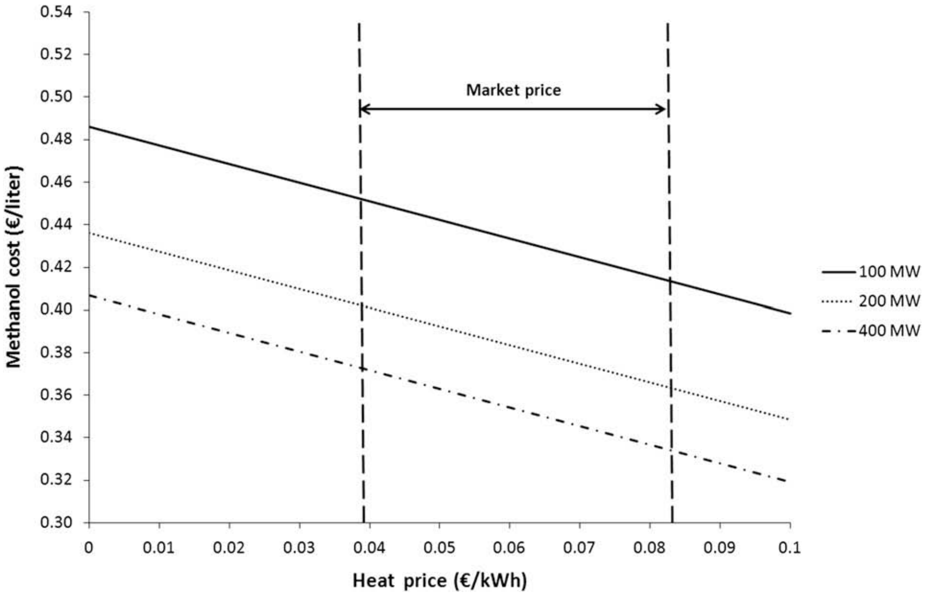

Fig. 3. Influence of the heat price on the methanol cost.

same rate as the heat price in the other municipalities of the county. The influence on the final methanol cost and the plant position from those parameters is analyzed for each plant size and each energy demand scenario. The scenarios studied in the sensitivity analysis are presented in Table 6.

The results are similar for all plant sizes and energy scenarios. Fig. 4 presents the change of the methanol cost in % from 2005 to 2025 compared with the 2005 value for a plant size of 100 MW$_{\text{biomass}}$ and the A-BAU scenario. The base scenario presented in Fig. 4 represents the simulation from the Section 4.2 adapted with different heat price for each town.

The parameter that has the most influence on the final methanol production cost is the biomass price. An increase of the biomass price by 54% by 2025 would mean an increase of the methanol production cost by 21%. If the transportation costs increase by 7%, the methanol production cost increases by 1%. Considering the increase of the energy price in general (heat and transport), the methanol cost would then decrease by about 0.5%, and considering only a low heat price in Luleå, the methanol cost would decrease by about 1%.

Considering the positions of the plants, the results are presented in Table 7. For the 100 MW$_{\text{biomass}}$ plant, the optimal position would be moved from the town of Boden to Kalix: all the heat produced can indeed be sold at a price in Kalix 33% higher than in Boden, which makes Kalix more attractive for this plant size. For the 200 MW$_{\text{biomass}}$ plant, all the heat produced can be sold in Boden. Finally, for the 400 MW$_{\text{biomass}}$ plant, all the heat produced can be sold in Luleå at present market price. But considering the very low heat price in Luleå, the location of the plant becomes more interesting in Boden.

Table 7
Position of the plant regarding the size and the energy scenarios.

Plant size (MW$_{\text{biomass}}$) Parameters	100 All	200 All	400 All except LHP[a]	400 LHP[a]
A-BAU	Kalix	Boden	Luleå	Boden
A-Green	Kalix	Boden	Luleå	Boden
B-BAU	Kalix	Boden	Luleå	Boden
B-Green	Kalix	Boden	Luleå	Boden

[a] LHP stands for low heat price only in Luleå.

Table 8
Increase radius of the collecting feedstock and fuel distribution and difference in emissions when the plant is relocated from Boden to Luleå.

Plant size, MW$_{\text{biomass}}$	Biomass transport, km	Methanol transport, km	Emissions difference per year				
			t_{CO2}	t_{NOx}	t_{PM}	t_{HC}	t_{CO}
400	20	67	2031	19.56	0.43	1.65	3.76

4.4. Influence on emissions

When the plant considers district heat production, the optimal position of the plant will be located closer to the heat demand, which implies changes in distances for the biomass and biofuel transportation. The emissions from the road transports are therefore affected. Table 8 presents the increase of emissions from the transportation of the feedstock and the produced biofuel if a plant is built in Luleå instead of in Boden. This change of position would

Table 6
Parameters used in the sensitivity analysis.

Scenarios	Units	2005	2010	2015	2020	2025	References
Biomass price	€/m^3	36.9	41.8	46.8	51.9	57.0	[17]
Transportation cost	%	0	2.9	5.2	6.3	7.3	[17]
Heat price	%	0	5.5	11.1	11.1	11.1	[17]
Energy price	The sum of transportation costs and heat price						
Low heat price in Luleå	Heat price in Luleå: 0.01 €/kWh Heat price in the rest of the county: unchanged						

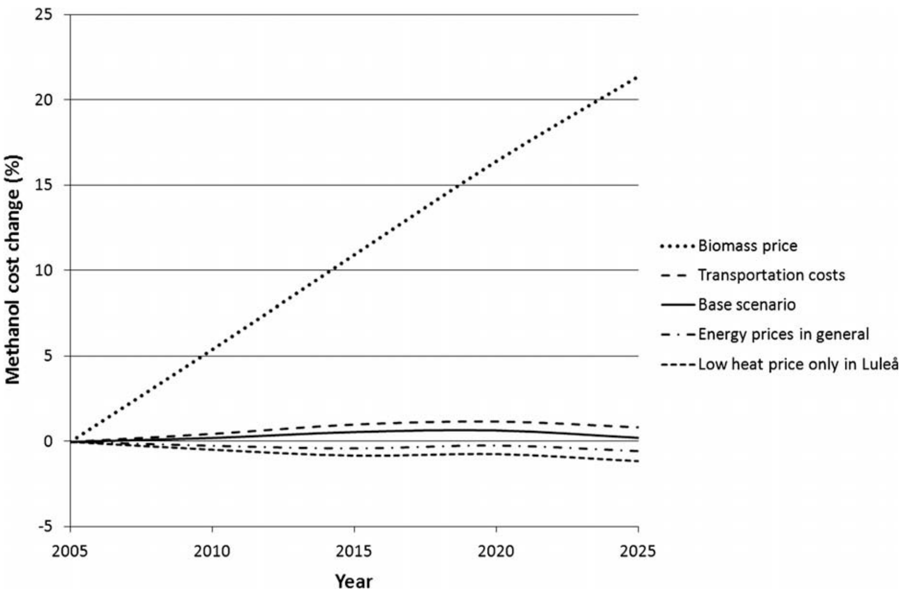

Fig. 4. Results from the sensitivity analysis: the change in percent of the methanol cost for the 100 MW plant and demand scenario A-BAU, from 2005 to 2025 in comparison with the 2005 level.

increase the emissions of CO_2 by 2031 t/year. This represents approximately 0.7% of the total CO_2 emissions from the road traffic in Norrbotten [16]. Emissions of nitrogen oxides (NO_x), particulate matters (PM), hydrocarbons (HC) and carbon monoxide (CO) are also presented in the table.

5. Concluding discussion

The main objective of this study was to illustrate the use of a dynamic model to optimize the geographic position of a biomass based methanol plant by minimizing the transport distances of raw material and the final product, methanol. Also the prerequisite that the plant should be able to sell the residual heat as district heating was taken into account in order to increase the profitability. The study was conducted on a twenty year perspective, for which the future methanol demand was assessed by scenarios and potential biomass supply calculated. The county of Norrbotten in northern Sweden served as a case study, for which appropriate locations of methanol plants of different sizes were computed for four different motor fuel demand scenarios.

The results of the case study show that methanol can be produced in the county of Norrbotten at a maximum specific cost of 0.48 €/l without heat sales. By selling the residual heat as district heating, the methanol production cost per liter fuel may decrease by up to 10% when the plant is located close to an area with high annual heat demand. Therefore, the revenue from heat sales is strongly affecting the location of the plant.

This model can be applied to any kind of biomass based production plant and become an essential tool to optimize the location of new plants on the regional or country level. In particular when long transport distances is an issue for the production cost. The model is therefore a useful tool for decision makers on the level of energy planning purposes. In an international perspective, trades of raw material and biofuels should be implemented. The model could be applied in significantly larger scales (e.g. continents like Europe, North America) to identify the appropriate locations for energy plants to obtain competitive products by minimizing transports and optimizing the use of residual energies. It is also of great importance to have a future time perspective as the feedstock resources as well as the demand for the final products (e.g. heat, motor fuel, electricity) may change radically during the technical and economic lifetime of the plant.

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