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International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

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Economies of Scale in Biomass Gasification Systems

Åse Lekang Sørensen (ase.lekang.sorensen@ntnu.no)

Approved by

Sten Nilsson
Deputy Director and Leader, Forestry Program

29 April 2005

Contents

Abstract

Renewable energy sources, such as biomass, may replace the use of fossil fuels and have therefore an active role in reducing carbon dioxide emissions. One conversion technology for energy production from biomass is gasification. The gasification options can differ with regard to scale, biomass fuel, energetic efficiencies, investment and operational costs, as well as energy carriers produced. In this study an atmospheric indirectly fired gasifier is used and the energy carrier produced is methanol.

The whole bioenergy chain is described in this study, from when the biomass is extracted in the forest until the produced methanol is distributed to the consumer. Five system-components are distinguished in the chain: biomass extraction and pre-treatment, transportation of biomass, biomass conversion to methanol, transportation of methanol and distribution of methanol.

The aim of this paper is to classify the cost and energy efficiencies of the system components when the scale of the system changes. The methanol plants described have a biomass input between 10 MW and 1000 MW. The scale of the gasification plant influences the unit cost of the produced methanol, and large-scale production plants will have the advantage in this respect. On the other hand, large-scale plants are likely to have higher transportation costs per unit biomass transported as a result of longer transportation distances.

When using the input variables described for the model the methanol unit cost decreases as plant size increases. The total unit cost of methanol is found to decrease from about 20.6 €/GJ_{MeOH} for a 10 MW plant to about 12.5 €/GJ_{MeOH} for a 200 MW plant. The unit costs stabilize for plant sizes between 200 MW and 1000 MW, but do however continue to decrease to about 11 €/GJ_{MeOH} for a 1000 MW plant. Included in the unit methanol cost are 50 kilometer (km) additional biomass transportation by truck and 100 km methanol transportation by train and 1000 km methanol transportation by ship.

This result depends on many different input variables, such as biomass, plant and transportation costs. In order to assess the influence the different variables produce on the final methanol unit cost, a sensitivity analysis is carried out.

The energy efficiencies for the different scaled biomass pathways are found to be more or less scale independent. Assuming that produced methanol is transported independent of plant size and using the same transportation means and distances, transportation of biomass is the only scale dependent factor. For truck transportation of biomass this energy consumption varies from 0.1% of the total input bioenergy for a 10 MW plant to 1.2% of the total input bioenergy for a 1000 MW plant.

Two geographical areas are analyzed using the model. An area in the north-west of Spain demonstrates the model for a large-scale methanol plant (935 $\mathrm{MW}_{\text{biomass input}}$) and an area in the west of Greece demonstrates the model for a medium-size methanol plant (380 $\mathrm{MW}_{\text{biomass input}}$).

Acknowledgments

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About the Author

Åse Sørensen graduated with a Master degree in environmental physics from the Agricultural University of Norway in June 2002. During this program she wrote her thesis within gasification of biomass. Her principle research area includes biomass-based energy systems and renewable energy researches in general. She was a participant of the 2004 Young Scientists Summer Program (YSSP) in IIASA's Forestry Program.

Economies of Scale in Biomass Gasification Systems

Åse Lekang Sørensen

1 Introduction

1.1 Bioenergy

Emissions from human activity are substantially increasing the atmospheric concentrations of greenhouse gases (GHG). It is widely understood that these increases enhance the natural greenhouse effect, which will in turn result in an additional warming of the Earth's surface and atmosphere. This may adversely affect natural ecosystems and humankind (UNFCCC, 1992).

The use of fossil fuels is responsible for a large part of global carbon dioxide (CO_2) emissions, one of the main GHGs. Renewable sources, such as biomass, may replace the use of fossil fuels and have therefore an active role in reducing CO_2 emissions. Due to plant intake of CO_2 from the atmosphere, bioenergy can be produced and consumed on a practically CO_2 neutral basis.

Biomass is an important source of energy in a number of countries and regions. Traditional biomass is currently playing an important role in developing countries and provides the main source of energy, i.e., firewood, for both cooking and heating. Part of this traditional biomass energy is considered not to be sustainable, and therefore not CO_2 neutral, as it may contribute to land degradation and sometimes even desertification (Hoogwijk, 2004). Modern use of biomass refers to biomass produced in a sustainable way and used for electricity generation, heat production, and liquid fuels for transportation (Goldemberg, 2004).

In 2001, traditional biomass contributed to about 39 EJ and modern biomass to about 6 EJ (Goldemberg, 2004). Hoogwijk (2004) estimated that the future world bioenergy supply may become 1100 EJ, without affecting the supply for food crops, assuming biomass productivity to be in the range 10–20 metric tonne $ha^{-1}y^{-1}$. This is exceeding the global primary energy use for 2001 of 418 EJ (Goldemberg, 2004).

Biomass productivity is mainly determined by local factors such as soil quality, climate, water availability and management factors. To what extent bioenergy will increase also depends on factors such as costs of primary biomass, development of conversion technologies, cost of converted biomass energy and implementation, and social and/or institutional factors (Hoogwijk, 2004).

One energy conversion technology for biomass is gasification. Gasification options can differ with regard to scale, biomass fuel, energy efficiencies, investment and operational costs as well as energy carriers produced. Methanol can be produced from biomass via gasification.

1.2 Methanol and Fuel Cells

Methanol is the simplest form of alcohol and has the chemical formula CH_3OH. It can be produced chemically from both biomass and fossil resources. About 90% of methanol produced is from natural gas (Ogden *et al.*, 1999).

Methanol is suitable as a transportation fuel, as a chemical building block and as a solvent. When used in the transportation sector methanol can be blended with other fuels, and it is also well suited for use in fuel cells. Since methanol is easier to transport and store than hydrogen, methanol may play an important role in the adoption of fuel cells (Ogden *et al.*, 1999).

There are several advantages of fuels cells, including high efficiency, low or zero emissions and low noise pollution. When using sustainable biomass to produce methanol for fuel cells, a transport system with minimal emissions of air pollutants (NO_x, CO, unburned HC, particulates, SO_x, etc.) and GHGs (CO_2, CH_4, N_2O, etc.) can be achieved (Jung, 1999).

There are several types of fuel cells currently being tested, such as phosphoric acid fuel cell (PAFC), alkaline fuel cell (AFC), direct methanol fuel cell (DMFC) and proton exchange membrane fuel cell (PEMFC). All of these fuel cells, apart from DMFC, require a fuel reformer if operated with carbonaceous fuels, such as methanol. The major advantage of DMFC is that the processing of methanol into a hydrogen rich gas is unnecessary.

1.3 Impacts of Energy Conversion Plant Sizes

Methanol can be produced in both centralized and decentralized (i.e., distributed) conversion plants and the plants can be both small and large scale. Presently, bioenergy production is mostly small-scale and decentralized. More emphasis is currently being placed on large-scale production.

Since bioenergy may provide power at a regional scale, Kaul and Edinger (2004) consider it advisable to combine the decentralized source of biomass with a distributed fuel production system. Both small and large-scale plants can be decentralized, and offer the opportunity to tap local resources and enhance regional independence from importing resources. Decentralized production also creates local employment opportunities. However, as the efficiencies of scale increase less people tend to be employed per volume of biomass harvested (IEA Bioenergy, 2002).

Sustainable biomass production is a major deciding factor in order for bioenergy to be an environmentally renewable source of energy. This is important for conversion plants of all sizes, and maybe especially for the larger sized plants. The issues of sustainable forest include slowing deforestation, regenerating natural forests, engaging in intensive forest management, and improving the management of agricultural and rangeland soil (IEA Bioenergy, 2002).

The scale of the gasification plant influences the produced unit cost of methanol, and large-scale production plants will have the advantage in this respect. On the other hand, large-scale plants are likely to have higher transportation costs per unit biomass transported as a result of longer transportation distances. This study will investigate the relationship between scaling effects, costs and energy efficiencies for the whole bioenergy chain. The methanol plants described have a biomass input between 10 MW and 1000 MW.

2 Production of Methanol

2.1 Gasification Technologies

Biomass gasification is one of the promising technologies for bioenergy. In a gasification cycle, biomass is thermally converted into a permanent gaseous fuel. A large number of variables influence the gasifier design, including gasification medium (oxygen or no oxygen), gasifier operating pressure, and gasifier type.

In the gasification process, the gas is formed by partial combustion of solid biomass in a reactor with either oxygen or air. The biomass is then converted to combustible gaseous products mainly consisting of carbon monoxide (CO) and hydrogen (H_2). In general, there are two fundamental processes converting the biomass to a low-to-medium-heating value gaseous fuel; pyrolysis and gasification (Yan, 1998). In the pyrolysis volatile vapors of the fuels are released at temperatures below 600ºC via a set of complex reactions. Included in these vapors are hydrocarbon gases, hydrogen, carbon monoxide, carbon dioxide, tars and water vapor. In the gasification the char, tar and volatile gas resulting from pyrolysis are converted into a combustible gas (syngas) by a reaction with steam, with or without oxygen.

The characteristics of the different types of gasifiers are described in Table 1. The composition and heating value of the gas varies according to feedstock, gasifier type used and operating parameters.

The heat needed for the endothermic carbon — steam and carbon — carbon dioxide reactions can be generated directly in the gasifier by burning a certain amount of solid fuels or char, or indirectly outside the gasifier by generating the heat through burning either biomass or product gas in a separate combustor. In the case of direct gasifiers, pyrolysis, gasification and combustion take place in one vessel; while in indirect gasifiers, pyrolysis and gasification occur in one vessel, and combustion in a separate vessel. Currently, indirect gasification systems operate near atmospheric pressure. Direct gasification has been demonstrated at both elevated and atmospheric pressure (DOE-EPRI, 1997).

Table 1: Gasification reactor types (Yan, 1998 quotes Bridgwater, 1995).

Fixed Bed:	
Downdraft	Solid moves down, gas moves down.
Updraft	Solid moves down, gas moves up.
Concurrent	Solid and gas move in same direction — downdraft.
Counter current	Solid and gas move in same direction — updraft.
Cross-current	Solid moves down, gas moves at right angles.
Variations	Stirred bed; two-stage gasifier.
Fluidized Bed	
Single reactor	Low gas velocity, insert solid stays in reactor.
Fast fluid bed	Inert solid is elutriated with product gas and recycled.
Circulating bed	Insert solid is elutriated, separated and recirculated; sometimes also referred to as fast fluidized bed or twin-reactor systems.
Entrained bed	Usually no inert solid; highest gas velocity of lean-phase systems; can be run as a cyclonic reactor.
Twin reactor	Steam gasification and/or pyrolysis occur in the first reactor, char is burned in the second reactor to heat the fluidized medium for recirculation; either can be any type of fluidized bed, although the combustor is often a bubbling fluidized bed.
Moving Bed	Mechanical transport of solids contact; careful design needed to avoid solids carryover.
Other	
Rotary kiln	Good gas-solid contact; careful design needed to avoid solids carryover.
Cyclonic reactors	High particle velocities give high reaction rates; similar to cyclonic reactors.

2.2 MeOH Production

Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following basic steps: Pretreatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification, see Figure 1 (Hamelinck and Faaij, 2001). Optional are a gas turbine or boiler to employ the unconverted gas, and a steam turbine; resulting in electricity co-production.

Methanol is produced by the hydrogenation of carbon oxides over a suitable (copper oxide, zinc oxide, or chromium oxide based) catalyst:

$$CO + 2H2 \leftrightarrow CH3OH$$

$$CO2 + 3H2 \leftrightarrow CH3OH + H2O\ .$$

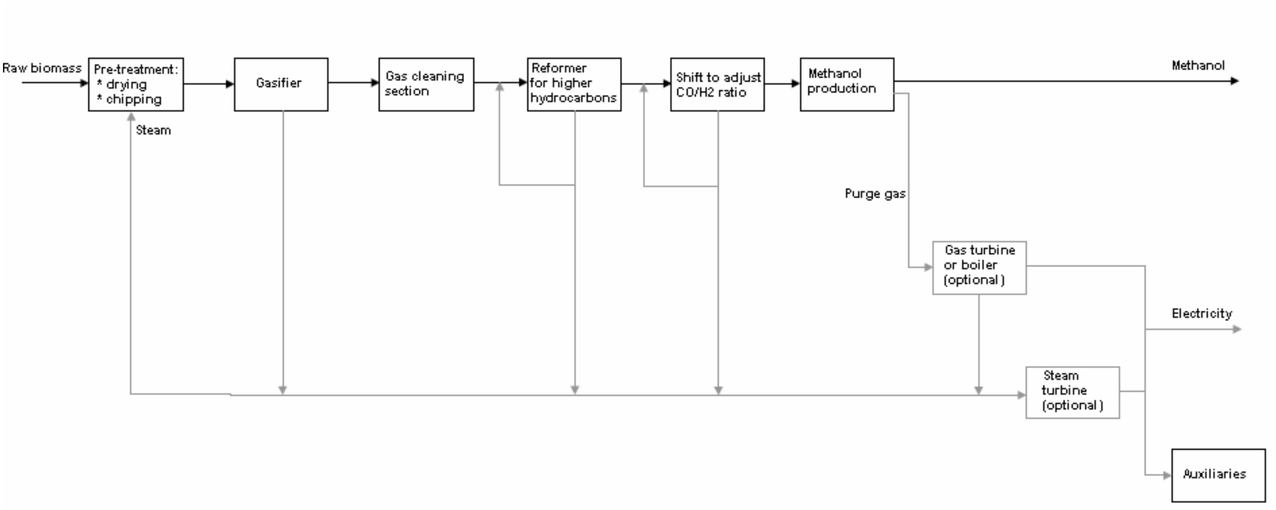

Figure 1: Key components in biomass to methanol production concepts (Hamelinck and Faaij, 2001).

These reactions are exothermic and give a net decrease in molar volume. Therefore, the equilibrium is favored by high pressure and low temperature. During production, heat is released and has to be removed to keep optimum catalyst life and reaction rate.

Conventionally, methanol is produced in two-phase systems: the reactants and products forming the gas phase and the catalyst being the solid phase. Processes under development at present focus on shifting the equilibrium to the product side to achieve higher conversion per pass. Examples are the gas/solid/solid trickle flow reactor, with a fine adsorbent powder flowing down a catalyst bed and picking up the produced methanol and liquid phase methanol processes where reactants, product, and catalyst are suspended in a liquid. Fundamentally different could be the direct conversion of methane to methanol, but despite a century of research this method has not yet proved its advantages.

2.3 Selected System

According to Hamelinck and Faaij (2001), only circulated fluidized bed gasifiers are suitable for large-scale fuel gas production. This conclusion is based on an analysis of throughput, cost, complexity and efficiency issues. Hamelinck and Faaij are analyzing two gasifiers for methanol production: A pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier.

In this paper the atmospheric indirectly fired gasifier is selected. This is a fast fluidized bed gasifier. The main performance characteristics of the gasifier are given in Appendix 2. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production.

The gas produced contains tars, dust, alkali compounds and halogens, which can cause problems later in the system. The gas can be cleaned using available conventional technology, by applying gas cooling, low temperature filtration, and water scrubbing at

100–250°C. In the described system, low temperature wet cleaning is used and particles are completely removed by the cyclone, the bag filters and the scrubbers.

The syngas produced has a low CO_2 content, but contains a considerable amount of methane and other light hydrocarbons. As a result, steam reforming is included to maximize the amount of product, by converting CH_4 and C_2H_6 into CO and H_2. Normally, this is followed by the water shift reactor, where CO is converted into H_2. This is not necessary in this system because of the use of a liquid phase methanol synthesis.

In the liquid phase, methanol synthesis (LPMEOH, registered trademark of Air Products and Chemicals) reactants, product, and catalyst are suspended in a liquid, see Figure 2. A shift reaction then takes place in the slurry bubble column reactor. Reactants from the gas bubbles dissolve in the liquid and diffuse to the catalyst surface, where they react. Products then diffuse through the liquid back to the gas phase. Heat is removed by generating steam in an internal tubular heat exchanger.

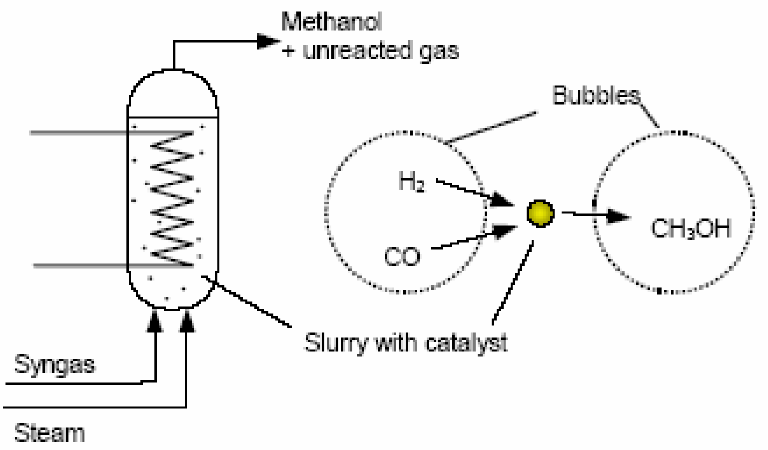

Figure 2: Liquid phase methanol synthesis (LPMEOH).

The heat transfer between the solid catalyst and the liquid phase is highly efficient, thereby allowing high conversions per pass without loss of catalyst activity.

3 Pathways

The whole bioenergy chain is described in this study, from when the biomass is extracted in the forest until the produced methanol is distributed to the consumer. Five system components are distinguished in the chain: biomass extraction and pretreatment, transportation of biomass, biomass conversion to methanol, transportation of methanol and distribution of methanol, see Figure 3.

For all of these system components there are several options and variables. There are therefore many possible solutions for one single bioenergy chain. The aim of this paper is to classify the cost and energy efficiencies of the system components when the scale of the system changes.

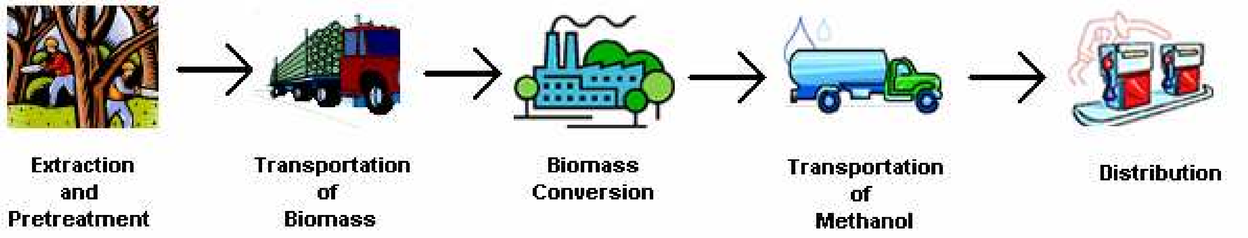

Figure 3: The bioenergy chain from extraction of biomass to distribution of methanol.

3.1 Biomass Extraction and Pretreatment

In the first system component of the chain, biomass is harvested. The biomass values used in this study are for wood, but the model can also be used for other kinds of biomass. Standing wood is available in all shapes and sizes, and ecological, biological and terrain specific properties restrict the amount of wood fuel available (Lundmark, 2004). Both the price for buying standing wood and the price for harvesting and extracting wood from the forest to the roadside will therefore change.

The energy density of biomass is much lower than that of traditional energy resources such as fossil fuel. This low density makes biomass fuel more expensive to transport, store and utilize than the traditional used fossil fuel (Brooking, 2002). To improve the combustion and transportation properties of the biomass, the forest fuel can be converted into several other forms, such as charcoal, torrefied wood, pellets, briquettes and wood powder besides gas, methanol, ethanol and electricity.

Wood energy conversion used today consists mainly of resizing, drying and charcoal production. Charcoal has advantages over wood, such as higher efficiencies in stoves, higher convenience and easier distribution (RWEDP, 2004). The charcoal-making process is however inefficient. In commercial operations, the product contains about 55% of the original biomass energy, while in traditional operations it may only retain 20% of the original energy content (Pentananunt *et al.*, 1990).

Another possibility of improving biomass properties is torrefacation. Torrefacation consists of slow heating of biomass in an inert atmosphere to a maximum temperature of 300ºC (Pach *et al.*, 2002). The treatment yields a solid uniform product with a lower moisture content and a higher energy content compared to those in the initial biomass. The process may be called mild pyrolysis, with the removal of smoke producing compounds and formation of a solid product, retaining approximately 70% of the initial weight and 80–90% of the original energy content.

The main advantages of torrefacation are that the energy density for the biomass increases; by losing materials with low or no energy density such as water, and that the biomass becomes hydrophobic; and is no longer in danger of losing energy density due to moisture exposure (Brooking, 2002).

Torrefied wood is easily packaged and transported, and thus constitutes an efficient fuel. The properties of torrefied biomass should lead to an improved operation in gasifiers for which the stability of the process is important. Torrefied fuel can therefore substitute charcoal and wood in a number of applications.

Transport chains based on transportation of high density energy carriers are the most attractive. The conversion may therefore be carried out early in the chain to improve the efficiency of the bioenergy transport (Hamelinck *et al.*, 2003).

In this study, the biomass is prepared for gasification by chipping. The fuel size necessary for fluidized bed gasification is between 0 and 50 millimeters (mm) (Hamelinck and Faaij, 2001 quote Pierik and Curvers, 1995). According to Suurs (2002), transportation of chips should be avoided due to low density, high production costs, and high energy consumption. We therefore assume the chipping to happen by the methanol plant, and costs and energy consumption for wood logs are used in the bioenergy transportation. After chipping, the fuel is dried to a moisture content of 10%. Initial moisture content is assumed to be 30%.

The costs and energy efficiencies when wood logs are transported are not compared with the transportation of refined wood. Other options should, however, be taken into consideration when planning a methanol plant.

3.2 Transportation of Biomass

One cubic meter of methanol contains about 15.8 GJ of energy, while the same volume of biomass contains approximately 5.8 GJ (see Appendix 1 for heating values and densities). Furthermore, the raw material is very bulky and therefore considered to be less efficient to transport than methanol (Noon *et al.*, 2002). According to Börjesson and Gustavson (1996), transportation costs for methanol are two to three times lower than those for logging residues. It therefore usually makes economical sense to favor plant locations close to the biomass supply, thereby minimizing the transportation distance for biomass.

In order to calculate the transportation distance to the methanol plant, the plant size and therefore biomass required for the plant has to be decided. When biomass is supplied by the surrounding areas, the required transportation distance can be calculated using the following relation (Nguyen and Prince, 1996):

$$x = \left(\frac{M_{bio}}{\pi \cdot Y \cdot a} \right)^{0.5} \tag{1}$$

where x is the average direct distance from the methanol plant [kilometers, km]; M is the total quantity of biomass (biomass input) [$\text{tonne}_{\text{bio}} \cdot \text{year}^{-1}$]; Y is agricultural yield per unit area [$\text{tonne}_{\text{bio}} \cdot \text{km}^{-2} \cdot \text{year}^{-1}$]; and a is the fraction of useful land.

The plant capacity, P, can be expressed by the total quantity of bioenergy, E, and plant efficiency, η:

$$P = E \cdot \eta \qquad \text{[GJ/year]} . \tag{2}$$

The relationship between the plant size[1] and actual distance to the methanol plant[2] can be found in Figure 4. As seen in the figure, the average transportation distance, *d*, is found to range from 8 km when the plant size is 10 MW, to 80 km when the plant size is 1000 MW.

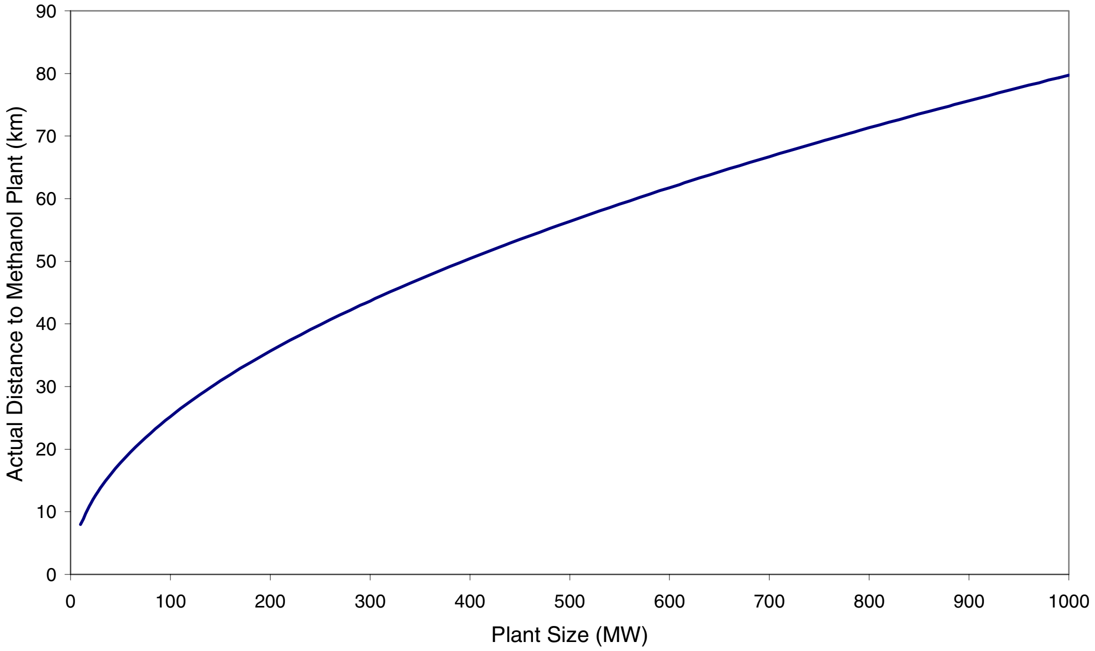

Figure 4: Relationship between plant size, *E*, and actual distance to the methanol plant, *d*. Agricultural yield used, *Y*, is 10 $\text{tonne}_{\text{bio}} \cdot \text{km}^{-2} \cdot \text{year}^{-1}$ and the ratio of actual road length to direct distance used, *b*, is 3.

For methanol plants with local biomass supply, tractors and trucks will essentially form the predominant method of transportation for the biomass. When biomass is transported longer distances, transportation by train and ship may also take place. In this study all of these transportation means are considered for this additional biomass transportation.

There are several advantages in using trains and ships when transporting biomass over longer distances. When using train transportation, for instance, transfer points may be avoided. This is the main advantage of middle-distance train transportation over ship transportation. The costs of train transportation depends on several factors, such as availability of return freights, total volume of transport in the same direction, transfer terminal policies and route (Hamelinck *et al.*, 2003). The costs and energy efficiencies for the different transportation means can be found in sections 4.2 and 5.

Sea transportation may be applied over longer distances. Compared to other transportation means the initial costs are high, but the variable costs are low and the energy efficiency high. The costs depend on several factors, such as changes in the oil

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[1] Plant size (MW) is defined as biomass input, *E* [GJ/h], divided by 3.6 [GJ/MWh].

[2] Actual distance to the methanol plant, *d*, is average direct distance multiplied with the ratio of actual road length to direct distance.

market, routes, time scheduling and port changes. It is therefore hard to calculate a generic price.

Ships can be specifically designed for biomass transportation or simply designed to carry out more general tasks. When purpose-built for biomass transportation, ships cannot be used effectively on their return trip.

3.3 Biomass Conversion to Methanol

Hamelinck and Faaij (2001) have modeled several methanol plant systems in ASPEN+, a widely used process simulation program. The modeled base-scale has a biomass input of 80 dry tonne/hour (430 MW). The system analysis for one of these systems is used in this paper for calculating data for the methanol plant, such as biomass input, methanol output and costs. A description of the methanol plant can be found in section 2.

An economic evaluation is carried out for the system considered, using scaling functions. The sizes of methanol plants described in this paper have a biomass input between 10 MW and 1000 MW. With the values described in Appendix 1, this gives a methanol production of 10.400–1.040.300 m^3/year. The cost calculations for the plants are described in section 4.3.

3.4 Transportation of Methanol

Methanol is generally transported by truck, train and ship, depending on volume, infrastructure and distance. Cost calculations for transportation by truck, train and ship are described in section 4.4.

Pipeline transportation is not considered likely for a number of reasons including interface management, water contamination and corrosion issues (JRC-WTT, 2003). The economics for pipeline transportation is therefore not included in this paper.

Truck transport is generally applied for relatively short distances, where flexibility is required, or where train and ship infrastructure is absent (Hamelinck *et al.*, 2003). Transportation by truck is likely to be used only to transport methanol and the trucks are empty on their return. For the transportation itself, a chemical tanker is needed.

Also for methanol, trains and ships are more cost and energy efficient than trucks for longer distances. This is described in more detail in sections 4.4 and 5. When transporting methanol by ship, tankers are used and the sizes of the tankers can vary from less than one to several hundred thousand of tonnes deadweight (Suurs, 2002; Hamelinck *et al.*, 2003).

A significant methanol distribution system already exists for methanol produced by natural gas. Of the total world production in 1995, roughly half or 12 million metric tonnes were shipped to remote users, 70% by sea and 30% by rail, tank wagon or barge (Ogden *et al.*, 1999). Typically, tank ships transport methanol from production plants sited near inexpensive sources of natural gas to marine terminals. At the terminals, the methanol is loaded into tank trucks and delivered to users.

3.5 Distribution of Methanol

The final stage of the chain is the distribution of methanol to the consumer. When using methanol as a fuel for fuel cell vehicles, the methanol will be transported to the refueling stations. In this study 'distribution' is, therefore, defined as the final part of the methanol distribution chain, namely refueling stations for the consumer. The most likely scenario for developing a methanol fuel distribution system would involve utilizing the existing gasoline distribution system by adding the methanol refueling capacity to existing retail gasoline outlets (AMF-EA Engineering, 1999). The refueling stations can either be converted from gasoline refueling stations to methanol or built in addition to the existing refueling stations. The storage tanks may be buried or located over ground. The equipment and organization is essentially the same as those found in retail gasoline or diesel stations.

4 Cost Analysis

The unit cost of methanol produced decreases with plant size. On the other hand, the biomass required increases, which leads to a longer average biomass transportation distance and subsequently an increase in transportation cost. There may therefore be an optimal plant size that will minimize the total production cost.

The calculations in this study include both scale dependent quantities and fixed costs. However, the emphasis is on scale dependent quantities. The economical model used is developed in MS Excel.

4.1 Cost of Biomass

The calculation of available biomass for a methanol plant, and subsequent biomass and extraction costs, are complex and there are several methods available to calculate the costs. Biomass costs are also highly dependent on the location, and hence these costs found in literature therefore differ. In this general model, we are using a fixed biomass cost of 2 $€/GJ_{bio}$ (3.5 $€/GJ_{MeOH}$ when plant efficiency is 57%).[3] The storage cost of the logs is not included in this model as it is assumed this is small.

Suurs (2002) compares different literature sources and finds the cost range of residue logs to be between 0.6 and 1.4 $€/GJ_{bio}$[4] for Finland, Estonia and Southern America.

Lundmark (2004) has calculated total harvesting costs for Sweden, basing his calculations on Obersteiner (1998). The total harvesting costs, per unit of output and for roadside delivery (biomass transportation to methanol plant is not included), are deduced from labor costs per unit, capital costs per unit, fuel and material costs per unit and overhead costs per unit. This total harvesting cost was then estimated to be between

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[3] All costs are in $€_{2003}$. Exchange rates and price deflators can be found in Appendix 3 (IMF, 2004).

[4] $1€_{2003} = 0.96€_{2001}$ (IMF, 2004).

3.2€/GJ$_{bio}$ and 5.9€/GJ$_{bio}$ for wood, and 2.9€/GJ$_{bio}$ and 5.9€/GJ$_{bio}$ for chipped forest residues. [5,6]

Hamelinck and Faaij (2001) use the biomass price of 2.6 €/GJ$_{bio}$, and suggest 2.2 €/GJ$_{bio}$ to be realistic, for example, for Brazil. From a short term point of view they suggest 3.9 €/GJ$_{bio}$ to be a realistic biomass cost for Western Europe.[7]

Harvesting and biomass costs may also be conducted in a geographic information system (GIS). By using a combination of marginal price surface for extraction costs and harvesting potential for a study region, the best plant locations can be found. A marginal price surface consists of a set of pixels subdividing the study region, each pixel is assigned a marginal biomass potential and harvesting cost. Noon *et al.* (2002) and Graham *et al.* (2000) use this method for generating the best plant locations. In their methodology, each pixel is considered as a potential plant location. Every pixel is assigned a marginal price corresponding to the given demand level. The project aimed to identify promising areas for locating switchgrass-to-ethanol conversion plants, but the method can also be used for wood-to-methanol conversion plants.

In the geographic explicit analysis in this study, available biomass for a specific cost is found using analysis in GIS. More information about the method used can be found in section 7.

4.2 Cost of Biomass Transportation to Methanol Plant

Transportation possibilities may restrict the supply of wood fuel. When the methanol plant has local biomass supply, tractor and truck transportation is the most commonly used method of transportation. For longer distances, the wood can be transported by train and ship after being harvested.

The model used in this paper is described by Nguyen and Prince (1996) and Dornburg and Faaij (2001). They define the total transport cost, *c*, for the biomass to be:

$$c = \frac{2}{3} \cdot \pi \cdot Y \cdot a \cdot k \cdot b \cdot x^3 \tag{3}$$

where Y is agricultural yield per unit area [tonne$_{bio}$ · year^{-1}]; a is the fraction of useful land; k is transport cost per unit distance and unit mass [€ · TJ^{-1} · km^{-1}]; b is the ratio of actual road length to direct distance, taken as a constant; and x is the average direct distance from factory [km].

Other factors, such as biomass moisture and road quality, can also be included in the model.

Transportation cost per unit distance and unit mass is described by Börjesson and Gustavson (1996), see equations 4 to 7.[8] The average actual distance from the methanol

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[5] 1€$_{2003}$ = 9.1SEK$_{2003}$ (IMF, 2004).

[6] Heating values and densities can be found in Appendix 1.

[7] 1€$_{2003}$ = 0.76US\$$_{2001}$ (IMF, 2004).

plant, d, is defined as the average direct distance, x, multiplied with the ratio of actual road length to direct distance, b.

Tractor	$226 + 12.78 \cdot d$	[€/TJ][9]	(4)
Truck	$344 + 7.77 \cdot d$	[€/TJ][10]	(5)
Train	$727 + 1.08 \cdot d$	[€/TJ][11]	(6)
Ship	$836 + 0.44 \cdot d$	[€/TJ][12]	(7)

The costs of transportation using tractor and truck are shown in Figure 5. These values correspond to the transportation costs when biomass is extracted from the surrounding areas. For a methanol plant of 1000 MW this distance is 80 km, see Figure 4. The result is highly dependent on yield and road density and the variable values used are shown in Appendix 1.

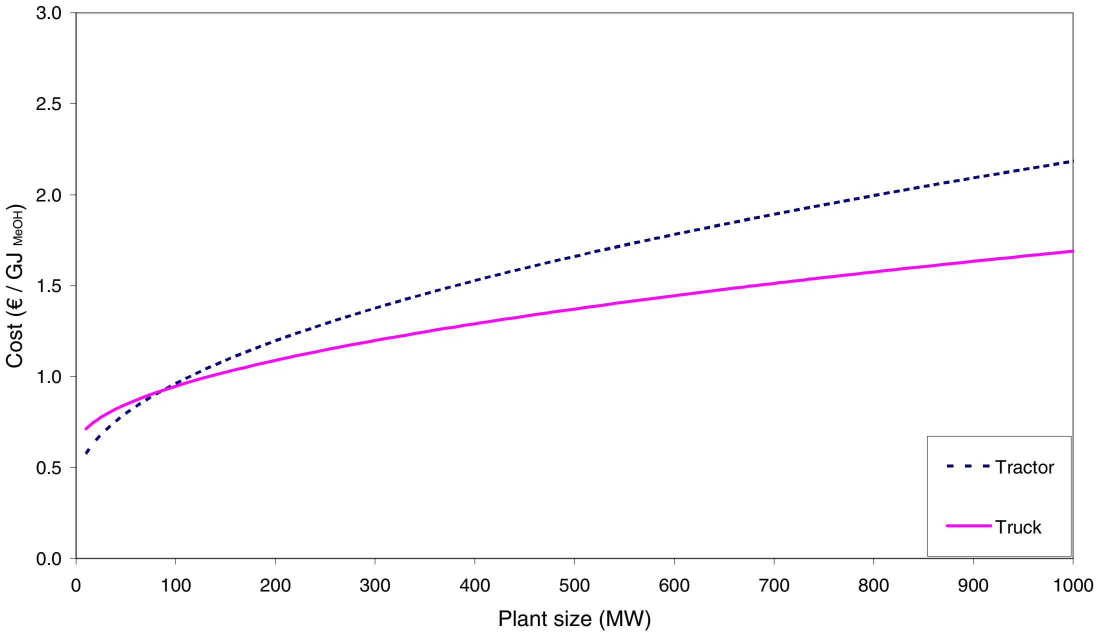

Figure 5: Transportation costs when biomass is extracted from the surrounding areas. Agricultural yield used is 10 tonne $_{\text{bio}} \cdot \text{km}^{-2} \cdot \text{year}^{-1}$ and the ratio of actual road length to direct distance used is 3. For a methanol plant of 1000 MW this distance is 80 km.

If biomass is not locally available the biomass can be transported longer distances after being harvested. This transportation may happen by tractors and trucks, or more likely by train or ship. The calculation of these additional transportations costs are shown in Figure 6. The train and ship transportation costs include 20 km feeder transportation by truck from the recovery area to a railway terminal or 50 km to a harbor.

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[8] See Appendix 3 for conversion rates. $1€_{2003} = 1.02\text{US\$}_{1994}$ (IMF, 2004).

[9] Tractor; $230 + 13 \cdot d$ [$\text{US\$}_{1994}$/TJ].

[10] Truck; $350 + 7.9 \cdot d$ [$\text{US\$}_{1994}$/TJ].

[11] Train; $740 + 1.1 \cdot d$ [$\text{US\$}_{1994}$/TJ].

[12] Ship; $850 + 0.45 \cdot d$ [$\text{US\$}_{1994}$/TJ].

When using these variables, the tractor is the most cost efficient way of transportation up to a distance of 25 km. For distances up to 50 km, truck transportation becomes the best option. For distances between approximately 50 and 150 km, train becomes the cheapest, and ship is the next most cost efficient for longer distances, see Figure 6.

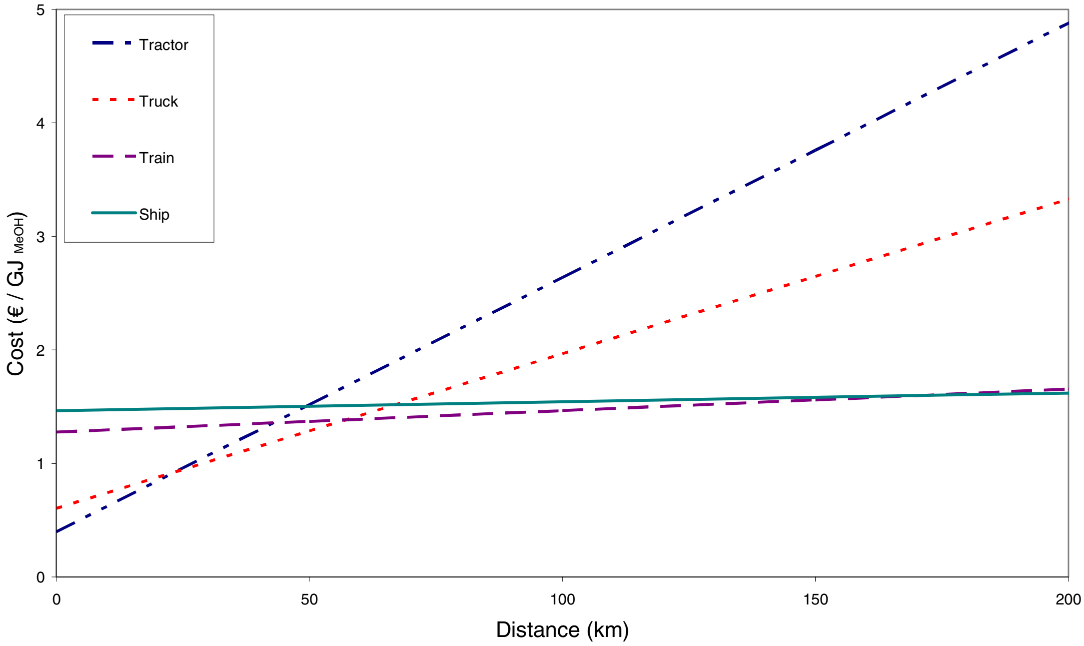

Figure 6: Transportation costs for biomass.

4.3 Cost of Biomass Conversion to Methanol

To find the costs for methanol plants with different sizes, a bottom-up engineering analysis is done, exploring the economies of scale of sub-components of the aggregated methanol plant. The installed investment costs for the separate units in the base methanol plant (430 MW) are presented in Table 2. The methanol production costs are calculated by dividing the total annual costs of a system by the produced amount of fuel. The total annual costs consist of annual investment, operating and maintenance, biomass feedstock and electricity supply/demand.[13]

Scale effects strongly influence the unit cost per capacity, and unit costs decrease with the upscaling of plants or components (such as boilers, turbines, etc.). For example, a methanol plant of 100 MW can be expected to be cheaper per GJ methanol produced than a 10 MW plant, even though both plants are based on the same technology. This difference can be adjusted using scaling functions, as shown in equation 8:

$$\frac{Cost_a}{Cost_b} = \left(\frac{Size_a}{Size_b}\right)^R \qquad \text{With } R = \text{Scaling factor} . \tag{8}$$

---

[13] The net electricity (gross internal) for the system used is 0.

Table 2: Methanol plant scale factors and costs (including biomass cost and pretreatment).

Gasification System	**Scaling Factor R**[a]	**430**	**MW Scale**[a,e]
Total Pretreatment	0.79	31.4	M €
BCL	0.65	25.0	M €
Gas Cleaning:			
Tar cracker	0.70	7.6	M €
Cyclones	0.70	5.6	M €
HT Heat Exchanger (total installed)	0.60	9.2	M €
Baghouse Filter	0.65	3.4	M €
Condensing Scrubber	0.70	5.6	M €
Syngas Processing:			
Compressor	0.85	13.9	M €
Steam Reformer	0.60	37.8	M €
Methanol Production:			
Make Up Compressor[b]	0.70	14.3	M €
Liquid Phase Methanol	0.72	3.6	M €
Recycle Compressor[b]	0.70	0.3	M €
Refining	0.70	15.7	M €
Power Generation:			
Steam Turbine + steam system	0.70	11.4	M €
Total Installed Investment (I_t)		***184.9***	***M €***
	Description of Calculation		
Total installed investment corrected for lifetime (I_c)	$I_c = I_t \cdot \left(1 - \frac{1}{(1+IR)^{t_e}} \cdot \frac{t_t - t_e}{t_t}\right)$	167.2	M €
HHV$_{\text{dry biomass}}$	Table Value[a]	19.46	GJ/tonne
Biomass input (E_{MW})	Plant Size[a]	430.0	MW
Biomass input (M_{bio})	$M_{bio} = \frac{E_{MW}}{HHV_{bio}}$	79.5	Dry tonne/hour
Load hours (t)	Chosen value[a]	8000	h
Biomass input ($E_{GJ/a}$)	$E_{GJ/a} = M_{bio} \cdot t \cdot HHV_{bio}$	**12.4**	GJ/year
Annual Costs:			
Capital ($c_{capital}$)[c]	$C_{capital} = I_c \cdot 0.4 \cdot 0.33$	22.1	**M €**
Operating and Maintenance	4% of I_c[a]	7.4	**M €**
Biomass	Biomass Costs = 2 US\$/GJ$_{bio}$[a,f]	20.4	**M €**
Costs/Income Power	Net electricity(gross internal) = 25GJ–25GJ	0.0	**M €**
Total Annual Costs (c_{total})		**49.8**	**M €**
Production:			
Efficiency fuel (η)[d]	Value from Hamelinck and Faaij (2001)	57.0	%
Fuel output (P)	$P = E_{MW} \cdot \eta$	245.1	MW HHV
Costs of fuel produced (c_{MeOH})	$c_{MeOH} = \frac{c_{total} \cdot \eta}{E_{GJ/a}}$	***7.1***	***€/GJ***

[a] Hamelinck and Faaij (2001).

[b] Scaling factor not described by Hamelinck and Faaij (2001).

[c] 33% investment is added to hardware (instrumentation and control 5%, buildings 1.5%, grid connections 5%, site preparation 0.5%, civil work 10%, electronics 7%, and piping 4%) and 40% installation costs to investment (engineering 5%, building interest 10%, project contingency 10%, fees/overheads/profits 10%, start-up costs 5%) (Hamelinck and Faaij, 2001). The scaling factor is not included for these costs.

[d] The power output is not included (-0.1 MW$_e$).

[e] 1€$_{2003}$ = 1.22US\$$_{2001}$ (IMF, 2004).

[f] The biomass cost of 2 US\$/GJ$_{bio}$ is included for the result to be directly comparable with Hamelinck and Faaij (2001).

Using this information, it is possible to calculate the costs for plant components with other sizes. When adding the installed investment costs for the separate units, we get the total investment cost for the new size, and we can then find the production cost for this size. For biomass systems *R* is usually between 0.6 and 0.8 (and Hooidonk, 2000). The uncertainty range of such estimates is up to ±30% (Hamelinck and Faaij, 2001).

Calculated production costs for methanol plants with biomass input between 10 MW and 1000 MW can be found in Figure 7.[14] A description of the calculations for the production costs can be found in Table 2 and Appendix 1.

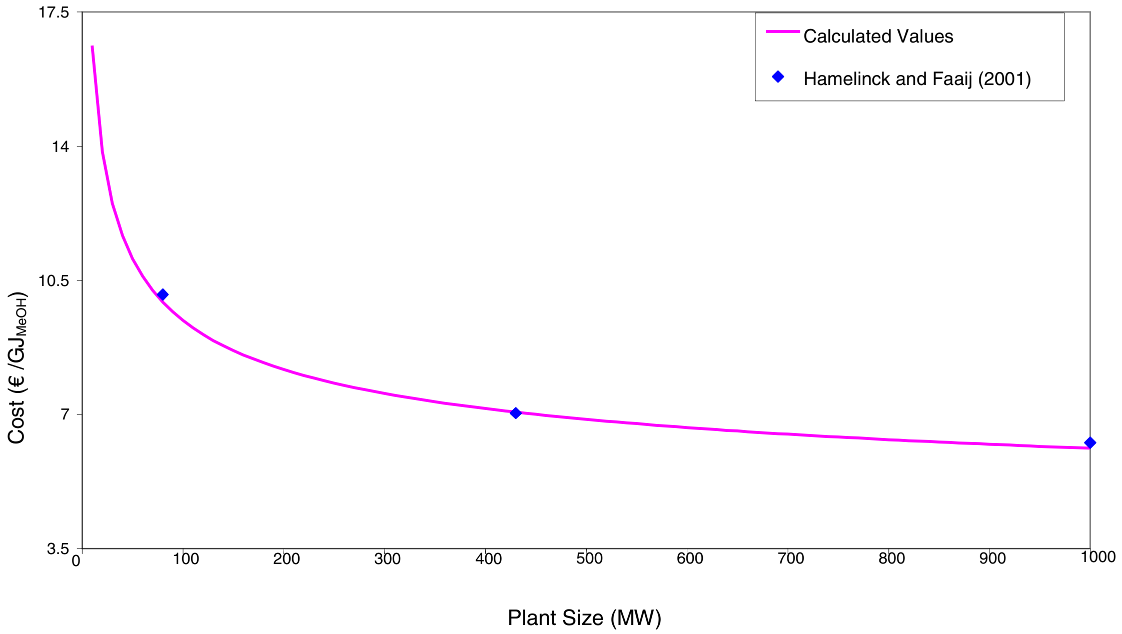

Figure 7: Calculated production costs for methanol plants with biomass input between 10 MW and 1000 MW, including biomass cost of 2.9 €/GJ$_{MeOH}$ and pretreatment of biomass.

The three points in Figure 7 are values calculated by Hamelinck and Faaij (2001), and the line is our calculated values.

Various system components have a maximum size, above which multiple units will be placed in parallel. This is not taken into consideration in these cost calculations, and the total annual investment for large scales will be higher than described in this study. When comparing the results achieved in our calculations with the results from Hamelinck and Faaij (2001), the differences in the calculations are 2.0% (80 MW), 0.4% (430 MW) and 2.3% (1000 MW), see Appendix 4.

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[14] 1€$_{2003}$ = 1.22US$\$_{2001}$ (IMF, 2004).

4.4 Cost of Transportation of Methanol

The costs of methanol transportation are calculated using figures from Börjesson and Gustavson (1996). The transportation costs are a function of actual transportation distance (*d*) in km, as shown in equations 9 to 11.[15]

Truck $138 + 3.05 \cdot d$ [€/TJ][16] (9)

Train $423 + 0.66 \cdot d$ [€/TJ][17] (10)

Ship $462 + 0.15 \cdot d$ [€/TJ][18] (11)

These calculated costs may differ from the transportation price, as the price may be reduced due to discounts or special agreements (Börjesson and Gustavson, 1996). In the calculations for transportation cost the costs are scale independent.

The costs for transporting methanol are shown in Figure 8. Truck transportation is the most cost efficient for shorter distances (less than 100 km), and trains and ships for longer distances. The transportation costs for trains or ships include 20 km feeder transportation by truck from the recovery area to a railway terminal or 50 km to a harbor.

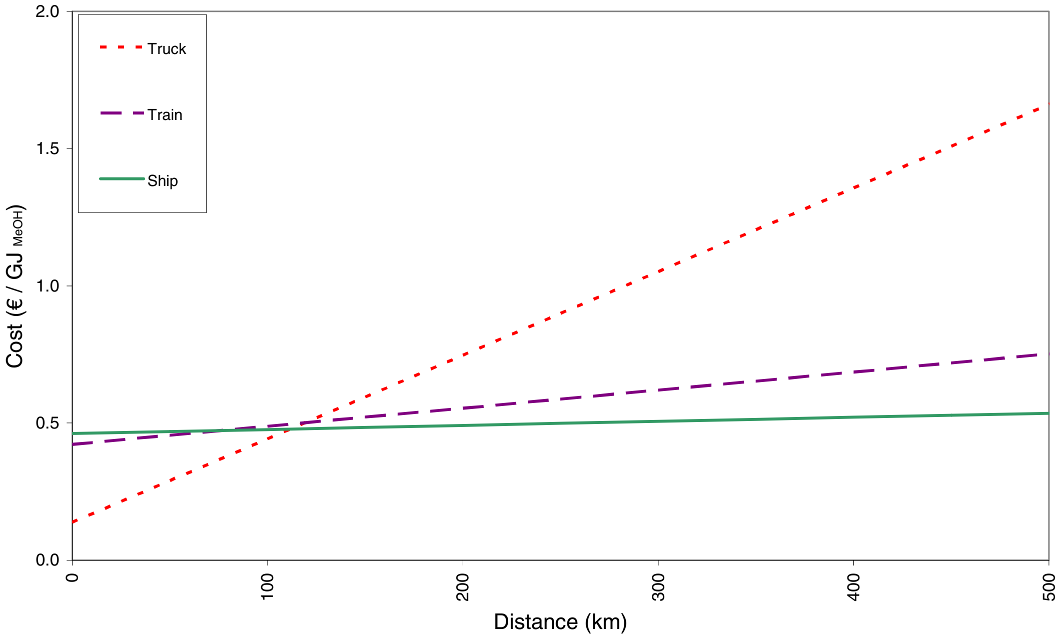

Figure 8: Costs for methanol transportation by truck, train and ship (Börjesson and Gustavson, 1996).

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[15] See Appendix 3 for conversion rates. $1€_{2003} = 1.02US\$_{1994}$ (IMF, 2004).

[16] Truck; $140 + 3.10 \cdot d$ [$US\$_{1994}$/TJ].

[17] Train; $430 + 0.67 \cdot d$ [$US\$_{1994}$/TJ].

[18] Ship; $470 + 0.15 \cdot d$ [$US\$_{1994}$/TJ].

4.5 Cost of Distribution of Methanol

Capital costs for refueling stations for dispensing methanol are summarized in Table 3. The scenarios are evaluated in a study of the American Methanol Foundation (AMF-EA Engineering, 1999). The costs are independent of the methanol plant size.

Table 3: Costs for refueling stations for dispensing methanol.

Capacity (l/month)[a]	113,562		
Capacity (GJ/year)[a,b]	21,505		
	Capital Costs (€)[c]	Yearly Payment (€)[d]	Cost (€/GJ_{MeOH})[f]
Increase storage capacity at existing stations			
Add new underground tank[e]	54,586	5,038	0.234
Add new above-ground tank[e]	47,758	4,408	0.205
Displace existing gasoline storage capacity with methanol			
Prepare existing underground tank[e,g]	43,909	4,053	0.188
Replace existing underground tank[e]	61,228	5,651	0.263
Average cost			0.223

[a] Capacity of the refueling station is 33000 gallons methanol/month.

[b] Density of methanol; 793 kg/m^3, LHV_{MeOH}; 19.9 GJ/tonne.

[c] AMF-EA Engineering (1999).

[d] Interest rate is 10%, lifetime 25 years.

[e] Tank volume is 10,000 gallons (37,850 liters).

[f] See Appendix 3 for conversion rates. 1€2003 = 1.14US$1999 (IMF, 2004).

[g] The preparation of the tanks consist of cleaning and installing fiberglass liner.

4.6 Total System Costs

Figure 9 illustrates the total unit costs of methanol production. A summary of variable values used in the system can be found in Appendix 1 and Table 2. Included in the unit methanol cost are 50 km additional biomass transportation by truck and 100 km methanol transportation by train and 1000 km methanol transportation by ship. These transportation costs are dependent on the distance to the demand center of methanol. More information about the effect of these transportation costs can be found in the sensitivity analysis in section 6.

The costs of biomass and distribution are scale independent in this study, while the biomass transportation costs, pretreatment costs and plant costs differ for increasing scales. As seen in the figure, the total unit cost of methanol is found to decrease from about 20.6 €/GJ_{MeOH} for a 10 MW plant to about 12.5 €/GJ_{MeOH} for a 200 MW plant. The unit costs stabilize for plant sizes between 200 MW and 1000 MW. They do, however, continue to decrease to about 11 €/GJ_{MeOH} for a 1000 MW plant.

5 Energy Balance

The energy consumption for the different steps in the biomass-to-methanol pathway is given in Table 4. The consumption values are based on Börjesson (1996), Börjesson and

Gustavson (1996), Suurs (2002) Hamelinck and Faaij (2001) and Hamelinck *et al.* (2003) and cover harvesting, chipping and drying, transportation of biomass, conversion to methanol and transportation of methanol. Most of the values are based on Swedish conditions, and the energy consumption will vary if less/more efficient technologies are used.

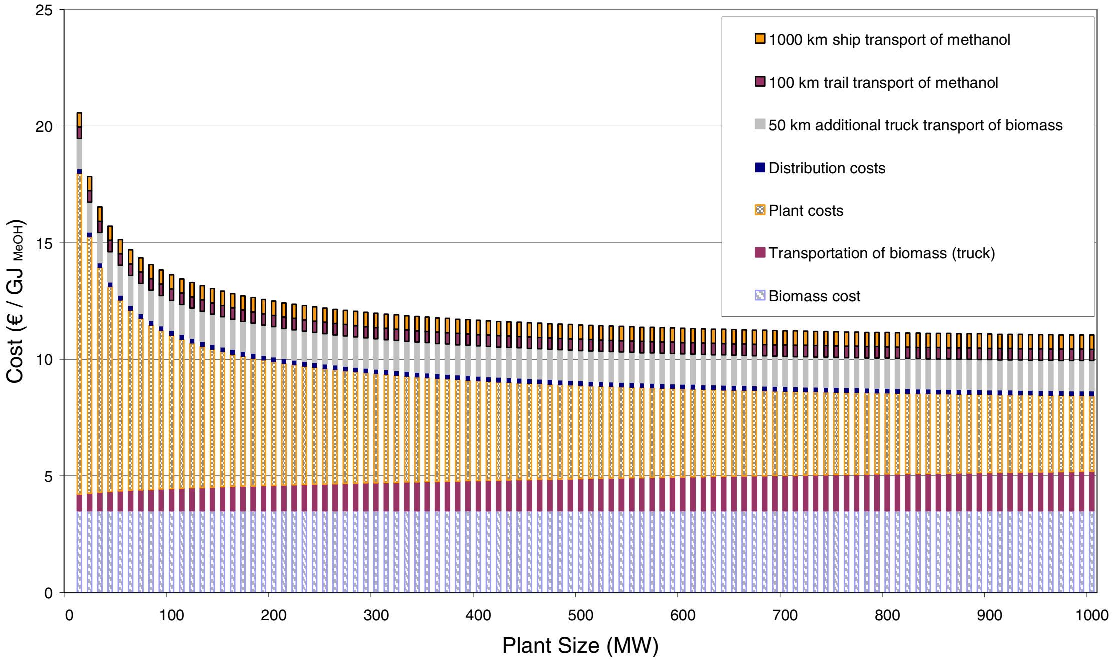

Figure 9: Total costs of the methanol, including all the different steps in the pathway. Included are additional biomass transportation of 50 km (truck) and methanol transportation of 100 km by train and 1000 km by ship.

Table 4: Energy consumption for different steps in pathway.

	Energy Consumption		**Source**
Harvesting[a]	37.9	$\text{MJ/tonne}_{\text{dry}}$	Hamelinck *et al.* (2003)
Chipping	0.18	$\text{GJ/tonne}_{\text{dry}}$	Suurs (2002)
Drying	10%	$\text{of input}_{\text{biomass}}$	Hamelinck and Faaij (2001)
Biomass transport:			
Tractor	310	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson (1996)
Truck	150	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson (1996)
Train	79	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson (1996)
Ship	39	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson (1996)
Conversion to methanol[b]	43%	$\text{of input}_{\text{biomass}}$	Hamelinck and Faaij (2001)
Methanol transport:			
Truck	57	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson and Gustavson (1996)
Train	29	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson and Gustavson (1996)
Ship	9	$\text{kJ} \cdot \text{km}^{-1} \cdot \text{GJ}^{-1}$	Börjesson and Gustavson (1996)

[a] Harvesting includes manual felling and forwarding/haulage of logs.

[b] Plant efficiency, η, is 57%.

The energy consumption for harvesting includes manual felling and forwarding/haulage of logs. The energy use for wood ash recirculation is not included in this calculation. However, this is important to compensate nutrient losses and to ensure high, long-term productivity (Börjesson, 1996).

The energy use in biomass and methanol transportation is based on Börjesson (1996) and is estimated for tractors, trucks, trains and ships. The energy input includes both direct energy use, such as motor fuels and electricity, and indirect energy use, such as vehicles and infrastructure. The energy consumption that results from transfer operations is not included.

To minimize the transportation distance for biomass, the methanol plant may be located in the center of the biomass supply. When calculating the energy efficiency of biomass transportation to the center, the transportation distances found in section 3.2 are used. This transportation is primarily carried out using a tractor or a truck. The energy consumption for this primary transportation distance is shown in Figure 10 as the ratio between energy use and bioenergy input. For a methanol plant of 1000 MW this distance is 80 km, see Figure 4. The primary distance is assumed to be the same even if the biomass is transported to the edge of the biomass supply area instead of the center. The energy consumption values are estimated using diesel as fuel. Biomass-based methanol can also be used as fuel. When methanol is used instead of diesel the energy use will increase by 20–30% (Börjesson and Gustavson, 1996).

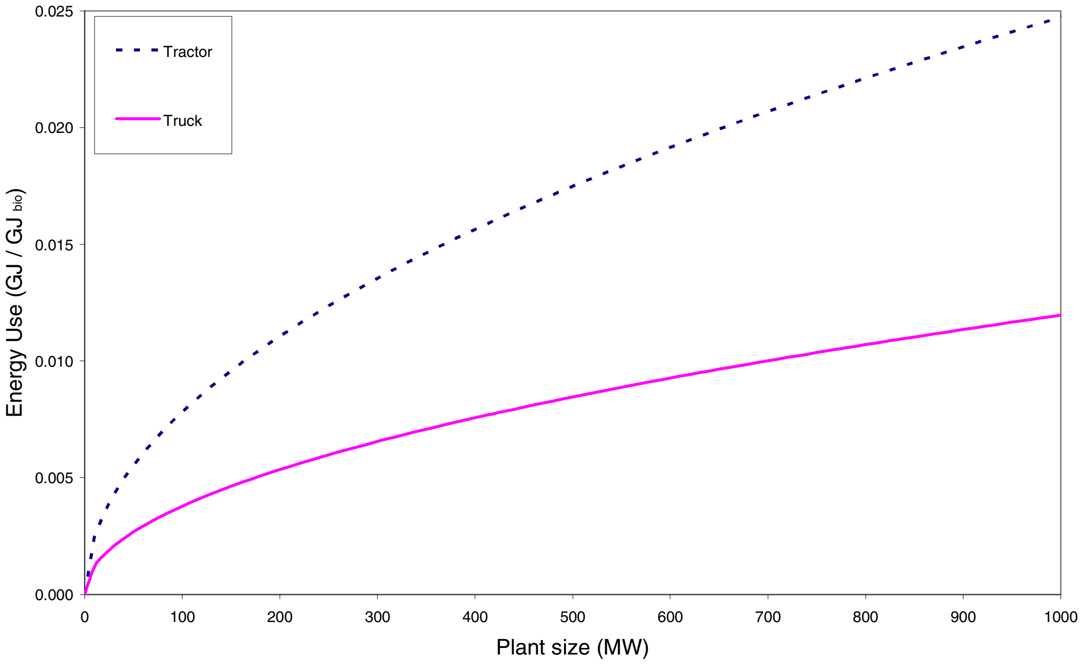

Figure 10: Energy consumption for biomass transportation by tractor and truck when the conversion plant is located in the center of biomass supply. Agricultural yield used is 10 tonne $_{bio}$ · km^{-2} · year^{-1} and the ratio of actual road length to direct distance used is 3. For a methanol plant of 1000 MW the transportation distance is 80 km.

When transporting biomass to additional distances, trains and ships can also be used. The energy consumption for these additional transport distances are shown in Figure 11.

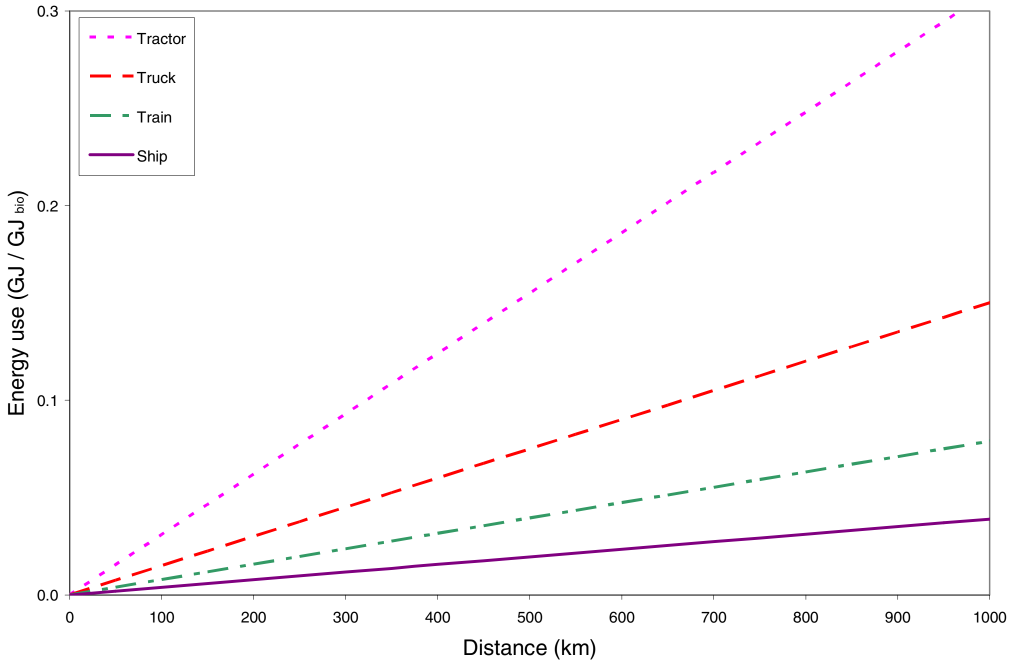

Figure 11: Energy consumption for biomass transportation by tractor, truck, train and ship.

The efficiency for the biomass-to-methanol conversion is 57%. The energy use for the plant is therefore 43% of input bioenergy.

The energy consumption for methanol transportation can be seen in Figure 12. The primary energy use of methanol transportation per unit energy transportation is about three to six times lower than that of biomass transportation.

The energy efficiencies for the different scaled biomass pathways are more or less scale independent. Assuming that produced methanol is transported independent of plant size and using the same transportation means and distances, transportation of biomass is the only scale dependent factor. For truck transportation of biomass this energy consumption varies from 0.1% of the total input bioenergy for a 10 MW plant to 1.2% of the total input bioenergy for a 1000 MW plant. When using a tractor for biomass transportation, the values vary from 0.2% to 2.5%.

In reality, methanol will often be transported over longer distances when the methanol plant is large. The transportation means in a large-scale situation may, however, be more energy efficient than the transportation means used in a small-scale situation, as it is more likely to use ship transportation in large-scale transportation.

If there is no additional transportation of biomass and no methanol transportation, the net energy for the pathways are about 46% of the total input bioenergy for a 10 MW plant and 44% for a 1000 MW plant. When using the values shown in Appendix 1, biomass can be transported by truck 3,000 additional km before the transportation energy and necessary energy consumption is equal to the energy of input biomass. The corresponding distances for tractor, train and ship are about 1,500 km, 5,800 km and 11,700 km respectively. When transporting methanol the corresponding distances for truck, train and ship are approximately 8,000 km, 15,800 km and 50,800 km. A transportation path will usually consist of more than one means of transportation, generally it will comprise of a combination of the various modes of transportation. It would normally not make sense to consume all the energy of the input biomass.

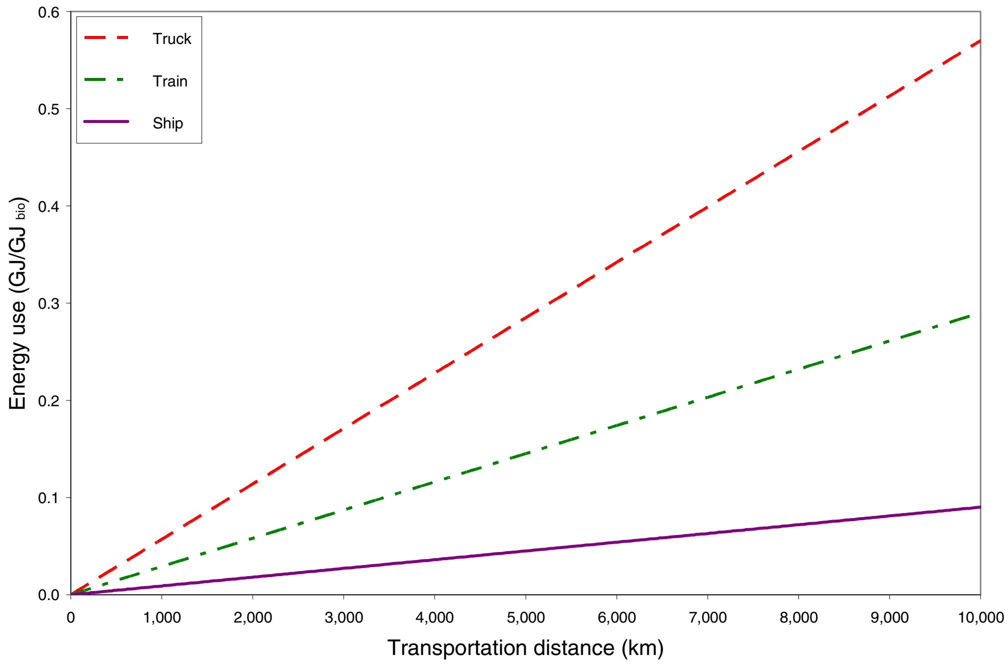

Figure 12: Energy consumption for methanol transportation.

If larger cargo ships are used, the energy use for biomass and methanol transportation by ship will be lower. The energy consumptions for train and truck have no scale profit.

6 Sensitivity Analysis

In order to assess the influence the different variables produce on the final methanol unit cost, a sensitivity analysis is carried out. First of all, potential maximum and minimum values of the input parameters are estimated and maximum and minimum costs for the different system components in the chain are calculated. Second, percentage changes of the reference case values are calculated, followed by the new unit costs of methanol. Truck is the main method of transportation of biomass in all of these calculations, unless otherwise stated.

Some of the system variables used in the sensitivity analysis are shown in Table 5, with attached minimum and maximum values.

Table 5: Variables with attached extreme values.

Description	**Symbol**	**Unit**	**Reference case**	**Minimum value**	**Maximum value**
Biomass cost	c_{bio}	€/GJ$_{bio}$	2.0	1.0	4.0
Agricultural yield per unit area	Y	tonne · km^{-2} · year^{-1}	10.0	5.0	20.0
Fraction of useful land	a		2/3	1/2	1.0
Ratio of actual road length to direct distance	b		3.0	1.0	6.0
Transportation cost per unit distance and unit energy	$k_{Tractor}$	€ · TJ$_{bio}^{-1}$ · km^{-1}	310/d + 17.54	-10%	+10%
	k_{Truck}	€ · TJ$_{bio}^{-1}$ · km^{-1}	472/d + 10.66	-10%	+10%
Methanol plant efficiency	η	%	57	54	58
Load hours, methanol plant	t	h	8000	7588	8760
Scale factors	R		Varies (0.6–0.85)	0.6	1

6.1 Biomass Cost

A biomass-cost of 2 €/GJ$_{bio}$ gives the cost of 3.5 €/GJ$_{MeOH}$.[19] Using the extreme costs for biomass in Table 5, the minimum cost will be 1.8 €/GJ$_{MeOH}$ and the maximum cost 7 €/GJ$_{MeOH}$. This will affect the total methanol unit cost as described in Figure 13.

6.2 Biomass Transportation to Methanol Plant

The cost of transporting biomass to the plant depends on several factors including agricultural yield per unit area, fraction of useful land, ratio of actual road length to direct distance, and transportation cost per unit distance and unit energy. When all of these minimum and maximum values are combined, the new methanol unit cost can be found in Figure 14.

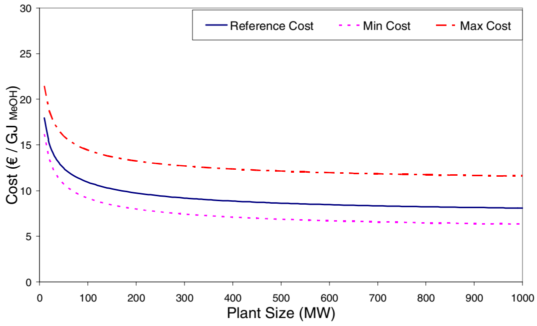

Figure 13: Unit cost of methanol; effect of biomass cost changes.

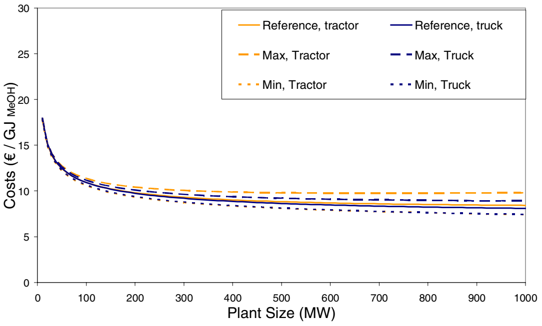

Figure 14: Unit cost of methanol; effect of biomass transportation cost changes

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[19] Using plant efficiency of 57%.

6.3 Methanol Conversion Plant

As described in section 4.3, the uncertainty range in calculating investment costs for the methanol plant using scaling factors is up to ±30%. Other factors, such as methanol plant efficiency and load hours, also affect the methanol plant cost. In Figure 15 the aforementioned values change, as seen in Table 5.

The plant efficiency for our chosen model is 57% and it is assumed that an increase in scale can barely further improve this efficiency (Hamelinck and Faaij, 2001). If upscaling improves the plant efficiency, the new methanol unit cost can be found in Figure 16. In this figure efficiency is constantly increasing, from 50% for the smallest plants analyzed (10 MW) to 65% for the largest plants analyzed in the model (1000 MW).

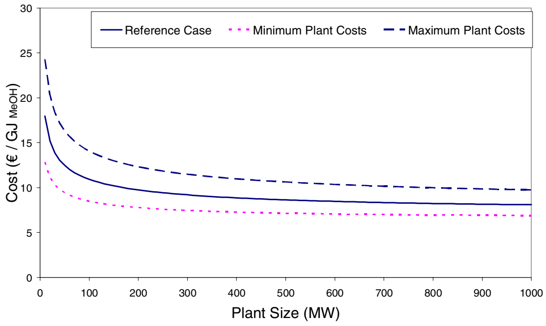

Figure 15: Unit cost of methanol; effect of plant cost changes.

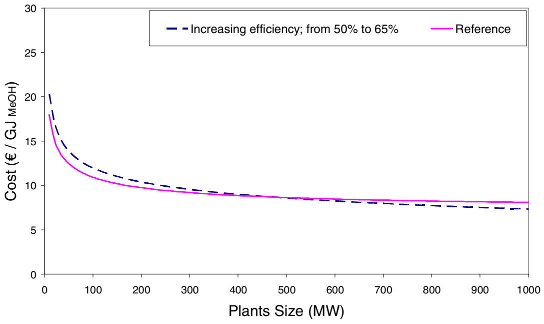

Figure 16: Unit cost of methanol; effect of efficiency changes.

In this study we have used constant scaling factors, *R*, and the scaling factors do not change in Figure 15. Jenkins (1997) argues that the scaling factor itself may be a function of capacity, and that *R* should be larger for large-scale plants than for small-scale plants. Very large-scale biomass facilities are not constructed yet and how the investment costs change according to size is highly uncertain. The use of favorable economies of scale, suggested by lower values of *R*, might therefore be too optimistic (Jenkins, 1997). If there is a constant change in the scaling factors, from 0.7 for a plant size of 10 MW to 1.0 for a plant size of 1000 MW, the methanol unit costs will be affected as seen in Figure 17. The figure also reflects the methanol unit costs when *R* is constant 0.6 and 0.8.

The variables as analyzed in Figures 13 to 17 are more or less fixed variables, which are subject to a high degree of uncertainty. There are also several flexible variables in this model that are more dependent on the specific situation, such as additional transportation distance of biomass and methanol. The final costs are very sensitive to these flexible variables.

Figures 18 and 19 show the corresponding methanol unit cost when some of these flexible variables are changed. In Figure 18, biomass is transported additional distances by truck, train and ship, and in Figure 19 methanol is transported various distances by the same transportation means.

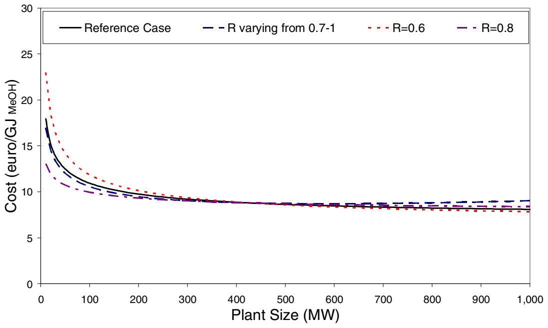

Figure 17: Unit cost of methanol; effect of scaling factor, *R*, changes.

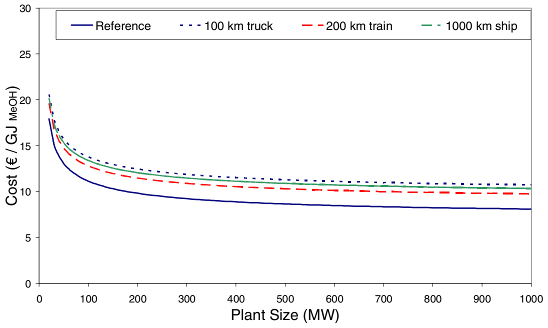

Figure 18: Unit cost of methanol; additional biomass transportation.

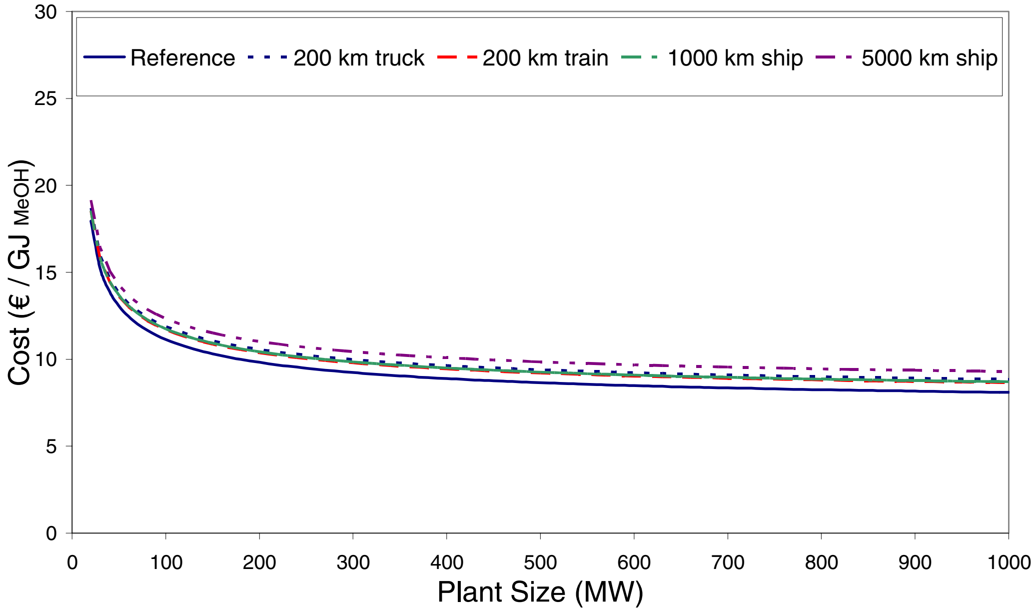

Figure 19: Unit cost of methanol; methanol transportation.

When the chosen minimum and maximum values are used, biomass cost change and methanol plant cost changes affect the unit cost of methanol the most. Biomass transportation costs also affect the unit costs significantly, and most for large methanol plants. Additional biomass transportation and methanol transportation are dependent on both the location of the plant and the demand center of methanol. These cost changes are independent on scale.

In the second part of this sensitivity analysis the value of different variables is changed by 25% of the range in Table 6. The unit cost of methanol is adjusted accordingly and the results of the calculations are shown in Figure 20. This exercise reveals that the cost of methanol is strongly influenced by a number of specific input parameters, while it is barely influenced by other parameters.

According to this sensitivity analysis the unit cost of methanol is most sensitive to biomass cost and transportation cost. As seen in Figure 20, a large scale facility is most sensitive to changes in biomass, since this cost is unchanged per unit methanol produced, while other costs are scaling according to scale. The transportation cost of biomass has also a significant effect on the area chosen for the methanol plant. Also here the large-scale facility is more sensitive, since the biomass is transported longer for large scales. The methanol unit cost is not as sensitive to change in costs associated with the methanol plant. Smaller plants are more sensitive than large plants when plant costs change.

Table 6: Variables with attached ranges used in sensitivity analysis.

Description	Symbol	Unit	Reference case	Minimum value	Maximum value	25% of Range
Biomass cost	c_{bio}	€/GJ_{bio}	2.0	1.0	4.0	0.75
Agricultural yield per unit area	Y	$tonne \cdot km^{-2} \cdot year^{-1}$	10.0	5.0	20.0	3.75
Fraction of useful land	a		2/3	1/2	1.0	0.125
Ratio of actual road length to direct distance	b		3.0	1.0	6.0	1.25
Transportation cost per unit distance and unit energy	$k_{Tractor}$	$€ \cdot TJ_{bio}^{-1} \cdot km^{-1}$	310/d + 17.54	-10%	+10%	32/d + 3.55
	k_{Truck}	$€ \cdot TJ_{bio}^{-1} \cdot\cdot km^{-1}$	472/d + 10.66	-10%	+10%	94.4/d + 2.13
Load hours, methanol plant	t	h	8000	7588	8760	293
Capital costs	$c_{capital}$	M€	$c_{capital} = I_c \cdot 0.4 \cdot 0.33$	-10%	+10%	25% of Range
Operating and Maintenance	O&M	M€	4% of I_c	-10%	+10%	25% of Range

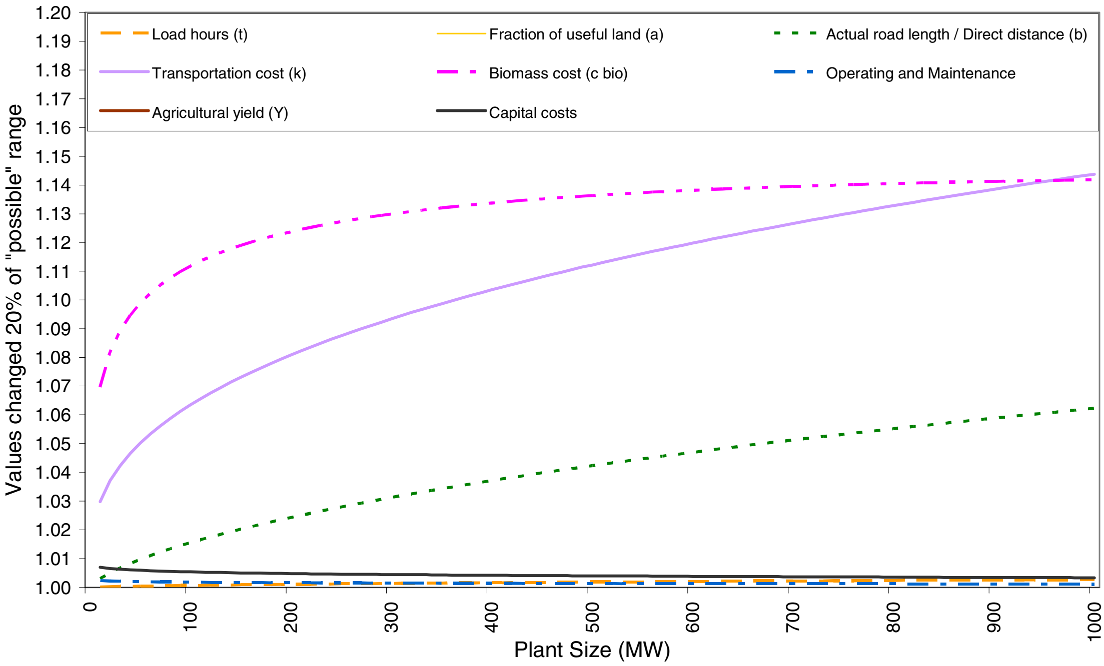

Figure 20: Change in total methanol costs when variables change 25% of the range described in Table 6.

7 Geographic Explicit Analysis

Two geographical areas are analyzed using the model, one area in Galicia in the north-west of Spain and one in the west of Greece.

The harvesting and biomass costs used for this area are based on an analysis conducted in GIS (Rokityanskiy, 2004). The analysis is using a constant biomass cost of 1\$/ha and calculates available biomass for this cost. The GIS model is originally half-degree spatial resolution (about 50 × 50 km). The forest area in each of these grids is assigned to the forest area in a GIS map with finer resolution (x–x km) (Neuvonen, 2004), resulting in more accurate data for available biomass in different locations. After calculating productivity per hectare forest, both available biomass for a specific area and fraction of useful land are found. A suitable methanol plant size for the geographical area is then found, and the model described earlier in this paper is used. The biomass in an area can either be transported to one single methanol plant, or be divided to several smaller plants. In this analysis we have looked at single plants, one large-scale plant for Spain, and one medium-scale plant for Greece.

The system values for the locations are selected arbitrarily and there may, therefore, be discrepancies between actual costs and costs calculated in the model. The geographic explicit analysis is carried out with the aim of demonstrating the model. When planning a methanol plant for a specific location more research must be done in order to find accurate system values and to include other important factors in the model.

7.1 Geographic Explicit Analysis, Large-sized Methanol Plant

Galicia is the leading Spanish region in relation to forest waste potential and has currently four thermoelectric power stations, accounting for a total of 40 MW of power (Xunta, 2004). Due to its climatic characteristics, population distribution and a tradition and importance of the timber industry, Galicia may have potential regarding bioenergy.

For the chosen area in Spain (Figure 21), the productivity is 6.5 tonne/ha for an area of 2130 km^2. If all this biomass is used for the methanol plant, this gives a plant size of 935 $MW_{biomass\ input}$. The geographic explicit data is summarized in Table 7. All other values and costs are assumed to be the same as those described for the general model.

Where methanol is distributed depends on the local distance to demand centers. We assume that the produced methanol is transported to Vigo, Galicia's largest city, where a quarter of the methanol will be distributed to the consumers in Vigo, and three-quarters of the methanol will be transported by ship from the port in Vigo. The transportation distance to Vigo is about 50 km by truck and 100 km by train. The following transportation distance by ship is assumed to be 1000 km, and the methanol is transported to, for example, Lisboa.

The total cost for this methanol chain is calculated to be 7.7 €/GJ_{MeOH} for the methanol transported to Vigo and 8.3 €/GJ_{MeOH} for the methanol also transported by ship afterwards. The cost for the different system components can be found in Figure 22. For comparison the Super gasoline price in Spain is 3.3 €/GJ[20] (World Bank, 2003).

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[20] Super gasoline: 83 US$_{2002}$/liter (World Bank, 2003). LVH: 43.2 MJ/kg. Density: 745kg/m^3. 1€$_{2003}$ = 0.77 US$_{2002}$ (IMF, 2004).

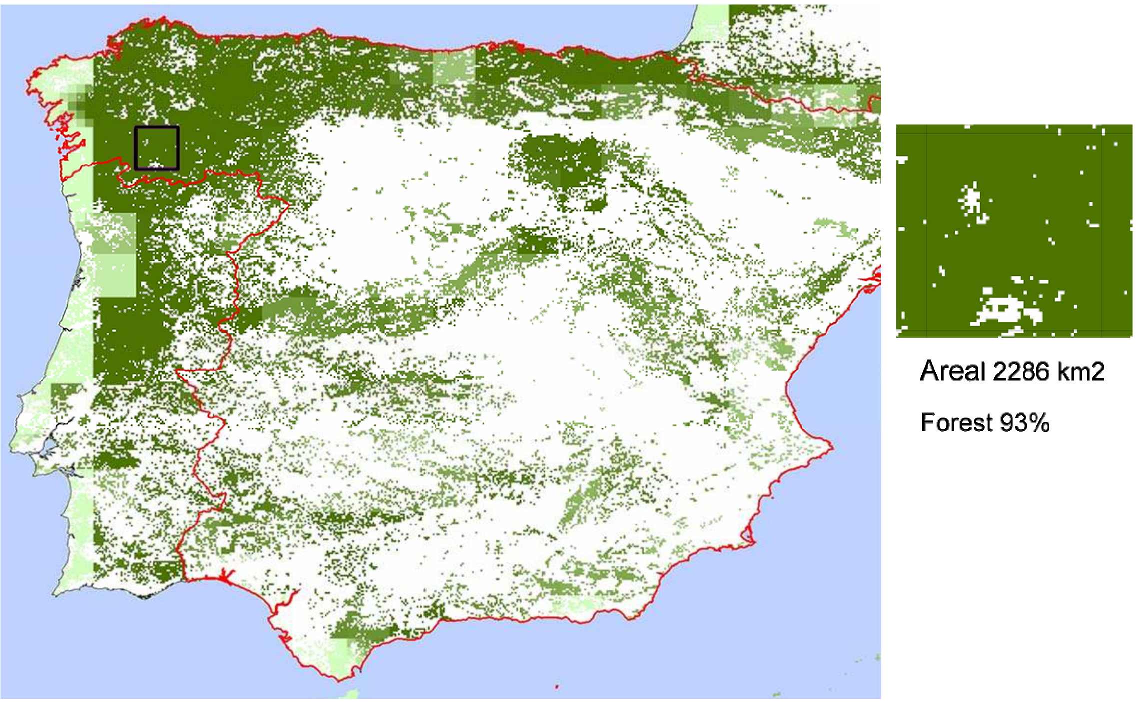

Figure 21: Map showing forest area used for the large scale geographic explicit analysis.

Table 7: Variables with belonging site-specific values.

Description	**Symbol**	**Unit**	**Value**
Plant Size	E	MW	935
Agricultural yield per unit area	Y	tonne · km^{-2} · $year^{-1}$	6.5
Fraction of useful land	a		93%
Biomass cost	c_{bio}	€/GJ_{bio}	1.3

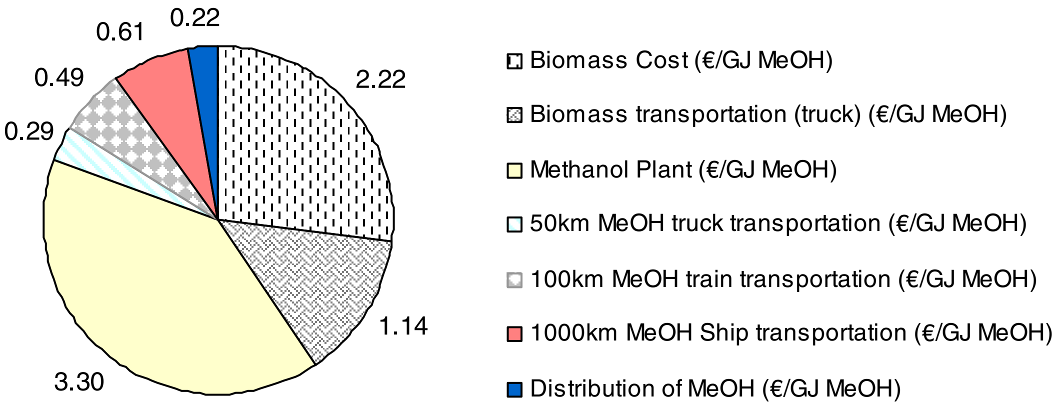

Figure 22: Cost of methanol production using geographic values. Plant size is 935 MW and the methanol is transported 50 km by truck, 100 km by train and 1000 km by ship.

7.2 Geographic Explicit Analysis, Medium-sized Methanol Plant

For the chosen area in Greece (Figure 23) the productivity is 6 tonne/ha. The chosen area is 950 km^2, which is 40% of the total area of the grid. We assume the fraction of useful land to be 90% for the forest. If all the available biomass is used for the methanol plant, this gives a plant size of 380 $MW_{biomass\ input}$. The geographic explicit data is summarized in Table 8. Here, also all other values and costs are assumed to be the same as those described for the general model.

Figure 23: Map showing forest area used for the medium-scale geographic explicit analysis.

Table 8: Variables with belonging site-specific values.

Description	Symbol	Unit	Value
Plant Size	E	MW	380
Agricultural yield per unit area	Y	tonne · km^{-2} · year^{-1}	6
Fraction of useful land	a		90%
Biomass cost	c_{bio}	€/GJ_{bio}	1.3

If the produced methanol is transported to Athens, the assumed transportation distances are approximately 50 km by truck and 400 km by train.

The total cost for the methanol chain is calculated to be 8.8 €/GJ_{MeOH}. The costs for the different system components can be found in Figure 24. The Super gasoline price in Greece is 3.1 €/GJ [21] (World Bank, 2003).

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[21] Super gasoline: 78 US$$_{2002}$/liter (World Bank, 2003). LVH: 43.2 MJ/kg. Density: 745kg/m^3. 1€$_{2003}$ = 0.77 US$$_{2002}$ (IMF, 2004).

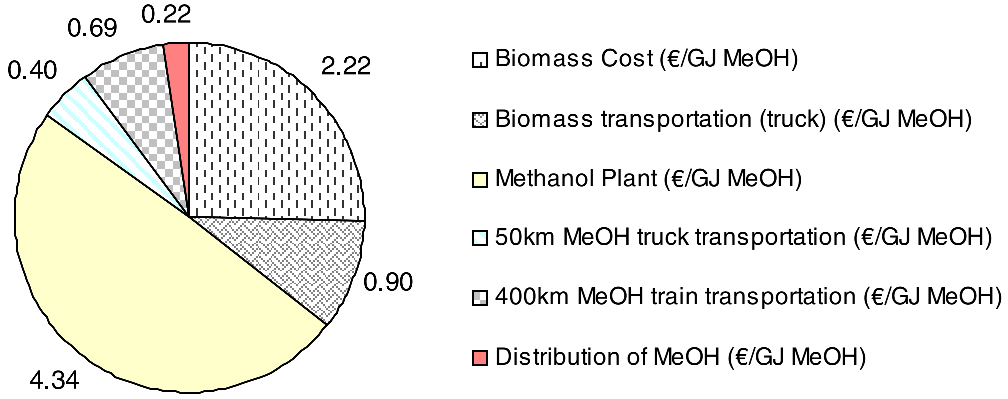

Figure 24: Cost of methanol production using geographic values. Plant size is 380 MW and the methanol is transported 50 km by truck and 400 km by train.

8 Discussion

The aim of this study was to find the theoretical plant size for different input data. When using the input variables described the output of the model — for methanol unit cost — decreases as plant size increases. The model, therefore, does not provide a minimum value for the methanol unit costs for a specific plant size. This result depends on many different input variables, such as biomass, plant and transportation costs. Cost and energy consumption are strongly dependent on local conditions and it is difficult to find general values.

The biomass used for this model is wood. Chipping of the wood is done by the plant site, after transportation of biomass. It may lead to favorable cost and energy balances to refine the biomass early on in the chain to, for example, torrefied wood. Cost and energy consumption of refined biomass should be investigated further.

In this study, both the cost of standing wood and harvesting are considered to be independent of the scale of the system. The values change according to location but not according to plant size. This may not always be the case since the price of wood is determined by supply and demand and the cost of harvesting the wood depends on the method used.

Only one methanol plant is considered in this study, however other options are available and the plant will subsequently have different efficiencies and plant costs. This paper focuses on methanol production, but the model may also be used for other promising conversion options for energy production from biomass.

When calculating the distance from biomass supply to methanol plant a circular biomass supply is assumed, with the plant located in the middle. This will often not be the case, but we assume the average distances still to be valid. When the biomass transportation distance differs considerably from this assumption, the cost or energy use for biomass transportation can be calculated using equations for additional biomass transportation.

To reduce energy use and cost of transportation, the means of transportation may be changed, from tractors and trucks to trains and ships. A large-scale plant is more likely to be able to use more cost and energy efficient transportation means, such as ship, as opposed to a small-scale plant, assuming that biomass and methanol are transported the same distance for both smaller and larger plants.

The need for biomass and methanol transportation depends on the balance between locally produced biomass and methanol and local demand for the fuels. In reality, the distances of additional biomass transportation and methanol transportation may be shorter for small plants. For the most part, in order to minimize the transportation costs it is advisable to locate the methanol plant close to both biomass supply and methanol consumer. This might be easier to achieve with a small or medium-sized plant, since neither biomass supply nor methanol production is as large as for a large-sized plant.

Calculation of energy consumption is relatively crude, and some energy consumption, such as transportation transfer operations and wood ash recirculation, are not included in the energy balance. The real energy consumption may therefore differ from the calculated consumption. Besides energy use, CO_2 emissions from supply chains are also critical aspects in discussing bioenergy sustainability. This is not investigated in this paper.

The quality of the analysis depends partly on the model and partly on the parameters. This is a simple model, and when planning a methanol plant more detailed information must be gathered, with site-specific data. The model may however be useful in providing an insight into different plant sizes suitable for different areas, considering cost and energy use for the site.

9 Conclusions

The aim of this study was to find the plant size with least cost and energy consumption, and to establish a simple relationship between transportation and methanol unit costs. Five system components are distinguished in the chain: biomass extraction and pretreatment, transportation of biomass, biomass conversion to methanol, transportation of methanol and distribution of methanol.

The unit cost of methanol is found to decrease from about 20.6 $€/GJ_{MeOH}$ for a 10 MW plant to about 12.5 $€/GJ_{MeOH}$ for a 200 MW plant. The unit costs stabilize for plant sizes between 200 MW and 1000 MW. They do, however, continue to decrease to about 11 $€/GJ_{MeOH}$ for a 1000 MW plant. Included in the unit methanol cost are 50 km additional biomass transportation by truck and 100 km methanol transportation by train and 1000 km methanol transportation by ship. As comparison, the hypothetical sales price for refined and distributed petroleum fuel, excluding fuel taxation, is 1.3 €/GJ[22] (World Bank, 2003).

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[22] Petroleum sales price: 32 $US\$_{2002}$/liter (World Bank, 2003). LVH: 43.2 MJ/kg. Density: 745kg/m^3. $1€_{2003}$ = 0.77 $US\$_{2002}$ (IMF, 2004).

According to the model, the methanol plant does not have a specific optimal size, if additional biomass transportation and methanol transportation are assumed to be the same for all sizes. This is, however, due to site-specific variables and transportation chains, and different locations have different possibilities and advantages. Economies of scale are therefore the overriding criteria as compared to the increase in transportation costs at longer scales.

In the sensitivity analysis, biomass cost and transportation cost was found to play the most important role for the unit cost of methanol. A large-scale facility is most sensitive to changes in these costs. Additional transportation and methanol transportation also plays a significant role. These costs are not dependent on the plant size.

If the methanol unit cost for a large-sized plant and a small/medium-sized plant are similar, it may be favorable to establish several smaller plants instead of one large plant. For most locations, it is highly recommended to locate the methanol plant close to both the biomass supply and the consumer of the methanol as this may reduce transportation costs for both biomass and methanol. The total methanol unit cost will therefore be less. If a choice has to be made between a location close to biomass supply and a location close to the consumer, the location close to biomass supply should generally be preferred as energy use and costs are higher for biomass transportation than for methanol transportation. The energy use and cost of transportation could be reduced for longer distances by changing the transportation mode.

When using only one mode of transportation and when energy consumption of the chain is as stated in this study, biomass can be transported 3,000 additional km by truck before the transportation energy and necessary energy consumption is equal to the energy of input biomass. Corresponding distances for tractor, train and ship are about 1,500 km, 5,800 km and 11,700 km, respectively. However, when transporting methanol the corresponding distances for truck, train and ship are approximately 8,000 km, 15,800 km and 50,800 km.

It is critical that the biomass supply is sustainable. This should be stressed for both small-scale and large-scale methanol plants. If there are difficulties obtaining sustainable forestry for a large-scale methanol plant, small-scale methanol plants should be preferred. Other relevant sustainability aspects of bioenergy production and transportation are the effects on local economies and local environment. Due to the positive social effects of distributed fuel production there are arguments for considering rural production even if this has higher cost and energy consumption than a central methanol plant. If the economy of small/medium and large-scale methanol plants is similar to that found in this model, it may be advisable to prefer small/medium scale methanol plants.

References

AMF-EA Engineering (1999). Methanol Refueling Station Costs. Paper prepared for the American Methanol Foundation by EA Engineering, Science and Technology, Inc., Silver Spring, USA. Available on the Internet: http://www.methanol.org/fuel cell/special/station_costs.cfm.

Börjesson, P. (1996). Energy Analysis of Biomass Production and Transportation. *Biomass and Bioenergy* **11**, 4: 305–318.

Börjesson, P. and L. Gustavson (1996). Regional Production and Utilization of Biomass in Sweden. *Energy* **21**, 9: 747–764.

Bridgwater, A.V. (1995). The Technical and Economic Feasibility of Biomass Gasification for Power Generation. Energy Research Group, Aston University, Birmingham, UK. *Fuel* **74**, 5: 631–653.

Brooking, E. (2002). Improving Energy Density in Biomass through Torrefaction. National Renewable Energy Laboratory. Golden, USA. Available on the Internet: http://www.nrel.gov/education/pdfs/e_brooking.pdf.

DOE-EPRI (1997). Renewable Energy Technology Characterizations. Topical Report, TR-109496. Prepared by the Office of Utility Technologies, Energy Efficiency and Renewable Energy, US Department of Energy (DOE), Washington DC and Electric Power Research Institute (EPRI), Palo Alto, California. Prepared for EPRI and the US DOE. Available on the Internet: http://www.eere.energy.gov/consumerinfo/pdfs/bio_gasification.pdf.

Dornburg, V. and A.P.C. Faaij (2001). Efficiency and Ecopnomy of Wood-firedd Biomass Energy Systems in Relation to Scale Regarding Heat and Power Generation using Combustion and Gasification Technologies. *Biomass and Bioenergy* **21**, (2): 91–108.

Goldemberg, J. (2004). World Energy Assessment: Overview — 2004 Update. United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council. Update to the original World Energy Assessment published in 2001. 85pp. Available on the Internet: http://www.undp.org/energy/weaover2004.htm).

Graham, R.L., B.C. English and C.E. Noon (2000). A Geographic Information System-based Modeling System for Evaluating the Cost of Delivered Energy Crop Feedstock. *Biomass and Bioenergy* **18**, 4: 309–329.

Hamelinck, C.N. and A.P.C. Faaij (2001). Future Prospects for Production of Methanol and Hydrogen from Biomass. Utrecht University, Copernicus Institute, Science Technology and Society, Utrecht, Netherlands, 81 pp. Available on the Internet: http://www.chem.uu.nl/nws/www/publica/e2001-49.pdf.

Hamelinck, C.N., R.A.A. Suurs and A.P.C. Faaij (2003). International Bioenergy Transport Costs and Energy Balance. Utrecht University, Copernicus Institute, Science Technology and Society, Utrecht, Netherlands, 31 pp.+annexes. Available on the Internet: http://www.chem.uu.nl/nws/www/publica/Carlo%20e2003-26.pdf.

Hoogwijk, M. (2004). On the Global and Regional Potential of Renewable Energy Sources. Ph.D. thesis, Utrecht University, Utrecht, Netherlands, 256 pp. ISBN: 90-393-3640-7. Available on the Internet: http://www.chem.uu.nl/nws/www/publica/e-2004-2.pdf.

IEA Bioenergy (2002). Sustainable Production of Woody Biomass for Energy. International Energy Agency (IEA) Bioenergy. Available on the Internet: http://www.ieabioenergy.com.

IMF (2004). International Financial Statistics, CD ROM: Database and Browser. International Monetary Fund (IMF), Washington, USA.

Jenkins, B.M. (1997). A Comment on the Optimal Sizing of a Biomass Utilization Facility under Constant and Variable Cost Scaling. *Biomass and Bioenergy* **13**, 1/2: 1–9.

JRC-WTT (2003). Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. Well to Tank (WTT) Report. Version 1, European Commission, Joint Research Center (JRC), 77 pp.+annexes.

JRC-WTW (2004). Well-To-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. Well to Wheels (WTW) Report. Version 1b, European Commision, Joint Research Center (JRC), 60 pp.+annexes.

Jung, P. (1999). Technical and Economic Assessment of Hydrogen and Methanol Powered Fuel Cell Electric Vehicles. Chalmers University of Technology, Göteborg University, Sweden, 89pp.+app.

Kaul, S. and R. Edinger (2004). Efficiency Versus Cost of Alternative Fuels From Renewable Resources: Outlining Decision Parameters. *Energy Policy* **32**, 929–935.

Lundmark, R. (2004). The Supply of Forest-based Biomass for the Energy Sector: The Case of Sweden. Interim Report IR-03-059. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Neuvonen, S. (2004). Personal communication.

Nguyen, M.H. and R.G.H. Prince (1996). A Simple Rule for Bioenergy Conversion Plant Size Optimisation: Bioethanol from Sugar Cane and Sweet Sorghum. *Biomass and Bioenergy* **10**, 5/6: 361–365.

Noon, C.E., F.B. Zhan and R.L. Graham (2002). GIS-based Analysis of Marginal Price Variation with an Application in the Identification of Candidate Ethanol Conversion Plant Locations. *Networks and Spatial Economics* **2**: 79–93. Kluwer Academic Publishers, Netherlands. Available on the Internet: http://uweb.txstate.edu/~fz01/Reprints/Zhan_NETS_2001.PDF.

Obersteiner, M. (1998). The Pan Siberian Forest Industry Model (PSFIM): A Theoretical Concept for Forest Industry Analysis. Interim Report IR-98-033. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Ogden, J.M., M.M. Steinbugler and T.G. Kreutz (1999). A Comparison of Hydrogen, Methanol and Gasoline as Fuels for Fuel Cell Vehicles: Implications for Vehicle Design and Infrastructure Development. Center for Energy and Environmental Studies, Princeton University, USA. *Journal of Power Sources* **79**, 143–168.

Pach, M., R. Zanzi and E. Björnbom (2002). Torrefied Biomass as Substitute for Wood and Charcoal. In: Farid Nasir Ani *et al.*, (eds.), Proceedings of the Sixth Asian-Pacific International Symposium on Combustion and Energy Utilization, Kuala Lampur, Malaysia. ISBN 983-52-0244-3, pp. 285–290. Available on the Internet: http://www.techtp.com/TW%20as%20a%20Substitute%20for%20Wood%20&%20Charcoal.pdf.

Pentananunt R., A.N.M.M. Rahman and S.C. Bhattacharya (1990). Upgrading of Biomass by Means of Torrefacation. Asian Institute of Technology, Bangkok, Thailand. *Energy* **15**, 12: 1175–1179.

Rokityanskiy, D. (2004). Personal communication.

RWEDP (2004). Wood Energy Conversion. Regional Wood Energy Development Programme (RWEDP) in Asia. Available on the Internet: http://www.rwedp.org/i_conversion.html.

Suurs, R.A.A. (2002). Long Distance Bioenergy Logistics. Utrecht University, Copericus Institute, Science Technology and Society, Utrecht, Netherlands, 65 pp.+annexes. Available on the Internet: http://nwi.geog.uu.nl/content/files/suurs_1069748951_Long%20Distance%20Bioenergy%20Logistics.pdf.

Tijmensen, M. and G.V. Hooidonk (2000). Long Term Perspectives for Production of Fuels from Biomass; Integrated Assessment and RD&D Priorities — Final Results. Utrecht University, Copernicus Institute, Science Technology and Society, Utrecht, Netherlands, 2 pp. Available on the Internet: http://bioproducts-bioenergy.gov/pdfs/bcota/abstracts/34/z199.pdf.

UNFCCC (1992). United Nations Framework Convention on Climate Change (UNFCCC). Available on the Internet: http://unfccc.int/resource/docs/co.

World Bank (2003). Fuel Prices and Taxation. Third Edition, May. German Technical Cooperation (GTZ), Energy, Transport, Eco-Efficiency. Available on the Internet: http://zietlow.com/docs/Fuel-Prices-2003.pdf

Yan, J. (1998). Biomass Gasification Power Generation Technologies. Royal Institute of Technology, Kungl Tekniska Hogskolan, Sweden.

Xunta (2004). Galicia 2004. Xunta de Galicia. Available on the Internet: http://www.xunta.es/galicia2004.

Appendix 1: Description of Values and Units Used in the Model

Constant Values	Unit	Description	Reference case	Source
HHV_{bio}	$GJ_{bio} \cdot tonne^{-1}$	Higher Heating Value, dry biomass	19.46	Hamelinck and Faaij (2001)
r_{bio}	$t_{dry} \cdot m^{-3}$	Bulk density, biomass	0.3	Suurs (2002)
LHV_{MeOH}	$MJ_{MeOH} \cdot kg^{-1}$	Lower Heating Value, methanol	19.9	JRC-WTT (2003)
ρ	$kg \cdot m^{-3}$	Density, methanol	793	JRC-WTT (2003)
Y	$tonne_{bio} \cdot km^{-2} \cdot year^{-1}$	Agricultural yield per unit area	10.0	Hoogwijk (2004)
a		Fraction of useful land	2/3	
b		Ratio of actual road length to direct distance	3.0	
η	%	Methanol plant efficiency	57	Hamelinck and Faaij (2001)
t	h	Load hours, methanol plant	8000	Hamelinck and Faaij (2001); Tijmensen and Hooidonk (2000)
c_{bio}	$€ \cdot GJ_{bio}^{-1}$	Biomass cost	2.0	
$c_{distribution}$	$€ \cdot GJ_{MeOH}^{-1}$	Average distribution cost	0.335	Based on AMF-EA Engineering (1999)

Scale Dependent Variables			Reference Case	Small-scale	Large-scale	
E_{MW}	MW	Plant size; Biomass input in methanol plant	Wanted value for plant size	10	1000	
E	$GJ_{bio} \cdot year^{-1}$		[MW] = 3.6 [GJ/h]	288,000	28,800,000	
M_{bio}	$tonne_{biomass} \cdot year^{-1}$		$M_{bio} = E/HHV_{bio}$ $M_{bio} = p\ a\ Y\ x^2 = E/HHV_{bio}$	14,800	1,479,959	
V_{bio}	$m^3{}_{biomass} \cdot year^{-1}$		$V_{bio} = M_{bio}/r_{bio}$	49,332	4,933,196	
P	$GJ_{MeOH} \cdot year^{-1}$		$P = E \cdot \eta$	164,160	16,416,000	
M_{MeOH}	$tonne_{MeOH} \cdot year^{-1}$		$M_{MeOH} = P/LHV_{MeOH}$	8,249	824,925	
V_{MeOH}	$m^3{}_{MeOH} \cdot year^{-1}$		$V_{MeOH} = M_{MeOH}/\rho$	10,403	1,040,258	
x	km	Average direct distance from methanol plant	$x = (M_{bio}/(\pi \cdot Y \cdot a))^{0.5}$			Nguyen and Prince (1996)
d	km	Average actual distance from methanol plant	$d = x \cdot b$	8	80	
$c_{transport}$	$€ \cdot year^{-1}$	Cost of transport	$c = 2/3\ \pi\ Y\ a\ k\ b\ x^3$			Nguyen and Prince, (1996); Dornburg and Faaij (2001)
k		Transportation cost per unit distance and unit energy				
$k_{Tractor}$	$€ \cdot TJ_{bio}^{-1} \cdot km^{-1}$	Transportation cost for tractor to central plant	$k_{Tractor} = 310/d + 17.54$	56.3	21.4	Börjesson and Gustavson (1996)
k_{Truck}	$€ \cdot TJ_{bio}^{-1} \cdot km^{-1}$	Transportation cost for truck to central plant	$k_{Truck} = 472/d + 10.66$	67.7	16.6	Börjesson and Gustavson (1996)

Appendix 2: Key Characteristics of Selected Gasifier

The main performance characteristics of the selected gasifier (Hamelinck and Faaij, 2001).

Indirectly Heated Fast Fluidized Bed	
Initial moisture content (%)	30
Dry moisture content (%)	10
Steam (kg/kg dry feed)	0.019
Oxygen (kg/kg dry feed)	0
Air (kg/kg dry feed)	2.06
Product temperature (°C)	863
Exit pressure (bar)	1.2
Gas yield (kmol/dry tonne)	45.8
Composition: mole fraction on wet basis (on dry basis)	
H_2O	0.999 (-)
H_2	0.167 (0.208)
CO	0.371 (0.463)
CO_2	0.089 (0.111)
CH_4	0.126 (0.157)
C_2H_4	0.042 (0.052)
C_2H_6	0.006 (0.0074)
O_2	0
N_2	0
LHV wet syngas (MJ/Nm^3)	12.7
Cold gas efficiency (%)	HHV 80.5/LHV 82.5

Appendix 3: Conversion Rates and Price Deflators

All the costs used in this study are converted to $€_{2003}$. The table shows market rates and change in consumer prices for 1995 to 2003 (IMF, 2004). When calculating changes in consumer prices for this study, rates for the world is used.

Country Name	Units	Descriptor	1995	1996	1997	1998	1999	2000	2001	2002	2003
United States	National Currency per SDR	Market rate	1.49	1.44	1.35	1.41	1.37	1.3	1.26	1.36	1.49
Euro Area	National Currency per SDR	Market rate	n.a.	n.a.	n.a.	n.a.	1.37	1.4	1.43	1.3	1.18
Sweden	National Currency per SDR	Official rate	9.9	9.88	10.63	11.35	11.7	12.42	13.41	12	10.68
World	Percent per Annum	Changes in consumer prices	14.49	8.44	5.95	5.83	5.18	4.31	4.08	3.43	3.62
Industrial Countries	Percent per Annum	Changes in consumer prices	2.43	2.22	2.03	1.41	1.33	2.35	2.17	1.43	1.85
United States	Percent per Annum	Changes in consumer prices	2.81	2.93	2.34	1.55	2.19	3.38	2.83	1.59	2.27
Euro Area	Percent per Annum	Changes in consumer prices	n.a.	2.15	1.58	1.09	1.12	2.34	2.11	2.25	2.07

An example of how the exchange and consumer price calculation is done follows:

The cost of “Total Pretreatment” is 38.2 $US\$_{2001}$ (Hamelinck and Faaij, 2001). To convert this to $US\$_{2003}$, the cost is multiplied with a change in consumer price for the US for 2002 and 2003. The currency is then converted to $€_{2003}$. The calculations can be found in the following equation:

$$38.2\ (US\$_{2001}) \cdot 1.0159\ (\text{Change, 2002}) \cdot 1.0227\ (\text{Change, 2003}) \cdot 1.18\ (€_{2003}/SDR)/1.49\ (US\$_{2003}/SDR) = 31.4\ €_{2003}$$

All other costs are converted using a similar method.

Appendix 4: Plant Size Calculations for Different Scales

Methanol Plant Size	**MW**	**10**	**80**	**200**	**300**	**430**	**500**	**600**	**700**	**800**	**900**	**1000**
Total Pretreatment	€	1.7	8.6	17.7	24.4	32.4	36.5	42.2	47.6	52.9	58.1	63.2
BCL	€	2.2	8.6	15.7	20.4	25.8	28.5	32.0	35.4	38.6	41.7	44.7
Gas Cleaning:												
Tar cracker	€	0.6	2.4	4.6	6.1	7.8	8.7	9.9	11.0	12.1	13.1	14.1
Cyclones	€	0.4	1.8	3.4	4.5	5.8	6.4	7.3	8.1	8.9	9.7	10.4
HT Heat Exchanger (total installed)	€	1.0	3.5	6.0	7.7	9.5	10.4	11.6	12.7	13.8	14.8	15.8
Baghouse Filter	€	0.3	1.2	2.1	2.8	3.5	3.8	4.3	4.8	5.2	5.6	6.0
Condensing Scrubber	€	0.4	1.8	3.4	4.5	5.8	6.4	7.3	8.1	8.9	9.7	10.4
Syngas Processing:												
Compressor	€	0.6	3.4	7.5	10.6	14.3	16.3	19.0	21.7	24.3	26.9	29.4
Steam Reformer	€	4.1	14.2	24.6	31.4	39.0	42.6	47.6	52.2	56.5	60.7	64.6
Methanol Production:												
Make Up Compressor	€	1.1	4.6	8.6	11.5	14.8	16.4	18.6	20.8	22.8	24.8	26.7
Liquid Phase Methanol	€	0.2	1.1	2.2	2.9	3.7	4.2	4.7	5.3	5.8	6.4	6.9
Recycle Compressor	€	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6
Refining	€	1.2	5.0	9.5	12.6	16.2	18.0	20.5	22.8	25.0	27.2	29.3
Power Generation:												
Steam Turbine + steam system	€	0.8	3.6	6.9	9.2	11.8	13.1	14.9	16.6	18.2	19.8	21.3
Total installed investment	***€***	***14.6***	***59.9***	***112.3***	***148.6***	***190.7***	***211.8***	***240.4***	***267.6***	***293.8***	***318.9***	***343.3***
Total installed investment corrected for lifetime	***€***	***13.2***	***54.1***	***101.6***	***134.4***	***172.5***	***191.5***	***217.4***	***242.0***	***265.6***	***288.4***	***310.4***
HHV dry biomass	GJ/tonne$_{dry}$	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46	19.46
Biomass input	tonne$_{dry}$/hour	1.8	14.8	37.0	55.5	79.5	92.5	111.0	129.5	148.0	166.5	185.0
Biomass input	MWth	10	8	200	300	430	500	600	700	800	900	1000
Load hours	h	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000	8000
Biomass input	GJ/year	0.3	2.3	5.8	8.6	12.4	14.4	17.3	20.2	23.0	25.9	28.8
Annual Costs:												
Capital	€	1.7	7.1	13.4	17.7	22.8	25.3	28.7	31.9	35.1	38.1	41.0
Operating and Maintenance	€	0.6	2.4	4.5	5.9	7.6	8.5	9.6	10.7	11.8	12.8	13.7
Biomass	€	0.5	3.9	9.8	14.7	21.0	24.4	29.3	34.2	39.1	44.0	48.9
Total Annual Costs	€	2.8	13.5	27.7	38.4	51.4	58.2	67.6	76.9	85.9	94.8	103.6
Production:												
Fuel output	MW	5.7	45.6	114.0	171.0	245.1	285.0	342.0	399.0	456.0	513.0	570.0
Efficiency fuel	%	57	57	57	57	57	57	57	57	57	57	57
Unit cost, produced MeOH (Biomass cost not included)	€/GJ$_{MeOH}$	17.15	10.24	8.43	7.79	7.28	7.09	6.87	6.69	6.54	6.42	6.31
Hamelinck and Faaij (2001)			10.45			7.26						6.46
Difference	€/GJ$_{MeOH}$		2.0%			-0.4%						2.3%
Unit cost, produced MeOH (Biomass cost not included)	**€/GJ$_{MeOH}$**	**14.17**	**7.26**	**5.45**	**4.81**	**4.31**	**4.11**	**3.89**	**3.71**	**3.56**	**3.44**	**3.33**