Development of an Optimization Model for the Location of Biofuel Production Plants

1 author:

Sylvain Leduc
International Institute for Applied Systems Analysis

DOCTORAL THESIS

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Sylvain Leduc

Luleå University of Technology

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Sylvain Leduc

Division of Energy Engineering
Department of Applied Physics and Mechanical Engineering
Luleå university of Technology
SE-971 87 Luleå, Sweden

2009

Tryck: Universitetstryckeriet, Luleå

ISSN: 1402-1544
ISBN 978-91-86233-48-8

Luleå 2009

www.ltu.se

Preface

This work was carried out in collaboration between the division of Energy Engineering at the Luleå University of Technology (LTU) and the International Institute of Applied System Analysis (IIASA) in Laxenburg, Austria between 2004 and 2009. Two projects funded this work: the INSEA (Integrated Sink Enhancement Assessment) project between 2004 and 2006, and the GEOBENE (Global Earth Observation - Benefit Estimation: Now, Next and Emerging) project during between 2006 and 2009. The Kempe foundation sponsored the travelling costs for a six month stay at IIASA in 2006.

I would like to thank my supervisor Prof. Jan Dahl for his support and guidance. I would also like to give special thanks to my co-supervisor Dr. Joakim Lundgren who gave me valuable advice and support during this thesis. My gratitude also goes to Dr. Michael Obersteiner, Dr. Keywan Riahi and Prof. Jinyue Yan who initiated the project and gave me a good start in this field. I would like to express my deepest gratitude to Prof. Erik Dotzauer with whom I had a close collaboration during this work and who taught me a lot in the modeling field. Thanks also to Dr. Steffen Fritz and Ian McCallum for their help in collecting and interpreting geographical information. Many thanks to Prof. Erwin Schmid, Dr. Georg Kindermann, Dr. Dagmar Schwab, Dr. Oskar Franklin, Johannes Schmidt and Fredrik Starfelt who contributed actively in the development of the model and with whom I have appreciated working with.

I would like to thank my colleagues in the division of Energy Engineering at LTU, with whom I had a good collaboration since the year 2001. Many thanks also to my colleagues in the forestry division at IIASA with whom I appreciate working with.

Finally I would like to give special thanks to my wife, Emma, who has been very patient, encouraging and has given me great support.

Sylvain Leduc, Laxenburg, May 4th 2009

Abstract

First generation biofuels have not achieved the expected greenhouse gas emission savings and the production may in some cases compete with food production. Issued from non arable land and certified wood, the production of the second generation biofuels are more adapted to tackling those issues. Very large production plants are however required to reach competitive production costs via economy of scale effects. This may cause large logistical issues as the biomass feedstock often is located on the countryside, while the production plants are situated near harbors to enable boat transports. Moreover negative social and environmental effects such as road damaging, noise perturbation, pollutant emissions increase with heavy traffic from the transport of the raw material as well as the final product. To face those intensive logistic issues, the geographical location and size of the plant should be determined optimally with respect to raw material and demand location prior to plant investment and construction.

The main aim of this thesis has therefore been to develop a model for optimization of the geographical location of second generation biofuel production plants by minimizing the cost of the complete supply chain, which comprises biomass harvesting, biomass transport, biofuel production, biofuel transport and biofuel distribution. The model is not intended to be applied to maximize the profitability of one single plant, but to minimize the final cost of biofuel for the region's welfare. The development of the model is illustrated via several case studies, where also analysis of critical parameters affecting the fuel production cost and the production plant location has been carried out. The model is a mixed integer program.

The production of two liquid biofuels for the transportation sector have been studied, methanol via biomass gasification and lignocellulosic ethanol via fermentation.

The model has been applied on areas as large as country levels. A set of optimal production plants can be determined to meet the biofuel demand of a selected area. It can be applied to different biofuel production processes and take into account the by-products geographically explicitly if required. The model can manage demands, costs and prices that change with time. Existing biomass based industries can be integrated to the model, and thus the competition on the biomass between these plants and possible bioenergy plants can be modeled, giving a better estimation of the available biomass for biofuel production. Biofuel imports from long distances are taken into account and finally policy tools such as carbon tax can be applied to limit the emissions from the transports or as a subsidy to the amount of fossil fuel emissions mitigated from the bioenergy production.

The developed model can be applied for any kind of biomass based production plant and feedstock as long as the input data is available. As geographical energy planning is important, the developed model may be a valuable tool for decision makers in order to determine the most suitable strategy regarding locations of new biofuel production plants.

Keywords: geographical energy planning, optimization model, mixed integer programming, biofuel production

List of appended papers

This thesis comprises the following articles:

Article I

Leduc, S., Schmid, E., Obersteiner, M., Riahi, K. Methanol from gasification using a geographically explicit model. Biomass and Bioenergy 2009, 33 (5) : 745-751 .

Article II

Leduc, S., Dotzauer, E., Schmid, E., Obersteiner, M. Methanol from gasification: a facility location problem. Energy Economics. (Submitted).

Article III

Leduc, S., Schwab, D., Dotzauer, E., Schmid, E. Obersteiner, M. Optimal location of wood gasification plants for methanol production with heat recovery. International Journal of Energy Research 2008, 32 (12): 1080-1091.

Article IV

Leduc, S., Lundgren, J., Franklin, O., Dotzauer, E. Location of a biomass based methanol production plant: a dynamic problem in northern Sweden. Applied Energy 2009. In Press, Corrected Proof.

Article V

Leduc, S., Starfelt, F., Dotzauer, E., Kindermann, G., McCallum, I., Obersteiner, M., Lundgren, J. Optimal location of ethanol ligno-cellulosic biorefineries with poly-generation in Sweden. Energy. (Submitted).

Article VI

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Greigeritsch, T., Schmid, E. Potentials of bioenergy production within the Austrian forest market. International scientific conference: The European forest-based sector: bio-responses to address new climate and energy challenges? 6-8 November, 2008, Nancy, France.

Related publications by the author of this thesis

Leduc, S., Natarajan, K., Dotzauer, E., McCallum, I., Obersteiner, M. Optimizing biodiesel production in India. Applied Energy, Special Supplementary Issue, Biofuels in Asia, 2009. (Submitted).

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E. Optimizing the supply chain of biofuel production including the use of waste heat: an Austrian case study. ÖGA Tagung 2008 - Österreichische Gesellschaft für Agrarökonomie, 18 - 19 September 2008, Vienna, Austria.

Obersteiner, M., Leduc, S. The geography of 2nd generation biofuel potentials in Africa. GFSE-6 Africa is energizing itself, 29 November - 1 December 2006, Vienna, Austria.

Leduc, S., Wang, C., Westerberg, M. Sweden in the forefront for a green society: a review on policy activities for greenhouse gas emission reduction. GHGT-8, 8th International Conference on Greenhouse Gas Control Technologies, 19-22 June 2006, Trondheim, Norway.

Leduc, S., Ji, X., Yan, J. A feasibility study of black liquor booster gasification with borate autocausticizing. ECOS 2005, 18th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, 20-22 June 2005, Trondheim, Norway.

Nomenclature

Abbreviations

AC	annual cost
CFB	circulating fluidized bed
CHP	combine heat and power
$Cost_a$	costs of equipment for the plant a
$Cost_b$	costs of equipment for the plant b
DH	district heating
IPCC	Intergovernmental Panel on Climate Change
GHG	greenhouse gas
GIS	Geographic Information Systems
IR	interest rate
MILP	mixed integer linear programming
MIP	mixed integer program
odt	oven dry ton
PPC	process plant cost
SF	scaling factor
$Size_a$	size of the biofuel production plant a
$Size_b$	size of the biofuel production plant b
SRF	short rotation forestry
TCR	total capital requirement
TPC	total plant cost
TPI	total plant investment
UST	underground storage tanks

Parameters

$\overline{b}_{i,y}$	available biomass at the supply region *i* year *y*
$\overline{b}^{import}_{i',y}$	available imported biomass at the import point *i'* the year *y*
$\overline{b}^{sawmill}_{m,y}$	available biomass from the sawmill *m* year *y*
C	number of additional commodities
$\widetilde{C}$	set of additional commodities
$c_{i,y}$	cost for producing biomass in supply region *i* year *y*
$c_{j,y}$	cost for producing biofuel in the plant *j* the year *y*
$c_{k,y}$	cost for handling biofuel at the gas station *k* the year *y*
$c^{emission}$	carbon tax for the transportation *t*

$c_{i',y}^{biomassimport}$	cost of imported biomass at the point *i'* the year *y*
$c_{i',y}^{import}$	cost of imported biofuel at the point *i'* the year *y*
$c_{s,y}^{sawmill}$	cost of biomass from the sawmill *s* the year *y*
D	number of demand regions
$\widetilde{D}$	set of regions
d	transport distance
$d_{l,y}$	biofuel demand in region *l* the year *y*
$d_{f,y}^{industry}$	biomass demand from the industry *f* the year *y*
e_j	cost for building the plant *j*
e_k	cost for setting up the gas station *k*
I	number of import points
$\widetilde{I}$	set of import points
F	number of biomass based industries
$\widetilde{F}$	set of biomass based industries
G	number of gas stations
$\widetilde{G}$	set of gas stations
M	number of sawmills
$\widetilde{M}$	set of sawmills
P	number of plants
$\widetilde{P}$	set of plants
$p_{j,c,y}$	price of the commodity *c* produced at the plant *j* the year *y*
$p_{l,y}^{fossil}$	fossil fuel price in the region *l* the year *y*
$q_{j,c,y}^{D}$	demand from the plant *j* of the commodity *c* the year *y*
T	number of transportation means
$\widetilde{T}$	set of transport
t_e	economic lifetime
$t_{i,f,t,y}$	biomass transportation cost from the supply region *i* to the existing industry *f* by the transportation means *t* the year *y*
$t_{i,j,t,y}$	biomass transportation cost from the supply region *i* to the plant *j* by the transportation means *t* the year *y*
$t_{i',f,t,y}$	biomass transportation cost from the import point *i'* to the existing industry *f* by the transportation means *t* the year *y*
$t_{i',j,t,y}$	biomass transportation cost from the import point *i'* to the plant *j* by the transportation means *t* the year *y*
$t_{i',k,t,y}$	biofuel transportation cost from the import point *i'* to the gas station *k* by the transportation means *t* the year *y*
$t_{j,k,t,y}$	biofuel transportation cost from the plant *j* to the gas station *k* by the transportation means *t* the year *y*

$t_{k,l,y}$	biofuel transportation cost from the gas station k to the demand region l the year y
$t_{m,f,t,y}$	biomass transportation cost from the sawmill m to the existing industry f by the transportation means t the year y
$t_{m,j,t,y}$	biomass transportation cost from the sawmill m to the plant j by the transportation means t the year y
$\bar{x}_j^{biofuel}$	biofuel capacity at the plant j
$\bar{x}_k^{biofuel}$	biofuel capacity of the gas station k
Y	number of years
$\widetilde{Y}$	set of years
$\rho_{j,c}$	efficiency at the plant j for producing the commodity c
$\rho_j^{biofuel}$	efficiency for biofuel production at plant j

Variables

$b_{i,f,t,y}$	amount of biomass delivered from the supply region i to the existing industry f by the transportation means t in the year y
$b_{i,j,t,y}$	amount of biomass delivered from supply region i to plant j by the transportation means t in the year y
$b_{i',f,t,y}^{import}$	amount of biomass delivered from the imports point i' to the existing industry f by the transportation means t in the year y
$b_{i',j,t,y}^{import}$	amount of biomass delivered from the import point i' to the plant j by the transportation means t in the year y
$b_{m,f,t,y}^{sawmill}$	amount of biomass delivered from the sawmill m to the existing industry f by the transportation means t in the year y
$b_{m,j,t,y}^{sawmill}$	amount of biomass delivered from the sawmill m to the plant j by the transportation means t in the year y
$f(b,x,q,u)$	total cost of the system
$g(b,x,u)$	total emissions from all transports
$h(b,x,q,u)$	objective function
$q_{j,c,y}$	amount of the commodity c produced from an alternative source located close to plant j the year y
$u_{j,y}$	binary variable indicating if the plant j is in operation the year y
$u_{k,y}$	binary variable indicating if the gas station k is in operation the year y
$x_{j,c,y}$	amount of commodity c that is produced at plant j the year y
$x_{i',k,t,y}^{import}$	amount of biofuel delivered from the import point i' to the gas station k and by the transportation means t in the year y

$x_{j,k,t,y}^{biofuel}$	amount of biofuel delivered from plant j to gas station k by the transportation means t in the year y
$x_{k,l,y}^{biofuel}$	amount of biofuel sold at gas station k to costumers from demand region l the year y
$x_{l,y}^{fossil}$	amount of fossil fuel sold to costumers from demand region l the year y

Subscripts

c	commodity number
f	existing biomass based industry number
i	biomass supply number
i'	import point number
j	plant number
k	gas station number
l	demand region number
m	sawmill number
t	transportation means number
y	year number

Superscript

D	commodity demand

Contents

1. Introduction

During the last century the global average temperature increased by 0.74 ± 0.18 ºC, and is expected to increase further, in the range of 0.8 to 2.6 ºC until the year 2050. Serious consequences have already been recorded. Glaciers and the sea ice in the arctic are melting at a higher rate than during the last thirty years, plants and animal ranges are moving closer to the pole and higher up, many of them are extinguishing, the sea level is increasing by 1-2 mm yearly, hurricanes are occurring with a higher magnitude etc. These are some clear indicators of global warming which is now considered unequivocal [1]. Scientists agree that intense human activities since the last fifty years are responsible for ninety per cent of the emissions of greenhouse gases (GHG). By increasing the greenhouse effect this leads to warming of the surface of the globe and lower atmosphere [1].

The main greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). Of all the greenhouse gases, CO_2 accounted for 83% of the GHG emissions in the year 2006 [2]. Since the beginning of the industrial revolution, the concentration of carbon dioxide in the atmosphere has increased drastically from 290 ppmv to 370 ppmv as shown in Figure 1. Between the years 1970 and 2004 the emissions of CO_2 increased by 80% [3] from which 40% emanated from coal, 40% from oil and 20% from fossil gas consumption [4]. A long-term EU target is that the world should not warm more than 2ºC above pre-industrial temperatures [5]. Such a target implies that the atmospheric concentration of carbon dioxide could not rise much above 400 ppm [6]. If the current emission trend continues, the 400 ppm limit would be reached by the year 2020 [7].

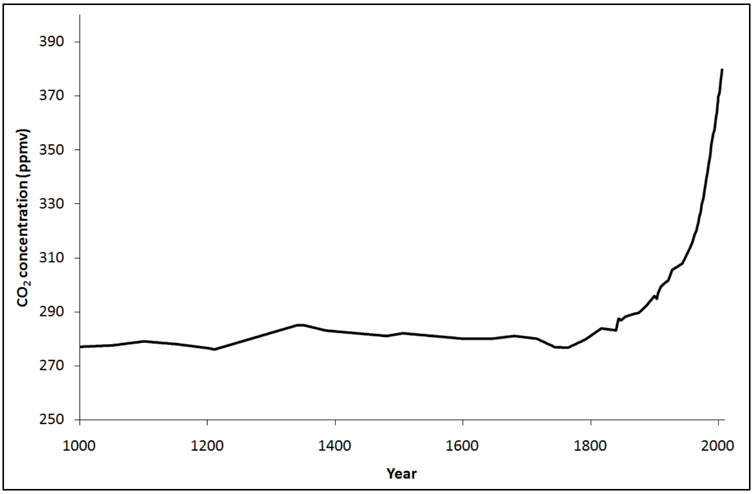

Figure 1: Atmospheric concentrations of carbon dioxide, 1000-2003 [8].

In order to limit and decrease the emissions of the main GHG, 168 countries and one regional economic integration organization (the EEC) have ratified the Kyoto Protocol that entered into force in February 2005. The industrialized countries that have signed this protocol are required to decrease their emissions for the period 2008-2012 by 5.2% compared to the 1990 level. An emission target is set to each of those countries to be reached by the year 2012. This target is set depending on the country's emissions in the base year [9].

Between the years 1990 and 2003, an overall decrease of the CO_2 emissions by 2.6% was noticed in the EU-25. However, as illustrated in Figure 2, the transport sector shows a constant increase (22% during the same period) presently representing 24% of the total anthropogenic CO_2 emissions in EU-25 in the year 2003. This sector is indeed almost fully dependent on fossil fuel (gasoline and diesel are still dominating the transport sector with a supply of 86 million barrels of oil per day in the year 2007 [10]), and its continued growth presents a problem for most Member States in terms of meeting their target under the Kyoto Protocol [11]. Emissions from the transport sector have thus become a great issue for many governments, and efforts are being made at producing fuels based on renewable resources that are carbon dioxide neutral for the atmosphere.

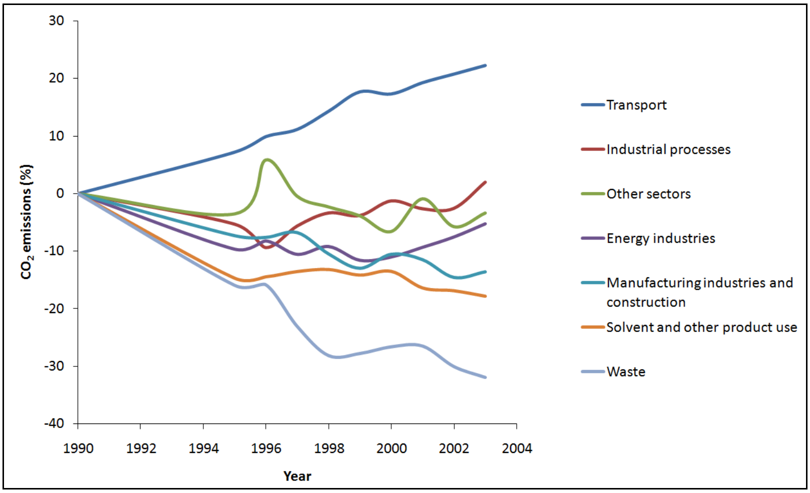

Figure 2: Evolution of the CO_2 emissions compared with 1990 for EU-25 [11].

In the year 2003, the Biofuels Directive set "reference values" of a 2% market share for biofuels in the year 2005 and a 5.75% share in the year 2010 [12]. In March 2007, EU heads of state and governments broadly endorsed the Commission's proposals for a common European energy and climate policy known as the 20-20-20 Rule referring to 20% less greenhouse gas emissions compared to the 1990 level, a 20% renewable energy share of the total primary energy supply, 20% energy efficiency improvement and finally a 10% biofuel for inland transport target by the year 2020 [13]. These policies need to be translated into national action plans.

1.1. From first to second generation biofuels

The global current biofuel portfolio in the transport sector is represented by ethanol, biodiesel and biogas. But due to lack of compatible vehicles and infrastructure for gaseous biofuels, ethanol and biodiesel dominate the biofuel market. The production of biofuels tripled between the years 2000 and 2007 (Figure 3), and represents 1.5% of the global road transport fuel consumption [14]. Energy supply security, support for agricultural industries and rural communities, reduction of oil import and the potential for GHG mitigation provided a large boost to the world biofuel production. Ethanol is mainly produced in Brazil from sugar cane and in the USA from corn, whereas biodiesel is more developed in Europe from vegetable oils and fats [14]. A global fuel production is currently in transition. In the year 2007 there were only 20 oil producing nations supplying the needs of over 200 nations. By the year 2010 more than 200 nations are expected to become biodiesel producers and suppliers [15].

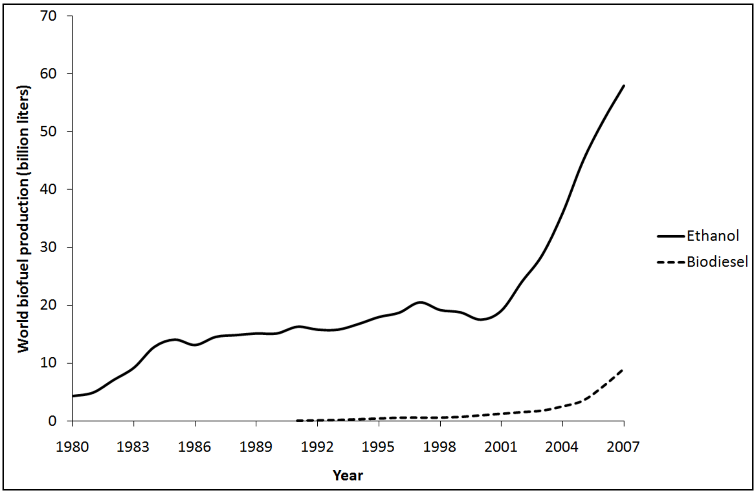

Figure 3: Global ethanol and biodiesel production, 1980-2007 [16, 17].

These biofuels are mainly produced from food sources (sugar cane, corn, wheat, palm oil, rapeseed, soybean etc.) and are regarded as the first generation of renewable motor fuels. But the production of these types of biofuels may have some drawbacks such as:

- contributing to higher food prices due to competition with food crops [18-22],
- expensive option for energy security (taking into account total production costs excluding government grants and subsidies) [23],
- providing only limited GHG reduction benefits [24, 25],
- accelerating deforestation (with other potentially indirect land use effects also to be accounted for) [24-26],
- potentially having a negative impact on biodiversity [27] and,

- competing for scarce water resources in some regions [28].

In order to tackle those issues, alternative biofuels may be manufactured from agricultural and forest residues and from non-food crop feedstocks. These so called second generation biofuels have the advantage of not interfering with the food production, and they are generally characterized by a better environmental performance than first generation biofuels [29]. The different pathways for the production of second generation biofuels are presented in Figure 4. This thesis focuses on the production of methanol via gasification and the production of ethanol via fermentation. The processes are briefly presented below.

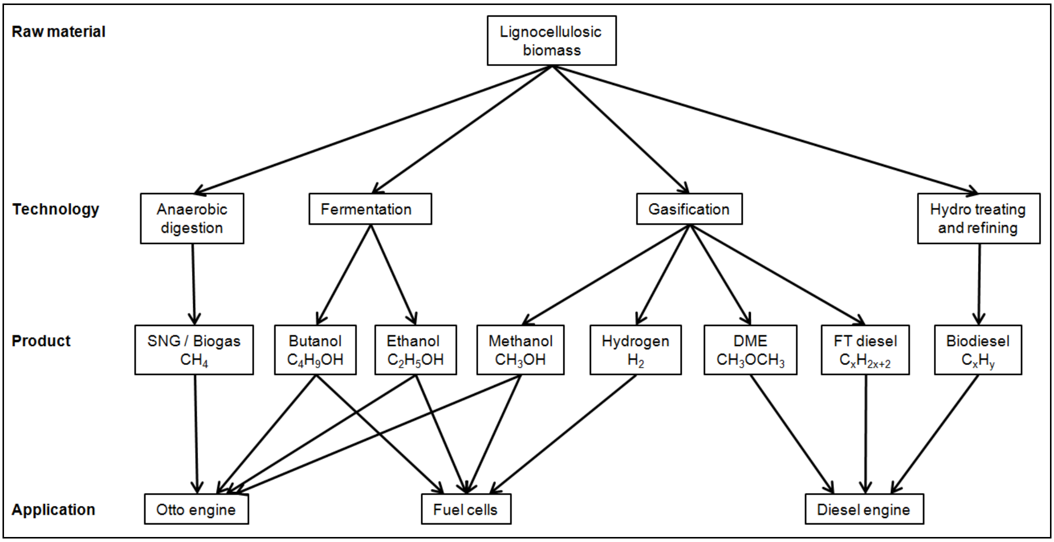

Figure 4: Outlook of different second generation biofuel production pathways.

1.2. Methanol production via biomass gasification

Methanol is the simplest form of alcohol and has the chemical formula CH_3OH. It can be produced chemically from biomass as well as fossil fuels. Methanol is suitable as transportation fuel, chemical building block, or as solvent. When used in the transportation sector, methanol can be used either in gasoline engines or in fuel cells. Methanol has become a popular choice especially in the Indy cars due to the high octane number (102) and safety characteristics. Mixed with 15% gasoline (M85), it can be used for the regular car fleet. This would however require minor modifications of the engines [30]. Methanol can also be used in fuel cells, and can therefore play an important role since it is easier to transport and store than hydrogen [31]. Ahlvik and Brandberg [32] showed that methanol was the fuel that has the highest system efficiency of all liquid fuels from biomass. Methanol is liquid at normal environmental conditions, which makes it easy to handle compared to hydrogen or dimethyl ether (DME).

Biomass based methanol can be produced in facilities which may consist of the following units: feedstock pre-treatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift reaction to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification (Figure 5). An optional installation is a gas turbine to employ the unconverted gas or a boiler and a steam turbine for co-production of heat and electricity.

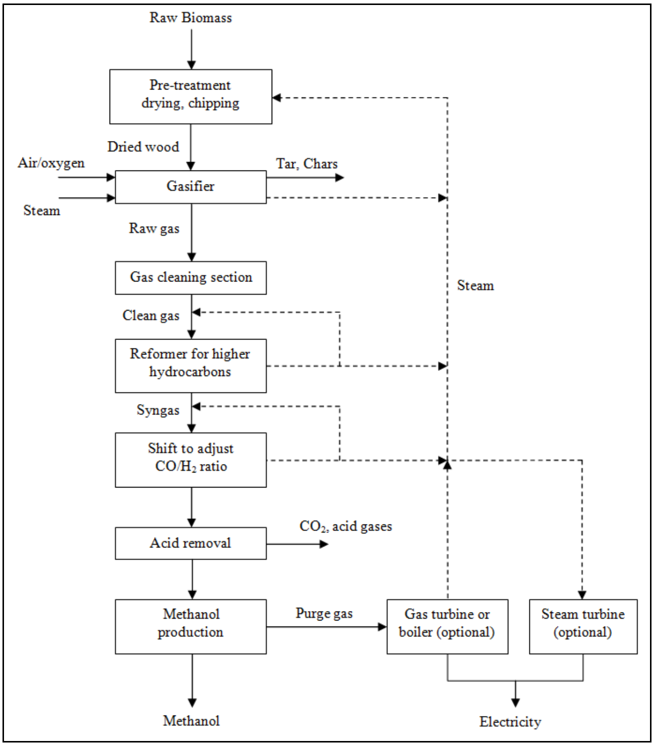

Figure 5: General process flow diagram for biomass based methanol production.

Before the gasification process, the feedstock may need to be pre-treated to meet the fuel quality requirements needed to produce a gas of high quality. The biomass moisture content should often be below 10-15% and artificial drying can be integrated, for example by utilizing waste heat from the engine/turbine [33]. Depending on the technology used, different biomass particle sizes are required: 10-20 cm for a downdraft bed gasifier, chips for a fluid bed gasifier or below 1 mm for an entrained flow gasifier [34].

Biomass gasification involves heating biomass in the presence of low levels of oxygen (i.e. less than required for combustion). Above 800˚C the biomass will break down into a gas stream and a solid residue. The composition of the gas stream is influenced by the operating conditions for the gasifier, with some gasification processes being more suited than others to produce a gas for methanol production.

The synthesis gas produced contains a range of contaminants (particles, alkali compounds, tars and halogens) which can block or poison the catalysts downstream. Particles can be removed with cyclones (particles above 5 μm), barrier filters (dry particles between 0.5-100 μm) and wet scrubbers. Alkalis can be removed with the same technology. Tars can be removed either by physical removal with the former technology, or by catalytic (at temperatures of about 800˚C) or thermal cracking (at temperatures between 900 and 1,300˚C) [35].

The raw gas from the gasifier contains significant quantities of methane and hydrocarbons representing a significant part of the heating value of the gas. Table 1 presents an example of the gas composition for an atmospheric indirectly fired gasifier. For the production of methanol it is important to reform these compounds into CO and H_2. This is done either through steam reforming or auto thermal reforming. Steam reforming is the most common method and is used to convert these compounds into CO and H_2 at high temperatures in the presence of a nickel catalyst [36].

Table 1: Gas composition from the atmospheric indirectly fired gasifier [37].

Composition	Mole fraction on wet basis
H_2O	0.199
H_2	0.167
CO	0.371
CO_2	0.089
CH_4	0.126
C_2H_4	0.042
C_2H_6	0.006
O_2	0
N_2	0

For methanol production the steam:carbon monoxide ratio should be around 3. A water gas shift reaction is then a common process operation to shift the energy value of the CO to H_2 and to reach this ratio. CO_2 is partially removed before the methanol production. Acid gases as well as minor gas impurities are removed to a large extent. The remaining CO_2 will help maintaining the catalyst activity during the methanol production. Once the synthesis gas is available the methanol synthesis takes place. Methanol is produced from the syngas via the synthesis reaction:

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \text{(R1)}$$

A crude methanol production is condensed by cooling the product gas of the methanol synthesis reactor, and is then sent to a distillation column. At this stage the methanol contains water and other impurities such as dissolved gases and higher alcohols in the synthesis reactor. Approximately 0.3% of the produced methanol reacts further to form DME. Other by-products like formaldehyde or higher alcohols are produced. Purification is achieved in multistage distillation dictated by the final methanol purity required [38].

1.3. Ethanol production via ligno-cellulosic biomass fermentation

Ethanol is already widely used in the transport sector (Figure 3) and offers many advantages over fossil fuels such as lowering levels of carbon emissions and providing octane enhancement to petrol/alcohol blends. Many countries have started to use ethanol as a complement to gasoline to lower the emissions of CO_2 in the transport sector. Wahlund *et al.* [39] compared different alternatives for motor fuels, and concluded that woody biomass based methanol, ethanol or DME appears to give about the same CO_2 reduction (30-60 $Mg_{CO2}/TJ_{biofuel}$).

Ethanol can be produced in plants consisting of the following units: feedstock pre-treatment, hydrolysis, fermentation and distillation.

It may be necessary to clean the raw material by washing. Clean feedstock, like stem wood, will in general not need this step. Subsequently, the raw material is sized: smaller chips give a larger surface area, so that transport of the catalysts, enzymes and steam to the fibers becomes easier and faster. This also allows the enzymes in the hydrolysis step to penetrate the fibers and to reach the sugar oligomers [40].

Cellulose and hemicellulose, which typically comprise two thirds of the dry mass, are polysaccharides that can be hydrolyzed. The first step involves hydrolysis: splitting the bonds in the cellulose to produce the sugar glucose, and in the hemicellulose to release xylose. The sugars can then be converted to ethanol using appropriately selected microorganisms for fermentation [40, 41]. One molecule of glucose produces two molecules of ethanol and two molecules of carbon dioxide (R2) and one molecule of xylose produce ethanol, carbon dioxide, and water (R3):

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \qquad \text{(R 2)}$$

$$C_5H_{10}O_5 \rightarrow C_2H_5OH + CO_2 + H_2O \qquad \text{(R 3)}$$

Lignin is present in all lignocellulosic biomass (20-30%). Therefore, any ethanol production process will have lignin as a residue. The lignin cannot be used for ethanol production. It is a large complex polymer of phenylpropane and methoxy groups, a non-carbohydrate polyphenolic substance that encrusts the cell walls and cements the cells together. It is degradable by only few organisms, into higher value products such as organic acids, phenols and vanillin.

The process studied combines the production of lignocellulosic ethanol together with heat and power. The technology for ethanol production used in Örnsköldsvik, Sweden, is applied [42]. It is based on biomass steam CHP technology with a grate-fired boiler and lignocellulosic ethanol production from lab and pilot scale plants. In Figure 6, the hydrolysis stage relates to hydrolysis of hemicellulose and cellulose with steam explosion and dilute acid. Steam is extracted from the turbine for hydrolysis and distillation of ethanol, and excess heat from the hydrolysis and distillation is utilized in the district heating system. The by-products from the ethanol production, mainly lignin, are combusted in the grate-fired steam boiler. Both C5 and C6 sugars are considered to be fermented to ethanol.

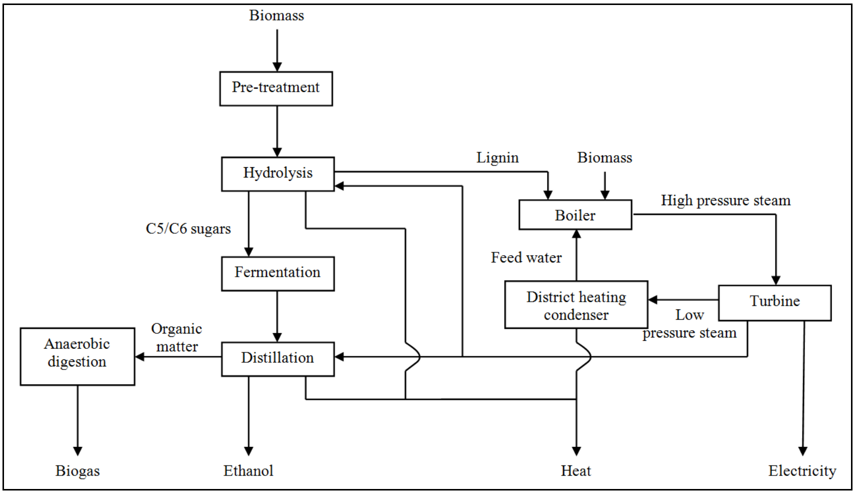

Figure 6: Configuration scheme of the poly-generation process.

Two cases with different hydrolysis yields are considered at 90% and 97% of theoretical yield of sugars from cellulose and hemicelluloses. The different energy yields are presented in Table 2 in terms of yields of ethanol, electricity, heat and biogas produced from the feedstock. The lower hydrolysis yield brings less ethanol fuel and biogas production (although higher heat and electricity production) than the higher yield, because the unconverted biomass is used for CHP production [43]. The yields are used as input data for the optimization model.

Table 2: Conversion factors in energy output per energy input for two hydrolysis cases (%) [43].

Hydrolysis yield cases	Ethanol	Power	Biogas	Heat
90	25.8	14.5	16.1	27.7
97	29.2	12.7	18.3	23.4

Currently, the second generation biofuels are at the pre-commercial stage. For example, Enerkern set up a demonstration plant in Westbury, Quebec, Canada, where lignocellulosic biomass is gasified for the production of methanol and ethanol [44]. Sekab in Örnsköldsvik, Sweden, operates a pilot plant where ethanol is produced via the fermentation of lignocellulosic biomass [42]. A commercial plant is preliminarily planned in Örnsköldsvik for the year 2014 with an annual production of 120,000 m^3 of ethanol [42]. Some studies have estimated the commercial costs of second generation ethanol to be in the range of US$ 0.55-1.00 per liter of gasoline equivalent [14, 45]. This range broadly relates to gasoline wholesale price when the crude oil is between US$ 70-130/barrel [14].

To be able to compete against fossil fuels, the biofuel production plants need to achieve efficient production and maximize their overall process economy [46]. The biofuel production plants need therefore to reach a size as large as is economically and physically possible with regard to the economy of scale and the local infrastructures. For instance, newer corn based ethanol plants require in the range of 1,500-2,500 tons of feedstock daily [47, 48], and when operative at commercial scale, second generation biofuels are expected to reach larger plant size. Larger plant sizes would then increase the collecting area for the biomass leading to higher transportation cost and logistics issues. Moreover social and environmental effects may also occur such as road damage, noise perturbation, pollutant emissions [49] as well as low public acceptance due to heavy traffic from the transport of both the raw material and the final product [50]. To face those intense logistics issues, the geographical location and size of the plant should be determined optimally with respect to raw material and demand location prior to plant investment and construction.

This thesis focuses on the full supply chain of the biofuel production - harvest, biomass transportation, biofuel production, biofuel transportation and biofuel delivery at the gas stations - to determine the optimal location of second generation biofuel production plants based on an economic point of view regarding local conditions.

1.4. Previous work

The supply chain comprises biomass harvest, biomass transportation, biofuel production, biofuel transportation and biofuel distribution to the consumers. Many studies have been made on the supply chain for bioenergy purposes. Sperling [51] first presented in 1984 a general analytical model to determine the optimal size and location of biofuel production plants. This analysis focused on the different distribution costs added to the processing cost and where the limits lie to find out the optimal plant size. According to Sperling, this analysis can be applied to any area with abundant biomass. Nguyen and Prince derived in 1996 a simple rule between biomass transportation and optimal size of the biofuel production plant for an operation at its optimum (least cost) capacity, generally applicable to all bioenergy conversion plants which require biomass to be transported from the surrounding areas [52].

The supply chain has also been analyzed in a geographically explicit way in a few studies. Panichelli and Gnansounou [53] and Perpiñá *et al.* [54] focused their work on the optimization of the location of bioenergy production plants for some provinces in Spain. Their studies focused on the biomass supply for electricity generation using a Geographic Information System (GIS). Shi *et al.* [55] made a similar investigation of the province of Guangdong, China. As electricity can be delivered to the grid without any major geographical constraints, the location of the plant is only dependent on the logistics of the biomass supply. GIS was also used by Bernotat and Sandberg [56] to study the optimal delivery of district heating in the county of Kalmar in Sweden. In their study, the supply of the raw material was not considered.

Another method that has been used to model the supply chain geographically explicitly of different biomass based products is a mixed integer linear programming model (MILP). Rentizelas *et al.* [57] optimized the location of a bioenergy plant (electricity, heating and cooling) for a municipality of Thessaly in Greece. The complete supply chain was covered but the study was concentrated to one plant only. Dunnett *et al.* [58] studied the influence of centralized and decentralized lignocellulosic bio-ethanol plants for a limited area under a general UK fuel demand and using an average of the European biomass availability and growth.

The biomass flows within the pulp industry was also optimized with a MILP model. Carlsson and Rönnqvist [59] studied first the supply chain of a pulp mill which was further analyzed by Bredström *et al.* [60] to optimize the production plants, the feedstock flow and storage of the Södra Cell's pulp mills. Gunnarsson then carried on the work and focused on different transport pathways within Europe. In that case the aim was to optimize the logistics of the chain for five existing pulp mills in Norway and Sweden [61-63].

In the above studies, the work was concentrated to one part of the supply chain regarding the final purpose of the plant, i.e. biomass distribution or final product distribution. When heat or electricity is considered, biomass distribution plays indeed the major role in the planning of the location of the plant, as the heat can be distributed locally and the electricity to the grid without geographical constraint. Dundett *et al.* [58] developed a tool that takes into account the complete distribution chain from the biomass to the bio-ethanol delivery in a general way. Anyhow those studies have mainly been applied to a specific region or local cases [59-63]. No greater areas on country level have been studied in order to find the optimal set of biofuel production plants needed to supply the country's demand.

1.5. Scope and objectives of the thesis

The main aim of the thesis was to develop a model that can be used to determine the most appropriate location and size of one or several second generation biofuel production plants where biomass availability, fuel demand, prices and costs have been considered. Additionally, the model should be able to

- identify a set of optimal production plants to meet a defined fuel demand,
- estimate the production cost ranges valid in the studied region. This thesis is however limited to the production of methanol and ethanol,
- manage large geographical areas, such as a country level,
- take into account the utilization of the by-products such as the residual heat,
- consider a time period for changes of the biofuel and the heat demand as well as the evolution of prices and costs,
- take into account the competition within the forestry market by integrating the existing forest industries,
- take into account biofuel imports,
- include policy tools such as setting a carbon emission tax on the emissions from the transport,
- identify the optimal bioenergy technology with the use of a carbon price as a subsidy on the mitigated fossil fuel emissions.

The model will not be used to optimize the profit of one single plant, but to minimize the final cost of biofuel for the region's welfare. The model is based on the minimization of the total cost of the biofuel supply chain. The development of the model is illustrated in several case studies, where analysis of critical parameters affecting the fuel production cost and the production plant location has been carried out.

2. Model description

The developed model presented takes into account the complete biofuel supply chain which comprises biomass harvest, biomass transportation, biofuel production, biofuel transportation and biofuel delivery to the consumers. This section gives a general description of the developed model, which is formulated as a Facility Location Problem and how each part of the chain has been treated in the model.

All monetary values in this thesis are expressed in Euro based on the year 2003 if not specified otherwise. Inflation rates and international exchange rates are considered [64]. The inflation on the prices from the year 2004 onwards was not considered, but would be implicitly included in the sensitivity analyses (for information, 1 $€_{2003}$ = 1.136 $€_{2009}$ [65]). In the following, the term *biomass* relates to woody biomass, and *biofuel* to liquid biofuel such as methanol or ethanol.

2.1. Variables description

S is the number of biomass supply regions, *P* is the number of production plants, *G* is the number of gas stations, *D* is the number of demand regions and *Y* the number of years. The corresponding sets are: $\widetilde{S}=\{1,...,S\}$, $\widetilde{P}=\{1,...,P\}$, $\widetilde{G}=\{1,...,G\}$, $\widetilde{D}=\{1,...,D\}$ and $\widetilde{Y}=\{1,...,Y\}$. Besides biofuel, a plant may be constructed to produce one or several additional commodities, (e.g. heat, power). Let *C* be the number of additional commodities and define $\widetilde{C}=\{1,...,C\}$ as the corresponding set. Biomass and biofuel can be transported by different means (truck, train or ship). Let *T* be the number of transportation means and define $\widetilde{T}=\{1,...,T\}$. Actual sawmills are regarded as biomass supplies, other actual biomass based industries (pulp and paper mills, CHPs, etc.) are considered as well as import points for biomass and/or biofuel. Let *M* be the number of sawmills, *F* the number of biomass based industries and *I* the number of import points. The corresponding sets are: $\widetilde{M}=\{1,...,M\}$, $\widetilde{F}=\{1,...,F\}$ and $\widetilde{I}=\{1,...,I\}$.

The following variables are: $b_{i,j,t,y}$ is the amount of biomass delivered from supply region *i* to production plant *j* by the transportation means *t* in the year *y*, $b^{import}_{i',j,t,y}$ is the amount of biomass delivered from the import point *i'* to the production plant *j*, $b^{sawmill}_{m,j,t,y}$ is the amount of biomass delivered from the sawmill *m* to the production plant *j*, $b_{i,f,t,y}$ is the amount of biomass delivered from the supply region *i* to the existing industry *f*, $b^{import}_{i',f,t,y}$ is the amount of biomass delivered from the import point *i'* to the existing industry *f* and $b^{sawmill}_{m,f,t,y}$ is the amount of biomass delivered from the sawmill *m* to the existing industry *f*. $x^{biofuel}_{j,k,t,y}$ is the amount of biofuel delivered from the production plant *j* to the gas station *k*, $x^{import}_{i',k,t,y}$ is the amount of biofuel delivered from the import point *i'* to the gas station *k* and $x^{biofuel}_{k,l,y}$ is the amount of biofuel sold at the gas station *k* to the customers from the demand region *l*. The variable $x_{j,c,y}$ represents the amount of commodity *c* that is produced at the production plant *j*. The variable $x_{l,y}^{fossil}$ is the amount of fossil fuel sold to the customers from the demand region *l*. The variables $b_{i,j,t,y}$, $b_{i',j,t,y}^{import}$, $b_{m,j,t,y}^{sawmill}$, $b_{i,f,t,y}$, $b_{i',f,t,y}^{import}$, $b_{m,f,t,y}^{sawmill}$, $x_{j,k,t,y}^{biofuel}$, $x_{i',k,t,y}^{import}$, $x_{k,l,y}^{biofuel}$, $x_{j,c,y}$ and $x_{l,y}^{fossil}$ are non-negative. The binary variables are $u_{j,y}$ and $u_{k,y}$, respectively, indicating if the production plant *j* and the gas station *k* are in operation in the year *y*. If $u_{j,y}$ ($u_{k,y}$) is equal to one, then the plant (station) is in operation, otherwise $u_{j,y}$ ($u_{k,y}$) is zero ($u_{j,initial}$ is initialized to zero).

2.2. Biomass availability

Biomass represents any organic matter derived from biological organisms like plants, animals (terrestrial and aquatic). It can be classified in many ways. One way is to differentiate between woody biomass and non woody biomass including herbaceous crops. This thesis concentrates on woody biomass in the temperate latitudes. The woody species of most interest for energy purposes are conifers (fir, spruce and pine) and fast growing trees (poplar, willow) with a rotation period lower and productivity higher than conifers. Poplar from short-rotation forestry is used in the articles I-III, and forest wood from conventional forestry is used in the articles IV-VI.

The amount of biomass delivered to the biofuel production plants and the existing plants is restricted by the amount of biomass available, denoted as $\overline{b}_{i,y}$, it is a certain percentage of the whole available biomass. The cost for producing biomass in the supply region *i* the year *y* is $c_{i,y}$. The biomass delivered from region *i* is then expressed by

$$\sum_{j=1}^{P}\sum_{t=1}^{T} b_{i,j,t,y} + \sum_{f=1}^{F}\sum_{t=1}^{T} b_{i,f,t,y} \le \overline{b}_{i,y}, \quad i \in \widetilde{S}, y \in \widetilde{Y}. \tag{1}$$

In the same way, the amount of imported biomass delivered to the biofuel production plants and the existing industries is restricted by the amount of biomass imported, denoted as $\overline{b}_{i',y}^{import}$. The imported biomass has a cost of $c_{i',y}^{biomassimport}$. The biomass delivered from the import point *i'* is then expressed by

$$\sum_{j=1}^{P}\sum_{t=1}^{T} b_{i',j,t,y}^{import} + \sum_{f=1}^{F}\sum_{t=1}^{T} b_{i',f,t,y}^{import} \le \overline{b}_{i',y}^{import}, \quad i' \in \widetilde{I}, y \in \widetilde{Y}. \tag{2}$$

Wood for non-fuel purposes normally has priority over the use of wood as fuel. Considerable waste is generated when trees are converted to wood products. Logs are removed to a specific dimension, and branch wood and crooked stem wood may be left when the trees are felled; this might amount to 15-30% of the above ground wood volume. All these waste materials are potentials for energy purposes [66]. Besides those logging residues, sawmill residues are a very important source of fuelwood as large quantities of waste can be generated.

Sawmill residues can be divided into slabs or offcuts, bark (if separated from the slabs) and sawdust. The amount of waste produced from a sawlog depends on the diameter of the log to be cut, the saving methods, and the market for the sawn wood [66].

The amount of biomass delivered from the sawmill to the biofuel production plants and the existing plants is restricted by the amount of biomass available from the sawmills, denoted as $\overline{b}_{m,y}^{sawmill}$. The biomass from the sawmill has a cost of $c_{s,y}^{sawmill}$. The biomass delivered from the sawmill m is then expressed by

$$\sum_{j=1}^{P}\sum_{t=1}^{T} b_{m,j,t,y}^{sawmill} + \sum_{f=1}^{F}\sum_{t=1}^{T} b_{m,f,t,y}^{sawmill} \leq \overline{b}_{m,y}^{sawmill}, \quad m \in \widetilde{M}, y \in \widetilde{Y}. \tag{3}$$

Figure 7 presents an example of the amount of biomass that can be used for the forest industry. This is divided into three groups: local production, sawmills, and imports. The blue points represent the import locations and the capacities of the biomass imports from the border countries of Austria. The green points represent the bigger sawmills and the amount of wood residuals they can deliver. The yellow points represent the amount of forestry wood available for the forest industries. This figure presents an example of the values that would be assigned to the available biomass from the local production ($\overline{b}_{i,y}$), the imports ($\overline{b}_{i',y}^{import}$) and the sawmills ($\overline{b}_{m,y}^{sawmill}$). Different percentages of these values are considered and analyzed.

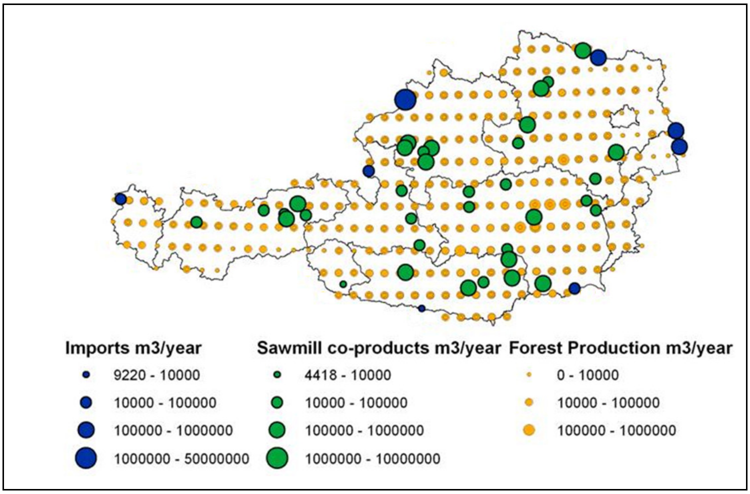

Figure 7: Biomass availability in Austria from the imports [67], sawmills [68] and forestry.

The cost of the harvested wood is between 25 and 50 $€_{2009}/m^3$ [69, 70]. This includes site maintenance, land, harvesting, chipping, and re-cultivation costs [69, 70]. The cost of feedstock from the imports is assumed to be around 48 $€_{2009}/m^3$ [71] and the residuals from the sawmills around 10 $€_{2009}/m^3$ [72]. Articles I-IV assume a fix cost of the biomass after felling and transportation to the side of the nearest forest road. The wood cost in the articles V and VI is scaled between a minimum and maximum cost per cubic meter depending on the population density, forest share, area slope and land cost level of the country. Residues from the sawmills are only considered in article VI. The reference costs for the biomass from the local production, the sawmills and the imports are presented in Table 10.

Table 3: Reference values for the biomass cost (€$_{2009}$/m^3).

Parameter	Symbol	Value	Reference
Local production	$c_{i,y}$	25-55	[69, 70]
Sawmill residues	$c_{s,y}^{sawmill}$	10	[72]
Import	$c_{i',y}^{biomassimport}$	48	[71]

Land availability also plays a major role in the planning of second generation biofuel production plants. Although the yields per hectare have been estimated, the proportion and dedicated biomass location among different industries are not considered in those estimations. The consideration of the available land for energy purposes is an important factor and difficult to estimate. Rentizelas *et al.* [57] used a yield ratio on the allocated biomass grid in order to get an estimate of the potential amount of residues, which is the feedstock used. When data is not available, an availability coefficient is used. For instance, Perpiñá *et al.* [54], Shi *et al.* [55] used such a coefficient. Such estimation is not geographically explicit and is applied evenly on the whole studied area. To avoid using such an estimation coefficient and to get a better picture of the wood flows, existing forest wood industries need to be incorporated into the model.

Article VI tackled this issue by including the whole wood demand based on the Austrian wood flow chart [73]. The potential harvestable forest wood was calculated with a distinction between wood for sawmills and other purposes (like energy or pulp and paper). Knowing the amount of wood that can be harvested per year, the forestry wood can be distributed to all existing forest wood industries and possible biofuel production plants. Location and capacities of present pulp and paper mills, CHP plants, local district heating plants and local wood demand are the existing plants considered for Austria. The model optimizes the wood proportion among those different industries and if there is enough biomass left, additional biofuel plants can be set up optimally.

The biomass is then used for these so-called existing industries. The biomass demand $d_{f,y}^{industry}$ from the industry f has then to be met using biomass from the local production, imports and sawmills. The existing industry f is then modeled using the following mass balance equation,

$$\sum_{i=1}^{S}\sum_{t=1}^{T} b_{i,f,t,y} + \sum_{i'=1}^{I}\sum_{t=1}^{T} b_{i',f,t,y}^{import} + \sum_{s=1}^{M}\sum_{t=1}^{T} b_{s,f,t,y}^{sawmill} = d_{f,y}^{industry}, \quad f \in \widetilde{F}, y \in \widetilde{Y}. \tag{4}$$

The locations and capacities of the existing forest wood industries were used for Austria in article VI only. Figure 8 presents an example of the actual location of these industries for Austria. The biomass demand presented is then aggregated in the studied corresponding grid.

The major wood demand points represent the demand from the pulp and paper mills, whereas the smaller ones represent the demand from CHP plants or local district heating plants.

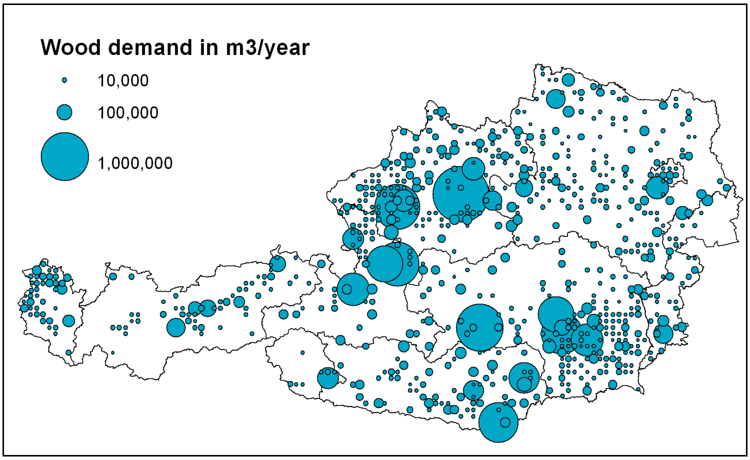

Figure 8: wood demand from the actual forest industries other than sawmills in Austria (the demand spots greater than 5,000 m^3/year are represented for reading simplicity).

2.3. Biofuel production plant

The biofuel production plant j is described by the following parameters and equations. The cost for building a plant with maximal biofuel capacity $\bar{x}_j^{biofuel}$ is e_j, and the cost for producing biofuel in the plant is $c_{j,y}$. The amount of biofuel which is produced at a plant, is limited by the capacity of the plant in question. The biofuel production is thus restricted by

$$\sum_{k=1}^{G}\sum_{t=1}^{T} x_{j,k,t,y}^{biofuel} \leq \bar{x}_j^{biofuel} u_{j,y}, \quad j \in \widetilde{P}, y \in \widetilde{Y}. \tag{5}$$

The plant is modeled using the following energy balance equation,

where the amount of biomass from the local production, the imports and the sawmills (left side), is processed to a certain amount of biofuel (right side) using the plant efficiency $\rho_j^{biofuel}$ at the production plant j.

$$\rho_j^{biofuel}\left(\sum_{i=1}^{S}\sum_{t=1}^{T} b_{i,j,t,y} + \sum_{i'=1}^{I}\sum_{t=1}^{T} b_{i',j,t,y}^{import} + \sum_{s=1}^{M}\sum_{t=1}^{T} b_{s,j,t,y}^{sawmill}\right) = \sum_{k=1}^{G}\sum_{t=1}^{T} x_{j,k,t,y}^{biofuel}, \quad j \in \widetilde{P}, y \in \widetilde{Y}, \tag{6}$$

Sales of additional commodities c (heat, electricity, and biogas) can be considered. Therefore, also define the variable $q_{j,c,y}$ as the additional commodity from an alternative source located close to the production plant j:

$$x_{j,c,y} + q_{j,c,y} \geq q^D_{j,c,y}, \quad j \in \widetilde{P}, c \in \widetilde{C}, y \in \widetilde{Y}, \tag{7}$$

where the parameter $q^D_{j,c,y}$ is the corresponding commodity demand around the production plant j. For heat, the alternative source, which typically is a heating boiler or a CHP plant, is associated with a production cost $c_{j,heat,y}$.

The relations between the biomass input and the commodities produced are modeled using the conversion efficiency $\rho_{j,c}$, giving

$$\rho_{j,c}\left(\sum_{i=1}^{S}\sum_{t=1}^{T} b_{i,j,t,y} + \sum_{i'=1}^{I}\sum_{t=1}^{T} b^{import}_{i',j,t,y} + \sum_{s=1}^{M}\sum_{t=1}^{T} b^{sawmill}_{s,j,t,y}\right) = x_{j,c,y}, \quad j \in \widetilde{P}, c \in \widetilde{C}, y \in \widetilde{Y}. \tag{8}$$

The commodity c can be sold by the production plant j the year y at a price $p_{j,c,y}$.

Scale effects strongly influence the unit cost per plant capacity, which decreases with larger plants or equipment (such as boilers, turbines etc.). For example, a production plant of 100 MW can be expected to be less expensive per GJ biofuel produced than a 10 MW plant, even though both plants are based on the same basic technology. This difference can be adjusted using scaling functions of the individual components of the production plant as described by $\left(Cost_a / Cost_b = \left(Size_a / Size_b\right)^{SF}\right)$ where *SF* is the scaling factor, $Cost_a$ and $Cost_b$ are the costs of the components for two different biofuel production plants with $Size_a$ and $Size_b$ respectively. Using this information it is possible to calculate the costs for different processing steps of biofuel production plants of different sizes. By adding the investment costs from the separate units, the total investment cost for another size can be determined, and production cost for the respective production plant can be calculated.

Hamelinck and Faaij [37] have analyzed two gasifiers for methanol production: A pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. The latter showed better performance, and according to their study, the lowest cost for methanol production and has therefore been chosen in this study. Technical differences between gasifiers are not discussed in this thesis. The reference size for the methanol production plant is 80 $t_{biomass}$/h. The investments for the separate units in the reference plant are presented in Table 4. The process plant cost is calculated as the sum of the different units in the process with regard to the economy of scale. For biomass systems, the scaling factor is usually between 0.6 and 0.8. The uncertainty range of such estimates is up to ± 30% of the investment for the separate units [37].

Table 4: Base scale factors for the 80 $t_{biomass}$/h methanol reference plant [37].

Gasification system	Scaling factor	Unit cost (M€)
Total pre-treatment	0.79	31.4
Gasifier	0.65	25
Gas cleaning		
Tar cracker	0.7	7.6
Cyclones	0.7	5.6
Heat exchanger	0.6	9.2
Baghouse filter	0.65	3.4
Condensing scrubber	0.7	5.6
Syngas processing		
Compressor	0.85	13.9
Steam reformer	0.6	37.8
Methanol production		
Make up compressor	0.7	14.3
Liquid phase methanol	0.72	3.6
Recycle compressor	0.7	0.3
Refining	0.7	15.7
Power generation (optional)		
Steam turbine + steam system	0.7	11.4
Process plant cost (*PPC*)		185

The reference size for the ethanol production plant is 70 $t_{biomass}$/h. The investments for the separate units in the reference plant are presented in Table 5. The equipment cost for a circulating fluidized bed (CFB) combustor is shown in Table 5. A grate-fired boiler was considered for this study, which might imply less equipment cost than a CFB boiler.

Table 5: Scale factors and equipment cost for the poly-generation system for a 70 $t_{biomass}$/h ethanol plant [74].

Component	**Scaling factor**	**Unit cost (M€)**
Pre-treatment		
Mechanical	0.67	4.44
Mill	0.70	0.91
Dilute acid	0.78	14.10
Steam explosion	0.78	1.41
Ion-exchange	0.33	2.39
Overliming	0.46	0.77
Hydrolysis + fermentation		
Seed fermentors	0.60	0.68
C5 fermentation	0.80	6.39
Hydrolyze-fermentation	0.80	6.39
Upgrading		
Distillation and purification	0.70	2.11
Molecular sieve	0.70	2.80
Residuals		
Solids separation	0.65	1.78
Anaerobic digestion	0.60	2.51
Power island		
Boiler	0.73	53.95
Steam system + turbine	0.70	14.34

The total capital requirement can be calculated as presented in Table 6. The total capital requirement is used for calculating the annual cost (AC) as given by $\left(AC = TCR \cdot IR/(1-1/(1+IR)^{te})\right)$ where IR is the interest rate (10%) and t_e, the economic lifetime (25 years).

Table 6: Total capital requirement [37].

Capital requirement	Description
Total plant cost (*TPC*)	
Engineering fee	10% of *PPC*
Process contingency	2.3% of *PPC*
General plant facilities	10% *PPC*
Project contingency	15% of (*PPC* +general plant facilities)
Total plant investment (*TPI*)	
Adjustment for interest and inflation	0.34% *PPC*
Total capital requirement (*TCR*)	
Prepaid royalties	0.5% of *PPC*
Startup costs	2.7% *TPI*
Spare parts	0.5% of *TPC*
Working capital	3% *TPI*
Land, 200 acres	200 Acres @ 6,500 Euro/acre

The annual operating and maintenance costs are calculated as the sum of the elements presented in Table 7. The total annual cost is then the sum of the annual cost (*AC*) and the annual operating and maintenance cost. The cost of biofuel per GJ is calculated by dividing the total cost by the amount of biofuel produced.

Table 7: Annual operating and maintenance costs.

Operating and maintenance	Description	Reference
Raw water	0.14 € / m^3	[75, 76]
Operator labour	3 % of *TPI*	[75]
Supervision and clerical labour	30% of operator labor	[76]
Maintenance costs	2.2% of *TPC*	[76]
Insurance and local taxes	2% of *TPC*	[76]
Operating royalties	1% of wood cost	[76]
Miscellaneous operating costs	10% of operator labor	[76]

Table 8 presents the reference values for both the methanol and ethanol plants. The set up cost and the production cost are calculated as presented above.

Table 8: Reference values for the biofuel production plants studied. The efficiencies are expressed as energy output per energy input. The values in brackets for the ethanol plant represent a second alternative as presented in section 1.3.

Parameter	Symbol	Unit	Methanol plant	Ethanol plant
Set up cost *	e_j	M€	280	236
Production cost *	$c_{j,y}$	€/GJ$_{biofuel}$	17.9	42.7
Maximal biofuel capacity *	$\overline{x}_j^{biofuel}$	PJ$_{biofuel}$	6.2	2.7
Biofuel efficiency	$\rho_j^{biofuel}$	%	55 [37, 77]	29.2 (25.8)
Heat efficiency	$\rho_{j,heat}$	%	10 [77]	23.4 (27.7)
Electricity efficiency	$\rho_{j,electricity}$	%	-	12.7 (14.5)
Biogas efficiency	$\rho_{j,biogas}$	%	-	18.3 (16.1)

* Value example for the reference production plant.

Article VI allows the possibility to set up CHP plants or local district heating (DH) plants. The values of set up and production costs are presented in Table 9.

Table 9: Production costs for the production of alternative commodities (heat or electricity) [78].

Technology	Set up cost (M€)	Production costs	Assumed Maximum Size (MW$_{biomass}$)
CHP	11	15.1 €/MWh$_{electricity}$	200
DH	5.4	18.9 €/MWh$_{heat}$	35

The value of the parameter $q^D_{j,c,y}$, which is the commodity demand around the plant *j*, depends on the location of the plant and can thus vary from zero for a no demand area to a value higher than the maximum plant production for a higher demand area. The sales prices from district heating, electricity and biogas sales are summarized in Table 10. The power price includes electricity certificates as well as the market price. The distribution costs for the produced electricity and biogas are not considered in the model, thus they are assumed to only generate an income at the production site. Electricity is assumed to be sold to the grid and biogas to be sold at the plant.

Table 10: Reference values for the alternative commodity prices (€$_{2009}$/MWh).

Parameter	Symbol	Value	Reference
Heat	$p_{j,heat,y}$	40 - 87	[69, 79]
Electricity	$p_{j,electricity,y}$	72	[80]
Biogas	$p_{j,biogas,y}$	21.5	[81]

2.4. Gas stations and biofuel demand

Methanol is distributed at the gas station. As methanol is not widely used in the transportation sector, changes to gas stations would be required. One can consider a station that has three underground storage tanks (UST) of three grades of gasoline, two pump islands, and four dispensers capable of refueling eight vehicles simultaneously. At an average fill-up of 13.5 gallons (51 liters) requiring six minutes, a station such as the one illustrated may service between 200 and 400 vehicles per day and have a gasoline throughput of 85,000 (321,800 liters) to 170,000 gallons (643,500 liters) per month [82]. Two scenarios can be analyzed, one is to add a methanol capacity to an existing station, and the other one is to consider that methanol would displace a fraction of existing gasoline storage capacity.

In the first scenario (to add a methanol capacity to an existing station), it is assumed that the capability of dispensing up to 33,000 gallons (124,900 liters) of methanol per month is added to an existing retail gasoline station, increasing the station's overall throughput. This may be accomplished by adding a new underground 10,000 gallons (37,900 liters) methanol fuel tank, remote from the existing tank field. An above ground tank might be added where space and permission allow [82].

In the second scenario (methanol displacing a fraction of existing gasoline storage capacity), it is assumed that a portion of the station's gasoline storage capacity is displaced by the 10,000 gallons (37,900 liters) methanol storage tank. Alternate ways of accomplishing this include:

- Eliminating one product from the mix of petroleum products and converting that storage capacity to methanol. This could be done by cleaning or upgrading one of the existing petroleum tanks and installing new methanol compatible piping and dispenser.
- Removing one of the existing petroleum tanks and replacing it with a methanol compatible tank and upgrading the balance of the system.

Capital costs for refueling stations for dispensing methanol are summarized in Table 11. The scenarios are evaluated in a study of the American Methanol Foundation [82]. The costs are independent of the methanol production plant size.

Table 11: Costs for refueling stations for dispensing methanol [82].

	Capital costs	Yearly payment	Cost
	€	€/year	€/GJ
Increasing storage capacity at existing stations			
Adding new underground tank	54,587	6,014	0.2542
Adding new above ground tank	47,758	5,261	0.2224
Displacing existing gasoline storage capacity with methanol			
Preparing existing underground tank	43,606	4,804	0.2031
Replacing existing underground tank	61,228	6,745	0.2851
Average cost		5,706	0.2412

The demand for biofuel is determined either by the location and size of actual gas stations when data is available, or by an average of the fuel consumption per inhabitants of the studied area. Knowing the location of inhabited areas, the number of inhabitants at those points and the national fuel consumption, the biofuel demand is then estimated for each of these demand points.

The cost for setting up a gas station *k* with the capacity $\overline{x}_k^{biofuel}$ is e_k. The cost for handling biofuel the year *y* at the station *k* is $c_{k,y}$. Like the plant procedure, the gas station is also modeled using the capacity and mass flow (the biofuel delivered must be equal to the biofuel-supply at the gas station) equations:

$$\sum_{l=1}^{D} x_{k,l,y}^{biofuel} \le \overline{x}_k^{biofuel} u_{k,y}, \quad k \in \widetilde{G}, y \in \widetilde{Y}, \tag{9}$$

and

$$\sum_{j=1}^{P}\sum_{t=1}^{T} x_{j,k,t,y}^{biofuel} + \sum_{i'=1}^{I}\sum_{t=1}^{T} x_{i',k,t,y}^{import} = \sum_{l=1}^{D} x_{k,l,y}^{biofuel}, \quad k \in \widetilde{G}, y \in \widetilde{Y}. \tag{10}$$

The imported biofuel is assumed to have an import cost of $c_{i',y}^{import}$. The demand for car fuel in region *l* year *y* is modeled by

$$\sum_{k=1}^{G} x_{k,l,y}^{biofuel} + x_{l,y}^{fossil} = d_{l,y}, \quad l \in \widetilde{D}, y \in \widetilde{Y}, \tag{11}$$

where $d_{l,y}$ is the demand. The fossil fuel is assumed to be available for a price $p_{l,y}^{fossil}$. Once a plant or a gas station is built, it is available the following years. This is modeled using

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

and

$$u_{k,y} \ge u_{k,y-1}, \quad k \in \widetilde{G}, y \in \widetilde{Y}. \tag{13}$$

The gas station parameters are summarized in Table 12. The set up cost (e_k) is not considered. As described above, only replacement or addition of a fuelling tank at the actual gas stations is assumed.

Table 12: Gas station parameters.

Parameter	Symbol	Unit	Value
Capacity	$\overline{x}_k^{biofuel}$	GJ	1,970
Biofuel handling cost	$c_{k,y}$	€/GJ	0.24

2.5. Transportation costs

The cost for transporting biomass from the supply region *i* to the production plant *j* by the transportation means *t* the year *y* is $t_{i,j,t,y}$. The cost for transporting the biomass from the import point *i'* to the production plant *j* is $t_{i',j,t,y}$, from the sawmill *m* to the production plant *j* is $t_{m,j,t,y}$, from the supply region *i* to the existing industry *f* is $t_{i,f,t,y}$, from the import point *i'* to the existing industry *f* is $t_{i',f,t,y}$ and from the sawmill *m* to the existing industry *f* is $t_{m,f,t,y}$.

The produced biofuel at the production plant *j* is transported to the gas station *k* at the cost $t_{j,k,t,y}$. The imported biofuel is transported from the import point *i'* to the gas station *k* at the cost $t_{i',k,t,y}$. The transportation cost $t_{k,l,y}$ is interpreted as the driving cost for people driving from the demand region *l* to the gas station *k*. For simplicity in the calculation, only one demand region is considered, and the value of $t_{k,l,y}$ is therefore zero.

The biomass transportation cost (in €/TJ) is described by Börjesson and Gustavsson, 1996 [83], and detailed in Table 13, for transportation by tractor, truck, train, and ship and different fuels. They are composed of a fixed cost and a variable cost. Fixed costs include loading and unloading costs. They do not depend on the distance of transport. Variable costs include fuel cost, driver cost, maintenance cost etc. They are dependent on the distance of transport.

Table 13: Transport costs in €/TJ regarding the transport distance (*d*) in km [83].

Fuel	Tractor	Truck	Train	Boat
Feedstock	226+12.78.*d*	344+7.77.*d*	727+1.08.*d*	836+0.44.*d*
Biofuel		423+0.66.*d*	138+3.05.*d*	462+0.15.*d*

A detailed report on logistic wood transport presented the transportation costs and loading and unloading costs. Loading and unloading costs lie between 200 and 1,000 €/TJ regarding the transportation used [84] which are similar to the fixed costs in Table 13. Recent technical notices on truck consumption and emissions show a 10% efficiency improvement in the truck engine between the years 1993 and 2006 [85]. Regarding the technology improvement, a fuel price varying between 0.9 and 1.1 €/l and a 25% share of the fuel price in the transport cost [83], the transportation costs in the year 2006 would then vary between -3% and +5% compared to the 1996 value [83]. As the oil price is highly volatile, a conservative approach to the transportation cost was adopted and the equations derived from Börjesson and Gustavsson, 1996 [83] were considered and updated in €$_{2003}$ for the current study.

Tractor is the most cost efficient way of feedstock transportation up to a distance of 25 km (Figure 9). For distances up to 50 km truck transportation is the best option. For distances between approximately 50 and 150 km, trains are the cheapest, and for longer distances ship is the next most cost efficient. Tractor and truck transportation are considered in the articles I-IV and VI and all means of transportation are then considered in article V.

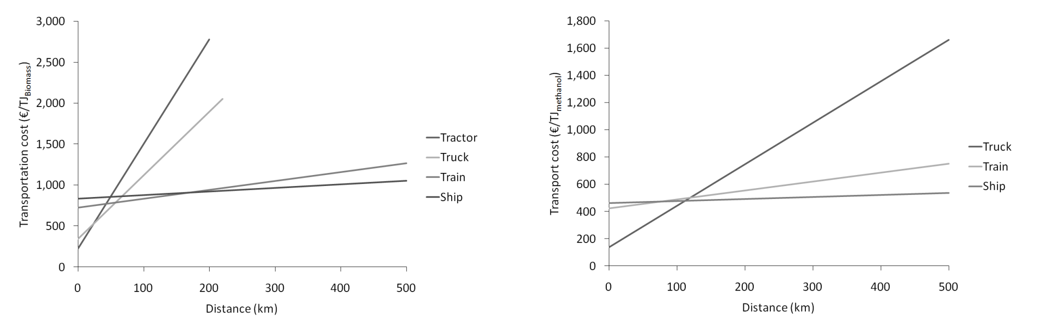

Figure 9: Transportation cost for biomass (left) and biofuel (right) by tractor, truck, train and ship [83].

In the calculations of transportation cost, the costs are scale-independent. Biofuel transportation by truck is the most cost efficient for shorter distances (less than 100 km), and train and ships for longer distances (Figure 9). These calculated costs might differ from the transportation price, as the price may be reduced due to discounts or special agreements [83].

Two ways are used to calculate the distance between two points: (1) the average actual distance (in km) to the methanol plant, *d*, is defined as the average direct distance multiplied by a dimensionless factor accounting for irregularities in the road network called the tortuosity factor [86, 87]. This ratio can vary from 1 for straight roads to 3 for mountainous terrain [86]. In the present studies straight distances from point to point were measured and compared with real distances, and a value of 1.4 appeared to be the most appropriate for the studied areas, a value also used by [57]. (2) A network map (roads, railways, shipping routes) can also be used. Considering the center of the grid cell, the distance to the closest network connection of one type (road, railway or river) is determined and from this center, the distance to the next cell center is then added to the former one and so on… until the final point is reached using the shortest way available. The total distance between two points will then be the sum of those distances and will be determined by setting a weight on each transportation type. For instance: once train is used, this facility has to be used as long as possible to get closer to the final point. The transportation costs from one point to another are then calculated for either by truck or Truck-train or truck-train-ship. Each route can then easily be compared in term of cost or/and emission. The first method is used in articles I-IV and VI, and the second one in the article V. In the same article, the emissions from the transport are considered. The emissions are defined for each transportation means. They are detailed in Table 14.

Table 14: Emissions from transportation in g_{CO2}/km/t [88].

Tractor	Truck	Train	Boat
810	48	0.003	22

2.6. Objective function

Given the costs and prices, the total cost of the system is defined by the function $f(b,x,q,u)$

$$
\begin{cases}
f(b,x,q,u) = \sum_{y=1}^{Y}\sum_{i=1}^{S}\sum_{j=1}^{P}\sum_{t=1}^{T}\left(c_{i,y} + t_{i,j,t,y}\right)b_{i,j,t,y} + \sum_{y=1}^{Y}\sum_{i=1}^{S}\sum_{f=1}^{F}\sum_{t=1}^{T}\left(c_{i,y} + t_{i,f,t,y}\right)b_{i,f,t,y} \\
+ \sum_{y=1}^{Y}\sum_{i'=1}^{I}\sum_{j=1}^{P}\sum_{t=1}^{T}\left(c_{i',y}^{biomassimport} + t_{i',j,t,y}\right)b_{i',j,t,y}^{import} + \sum_{y=1}^{Y}\sum_{i'=1}^{I}\sum_{f=1}^{F}\sum_{t=1}^{T}\left(c_{i',y}^{biomassimport} + t_{i',f,t,y}\right)b_{i',f,t,y}^{import} \\
+ \sum_{y=1}^{Y}\sum_{s=1}^{M}\sum_{j=1}^{P}\sum_{t=1}^{T}\left(c_{s,y}^{sawmill} + t_{s,j,t,y}\right)b_{s,j,t,y}^{sawmill} + \sum_{y=1}^{Y}\sum_{s=1}^{M}\sum_{f=1}^{F}\sum_{t=1}^{T}\left(c_{s,y}^{sawmill} + t_{s,f,t,y}\right)b_{s,f,t,y}^{sawmill} \\
+ \sum_{y=1}^{Y}\sum_{j=1}^{P} e_{j,y}\left(u_{j,y} - u_{j,y-1}\right) + \sum_{y=1}^{Y}\sum_{j=1}^{P}\sum_{k=1}^{G}\sum_{t=1}^{T}\left(c_{j,y} + t_{j,k,t,y}\right)x_{j,k,t,y}^{biofuel} \\
+ \sum_{y=1}^{Y}\sum_{j=1}^{P}\sum_{c=1}^{C} c_{j,c,y}q_{j,c,y} - \sum_{y=1}^{Y}\sum_{j=1}^{P}\sum_{c=1}^{C} p_{j,c,y}x_{j,c,y} \\
+ \sum_{y=1}^{Y}\sum_{k=1}^{G} e_{k,y}\left(u_{k,y} - u_{k,y-1}\right) + \sum_{y=1}^{Y}\sum_{k=1}^{G}\sum_{l=1}^{D}\left(c_{k,y} + t_{k,l,y}\right)x_{k,l,y}^{biofuel} \\
+ \sum_{y=1}^{Y}\sum_{i'=1}^{I}\sum_{k=1}^{G}\sum_{t=1}^{T}\left(c_{i',y}^{import} + t_{i',k,t,y}\right)x_{i',k,t,y}^{import} + \sum_{y=1}^{Y}\sum_{l=1}^{D} p_{l,y}^{fossil}x_{l,y}^{fossil}.
\end{cases}
\tag{14}
$$

The different summands are:

(1) production (parameter) plus transportation cost (parameter) of biomass times the amount of biomass which is actually used for the biofuel production plants (variable),

(2) production (parameter) plus transportation cost (parameter) of biomass times the amount of biomass which is actually used for the present industries (variable),

(3) import (parameter) plus transportation cost (parameter) of biomass times the amount of biomass which is actually used for the biofuel production plants (variable),

(4) import (parameter) plus transportation cost (parameter) of biomass times the amount of biomass which is actually used for the present industries (variable),

(5) cost of the sawmills residues (parameter) plus transportation cost (parameter) times the amount of residues which is actually used for the biofuel production plants (variable),

(6) cost of the sawmills residues (parameter) plus transportation cost (parameter) times the amount of residues which is actually used for the present industries(variable),

(7) plant setup cost (parameter) times the “decision” (binary) of building a power plant (variable) (considering the plants which already exist),

(8) plant production cost (parameter) plus transportation cost of biofuel from the power plant to the gas stations (parameter) times the amount of biofuel being produced at the plant (variable),

(9) cost of the commodity production (parameter) times the amount of commodity produced from an alternative source (variable),

(10) price of the commodities (parameter) times the amount of commodities produced at the plant (variable),

(11) setup cost of gas stations (parameter) times the “decision” (binary) of setting up a gas station (variable),

(12) gas station production-handling cost (parameter) plus transport cost from the gas station to the living area (parameter) times the amount of biofuel taken from the gas station (variable),

(13) import (parameter) plus transport (parameter) of biofuel times the amount of imported biofuel which is delivered at the gas stations (variable),

(14) price of fossil fuel (parameter) times the amount of fossil fuel used (variable).

The emissions can also be considered. Let define $c^{emission}$ a carbon tax. Considering the function $g(b,x,u)$ as the sum of the emissions from all transports described above, the objective function is defined as:

$$h(b,x,q,u) = f(b,x,q,u) + c^{emissions}.g(b,x,u) \tag{15}$$

Finally, the mixed integer problem is defined as

$$\begin{cases} \min\limits_{b,x,q,u}\left[h(b,x,q,u)\right] \\ s.t. \\ (1)-(15) \\ b_{i,j,t,y}, b_{i,f,t,y}, b^{import}_{i',j,t,y}, b^{import}_{i',f,t,y}, b^{sawmill}_{s,j,t,y}, b^{sawmill}_{s,f,t,y}, x^{biofuel}_{j,k,t,y}, x_{j,c,y}, x^{biofuel}_{k,l,y}, x^{import}_{i',k,t,y}, x^{fossil}_{l,y}, q_{j,c,y} \geq 0, \\ i \in \widetilde{S}, i' \in \widetilde{I}, j \in \widetilde{P}, f \in \widetilde{F}, s \in \widetilde{M}, t \in \widetilde{T}, c \in \widetilde{C}, k \in \widetilde{G}, l \in \widetilde{D}, y \in \widetilde{Y} \\ u_{j,y} \in \{0,1\}, u_{k,y} \in \{0,1\}, \qquad j \in \widetilde{P}, k \in \widetilde{G}, y \in \widetilde{Y}. \end{cases} \tag{16}$$

The problem is an ordinary Mixed Integer Program (MIP) and can thus be solved using standard MIP techniques [89]. The model was developed in the commercial software GAMS using the solver CPLEX [90]. The model will choose the less costly pathways from one set of biomass supply points to a specific plant and further to a set of biofuel demand points. The final result of the optimization problem would then be a set of plants together with their corresponding biomass and biofuel demand points.

For information, Table 15 shows the characteristics of the model for each article. These problems are large, and to find out the optimal plant location, it is often better to divide the problem into smaller ones. For example instead of running the model to find the optimal location between 300 possible positions, it would be more time efficient to divide the problem into 3 runs for 100 possible plants and then run the model for the remaining optimal plants from the first three calculations.

Table 15: Characteristics of the model for each article.

	Article II	Article III	Article IV	Article V	Article VI
Time step	1	1	5	1	1
Number of variables	2,077,653	1,085,478	1,175,174	2,077,653	1,035,091
Number of binary variables	441	2,080	589	441	1,945
Number of constraints	6,337	15,961	6,869	6,337	21,061

An overview of the steps of the modeling work is presented in Figure 10 . The input data is first treated into the right units and format before the optimization. After the optimization has reached a solution, the results on the costs of the supply chain, the amount of biomass used, the amount of biofuel produced, the characteristics of the production plants, and the emissions are read in Excel. The results can further be plotted geographically explicitly [91].

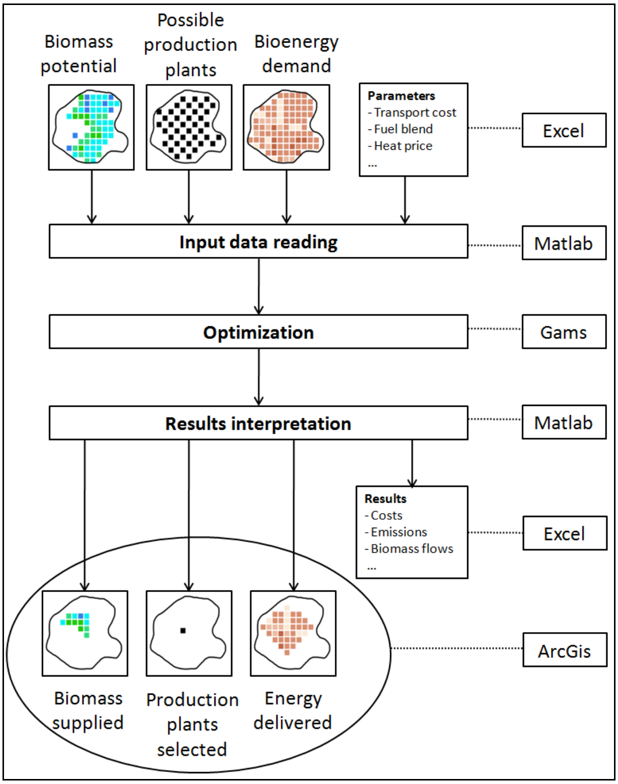

Figure 10: Overview of the modeling procedure together with the software used at each step.

3. Summary and comments on the appended papers

This section presents a summary of each article appended. Each article introduces a new development in the model together with a case study as an illustration.

Article I presents an introduction to the biofuel supply chain for methanol production via biomass gasification in Baden-Württemberg in Germany using a simple non-optimizing model. Article II introduces the optimization problem for the same area and biofuel production route. In Article III, the residual heat from the process and the possibility to meet the demand with fossil fuel are taken into account in the model, Austria serves as a case study. Article IV integrates the time dependency into the model due to changes in the biofuel and heat demand. A smaller study area, the county of Norrbotten in Sweden was chosen as the case study. Article V integrates the production of ligno-cellulosic ethanol via fermentation into the model. Furthermore, a full network communication map as well as the possibility to include biofuel imports and a carbon tax into the model is presented. Sweden serves as a case study. Finally Article VI integrates the complete forestry market of Austria. An overview of the linkage between the six articles is presented in Table 16.

Table 16: Overview of the linkage between the six articles attached to this thesis.

Article	Overview	Products	By-products	Case Study
I	Introduction to the supply chain with a simple transportation model.	Methanol	-	Baden-Württemberg, Germany
II	Article I + Optimization problem is presented.	Methanol	-	Baden-Württemberg, Germany
III	Article II + Integration of the fossil fuel in competition with the biofuel production. The residual heat from the production plant is considered.	Methanol	Heat	Austria
IV	Article III + Biofuel demand, heat demand, prices and costs change over time.	Methanol	Heat	Norrbotten, Sweden
V	Article IV + Biofuel imports are considered. A detailed logistics network map is used for a better choice between truck/train/boat transportation.	Ethanol	Heat, electricity, biogas	Sweden
VI	Article V + The competition of the available biomass with the existing forest industries is integrated.	Ethanol	Heat, electricity, biogas	Austria

3.1. Article I

Methanol from gasification using a geographically explicit model

Article I presents a geographically explicit model based on the biofuel supply chain. This model calculates the final biofuel cost from a given biofuel production plant. The location and the capacity of the production plant were chosen arbitrarily. The biomass cost is here assumed to be constant in the area studied. Therefore the selection of the biomass supplied does not depend on the cost, but on the distance from the production plant. The closest biomass to the production plant is then selected. In the same way the closest gas stations around the production plant are selected for the delivery of biofuel.

The main objectives of this article are to introduce the biofuel supply chain geographically explicitly with a simple transport model and estimate a production cost range in the studied area.

The region of Baden-Württemberg in Germany was chosen as a case study. Methanol is produced via gasification from short rotation poplar coppice.

The results show that for a production plant of 40 $t_{biomass}$/h, the total cost of the methanol production chain consists of 36% from the biomass, 17% from the biomass transport, 3% from the methanol transport, 1% from the methanol distribution, and 43% from the methanol production. The methanol cost for such a plant is estimated to be below 30 €/GJ, which corresponds to 0.50 €/$l_{methanol}$, or 1.0 €/$l_{gasoline\_equivalent}$.

Figure 11 shows the methanol cost geographically explicitly in a 3D representation for Baden-Württemberg. Four production plant sizes were selected. The cost of the methanol produced from each of them is calculated for each grid point of the area. Each point of the surface indicates the final methanol cost if a production plant were set up at that particular point. For a production plant of 20 $t_{biomass}$/h, the surface has two minimums, whereas for higher production plant capacities, the shape of the surface is flattening around these two minimums. Moreover the costs decrease from 0.47 €/l to 0.385 €/l as the plant capacity increases from 20 $t_{biomass}$/h to 100 $t_{biomass}$/h. This figure emphasizes the concept of economy of scale: as the production plant capacity increases, the methanol cost decreases.

The results of the sensitivity analysis show that the parameters that are the most sensitive to the methanol cost are the plant efficiency and the biomass cost. It is shown that an increase of the feedstock cost by 40% increases the methanol cost by 9%. Those figures can be compared to a recent study that showed that a change of the feedstock cost by 40% would increase the product cost by 5-12% [92].

In this article, the location and the size of the production plant have been set arbitrarily. An optimization model would avoid this step and would enable the selection of the optimal location of the production plant regarding feedstock availability, cost and productivity and fuel demand location. Article II introduces the optimization problem.

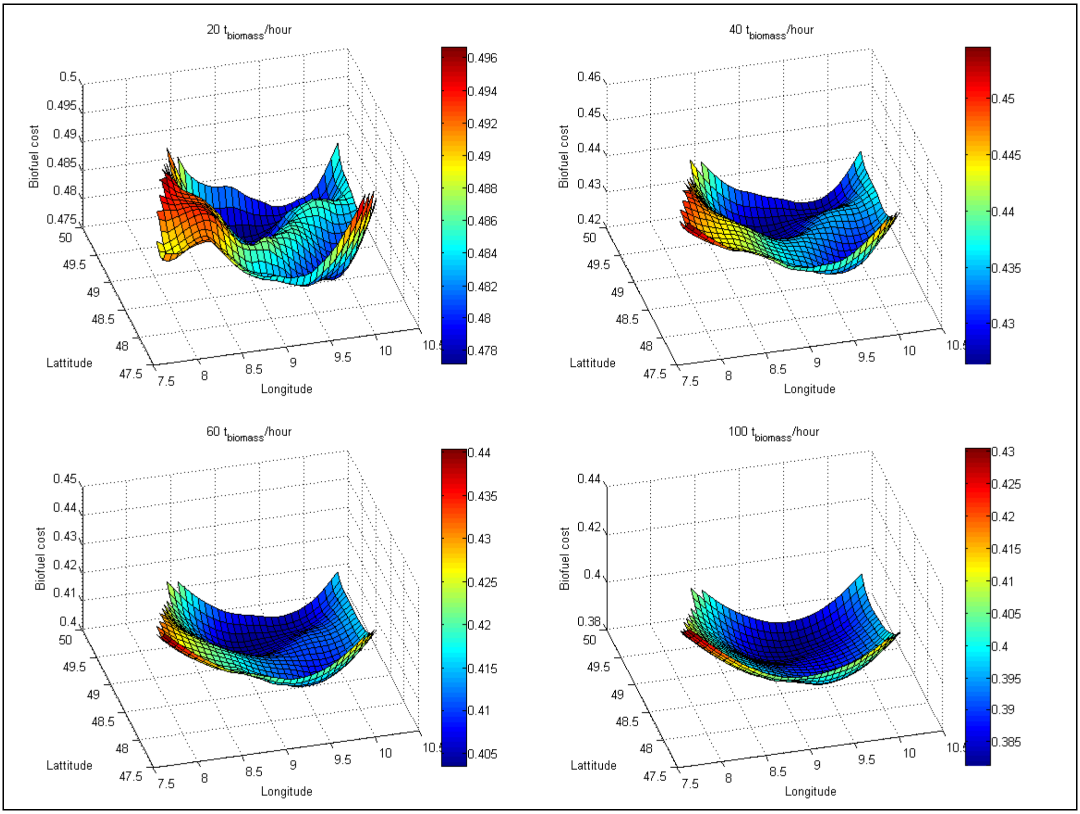

Figure 11: 3D representation of the economy of scale in the region of Baden-Württemberg for four production plant sizes. From left to right and top to down, the size of the production plants are 20, 40, 60 and 100 tons of biomass per hour. Each graph represent the methanol cost in €/$l_{methanol}$. Each point on the area represents the methanol cost from a production plant if it is set up at that particular point.

3.2. Article II

Methanol from gasification: a facility location problem

The first version of the optimization model is presented in this article. To meet the motor fuel demand the model optimizes the number, the location and the size of the biofuel production plants. For each plant selected the locations of the biomass supplied and the gas stations are optimally selected.

The main objective in this article is to optimize the location of a set of biofuel production plants to meet a fuel demand.

The feedstock, the biofuel technology and the studied area are the same as in article I. The locations of the actual gas stations are known, and from their fuel capacity the fuel demand have been estimated. The optimal locations and sizes of the methanol production plants have been determined for the studied area, and a sensitivity analysis on how crucial parameters influence the fuel cost has been made for this set of plants.

The results showed that six methanol production plants were needed to meet the fuel demand in Baden-Württemberg. Figure 12 presents an example of the results from the model. Figure 12 (left) shows an example of the distribution of the biomass per production plant. The production plants are represented by a star. Each of them is supplied in biomass from the delimited region. Figure 12 (right) shows in a similar way the distribution of the gas stations to where the biofuel will be delivered from each production plant. The plant capacities range from 40 to 80 $t_{biomass}$/h. The final methanol cost ranges from 20 to 30 €/GJ. Neither costs for blending with gasoline nor marginal profits are however included.

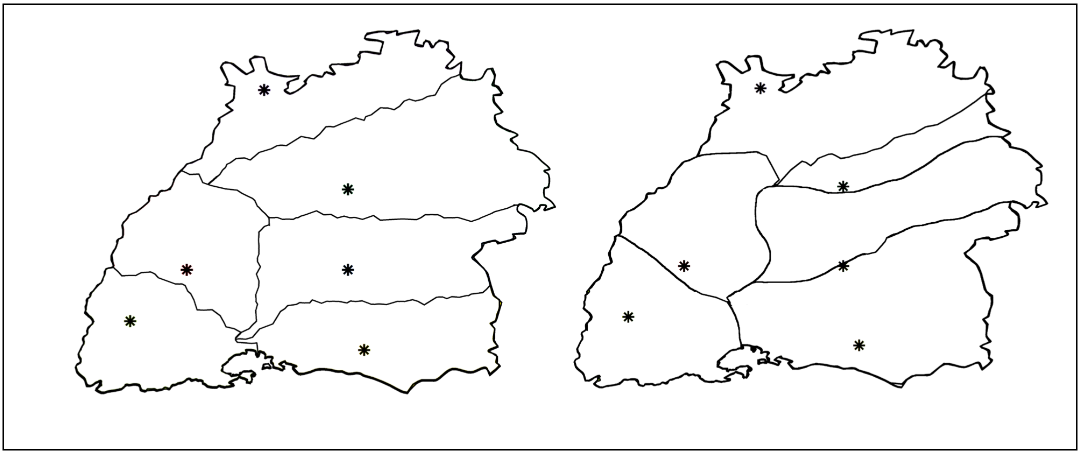

Figure 12: Baden-Württemberg. Left: Feedstock areas supplying each of the production plants symbolized by a star. Right: Biofuel distribution regions for each of the production plants.

The sensitivity analysis shows that the number of annual operational hours and the feedstock cost have a major impact on the competitiveness of a plant. A plant shutdown for one month would increase the total cost by more than 10%. A shutdown exceeding three months would mean that the methanol plant is no longer competitive. And an increase of the feedstock cost by 25% will change the optimal size of the plants significantly.

It is of great importance to consider the residual heat from the production plant which accounts for approximately 10% of the fuel input energy. Selling the residual heat to a district heating network will influence the methanol cost as well as the location of the plant. In Article III, the recovery of the residual heat for district heating purposes is included in the model.

3.3. Article III

Optimal location of wood gasification plants for methanol production with heat recovery

In this article the residual heat from the biofuel production plant is included in the model. The residual heat is assumed to be sold to an already existing district heating network. The biofuel is supplied at the least cost to the consumers. A complement from fossil fuel might be required if the amount of biofuel produced is not sufficient to meet the fuel demand or if the fossil fuel price is more attractive than that of biofuel, as illustrated in Figure 13.

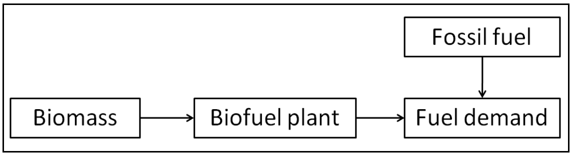

Figure 13: Supply chain of the model with fossil fuel.

The objective of this article is to take into account the utilization of the by-products such as the residual heat.

This article presents a case study for Austria where methanol is produced via gasification from short rotation forestry. Methanol is blended with gasoline and three blends are considered (M5, M10 and M20). The locations and sizes of the methanol production plants are determined by the optimization model. The locations of the gas stations are not known. Therefore the fuel demand is dependent on the consumption per inhabitant on a yearly basis. Knowing the number of inhabitants per city, the number of gas stations can be estimated.

A cost map is presented in Figure 14 for a M5 blend. This map shows the range of the methanol cost defined by the iso-lines, if produced at one particular point on the map. The pattern of the map would be similar for the other blends (M10 or M20). The land used for poplar plantation is located in the west part of Austria. The iso-line 0.4 €/$l_{methanol}$ follows the frontier delimited by the poplar plantations. The lower cost of methanol is then found within this frontier close to both high biomass production and high fuel demand. Two lower cost areas below 0.39 €/l can be identified, where at these places the biomass production is higher than in the rest of the country. Taking into account sales of the residual heat from the process, a decrease of the methanol cost by 12% can be expected if the heat can be sold at a price of 0.06 €/kWh.

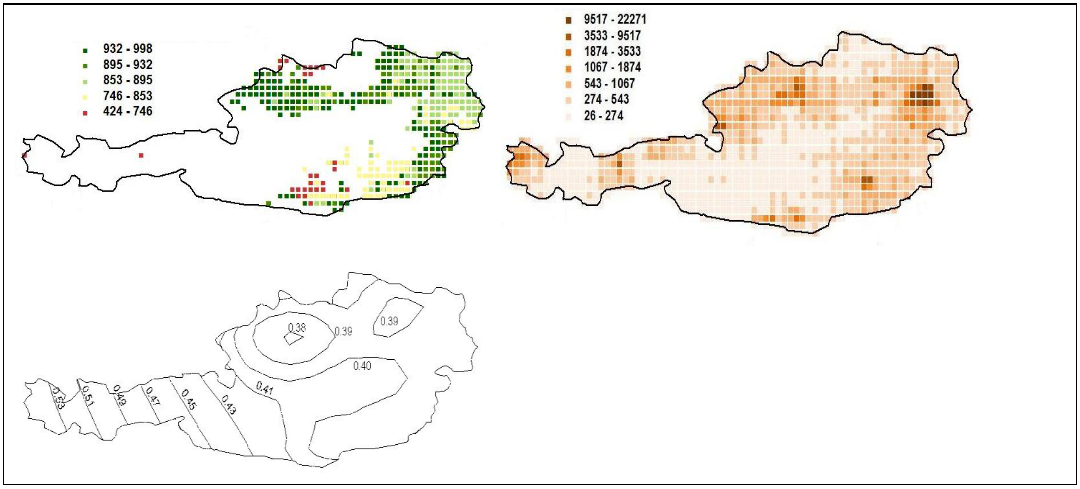

Figure 14: Austria. Top left: Potential production of poplar coppice in ton per grid cell per year. Top right: Number of inhabitants per grid cell. Bottom left: cost of methanol in €/$l_{methanol}$ regarding the position of a production plant of 846 $t_{biomass}$/day. The methanol-gasoline blend M5 is considered, but not the distribution of residual heat.

The effect of the residual heat on the biofuel cost was introduced in this article. As the heat sold influences the biofuel cost, the heat demand needs to be taken into account in order to analyze its impact on the production plant location. Moreover the biofuel demand might change over time as it is just coming into the market. The model thus needs to consider changes of the demand over time. Article IV tackles these issues, where the biofuel and the heat demand as well as the prices and the costs will be changing over a time period.

3.4. Article IV

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

Article IV introduces the model as time dependent. The time period studied is divided into several time steps of equal intervals. The biofuel and the heat demand are defined for each time step, as well as the biomass cost, the transport costs, and the selling heat price. The total cost of the supply chain is minimized over the whole time horizon studied. The model optimizes the location of the biofuel production plants. Moreover the year when the biofuel production plant should be set up is determined in order to get a biofuel cost as low as possible over the time period. The location of the biomass needed for the production plant is determined for each time step. And the same applies for the gas stations that will be supplied with biofuel. Figure 15 illustrates the new version of the model, where the heat demand is considered.

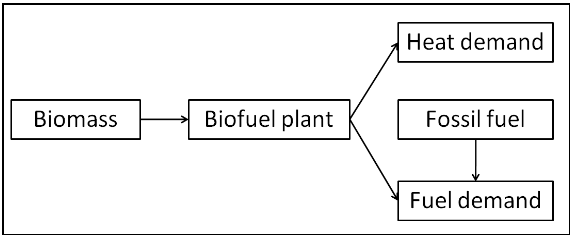

Figure 15: Supply chain of the model with heat demand.

The objective in this article is to integrate into the model a time period for the changes in biofuel and heat demand as well as the changes of prices and costs.

The County of Norrbotten in Sweden was chosen as a case study. Methanol is produced via gasification from forest wood. A time period of 20 years (2005-2025) with a five year time step is considered. The methanol can be delivered to the actual gas stations of the county and to the port of Luleå where exports are assumed to be possible. However, further transportation by boat from the port of Luleå is not covered in this article. The model optimizes the location for one plant only. Three different plant sizes were considered: 100, 200 or 400 MW (20, 40 or 80 $t_{biomass}$/h).

The results show that each plant is optimally located at different towns, where they can sell all the residual heat at the highest price. The 100 MW plant is indeed located where the heat price is higher, and the 400 MW plant where the heat price is lower. Changing the heat price for the location chosen from the 400 MW plant to a very low value would change the optimal location of this plant to a new position. In this new position, only 90% of the residual heat would be sold but at a higher price. The heat demand and the heat price are critical factors in the location of a methanol production plant.

The sensitivity analysis showed that the biomass cost has the greatest influence on the final methanol cost. An increase of the biomass price by 54% which is expected by the year 2025 [69, 70] would mean an increase of the methanol production cost by 21%.

This model was used for a time period defined over several years. As the heat demand also varies over a year, the same model can be applied to one year, where the time step can for example be defined as three months. Four time steps would then cover one year. This approach would cover the issues of the yearly biomass supply and storage which are not dealt with in this thesis.

The model is limited to the methanol production and does not include a full logistics network map for the transportation. In Article V the production of ligno-cellulosic ethanol is considered, and a full logistics network map for truck, train and boat transportation is presented.

3.5. Article V

Optimal location of ethanol ligno-cellulosic biorefineries with poly-generation in Sweden

This article considers the production of ligno-cellulosic ethanol. Ethanol is produced by means of fermentation and heat, electricity and biogas are the by-products. As presented earlier, the residual heat is delivered to the district heating network, whereas the electricity and the biogas are supposed to be sold at the production plant. As a complement to the fossil fuel, biofuel imports can also be added to the fuel demand. Figure 16 presents the new overview of the model. The biogas and the electricity demand are not represented as they anyhow provide an extra income to the production plant. Moreover a detailed network connection map is integrated in the model [93-95]. From each point of the grid, the distances to any other point by truck or the combinations truck-train or truck-train-boat are defined. A carbon tax on the emissions from the transports is also added to the total cost.

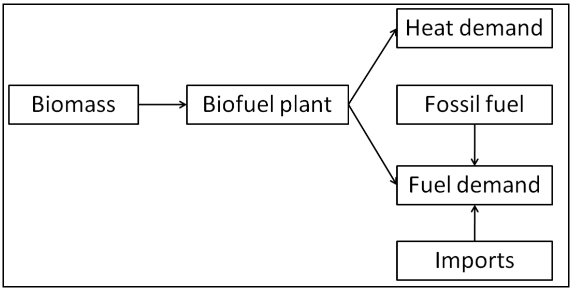

Figure 16: Supply chain of the model with biofuel imports.

The objectives of this article are to operate calculations on a large area, integrate biofuel imports and a carbon tax on the emissions from the transport sector.

Sweden is used as a case study; forestry wood is the feedstock and ethanol can be imported by boat from Brazil. The model is no longer dynamic due to high calculation time for this study area.

To enable the calculations on such a large study area, the data on the biomass and the demand location have to be aggregated into an adequate grid. For this case study, a half-degree grid was chosen. This would be equivalent to a grid size of about 50*50 km. It is assumed that the plant would be built in the center of the grid, where all the heat demand within the cell can be reached. The heat delivered on the district heating network can indeed be supplied on distances over 25 km. In the case of Sweden, such a grid provides 380 grid points. Each grid point provides information on the biomass availability and cost as well as the fuel demand. From the beginning of the problem each point is considered as a possible location for a biofuel production plant. It is anyhow possible to simplify the problem by omitting scarce biomass location areas and inexistent biofuel demand areas. As mentioned earlier, such a problem would be divided into three sub-problems. The optimal locations from the first three calculations would then be used as possible locations for a final optimization run.

The results show that the optimal locations are in towns with a range of about 50,000 to 140,000 inhabitants. The optimal size for each plant depends on the heat demand in the region where the plant is located. The by-products, electricity and biogas are assumed to be distributed without constraints; and therefore only the heat distribution to residential areas would have an impact on the location of the plant. Thus, in order to generate an income from heat produced for district heating, the plant is best located in populated areas.

If no ethanol is imported, the introduction of a carbon tax does not affect the production plant locations and the ethanol cost. The biomass is indeed transported from close areas to the plant at the least cost. If ethanol is imported, the introduction of a carbon tax in the transport sector would then increase the cost on the ethanol imports. The ethanol imports via boat from Brazil would then decrease which would be beneficial for the local ethanol production. A carbon tax would then favor the domestic production over overseas imports. A value of the carbon tax of 100 €/t_{CO2} has been shown to be significant for such changes to occur.

Parameters such as biomass cost, land availability, ethanol yield have also been analyzed. Looking at a set of plants and on an average for the entire country, an increase of the biomass cost by 20% can increase the final product cost by an average of 30%. Decreasing the land available by 80% would increase the ethanol cost by 70% and change the optimal location of three production plants out of six, compared to a baseline scenario. Reducing the ethanol yield gave the lowest ethanol production cost, which strongly points to the importance of utilizing the by-products of poly-generation rather than producing it separately.

In this case study, the model was run as a snap shot for the fuel demand in Sweden. The locations of the plants were determined by the heat demand and the heat price. It is expected that running the model on a time horizon would give different results than the static calculations if the heat demand areas are slightly similar (comparable prices and amount of heat requested) and change in different ways over time. To save high calculation time, the static model may then be used when the changes in the heat demand and the heat price are uniform over the area studied.

In the articles previously summarized, a share of the biomass was assumed to estimate the amount of biomass available. Assuming an even share of the biomass all over the studied area may lead to inaccuracy on both the amount and the location of the biomass available. A high concentration of forest industries in a certain region of the studied area may indeed lead to an exhaustive use of the biomass in this particular region. The location and the price of the biomass play a major role in the location of the production plant and the biofuel cost. Integrating other biomass based industries is then crucial for the accuracy of the results. Article VI presents such an approach to the problem.

3.6. Article VI

Potentials of bioenergy production within the Austrian forest market

This article integrates the forestry market into the model. In addition to the domestic biomass production, biomass can be imported and the residuals from the sawmills can be sold to the forest industries. The existing wood demand is represented by the existing pulp and paper mills, CHP plants, local district heating plants and personal wood consumption. The new bioenergy plants relate to possible biofuel production plants, CHP plants or smaller district heating plants. The model then integrates the competition for the biomass among the existing industries and the potential bioenergy plants. The bioenergy production plants also compete for the heat and power demand. Figure 17 illustrates this addition to the model. In the figure, the sawmills do not compete for the biomass, as it is assumed that the wood reserved for the sawmills has a higher diameter (>15cm) than the wood reserved for the industries like pulp and paper mills or energy plants. In this case either biofuel production plants or/and CHP plants or/and local district heating plants can be set up. A carbon tax is kept on the transport sector. In addition the carbon tax can be applied as a subsidy to the amount of mitigated fossil fuel emissions from the bioenergy production.

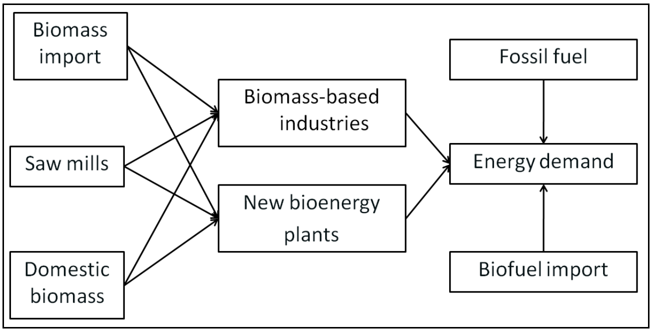

Figure 17: Latest version of the supply chain. The biomass is provided from a domestic production, the sawmill residues and the imports. The biomass-based industries and the potential bioenergy plants compete for the biomass and the energy demand. The energy demand comprises the transport fuel demand and the heat demand. Fossil fuel and imported biofuel compete for the transport fuel demand.

The objective in this article is to analyze how a carbon tax can affect the choice between setting up a biofuel production plant or a conventional heat and power production plant.

Austria was chosen as a case study, biomass imports from the boarder countries are possible but no biofuel imports are considered. The ethanol via fermentation is the technology chosen.

In this case study, a half-degree grid was used due to a huge amount of data from the biomass supply, the sawmills location, and the existing forest industries. This leads to a total amount of points equal to 320. A similar method as in Article V is applied to select the optimal production plant locations.

The commodities produced from the production plants replace fossil fuels in transportation, power generation and heat generation. The amount of GHG emissions offset by the bioenergy produced are estimated [96]. Figure 18 presents the expansion of the bioenergy production with increasing carbon price. For a carbon price below 140 €/t_{CO2}, conventional CHP plants are promoted over ethanol production. For a carbon tax higher than 140 €/t_{CO2}, ethanol plants would be more in demand. The reference technologies for heat and power production (the fuels currently consumed in heat and gas fired power generation) emit less GHG (55.4 t_{CO2}/TJ [97]) than the reference technology in transportation (78 t_{CO2}/TJ [97]). In addition, the energy produced per unit of biomass is higher for ethanol plants than for CHP although the total theoretical efficiency is better for CHP (90% for CHP, 84% for ethanol plant). This is due to the fact that CHP plants produce a high proportion of heat all year long. The heating demand for district heating is subject to significant demand variations and it is not possible to use the co-produced heat for other useful purposes during periods of low heat demand. Ethanol plants produce less heat per unit of biomass which reduces losses of heat due to demand constraints. The total emission saved ranges from 200,000 t_{CO2} for the zero emission price scenario up to 2.5 million t_{CO2} for a high emission price scenario. In the year 2007, the total emissions in Austria amounted to 88 million tons of CO_2 equivalent [98]. A limit of the energy production is reached at 40 PJ due to full feedstock consumption.

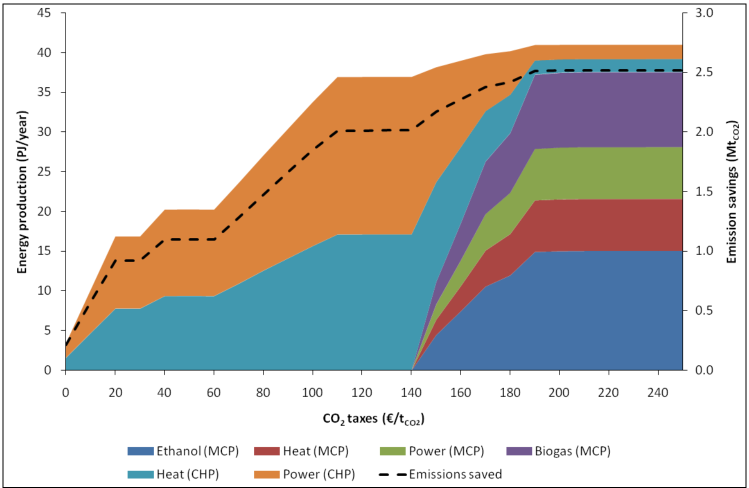

Figure 18: Diffusion of technologies and emission savings depending on CO_2 taxes (MCP stands for multi commodity plant).

This carbon price limit of 140 €/t_{CO2} (or 40 €/t_C) can be compared to the results from Grahn *et al.* [99]. They globally showed on a 60 year time frame that depending on the year, only heat production would be more beneficial with a carbon tax below 50-100 USD/t_C. Biofuel production can be most cost-effectively used for carbon taxes higher than this range.

4. Additional work

This section presents some additional calculations for a better overall understanding of the sensitivity of the parameters on the final biofuel cost and the production plant location. The model used is the one developed for Article V, since a full network map was used for that article. None of the following results have either been published or presented earlier.

4.1. Sensitivity analysis

A sensitivity analysis was carried out for the methanol and the ethanol costs for a fixed size of the production plant (40 $t_{biomass}$/h). The plant location also remains the same for the different parameters studied and forest wood is the raw material used. The influence on the biofuel cost by critical parameters such as process efficiency, the plant operational hours, the district heating price, the amount of biomass available for bioenergy purposes, the cost for transportation, biomass and the investment are the parameters that have been studied for both technologies. For the production of ethanol, the electricity price and the biogas price have been studied as well. The influence of each parameter is analyzed with a change by ± 20%, except for the ethanol efficiency for which the two efficiencies described in section 2.3 are considered. The results from the sensitivity analysis are presented in Figure 19.

For the methanol production, the parameters can be sorted into three groups. (1) The transportation cost, biomass availability and heat price have an influence on the methanol cost below 4%, (2) the biomass cost has an influence between 5-10%, (3) and the investment cost, the load hours and the plant efficiency have an influence between 15-25% on the methanol cost.

For the ethanol production, four groups can be formed. (1) The biogas price and the biomass availability change the ethanol cost by less than 10%, (2) the transportation cost by 15-20%, (3) the investment cost, the biomass cost, the plant load hours, the heat price and the electricity price have an influence of 25-40% and (4) when the ethanol efficiency is 12% lower, the ethanol cost decreases by 42%. It has to be considered that the production of both heat and electricity increases when the ethanol efficiency decreases by 12%.

Comparing both figures, the biofuel efficiency has in both processes the most influence on the final cost. The investment, the biomass availability and the load hours have the same influence on the biofuel cost. The heat price influences the ethanol cost more than the methanol cost: the amount of heat produced per quantity of biofuel produced is indeed four times higher in the ethanol production than in the methanol production.

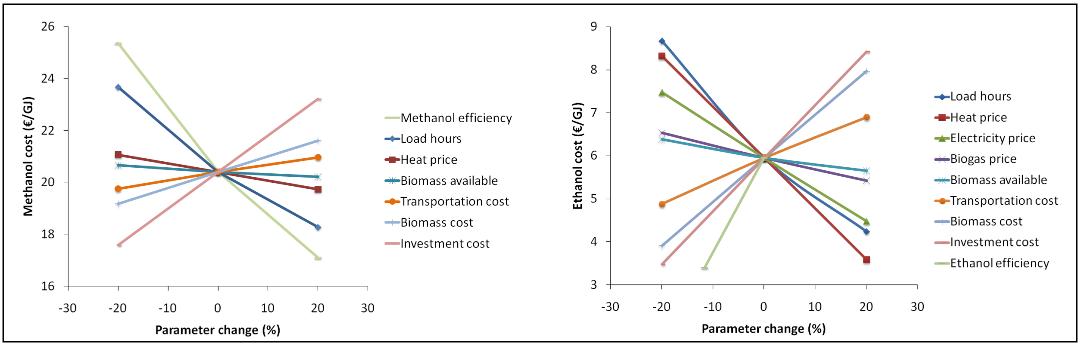

Figure 19: Sensitivity on the methanol (left) and ethanol (right) cost.

Transportation costs include biomass and biofuel transportation. For the ethanol production, the biofuel efficiency is lower than for the methanol production, therefore the ethanol cost is influenced more by the transportation cost for the biomass. The transportation cost influences the ethanol cost by more than 10%, whereas it influences the methanol cost by 7% for a production plant of the same capacity. For the same reason, the biomass cost has a similar effect on the ethanol and methanol costs.

4.2. Biofuel costs and emissions

In the following case, the ethanol cost and the emission offset are studied. Five parameters (the heat price, biomass cost, carbon tax, electricity price and ethanol import cost) have been varied between the limits presented in Table 17. The biomass cost and the heat price are compared with the values from Article V which are not uniform over the country. An increase of the biomass cost by 50% and a fluctuation of the heat cost by ± 20% are assumed. The value of each parameter varies between the ranges specified with a certain increment (Table 17). All possible combinations within the different values of the five parameters are then run. Each run optimizes the locations of the possible plants presented in Article V, and the costs and emission offset are derived.

Table 17: Parameter values for the analysis.

Parameter	Unit	Lower limit	Upper limit	Increment
Biomass cost	%	0	50	5
Carbon tax	€/t_{CO2}	0	200	100
Heat price	%	-20	20	5
Electricity price	€/MWh	50	80	5
Ethanol import cost	€/l	0.39	0.52	0.065

A set of points was obtained and sorted by carbon tax. From those sets, three outer boundaries have then been drawn (Figure 20). The costs represent the average cost all over the country. Only emission offsets from the ethanol produced in Sweden are considered in the calculations, and if no ethanol is produced, the offset is zero. When an emission offset of 2.5 Mt_{CO2} is reached, the domestic production reaches the demand set (36 PJ). When the emission offset decreases, the domestic production decreases because ethanol imports are more beneficial. Increasing the carbon tax raises the price of ethanol for the same emission offset level, which means that imports occur when the ethanol cost is higher. Increasing the carbon tax is then beneficial to local ethanol production. The interactions between the five parameters and the geographical results make the outer boundary non linear.

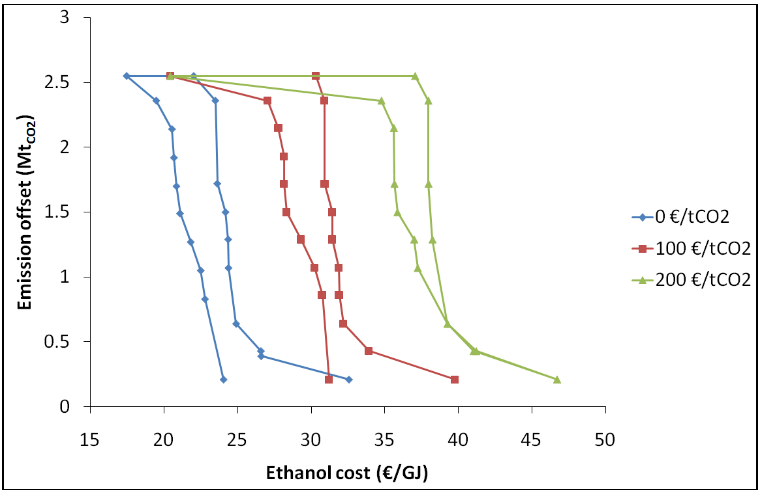

Figure 20: Outer boundaries for three carbon taxes. The values within the boundaries are possible values.

Such a boundary shows the efficient limit to costs and emissions that is possible to reach under a given set of circumstances. The values within the curve are possible values. In this case the optimal emission offset cannot be greater than 2.5 Mt_{CO2}. In other words solving the facility location problem can define the optimal potential to mitigate emissions at an optimal biofuel cost by considering international trade for a given area.

The sensitivity of those parameters on both the emission offset and the ethanol cost has been studied from the different runs. Alternatively, four parameters are fixed and the influence from the remaining parameter on the cost and the emission offset is analyzed. The parameters are fixed for the mean value of their range defined in Table 17. From each set of results, one can derive the ranges of costs and emission offsets defined as (Δ_{Cost} = $Cost_{max}$-$Cost_{min}$) and ($\Delta_{Emission\_Offset}$ = $Emission\_Offset_{max}$-$Emission\_Offset_{min}$) respectively for each parameter. Those results are presented in Figure 21. The more the value of Δ_{Cost} ($\Delta_{Emission\_Offset}$) is high, the more the parameter is sensible to the ethanol cost (emission offset). The biomass cost appears to be the most sensible parameters on the ethanol cost and the emission offset. The carbon tax and the heat price have a similar influence whereas the electricity price has less influence on both cost and emission offset. The import cost mainly influences the emission offset, indeed importing at a lower cost would not benefit local production and therefore affect the emission offset. In other words, those results show that the biomass cost plays a major role, and to face an increasing biomass cost, considering selling the residual heat and introducing a carbon tax may have a beneficial effect.

It has to be emphasized that those results are valid for the average values from the ranges defined in Table 17.

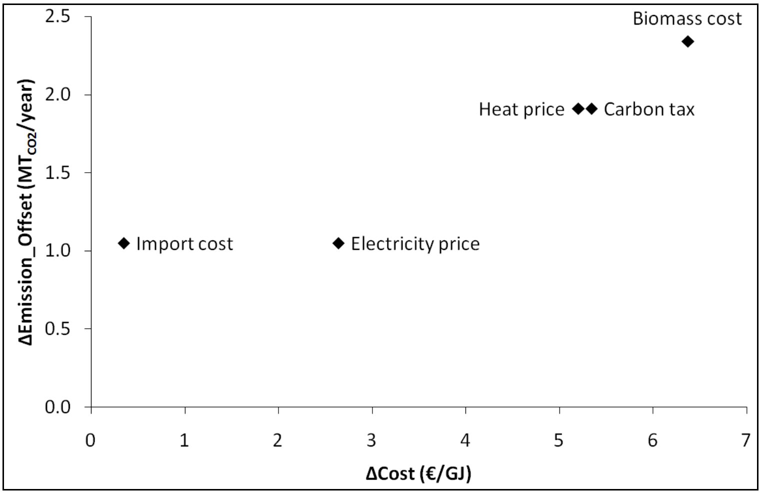

Figure 21: Parameter sensitivity.

4.3. Plant location

The costs of methanol and ethanol for a plant of 40 $t_{biomass}$/h over Sweden are geographically presented in Figure 22. The costs have been calculated for each grid point alternatively for this particular plant only. Comparing the two figures, one notices the major influence from the two technologies. The methanol and the ethanol cost figures have the same shape. Nevertheless, the methanol cost (which production of which has a 55% fuel efficiency) has less disparity than the ethanol cost. With a 29% fuel efficiency, the ethanol is much more sensitive to the heat price (23% efficiency), and therefore the locations closer to heat demand areas are more attractive. Regarding ethanol, Figure 22 can be compared to the figure from Article V. Anyhow, one has to consider that the article considered an optimal set of ethanol plant whereas Figure 22 considers one plant only, and imports are also not considered which explains the higher attraction towards Stockholm and Gothenburg, two major ethanol import ports in the article. Those results are valid for one particular biomass cost and heat price scenario outlined in Article V.

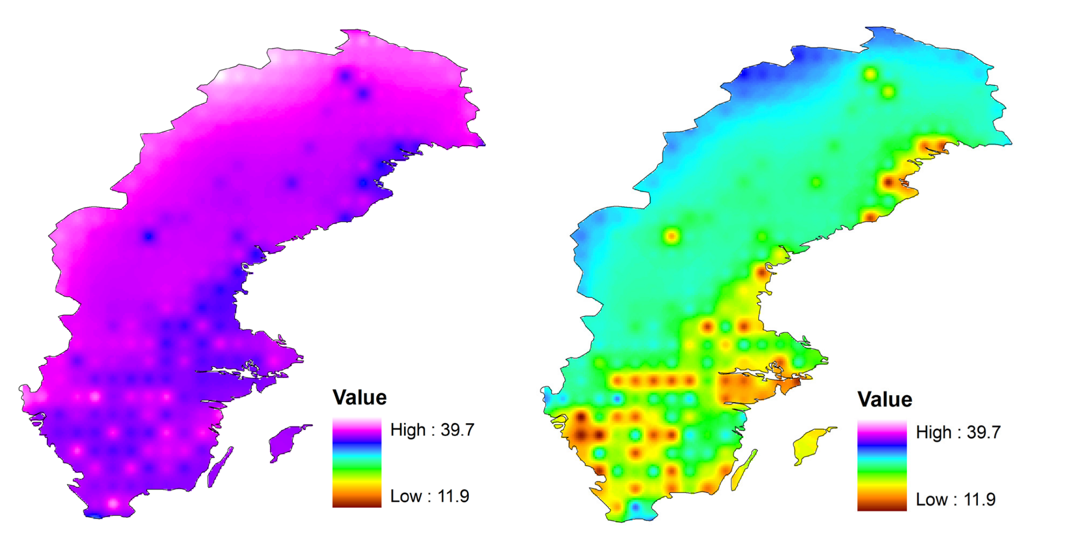

Figure 22: Methanol (left) and ethanol (right) cost in €/GJ for a 40 $t_{biomass}$/h plant in Sweden.

Ethanol via fermentation has a higher overall efficiency (84%) compared to methanol via gasification (65%). The yield for ethanol produced is anyhow lower (25%) than for methanol production (55%). Moreover the ethanol production plants are very dependent on their location in order to be able to sell the heat to the appropriate heat demand area. The heat demand can lower significantly due to insulation improvement, roof solar panels, lowering indoor temperature [100]. Opportunities exist to decrease the heat demand, and other alternatives than building new heat plants may be more profitable options. A biofuel oriented policy would rather be interested in methanol production; the location is indeed less dependent on the heat demand and less sensitive to the feedstock cost. Ethanol production would then be more adapted to an area where a larger amount and a wider portfolio of fossil fuel energy have to be replaced by renewable energy.

5. Conclusions

This thesis presents the development of an optimization model for the location of biofuel production plants. The production of two second generation biofuels has been considered, methanol production via gasification and ligno-cellulosic ethanol production via fermentation. The main results of this thesis are presented as follows.

- The model can determine a set of biofuel production plants, optimally located to fulfill a defined fuel demand. For each plant the corresponding biomass areas and gas stations supplied are optimally selected.
- The model provides an estimated biofuel (either methanol or ethanol in this study) cost at the gas stations for the studied area in regards with fuel competition.
- The model can handle calculation on the regional level as well as larger areas like the country level (like Sweden). On a large scale, a grid size of half a degree was used and found to be adequate in order not to lose information on the amount of heat sold to the district heating network.
- The by-products from the production plant can be used geographically explicitly in the model. The residual heat has been studied, and can be sold to the district heating network regarding the heat demand and the selling heat prices of the studied area.
- The fuel and the heat demand can vary over time as well as costs and prices. The model can be used dynamically over a chosen time period.
- The model can consider the location and capacity from the existing biomass based industries. The potential of the available biomass can thus be better estimated by integrating the competition for the biomass among these industries and the new bioenergy production plants. This gives more accuracy to the results.
- International trades are important factors for biofuel production planning. The model can consider the biofuel import if the location of origin of these imports to the studied area is known.
- Policy tools can be used to control the emissions. The model can consider setting a carbon tax on the emissions from the transports of the supply chain.
- The model can identify the optimal technology for a bioenergy production plant to be set up by considering a carbon price used as a subsidy on the mitigated fossil fuel emissions.

This model can be used for any kind of biomass based production plant, and feedstock as long as the input data is available. As geographical energy planning is important, the developed model may be a valuable tool for decision makers in order to determine the most suitable strategy regarding locations of new biofuel production plants.

6. Future Work

Process integration studies the design and optimization of the process of a production plant where the aim is to get the highest energy output from the raw material. Such a process is essential to reach an optimal economic system before the set up of a new production plant or integrating a new unit in an existing plant. If the cost and the origin of the raw material play an important role for the cost of the final product, the model developed in this study would then be an important tool for the analysis in the process integration. Such a combination would then enhance the value of the analysis.

Black liquor from the pulp and paper mills can be used for methanol or DME production via gasification. For Sweden the annual production of black liquor is around 40 TWh. The biofuel production via black liquor gasification could supply 30% of the Swedish road fuel consumption [101]. The biofuel potential from these mills is significant. It would then be of interest to implement into the model the combination between the biofuel potential from the pulp and paper mills with the possible biofuel production plants. This would provide a better picture of the geography of the future biofuel production plants and the biofuel potential of the studied area.

Introducing new feedstocks such as household wastes is also an important task. Local incineration plants usually face low public acceptance [102]. Emphasizing the cost benefit of the optimal location for bioenergy production plant would help facing this issue. In this case it would be of interest to build a model for Europe and study emissions savings of carbon dioxide and methane as well as the consequences on a continental level.

In the present study, the model is dependent on the demand based on the consumption statistics for the area studied. A certain amount of the demand is met regarding the amount of biomass available. One way to develop the model would be to create an endogenous demand driven by a cost curve function. Depending on the cost of the biofuel produced, the demand would either increase or decrease on a time horizon.

A further task of importance is to study the interaction of the parameters with a more detailed method. Uncertainties inherent to input parameters should be modeled by applying a Monte Carlo analysis, where the results are not single values but probability distributions. Such a study is actually ongoing and was not completed at the time of the revision of the thesis.

Depending on the heat price and the biomass cost, the plant should optimally be closer to heat demand areas, which means closer to inhabited areas. Considering the biomass transportation, the number of trucks coming and leaving a production plant is growing in relation with its capacity. For instance a production plant of 80 $t_{biomass}/h$ would need four trucks fully loaded every hour (with a loading capacity of 20 tons and 8 hours working day), or one truck every 8 minutes passing one point either empty or fully loaded. The position of such plants close to communities will then affect the local traffic consistently, and such a heavy traffic may face poor public acceptance (road damage, noise perturbation, pollutant emissions from the wood supply, etc.) [50]. A particular plant location would be an economic benefit for the surrounding communities such as lower biofuel cost or available heat from renewable energy. Such benefits may play a positive influence on the local public acceptance as pointed out by Zoellner *et al.* [103]. The public acceptance was not covered in this thesis and should be considered in parallel for practical application.

7. References

[1] Bernstein L, Bosch P, Osvaldo C. Climate Change 2007: Synthesis Report. Summary for Policymakers, an Assessment of the Intergovernmental Panel on Climate Change. (2009).

[2] European Environment Agency. Annual European Community Greenhouse Gas Inventory 1990–2006 and Inventory Report 2008 - Submission to the Unfccc Secretariat. European Commission, DG Environment. Brussels: (2008).

[3] Barker T, Bashmakov I, Bernstein L, Bogner JE, Bosch PR, Dave R, et al. Technical Summary. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer, ed, Cambridge University Press, Cambridge, United Kingdom, New York, NY, USA.: (2007).

[4] IEA. International Energy Agency, Key World Energy Statistics. Paris: (2008).

[5] CEU-Council of the European Union. Luxembourg, 1996.

[6] Meinshausen M. On the Risk of Overshooting 2°C. International Symposium on Stabilisation of Greenhouse Gases, Exceter, 2005.

[7] Keeling CD, Whorf TP. Atmospheric CO2 Records from Sites in the SIO Air Sampling Network. Trends: A Compendium of Data on Global Change: Carbon Dioxide Information Analysis Center, Oak Ridge, Oak Ridge National Laboratory, 2005.

[8] Marland G, Boden TA, Andres RJ. Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A., 2007.

[9] UNFCCC. Kyoto Protocol, Reference Manual, on Accounting of Emissions and Assigned Amount. United Nations Framework Convention on Climate Change. (2008).

[10] Energy Information Administration, Official Energy Statistics from the US Government. International Energy Statistics. www.eia.doe.gov, [06-02-2009], 2009.

[11] European Environment Agency. Indicator: En01 Energy Related Greenhouse Gas Emissions [2008.11]. www.eea.europa.eu/themes, [05-02-2009], 2009.

[12] EU. Communication from the Commission - an EU Strategy for Biofuels. SEC(2006) 142: Commission of the European Communities ed, Brussels: (2006).

[13] EU. Proposal for a Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources. {COM(2008) 30 final} {SEC(2008) 57} SEC(2008) 85: Commission of the European Communities ed, Brussels: (2008).

[14] IEA/OECD. From 1st-to-2nd-Generation Biofuel Technologies, an Overview of Current Industry and RD&D Activities. International Energy Agency. Paris, France: (2008).

[15] Biodiesel 2020: A Global Market Survey, Feedstock Trends and Forecasts. (2008).

[16] F.O. Licht's World Ethanol & Biofuels Report. 3. (2007).

[17] Aeck M. Biofuel Use Growing Rapidly, Vital Signs 2005. Worldwatch Institute. Washington, DC: (2005).

[18] Goldemberg J, Guardabassi P. Are Biofuels a Feasible Option? Energy Policy 37 (2009) 10-14.

[19] De La Torre Ugarte D, He L. Is the Expansion of Biofuels at Odds with the Food Security of Developing Countries? Biofuels, Bioproducts and Biorefining 1 (2007) 92-102.

[20] Mathews JA. Opinion: Is Growing Biofuel Crops a Crime against Humanity? Biofuels, Bioproducts and Biorefining 2 (2008) 97-99.

[21] Kenneth G. Cassman AJL. Food and Fuel for All: Realistic or Foolish? Biofuels, Bioproducts and Biorefining 1 (2007) 18-23.

[22] Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels. Proceedings of the National Academy of Sciences 103 (2006) 11206–11210.

[23] Scharlemann JPW, Laurance WF. How Green Are Biofuels? Science 319 (2008) 43-44.

[24] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land Clearing and the Biofuel Carbon Debt. Science 319 (2008) 1235-1238.

[25] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change. Science 319 (2008) 1238-1240.

[26] Laurance WF. Switch to Corn Promotes Amazon Deforestation. Science 318 (2007).

[27] Koh LP, Ghazoul J. Biofuels, Biodiversity, and People: Understanding the Conflicts and Finding Opportunities. Biological Conservation 141 (2008) 2450-2460.

[28] Khan S, Hanjra MA, Mu J. Water Management and Crop Production for Food Security in China: A Review. Agricultural Water Management 96 (2009) 349-360.

[29] Righelato R, Spracklen DV. Carbon Mitigation by Biofuels or by Saving and Restoring Forests? Science 317 (2007) 902.

[30] (PPRC) TPNPPRC. Alternative Fuels for Fleet Vehicles. www.pprc.org/pubs/altfuels.cfm, [15-07-2006], 2006.

[31] Ogden J, Steinbugler M, Kreutz T. A Comparison of Hydrogen, Methanol and Gasoline as Fuels for Fuel Cell Vehicles. Journal of Power Sources 79 (1999) 142-168.

[32] Ahlvik P, Brandberg A. Well-to Wheel Efficiency for Alternative Fuels from Natural Gas or Biomass. Swedish National Road Administration. Borlänge: (2001).

[33] Knoef HAM. Practical Aspects of Biomass Gasification. In: Knoef H.A.M., editor, Handbook Biomass Gasification, BTG biomass technology group B.V., Netherlands, 2005, p. 13-37.

[34] Knoef HAM. Feedstock and Fuel Feeding. In: Knoef H.A.M., editor, Handbook Biomass Gasification, BTG biomass technology group B.V., Netherlands, 2005, p. 181-188.

[35] Knoef HAM. Update on Gas Cleaning Technologies. In: Knoef H.A.M., editor, Handbook Biomass Gasification, BTG biomass technology group B.V., Netherlands, 2005, p. 189-210.

[36] Katofsky RE. The Production of Fluid Fuels from Biomass. The Production of Fluid Fuels from Biomass (1993).

[37] Hamelinck CN, Faaij APC. Future Prospects for Production of Methanol and Hydrogen from Biomass. Journal of Power Sources 111 (2002) 1-22.

[38] Enecon PL. Wood for Alcohol Fuels: Status of Technology and Cost/Benefit Analysis of Farm Forestry for Bioenergy. Canberra: (2003).

[39] Wahlund B, Yan J, Westermark M. Increasing Biomass Utilisation in Energy Systems: A Comparative Study of CO2 Reduction and Cost for Different Bioenergy Processing Options. Biomass and Bioenergy 26 (2004) 531-544.

[40] Hamelinck CN, Van Hooijdonk G, Faaij APC. Ethanol from Lignocellulosic Biomass: Techno-Economic Performance in Short-, Middle- and Long-Term. Biomass and Bioenergy 28 (2005) 384-410.

[41] Shleser R. Ethanol Production in Hawaii. Final Report (1994).

[42] SEKAB. Towards Sustainable Transport. www.sekab.com, [20-04-2009], 2009.

[43] Starfelt F, Thorin E, Dotzauer E, Yan J. Performance Evaluation of Adding Ethanol Production into an Existing Combined Heat and Power Plant. Bioresource technology (2009).

[44] Enerkem. www.enerkem.com, [25-04-2009], 2009.

[45] Faaij A. Modern Biomass Conversion Technologies. Mitigation and Adaptation Strategies for Global Change 11 (2006) 343-375.

[46] van Ree R, Annevelink B. Status Report Biorefinery 2007. SenterNovem. Wageningen, Netherlands: (2007).

[47] Panda Ethanol, Inc. www.pandaethanol.com, [13-04-2009], 2009.

[48] Pacific Ethanol, Inc. www.pacificethanol.net, [13-04-2009], 2009.

[49] Madlener R, Vögtli S. Diffusion of Bioenergy in Urban Areas: A Socio-Economic Analysis of the Swiss Wood-Fired Cogeneration Plant in Basel. Biomass and Bioenergy 32 (2008) 815-828.

[50] Upreti BR, van der Horst D. National Renewable Energy Policy and Local Opposition in the UK: The Failed Development of a Biomass Electricity Plant. Biomass and Bioenergy 26 (2004) 61-69.

[51] Sperling D. An Analytical Framework for Siting and Sizing Biomass Fuel Plants. Energy 9 (1984) 1033-1040.

[52] Nguyen MH, Prince RGH. A Simple Rule for Bioenergy Conversion Plant Size Optimisation: Bioethanol from Sugar Cane and Sweet Sorghum. Biomass and Bioenergy 10 (1996) 361-365.

[53] Panichelli L, Gnansounou E. GIS-Based Approach for Defining Bioenergy Facilities Location: A Case Study in Northern Spain Based on Marginal Delivery Costs and Resources Competition between Facilities. Biomass and Bioenergy 32 (2008) 289-300.

[54] Perpiñá C, Alfonso D, Pérez-Navarro A, Peñalvo E, Vargas C, Cárdenas R. Methodology Based on Geographic Information Systems for Biomass Logistics and Transport Optimisation. Renewable Energy 34 (2009) 555-565.

[55] Shi X, Elmore A, Li X, Gorence NJ, Jin H, Zhang X, et al. Using Spatial Information Technologies to Select Sites for Biomass Power Plants: A Case Study in Guangdong Province, China. Biomass and Bioenergy 32 (2008) 35-43.

[56] Bernotat K, Sandberg T. Biomass Fired Small-Scale CHP in Sweden and the Baltic States: A Case Study on the Potential of Clustered Dwellings. Biomass and Bioenergy 27 (2004) 521-530.

[57] Rentizelas AA, Tatsiopoulos IP, Tolis A. An Optimization Model for Multi-Biomass Tri-Generation Energy Supply. Biomass and Bioenergy (2008).

[58] Dunnett A, Adjiman C, Shah N. A Spatially Explicit Whole-System Model of the Lignocellulosic Bioethanol Supply Chain: An Assessment of Decentralised Processing Potential. Biotechnology for Biofuels 1 (2008).

[59] Carlsson D, Rönnqvist M. Supply Chain Management in Forestry - Case Studies at Södra Cell AB. European Journal of Operational Research 163 (2005) 589-616.

[60] Bredström D, Lundgren JT, Rönnqvist M, Carlsson D, Mason A. Supply Chain Optimization in the Pulp Mill Industry - Ip Models, Column Generation and Novel Constraint Branches. European Journal of Operational Research 156 (2004) 2-22.

[61] Gunnarsson H, Rönnqvist M. Solving a Multi-Period Supply Chain Problem for a Pulp Company Using Heuristics-an Application to Södra Cell AB. International Journal of Production Economics 116 (2008) 75-94.

[62] Gunnarsson H, Rönnqvist M, Carlsson D. A Combined Terminal Location and Ship Routing Problem. Journal of the Operational Research Society 57 (2006) 928-938.

[63] Gunnarsson H, Rönnqvist M, Carlsson D. Integrated Production and Distribution Planning for Södra Cell AB. Journal of Mathematical Modelling and Algorithms 6 (2007) 25-45.

[64] Organisation for Economic Co-Operation and Development. www.oecd.org, [13-02-2009], 2009.

[65] Eurostat. ec.europa.eu/dgs/eurostat, [01-04-2009], 2009.

[66] Rosillo-Calle F, Groot Pd, Hemstock SL. Assessment Methods for Woody Biomass Supply. In: Rosillo-Calle F., editor, The Biomass Assessment Handbook, Bioenergy for a Sustainable Environment, London, UK, Earthscan, 2007, p. 69-109.

[67] Ebner G. Außenhandel Nahm Nadelschnittholz-Mehrproduktion Ab. Holzkurier 13 (2008).

[68] Rebernig C. Österreichisches Holz-Jahrbuch 2006. avBUCH im Österreichischen Agrarverlg (2005).

[69] Långsiktsprognos 2006 - Enligt Det Nationella Systemet För Klimatrapportering (in Swedish). The Swedish Energy Agency. (2007).

[70] Schönhart M. Profitability of Short Rotation Forestry in Austria. International Institute for Applied Systems Analysis (IIASA). Laxenburg, Austria: (2008).

[71] Ebner G. External Trade Bought Overproduction of Coniferous Saw Wood. (Außenhandel Nahm Nadelschnittholz-Mehrproduktion Ab). Holzkurier 13 (2008) 3-8.

[72] Kuneth G. Monthly Price Statistics of Wood Carinthia (Monatliche Holzpreisstatistik Kärnten). Landwirtschaftskammer Kärnten. (2008).

[73] Hagauer D, Lang B, Nemestothy K. Woodflow Austria 2005. Vienna, Austrian Energy Agency 2007.

[74] Hamelinck C, van Hooijdonk G, Faaij A. Prospects for Ethanol from Lignocellulosic Biomass: Techno-Economic Performance as Development Progresses, Utrecht University, Copernicus Institute, Science Technology Society, 2003.

[75] Craig K, Mann M. Cost and Performance Analysis of Biomass-Based Integrated Gasification Combined-Cycle (Bigcc) Power Systems. NREL/TP-43021657 UC Category: 1311-DE96013105 (1996).

[76] Parsons E, Shelton W, Lyons J. Advanced Fossil Power Systems Comparison Study. NETL USDOE Final Report (2002).

[77] Wahlund B. Rational Bioenergy Utilisation in Energy Systems and Impacts on Co2emissions. KTH, Chemical and Engineering and Technology, Stockholm, KTH, 2003.

[78] Dornburg V, Faaij APC. Efficiency and Economy of Wood-Fired Biomass Energy Systems in Relation to Scale Regarding Heat and Power Generation Using Combustion and Gasification Technologies. Biomass and Bioenergy 21 (2001) 91-108.

[79] Nilsholgersson. The Rate Survey "Nils Holgersson" (in Swedish: Avgiftsundersökningen "Nils Holgersson"). www.nilsholgersson.nu, [14-02-2008], 2008.

[80] Nordpool. Nordpool Electricity Spot Market. www.nordpool.com, [15-02-2008], 2008.

[81] Kärrman E, Olofsson M, Persson B, Sander A, Aberg H. Food Waste Disposers – a Technical Solution for Sustainable Resource Management? A Pre-Study in Gothenburg (in Swedish: Köksavfallskvarnar – En Teknik För Uthållig Resursanvändning? En Förstudie I Göteborg). VA-Forsk. (2001).

[82] Methanol Refueling Station Costs. Technical report, EA Engineering, Science and Technology Inc.: Silver Spring, MD, February Prepared for the American Methanol Foundation. (1999).

[83] Börjesson P, Gustavsson L. Regional Production and Utilization of Biomass in Sweden. Energy 21 (1996) 747-764.

[84] Kühmaier M, Kanzian C, Holzleitner F, Stampfer K. Wertschöpfungskette Waldhackgut, Optimierung Von Ernte, Transport Und Logistik (in German). Institute of Forest Engineering, University of Natural Resources. Vienna: (2007).

[85] Mårtensson L. Emissions from Volvo's Trucks. Volvo Truck Corporation. (2006).

[86] Heller MC, Keoleian GA, Mann MK, Volk TA. Life Cycle Energy and Environmental Benefits of Generating Electricity from Willow Biomass. Renewable Energy 29 (2004) 1023-1042.

[87] Overend RP. The Average Haul Distance and Transportation Work Factors for Biomass Delivered to a Central Plant. Biomass 2 (1982) 75-79.

[88] NTM. The Network for Transport and Environment. www.ntm.a.se, [20-02-2008], 2008.

[89] Wolsey L. Integer Programming, Wiley-Interscience New York, NY, USA, 1998.

[90] McCarl BA, Meeraus A, Eijk Pvd, Bussieck M, Dirkse S, Steacy P. Mccarl Expanded Gams User Guide Version 22.9. GAMS Development Corporation. (2008).

[91] ESRI. www.esri.com/software/arcgis/arcinfo/index.html, [03-05-2009], 2009.

[92] Piccolo C, Bezzo F. A Techno-Economic Comparison between Two Technologies for Bioethanol Production from Lignocellulose. Biomass and Bioenergy 33 (2009) 478-491.

[93] ESRI. www.esri.com, [20-02-2008], 2008.

[94] General Dynamics Advanced Information Systems. www.gd-ais.com, [20-02-2008], 2008.

[95] Digital Chart of the World Data Server. www.maproom.psu.edu/dcw, [02-20-2008], 2008.

[96] Wieser M, Poupa S, Hrabal A, Wappel D, Lichtblau G, Ortner R, et al. Austria's National Inventory Report 2003. umweltbundesamt. Vienna: (2003).

[97] Anderl M, Freudenschuß A, Kampel E, Köther T, Muik B, Poupa S, et al. Austria's National Inventory Report 2007 Submission under the United Nations Framework Convention on Climate Change. Umweltbundesamt. Umweltbundesamt GmbH ed, Vienna: (2007).

[98] Umweltbundesamt, Greenhouse Gases. www.umweltbundesamt.at, [19-02-2009], 2009.

[99] Grahn M, Azar C, Lindgren K, Berndes G, Gielen D. Biomass for Heat or as Transportation Fuel? A Comparison between Two Model-Based Studies. Biomass and Bioenergy 31 (2007) 747-758.

[100] Akpan IE, Sasaki M, Endoh N. Optimization of Domestic-Size Renewable Energy System Designs Suitable for Cold Climate Regions. JSME International Journal, Series B: Fluids and Thermal Engineering 49 (2007) 1241-1252.

[101] Mistra. Svartlutsförgasning. www.mistra.org, [05-02-2009], 2009.

[102] Joos W, Carabias V, Winistoerfer H, Stuecheli A. Social Aspects of Public Waste Management in Switzerland. Waste Management 19 (1999) 417-425.

[103] Zoellner J, Schweizer-Ries P, Wemheuer C. Public Acceptance of Renewable Energies: Results from Case Studies in Germany. Energy Policy 36 (2008) 4136-4141.

Article I

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BIOMASS AND BIOENERGY 33 (2009) 745–751

Available at www.sciencedirect.com

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Review

Methanol production by gasification using a geographically explicit model

Sylvain Leduc[a,b,*], *Erwin Schmid*[c], *Michael Obersteiner*[b], *Keywan Riahi*[b]

[a]*Division of Energy Engineering, Luleå University of Technology, SE-97187 Luleå, Sweden*
[b]*International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria*
[c]*University of Natural Resources and Applied Life Sciences (BOKU), A-1180 Vienna, Austria*

ARTICLE INFO

Article history:
Received 21 August 2007
Received in revised form
7 November 2008
Accepted 22 December 2008
Published online 25 January 2009

Keywords:
Poplar
Methanol
Gasification
Economic analysis
Bioenergy
Spatial modeling

ABSTRACT

Methanol mixed with 15% gasoline appears to be a viable alternative energy source for the transportation sector. Produced from gasification of certified wood coming from well-managed forests, its production could be considered as sustainable and the well-to-wheel emissions can be reduced significantly. The physical flows of the entire bio-energy chain consisting of harvesting, biomass transportation, methanol production by gasification, methanol transportation, and methanol distribution to the consumers are assessed and costs are estimated for each part of the chain. A transportation model has been constructed to estimate the logistic demands of biomass supply to the processing plant and to the supply of gas station. The analysis was carried out on a case study for the geography of Baden-Württemberg, Germany. It has been found that a typical optimal size for methanol production of some 130,000 m^3, supplies about 100 gas stations, and the biomass supply requires on average 22,000 ha of short-rotational poplar, with an average transportation distance of biomass of some 50 km to the methanol processing plant. The methanol production costs appear to be most sensitive with respect to methanol plant efficiency, wood cost, and operating hours of the plant. In an area where biomass is spread heterogeneously, apart from the demand, the geographical position of the plant would appear to have a major impact on the final biofuel cost.

1. Introduction

1.1. Background

Methanol is the simplest form of alcohol and has the chemical formula CH_3OH. It can be produced chemically from both biomass and fossil fuels. Today, 90% of methanol produced originates from natural gas [1] and represents 37.5 million tones methanol per year [2]. Methanol is suitable as transportation fuel, chemical building block, or as solvent. When used in the transportation sector, methanol can be used either in compression ignited (CI) engines or in fuel cells. For CI engines, it has become a popular choice especially for the Indy cars for its high octane (102) and safety characteristics. Mixed with 15% gasoline (M-85), it can be used for the regular car fleet. This would though require minor modifications on the engines leading to significant environmental benefits due to the reduction of reactive emissions [3] compared to CI engines.

* *Corresponding author*. International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria. Tel.: +43 2236 807 267; fax: +43 2236 807 599.
E-mail address: leduc@iiasa.ac.at (S. Leduc).
0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2008.12.008

Concerning fuel cells, methanol may play an important role since it is easier to transport and store than hydrogen [1].

Ahlvik and Brandberg [4] showed that methanol was the fuel that has the highest system efficiency of all liquid fuels from biomass. Methanol is liquid at normal environmental conditions, which makes it easy to handle compared to hydrogen or dimethyl ether (DME). Regarding greenhouse gas (GHG) reduction potentials, biomass-based fuels can have a magnitude of 80–90% [4]. Wahlund et al. [5] compared different alternatives for motor fuels, and concluded that methanol, ethanol or DME appears to give about the same CO_2 reduction. However, when the heat can be used, methanol and DME production give somewhat higher CO_2 reduction than ethanol production.

1.2. *Objectives*

The aim of this study is to analyze the cost of biomass-based methanol on a geographic region and its sensibility to different parameters. Thus the supply chain of biomass-based methanol production and distribution is analyzed. This chain includes biomass harvesting, biomass transportation to the plant, methanol production, methanol transportation to the gas station, and handling of methanol at the gas station. Each system of the supply chain is studied separately and costs are estimated in a consistent manner. This supply chain is applied explicitly to the geographic region of Baden-Württemberg, Germany. A sensitivity analysis is carried out to analyze the most influential parameters of the chain. This analysis is carried out with a factorial design allowing an interpretation of the importance of each parameter in the final methanol cost. This study is mainly built on the energy chain described by Sørensen [7], and the economic data on the methanol production presented by Hamelinck and Faaij [8]. Unless other studies [6] this analysis is based on geographically explicit data, allowing the costs to be closer to expectation. This study would be an introduction tool for geographically explicit energy planning for policy makers.

2. The methanol chain

2.1. *Biomass production*

A methanol processing plant can be supplied by biomass from woody species. Short-rotational poplar coppice provides high potentials for producing biomass in an environmentally benign manner and at relatively low unit costs [9]. In the case of Baden-Württemberg, biomass production of a short-rotational poplar coppice system has been modeled by Schmid et al. [10], using the latest version of the bio-physical process model EPIC [11]. The poplar coppice system is fertilized with nitrogen only in the first two years of each rotation period. Biomass is harvested every six years over a rotation period of 30 years. It is assumed that poplar coppice is planted only on agricultural lands with decent slopes (<5%), because of large harvesting machines to keep harvesting costs per unit competitive. The results on the yields per annum from Schmid et al. [10] have been used in this study.

Although biomass production costs depend on inter alia plant species, type of production system, and land type, the biomass price may have a different value regarding the size of the plant, but as no data were specifically available, a biomass market price was assumed to be constant and equal to 30 € m^{-3} for the average set-up [9]. The biomass price depends mainly on the long-term contracts a plant can sign with its supplier. We further assume that the biomass is provided by only short-rotation poplar coppice, and the harvest losses are 25%.

2.2. *Biomass transportation*

The cost of biomass transportation (in € TJ^{-1}) is described by Börjesson and Gustavson [12], and represented by equations (1) and (2), for tractor-trailer and truck transportation systems, respectively. Although these estimations are from 1996, they are still valid 10 years later, with consideration of a 7% consumption improvement, and 35% consumption increase due to regular stops during transportation [13].

$$C_{\text{Tractor}} = 226 + 12.78d \tag{1}$$

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

The actual distance (in km) to the methanol plant, d, is defined as the direct distance multiplied by the ratio of actual road length to direct distance. These values correspond to the transportation costs when biomass is extracted from the surrounding areas. The ratio of actual road length to direct distance can be between 1 (straight and flat roads) and 3 (mountainous landscape). For Baden-Württemberg, an average value for d of 1.6 has been found.

Under these conditions, a tractor-trailer system is typically the most cost efficient way of transportation up to a distance of 25 km. For longer distances truck transportation becomes cost efficient. Although train and ship are more cost efficient for distances above 50 km, only tractor and truck transportation systems are considered in this study as average transportation distances for plant supply are hardly much longer.

2.3. *Methanol production*

Methanol is assumed to be produced from biomass via gasification. The methanol production facilities typically consist of the following units: Pretreatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift reaction to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification [8]. The unconverted gases can be used in a gas turbine or boiler and a steam turbine resulting in heat and electricity co-production.

According to Hamelinck and Faaij [8], only circulated fluidized bed gasifiers are suitable for large-scale fuel gas production. Hamelinck and Faaij [8] analyzed two gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. The later appeared to have an advantageous combination of lower investment costs and higher efficiency. In this paper an atmospheric indirectly fired gasifier is selected. This is a fast fluidized bed gasifier fed by air [8]. Electricity production through a steam turbine is also considered in this study.

The installed investment costs for the separate units in the base 280,000 m^3 methanol plant are presented in Table 1. Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (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 basic technology. This difference can be adjusted using scaling functions of the individual components of the plant as described in equation (3):

$$\mathrm{Cost}_a/\mathrm{Cost}_b = (\mathrm{Size}_a/\mathrm{Size}_b)^R \tag{3}$$

where R is the scaling factor, Cost_a and Cost_b are the costs of the components for two different biofuel plants with Size_a and Size_b. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding investment costs from the separate units, the total investment cost for another size can be determined, and production cost for the respective methanol plant can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [14]. The uncertainty range of such estimates is up to ±30% [8].

From the process plant costs (Table 1), the total capital requirement can be calculated as presented in Table 2. The total capital requirement is used for calculating the annual cost (AC) as given by equation (4):

$$\mathrm{AC} = \mathrm{TCR}\cdot\mathrm{IR}/\left(1 - 1/(1+\mathrm{IR})^{t_e}\right) \tag{4}$$

where TCR is the total capital requirement, IR is the interest rate and t_e, the economical lifetime. The annual operating and maintenance costs are calculated as the sum of the elements presented in Table 3.

Table 1 – Base scale factors for a 430 $MW_{biomass}$ methanol plant [7,8].

Gasification system	R	Base scale (M €)
Total pretreatment	0.79	31.4
Gasifier	0.65	25
Gas cleaning:		
Tar cracker	0.7	7.6
Cyclones	0.7	5.6
Heat exchanger	0.6	9.2
Baghouse filter	0.65	3.4
Condensing scrubber	0.7	5.6
Syngas processing:		
Compressor	0.85	13.9
Steam reformer	0.6	37.8
Methanol production:		
Make up compressor	0.7	14.3
Liquid phase methanol	0.72	3.6
Recycle compressor	0.7	0.3
Refining	0.7	15.7
Power generation:		
Steam turbine + steam system	0.7	11.4
Process plant cost (PPC)		184.8

Table 2 – Total capital requirement [15,16].

Capital required	Description
Total plant cost (TPC)	
Engineering fee	10% of PPC
Process contingency	2.345% of PPC
General plant facilities	10% PPC
Project contingency	15% of (PPC + general plant facilities)
Total plant investment (TPI)	
Adjustment for interest and inflation	0.34% PPC
Total capital requirement (TCR)	
Prepaid royalties	0.5% of PPC
Start-up costs	2.7% TPI
Spare parts	0.5% of TPC
Working capital	3% TPI
Land, 200 acres	200 acres at 6500 € Acre^{-1}

2.4. *Transport of methanol to the filling stations*

Depending on the quantity, infrastructure and distance, methanol can be transported by truck, train, or ship. Truck transportation is cost efficient for shorter distances, and train and ships for longer distances [7]. As methanol is transported to gas stations on distances around 100 km in Baden-Württemberg, only truck transportation is considered for the distribution of methanol. The costs of methanol transportation are calculated using figures from Börjesson and Gustavson [12], shown in equation (5).

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

The transportation costs by truck (in € $TJ^{-1}_{methanol}$) are a function of actual transportation distance, d in km.

2.5. *Methanol distribution*

It is assumed that all gas stations are able to distribute methanol. As methanol is not widely used in the transportation sector, changes to gas stations would be required. Therefore, two scenarios may apply as outlined next. One can consider a station that has three underground storage tanks of three grades of gasoline, two pump islands, and four dispensers capable of refuelling eight vehicles simultaneously. At an average fill-up of 51 l requiring 6 min, a station

Table 3 – Annual operating and maintenance costs [15,16].

Operating and maintenance	Description
Wood	30 € m^{-3}
Operator labor	3% of TPI
Supervision and clerical labor	30% of O&M labor
Maintenance costs	2.2% of TPC
Insurance and local taxes	2% of TPC
Operating royalties	1% of wood cost
Miscellaneous operating costs	10% of O&M labor

such as the one illustrated may service between 200 and 400 vehicles per day and have a throughput of 321,760 l–643,520 l per month [17]. Two scenarios can be analyzed: (i) the first is to add a methanol capacity to an existing station, and (ii) the second considers that methanol would displace a fraction of existing gasoline storage capacity.

In the first scenario, it is assumed that the capability of dispensing up to 125,000 l of methanol per month is added to an existing retail gasoline station, increasing the overall throughput of a station. This may be accomplished by adding a new underground 37,900 l methanol fuel tank, remote from the existing tank field. An above ground tank might be added where space and permission is granted [17].

In the second scenario, it is assumed that a portion of the gasoline storage capacity of a station is displaced by a 38,000 l methanol storage tank. Alternative ways would be to eliminate one product from the mix of petroleum products and convert that storage capacity to methanol. This could be done by cleaning or upgrading one of the existing petroleum tanks and installing new methanol compatible piping and dispenser. It also includes removing one of the existing petroleum tanks and replaces it with a methanol compatible tank to upgrade the balance of the system.

The costs for handling a gas station of methanol with a capacity of 125,000 l per month are between 0.20 and 0.24 € $GJ^{-1}_{Methanol}$ regarding the chosen scenario. The later value is considered in the model.

2.6. Other technical and site specific data

First, the relation between the costs and the methanol plant size is studied. The different parameters and their values are presented in Table 4. In addition, a sensitivity analysis was carried out elucidating the impact of another five parameters on the methanol production costs. The calculations were performed for 2 methanol plants situated at 48.15°N, 9.5°E, and 49°N, 9°E, where the first one (plant A) is situated closer to high biomass production areas and the second one (plant B) is located closer to a high demand areas. The wood cost has been studied with an upper and lower value equal to twice and half the reference cost respectively. The upper value would represent an increase of the wood cost due to a shortage in wood. The land allocation to energy wood is a parameter difficult to estimate; therefore we assume a range between 2.5 and 0.5 times of the reference value. Regarding the plant efficiency, as the technology is not fully commercialized, a reference value of 40% was chosen. About 57% was the value suggested by Hamelinck and Faaij [8], and an extreme lower value of 25% was assumed in case of technology deficiency. Finally concerning the plant operating hours, Hamelinck and Faaij [8] suggested 8000 h; Wahlund [18] reported operating hours below 6500 h per year for biomass-based heat and power plants. A reference value of 7200 h per year was then chosen where two months would be left for maintenance and eventual repairs. Those parameters are presented in Table 5 together with their extreme values (−1 and +1 levels). The sensitivity of these parameters is analyzed by a 2^{5-1}_{V} factorial design, where the influences on the costs of five parameters are studied, as well as their interactions with each other. This study is carried out with 16 runs with different combination between the parameters. The six columns on the left side of Table 6 present the combinations studied.

Table 4 – Reference parameters.

Description	Unit	Value
Wood cost [9]	€ m^{-3}	30
Land allocation[a]	ha	1852
Road to direct distance ratio		1.6
Plant efficiency [8]	%	40
Plant operating hours [8]	h	7200
Technical lifetime [8]	years	25

a The land allocation represents the area reserved for energy production for 1% of the total possible methanol consumption in Baden-Württemberg.

3. Results

3.1. Cost of methanol as a function of plant size

The total cost of methanol (from harvesting of biomass to methanol distribution to the consumers) with costs in € $GJ^{-1}_{Methanol}$ is presented in Fig. 1. The figure shows the cost components of biomass production and transportation, methanol production, transportation and distribution. The transportation costs increase with the size of the methanol plant while methanol production costs exponentially decrease with the size. The economy of scale offsets potential additional costs from biomass and methanol transportation assuming a scale independent region with uniform roadside and biomass market price.

3.2. Sensitivity analysis

In order to study the sensitivity and interactions of the parameters, a 2^{5-1}_{V} factorial design is analyzed. For each run, the different costs of the chain of methanol production are determined as previously outlined.

The normal probability plot of the effect is presented in Fig. 2 and results are listed in Table 6.

The larger effects that appear can be sorted into 3 groups (Fig. 2):

- the plant efficiency (D) which has the strongest influence,
- the wood cost (A) which is the second most influencing parameter,

Table 5 – Variables studied with attached extreme values.

Description	Unit	−1	Ref.	1
Wood cost [9]	€ m^{-3}	15	30	60
Land allocation	ha	4628	1852	926
Plant position	°E	9.5	–	9
	°N	48.15		49
Plant efficiency	%	57	40	25
Plant operating hours	h	8000	7200	6500

Table 6 – Results from the factorial design.

Run number	Wood cost, € m^{-3}	Land allocation, ha	Plant position	Efficiency	Plant operation hours, h	Transport cost, € $GJ^{-1}_{methanol}$	Production cost, € $GJ^{-1}_{methanol}$	Total, € $GJ^{-1}_{methanol}$
1	15	4628	A[a]	0.57	8000	1.76	9.76	15.03
2	15	926	B[b]	0.57	8000	2.43	9.76	15.7
3	15	4628	B	0.57	6500	1.74	12	17.24
4	15	926	A	0.57	6500	2.46	12	17.97
5	60	4628	B	0.57	8000	1.8	9.85	24.96
6	60	926	A	0.57	8000	2.62	9.85	25.78
7	60	4628	A	0.57	6500	1.71	12.1	27.12
8	60	926	B	0.57	6500	2.31	12.1	27.72
9	15	4628	B	0.25	8000	3.78	22.24	33.72
10	15	926	A	0.25	8000	5.51	22.24	35.44
11	15	4628	A	0.25	6500	3.45	27.36	38.5
12	15	926	B	0.25	6500	4.96	27.36	40.01
13	60	4628	A	0.25	8000	3.56	22.47	56.06
14	60	926	B	0.25	8000	5.24	22.47	57.74
15	60	4628	B	0.25	6500	3.65	27.58	61.27
16	60	926	A	0.25	6500	5.16	27.58	62.78

a Position A: 9.5°E, 48.15°N.
b Position B: 9°E, 49°N.

- and the interaction between the plant efficiency and the wood cost (AD), the plant operating hours (*E*), the interaction between the plant efficiency and the operating hours (DE), and the Land allocation (*B*).

3.3. *A geographical analysis*

In the geographical analysis, two methanol plants of 200 $MW_{Biomass}$ each were studied with the model detailed earlier based on minimization of the costs of the supply chain. The methanol plant A is situated in an area with high biomass production and the methanol plant B is situated in an area with a high methanol demand, in the proximity of Stuttgart. For the road to direct distance factor, the values of 1.5 and 1.45 for the methanol plants A and B were used respectively. Other parameters are presented in Table 4.

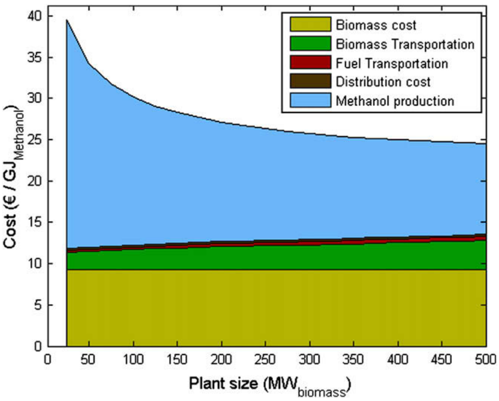

Fig. 1 – Cost of methanol (in € GJ^{-1}) by the size of the biofuel plant (in $MW_{biomass}$).

Such methanol plants are able to supply 147 gas stations per year using biomass that is produced within a circle of 50 km of radius (Fig. 3). Table 7 lists the production characteristics and costs for the 200 $MW_{Biomass}$ plants.

4. Discussion

4.1. *Energy demand*

Fig. 3 illustrates the geography of biomass production supplying each methanol plant. The largest distance of biomass supply for plant A is 55 km and for plant B, 70 km.

There are 1032 gas stations located in Baden-Württemberg. If all stations deliver methanol to consumers, then about 6.78 T $Wh_{Methanol}$ $year^{-1}$ need to be supplied. The simulated average annual production of short-rotational poplar coppice in Baden-Württemberg is 13.48 Mt $year^{-1}$, which corresponds to 67.04 T Wh $year^{-1}$. About 234,200 hectares of short-rotational poplar coppice would be needed to make Baden-Württemberg self-sufficient in methanol production.

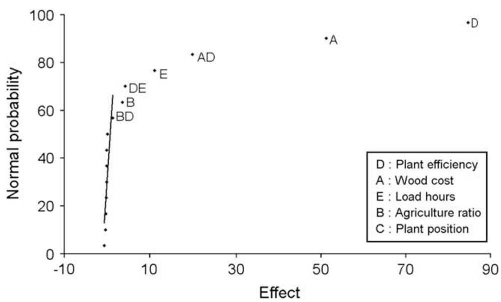

Fig. 2 – Normal probability plot of effects. Parameters with large effect have more influence on the total cost.

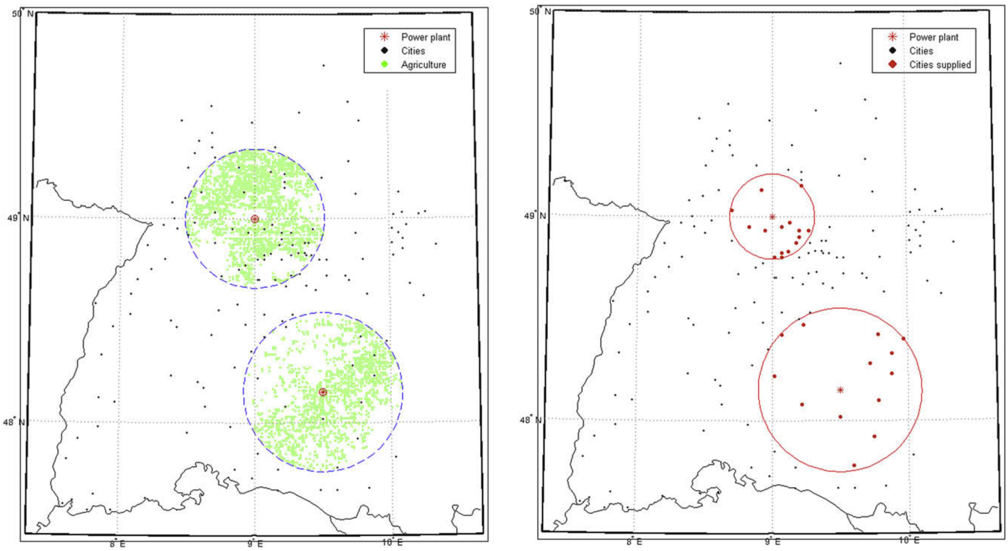

Fig. 3 – Geography of two 200 $MW_{biomass}$ methanol plants in the county of Baden-Württemberg. Left: the circles represent the woody biomass used by each plant (center of circles). Right: the circles represent the cities that are delivered in methanol by each plant (center of circles). The remaining black cities are not delivered in methanol.

The effect of scale economies in methanol production is illustrated in Fig. 1. For a plant of 200 $MW_{Biomass}$, the total cost of the methanol production chain consists of biomass costs (36%), biomass transport costs (17%), methanol transport costs (3%), methanol distribution costs (1%), and methanol production costs (43%). The costs for the average set-up are estimated to be below 30 € $GJ^{-1}_{Methanol}$, which corresponds to 0.50 € $l^{-1}_{Methanol}$, or 1.0 € $l^{-1}_{Gasoline\ equivalent}$. Sensitivity analysis reveals a wide range of plausible cost estimates, some 50% higher and lower this central estimate.

Table 7 – Production characteristics and costs for the 200 $MW_{biomass}$ methanol plants.

Results	Units	Plant A	Plant B
Longitude	°East	9.5	9
Latitude	°North	48.15	49
Wood	$t\,h^{-1}$	40	40
Methanol sold	$l\,day^{-1}$	438,000	438,000
Area	ha	28,140	351,400
Gas stations		99	106
Population		409,149	538,855
Biomass transports			
Mean	€ $GJ^{-1}_{methanol}$	2.21	2.13
Max	€ $GJ^{-1}_{methanol}$	2.72	2.52
Biomass radius	km	65.1	54.92
Fuel transports			
Mean	€ $GJ^{-1}_{methanol}$	0.29	0.22
Max	€ $GJ^{-1}_{methanol}$	0.34	0.24
Delivering radius	km	66.79	35
Production costs	€ $GJ^{-1}_{methanol}$	15.03	15.03
Annual costs	€ $GJ^{-1}_{methanol}$	8.91	8.91
Operating costs	€ $GJ^{-1}_{methanol}$	6.11	6.11
Gas station costs	€ $GJ^{-1}_{methanol}$	0.24	0.24
Fuel cost			
Min	€ $GJ^{-1}_{methanol}$	26.99	26.33
Max	€ $GJ^{-1}_{methanol}$	27.07	26.8

4.2. *Model parameter sensitivity*

The most important factor influencing costs in the methanol production chain is the plant efficiency (factor *D*). A difference from 0.25 to 0.57 in the methanol plant efficiency would double the production costs as well as the total methanol cost (comparisons between the runs 4 and 12). However, the technology for methanol production through gasification is not yet proven or commercially available, process efficiencies over 50% might be expected as analyzed from Hamelinck and Faaij [8].

The biomass cost is the second parameter that substantially influences the final methanol cost. An increase in the raw material by a factor 4 would raise the final methanol cost by 63% (comparisons between the runs 10 and 14).

The plant operating hours and the land availability are the two last parameters that influence the final methanol cost. A difference of the plant operating hours from 6500 to 8000 h may lead to an increase in the production cost by 23% and in the final methanol cost by 14.8% (comparisons between the runs 9 and 11). If there is, for instance 20% less land available within each grid cell for biomass production in this region then it would increase transport costs by 41.8%, and the final methanol cost would rise by 4.2% (comparisons between the runs 3 and 4).

The location of the methanol plant can influence the methanol cost. Biomass transport costs are higher for the plant A ($2.21 € GJ^{-1}_{Methanol}$) than for the plant B ($2.13 € GJ^{-1}_{Methanol}$), as well as the methanol transport ($0.34 € GJ^{-1}_{Methanol}$ for the plant A, and $0.24 € GJ^{-1}_{Methanol}$ for the plant B, see Table 7). The plant B is indeed situated closer to the demand, and the transport infrastructure is more developed than in the area of the plant A, which was interpreted in the model with two different road to direct distance ratios. Moreover, the simulated yields of poplar coppice vary between 750 ODT year^{-1} (oven dry tones per year) and 1150 ODT year^{-1} in Baden-Württemberg, and the geographical repartition of poplar coppice is very dense all over the county, which can explain the small changes in the transport cost.

A 200 $MW_{Biomass}$ methanol plant needs about 140 ODT h^{-1} of biomass. Considering a 12 working hour day for the biomass transport by truck, one would see a truck (alternatively empty or fully loaded) between the biomass production site and the methanol plant every 4 min. Such heavy traffic would face poor public acceptance and thus emphasizes the importance of locating the methanol plant optimally given further geographic and social constraints.

5. Conclusion and future work

Methanol production through gasification carries the potential of considerable environmental benefits while producing transport fuels potentially in a cost competitive manner. To achieve the latter, an efficient production and processing technology as well as optimal plant location and logistics are required. Indeed, the process efficiency and the plant operating hours of the methanol plant, together with the biomass cost, appeared to have the biggest impact on the final methanol cost. Methanol cost can double between process efficiencies of 0.25 and 0.57. The location of the methanol plant may influence the transport cost by 60%. Baden-Württemberg is a particular example where biomass and gas stations are evenly spread all over the region; in a country where wood supply and fuel demand are at two different geographic positions, methanol plant location would have a decisive impact on the methanol price.

REFERENCES

[1] Ogden JM, Steinbugler MM, Kreutz TG. A comparison of hydrogen, methanol and gasoline as fuels for fuel cell vehicles. Journal of Power Sources 1999;79:142–68.

[2] RIRDC. Wood for alcohol fuels, status of technology and cost benefit analysis of farm forestry for bioenergy. RIRDC Publication No 02/141; 2002.

[3] Pacific Northwest Pollution Prevention Resource Center (PPRC). Alternative fuels for fleet vehicles. Available from: <www.pprc.org/pubs/altfuels.cfm>; 1999.

[4] Ahlvik P, Brandberg AR. Well-to-wheel efficiency for alternative fuels from natural gas or biomass. p. 85. Borlänge, Sweden: Swedish National Road Administration; 2001.

[5] Wahlund B, Yan J, Westermark M. Increasing biomass utilisation in energy systems: a comparative study of CO_2 reduction and cost for different bioenergy processing options. Biomass and Bioenergy 2004;26:531–44.

[6] Dornburg V, Faaij APC. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass and Bioenergy 2001;21:91–108.

[7] Sørensen ÅL. Economies of scale in biomass gasification systems. Laxenburg: International Institute for Applied Systems Analysis (IIASA); 2005.

[8] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. Utrecht: Utrecht University, Copernicus Institute, Science Technology and Society; 2001.

[9] Schönhart M. Profitability of short rotation forestry in Austria. Laxenburg: International Institute for Applied Systems Analysis (IIASA); 2006.

[10] Schmid E, Balkovic J, Moltchanova E, Skalsky R, Poltarska K, Müller B, et al. Bio-physical process modelling for EU25 – concept, data, methods and results. Final research report for the EU-FP6 research project INSEA. p. 76. Laxenburg: International Institute of Applied System Analysis (IIASA); 2006.

[11] Williams JR. The EPIC model. In: Computer models of watershed hydrology. Highland Ranch, Colorado: Water Resources Publication; 1995. p. 909–1000.

[12] Börjesson P, Gustavson L. Regional production and utilization of biomass in Sweden. Energy 1996;21:747–64.

[13] Volvo Truck Corporation. Emissions from volvo's trucks. Available from: <www.volvotrucks.com>; 2006.

[14] Tijmensen M, Hooidonk GV. Long term perspectives for production of fuels from biomass; integrated assessment and RD & D priorities – final results. Utrecht: Utrecht University, Copernicus Institute, Science Technology and Society; 2000.

[15] Craig KR, Mann MK. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems. NREL/TP-43021657; 1996.

[16] Parsons EL, Shelton WW, Lyons JL. Advanced fossil power systems comparison study. NETL USDOE final report; 2002.

[17] Amf-Ea. Engineering, methanol refueling station costs. Prepared for American methanol foundation. Silver Spring: Science and Technology, Inc.; 1999.

[18] Wahlund B. Rational bioenergy utilisation in energy systems and impacts on CO_2 emissions. Stockholm: Chemical and Engineering and Technology; 2003.

Article II

Methanol from gasification: a facility location problem

METHANOL FROM GASIFICATION: A FACILITY LOCATION PROBLEM

Sylvain Leduc[1,2,*] , Erik Dotzauer[3], Erwin Schmid[4], Michael Obersteiner[2]

[1]Div. of Energy Engineering, Luleå University of Technology, SE-97187 Luleå, Sweden
[2]International Institute for Applied Systems Analysis (IIASA), A-2361 Laxemburg, Austria
[3]Dept. of Public Technology, Mälardalen University, SE-72123 Västerås, Sweden
[4]University of Natural Resources and Applied Life Sciences (BOKU), A-1180 Vienna, Austria

ABSTRACT

Methanol from biomass gasification has the potential to be a competitive alternative to fossil fuels. In this paper, the supply of the entire methanol energy chain - biomass production, biomass transport, methanol production, methanol transport, and methanol distribution - is studied. A mixed integer programming model is developed to find the optimal locations and sizes of methanol production plants for the geographic region of Baden-Württemberg in Germany. Six methanol plants between 200 $MW_{biomass}$ and 400 $MW_{biomass}$ were found to optimally supply current fuel demands for the entire region. Feedstock cost, biomass transportation and availability appear as crucial factors determining the optimal location of the plants. Competitiveness of 2[nd] generation biofuel also depends of technological readiness. Sensitivity analysis shows that shutting down a methanol plant for maintenance during a period of one month increases the methanol production cost by more than ten percent.

Keywords: methanol, gasification, facility location, mixed integer programming

* Corresponding author. International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria. Tel.: +43 2236 807 267; fax: +43 2236 807 599.
E-mail address: leduc@iiasa.ac.at (S. Leduc).

1. INTRODUCTION

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. Today, 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. In the transportation sector, methanol can be used either in compression ignited (CI) engines or in fuel cells. For CI engines, methanol can be mixed with gasoline up to 85%. This alternative fuel (M-85) has become a common choice in the fuel mix, because of its high octane (102) and performance characteristics, minor modifications on gasoline engines, and the significant reduction of reactive emissions (PPRC, 2005). Concerning fuel cells, methanol may play an important role since it is easier to transport and store than hydrogen (Ogden et al., 1999).

This study describes the whole bio-energy chain including biomass extraction and pre-treatment, biomass transportation, biomass conversion to methanol, methanol transportation, and methanol distribution. Each system of the chain is studied and costs are estimated. A geographic analysis is carried out using data describing number and location of gas stations, and biomass production from Baden-Württemberg, Germany (Figure 1). This study aims at testing a model to find the best geographical locations of methanol plants to distribute methanol at least cost.

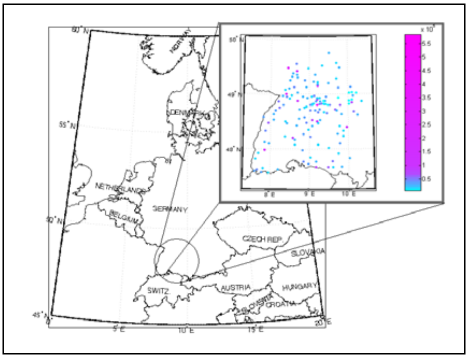

Figure 1: Cities in Baden-Württemberg ranging by the number of inhabitants

2. THE METHANOL PRODUCTION CHAIN

2.1. Biomass supply

Biomass production of a short-rotational poplar coppice system has been modeled by Schmid et al., (2006) using the latest version of the bio-physical process model EPIC[†] (Environmental Policy Integrated Climate; Williams, 1995). The poplar coppice system is fertilized with nitrogen only in the first two years of each rotation period. Biomass is harvested every six years over a simulation period of 30 years. It is assumed that poplar coppice can only be planted on agricultural lands with decent slopes (<5%) to keep harvesting costs low. Although biomass production costs depend on plant species, production system, land type, etc., the biomass cost is assumed to be constant and amounts to 40 €/m^3 (which includes extraction and pre-treatment).

[†] The EPIC model version EPIC3060 with the program code from 02/03/2006 is used for this analysis.

2.2. Biomass transportation

The biomass transportation cost (in €/TJ) is described by Börjesson et al. (1996), and is represented by equations (1) and (2), for tractor-trailor and truck transportations, respectively.

$$C_{\text{Tractor}} = 226 + 12.78d \tag{1}$$

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

The actual distance (in km) to the methanol plant, *d*, is defined as the direct distance multiplied by the ratio of actual road length to direct distance. These values correspond to the transportation costs when biomass is extracted from the surrounding areas.

2.3. Methanol production

Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following steps: pre-treatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification (Hamelinck et al., 2001). Optional are a gas turbine or boiler to employ the unconverted gas, a steam turbine for electricity co-production, and equipments for heat production.

According to Hamelinck et al. (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 (2001) analyzed two gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. In this paper an atmospheric indirectly fired gasifier is selected. This is a fast fluidized bed gasifier. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production. Figure 2 presents the production chain of methanol.

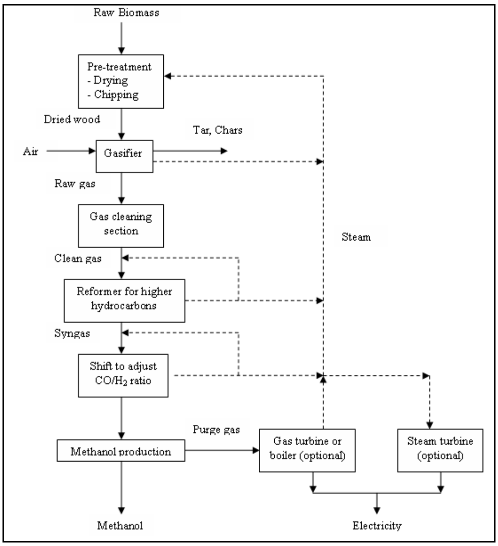

Figure 2: Process flow diagram of methanol production

The investment costs for different units of the base methanol plant (430 $MW_{biomass}$) are listed in Table 1. Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (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 (equation (3)):

$$\frac{Cost_a}{Cost_b} = \left(\frac{Size_a}{Size_b}\right)^R \tag{3}$$

where R is the scaling factor, $Cost_a$ and $Cost_b$ are the costs of equipments for the biofuel plant (a) and (b) respectively, and $Size_a$ and $Size_b$ are the sizes of the biofuel plant (a) and (b), respectively. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding investment costs from the separate units, the total investment cost for the new size is determined, and production cost for this methanol plant size can be calculated. For biomass systems, R is usually between 0.6 and 0.8 (Tijmensen et al., 2000). The uncertainty range of such estimates is up to ± 30% (Hamelinck and Faaij, 2001). The following table lists the scaling factors based on a 430 $MW_{biomass}$ methanol plant.

Table 1: Base scale factors for a 430 $MW_{biomass}$ methanol plant

Gasification System	R	Cost (M€)
Total pre-treatment	0.79	31.4
Gasifier	0.65	25
Gas Cleaning:		
Tar Cracker	0.7	7.6
Cyclones	0.7	5.6
Heat Exchanger	0.6	9.2
Baghouse Filter	0.65	3.4
Condensing Scrubber	0.7	5.6
Syngas Processing:		
Compressor	0.85	13.9
Steam Reformer	0.6	37.8
Methanol Production:		
Make Up Compressor	0.7	14.3
Liquid Phase Methanol	0.72	3.6
Recycle Compressor	0.7	0.3
Refining	0.7	15.7
Process Plant Cost (PPC)		173.4

Source: Hamelinck et al., 2001.

The total capital requirement for a process plant can be calculated from the process plant costs, as listed in Table 2.

Table 2: Total capital requirement for a process plant

Capital Required	Description
Total Plant Cost (TPC)	
Engineering Fee	10% of PPC
Process Contingency	2.345% of PPC
General Plant Facilities	10% PPC
Project Contingency	15% of (PPC + General Plant Facilities)
Total Plant Investment (TPI)	
Adjustment for Interest and Inflation	0.34% PPC
Total Capital Requirement (TCR)	
Prepaid Royalties	0.5% of PPC
Start-up Costs	2.7% TPI
Spare Parts	0.5% of TPC
Working Capital	3% TPI
Land, 200 Acres	200 Acres at 6,500 €/Acre

Craig et al, 2006 and Parsons et al, 2002

The total capital requirement (TCR) provides an annual cost (AC) that can be calculated with equation (4):

$$AC = \frac{IR}{1 - \frac{1}{(1+IR)^{t_e}}} \cdot TCR \tag{4}$$

where IR is the interest rate and t_e the economical lifetime, or pay down period. The annual operating and maintenance costs are calculated as the sum of the elements listed in Table 3.

Table 3: Annual operating and maintenance costs

Operating and Maintenance	Description
Wood	40 €/m^3
Operator Labor	3% of TPI
Supervision and Clerical Labor	30% of O&M Labor
Maintenance Costs	2.2% of TPC
Insurance and Local Taxes	2% of TPC
Operating Royalties	1% of Wood Cost
Miscellaneous Operating Costs	10% of O&M Labor

Craig et al, 2006 and Parsons et al, 2002

In this study the production of heat and electricity is not considered.

2.4. Methanol transportation

Methanol can be transported by truck, train, or ship depending on the quantity, infrastructure and distance. The costs of methanol transportation are calculated using figures from Börjesson et al. (1996). The transportation costs by truck (in €/$TJ_{methanol}$) are a function of actual transportation distance, d (in km), which is shown in equation (5).

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

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

2.5. Methanol distribution

It is assumed that all the gas stations are able to distribute methanol. As methanol is not yet widely used in the transportation sector, changes to gas stations would be required. Therefore, two scenarios may apply as outlined next. One can consider a station that has three underground storage tanks (UST) of three grades of gasoline, two pump islands, and four dispensers capable of refueling eight vehicles simultaneously. At an average fill-up of 51 liters requiring six minutes, a station such as the one illustrated may serve between 200 and 400 vehicles per day and have a gasoline throughput of 322,000 liters to 644,000 liters per month (AMF-EA Engineering, 1999). Two scenarios can be analyzed, one is to add a methanol capacity to an existing station, and the second is considered that methanol would displace a fraction of existing gasoline storage capacity.

In the first scenario, it is assumed that the capability of dispensing up to 125,000 liters of methanol per month is added to an existing retail gasoline station, increasing the overall throughput of a station. This may be accomplished by adding a new underground 38,000 liter methanol fuel tank, remote from the existing tank field. An above ground tank might be added where space and permitting is allowed (AMF-EA Engineering, 1999).

In the second scenario, it is assumed that a portion of the gasoline storage capacity of a station is displaced by a 38,000 liters methanol storage tank. Alternative ways would be to eliminate one product from the mix of petroleum products and convert that storage capacity to methanol. This could be done by cleaning or upgrading one of the existing petroleum tanks and installing new methanol compatible piping and dispenser. It also includes removing one of the existing petroleum tanks and replaces it with a methanol compatible tank to upgrade the balance of the system.

The costs for handling a gas station of methanol with a capacity of 125,000 liters/month are between 0.2031 and 0.2412 €/$GJ_{methanol}$ regarding the chosen scenario. The costs are assumed to be independent of the methanol plant size.

2.6. A Facility Location Problem

This section describes a Facility Location Problem (FLP). Solving such problem will result in the optimal locations and sizes of plants and gas stations.

First, let S be the number of biomass supply points, let P be the number of plants, let G be the number of gas stations, and let D be the number of demand regions. Also define the corresponding sets: $\widetilde{S} = \{1,...,S\}$, $\widetilde{P} = \{1,...,P\}$, $\widetilde{G} = \{1,...,G\}$ and $\widetilde{D} = \{1,...,D\}$.

Next, variables are defined. Let $b_{i,j}$ be amount of biomass delivered from supply point i to plant j, let $x^{del}_{j,k}$ be the amount of methanol delivered from plant j to gas station k, and let $x^{sold}_{k,l}$ be the amount of sold methanol at gas station k to costumers from region l. The variables $b_{i,j}$, $x^{del}_{j,k}$ and $x^{sold}_{k,l}$ are non-negative. Let the binary variables u_j and v_k, respectively, indicate if plant j and gas station k are set up. If u_j (v_k) is equal to one, then the plant (station) is built, otherwise u_j (v_k) is zero.

The cost for producing biomass at supply point i is c_i^{bio}. The biomass delivered from i is restricted by

$$\sum_{j=1}^{P} b_{i,j} \leq \bar{b}_i, \quad i \in \tilde{S}, \tag{6}$$

where $\bar{b}_i$ is the amount of biomass available. The cost for transporting biomass from supply point i to plant j is $t_{i,j}^{bio}$.

Plant j is described by the following parameters and equations. The cost for building a plant with maximal capacity $\bar{p}_j$ and minimal capacity $\underline{p}_j$ is e_j^{plant}, and the cost for converting biomass to methanol in the plant is c_j^{plant}. The methanol production is thus restricted by

$$\sum_{k=1}^{G} x_{j,k}^{del} \leq \bar{p}_j u_j, \qquad j \in \tilde{P}, \tag{7}$$

and

$$\underline{p}_j u_j \leq \sum_{k=1}^{G} x_{j,k}^{del}, \qquad j \in \tilde{P}. \tag{8}$$

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The plant efficiency is a_j, giving

$$\sum_{i=1}^{S} a_j b_{i,j} = \sum_{k=1}^{G} x_{j,k}^{del}, \quad j \in \tilde{P}. \tag{9}$$

The produced methanol in plant j is then transported to gas station k for the cost $t_{j,k}^{del}$.

The cost for setting up a gas station k with the capacity $\bar{g}_k$ is e_k^{stat}. The cost for handling methanol at the station is c_k^{stat}. Similar to the plant model, also the gas station is modeled using capacity and mass flow equations, i.e.

$$\sum_{l=1}^{D} x_{k,l}^{sold} \leq \bar{g}_k v_k, \quad k \in \tilde{G}, \tag{10}$$

and

$$\sum_{j=1}^{P} x_{j,k}^{del} = \sum_{l=1}^{D} x_{k,l}^{sold}, \quad k \in \tilde{G}, \tag{11}$$

must hold.

The demand for methanol in region l is modeled by

$$\sum_{k=1}^{G} x_{k,l}^{sold} = d_l, \quad l \in \tilde{D}, \tag{12}$$

where d_l is the demand. The corresponding transportation cost is $t_{k,l}^{sold}$, which shall be interpreted as the cost for people driving from region l to gas station k.

Finally, the Facility Location Problem is defined as:

$$\begin{cases} \min\limits_{b,x,u,v} \left[\sum_{i=1}^{S} \sum_{j=1}^{P} \left(c_i^{bio} + t_{i,j}^{bio}\right) b_{i,j} + \sum_{j=1}^{P} e_j^{plant} u_j + \sum_{j=1}^{P} \sum_{k=1}^{G} \left(c_j^{plant} + t_{j,k}^{del}\right) x_{j,k}^{del} + \sum_{k=1}^{G} e_k^{stat} v_k + \sum_{k=1}^{G} \sum_{l=1}^{D} \left(c_k^{stat} + t_{k,l}^{sold}\right) x_{k,l}^{sold} \right] \\ s.t. \\ (6)-(12) \\ b_{i,j}, x_{j,k}^{del}, x_{k,l}^{sold} \geq 0 \qquad i \in \tilde{S}, j \in \tilde{P}, k \in \tilde{G}, l \in \tilde{D} \\ u_j \in \{0,1\}, v_k \in \{0,1\} \qquad j \in \tilde{P}, k \in \tilde{G}. \end{cases} \tag{13}$$

The problem is an ordinary Mixed Integer Program (MIP) and can thus be solved using standard MIP techniques (Wolsey, 1998).

2.7. Case study input data

In order to find the optimal locations of the methanol plants, problem (13) is solved with the possibility to build methanol plants of different sizes on a 0.2 degree grid. It is assumed that up to 20% of the agricultural land is reserved for the energy production.

Once the optimization problem is solved (called the reference scenario 0), different scenarios are studied for the selected methanol plants in order to analyze the sensitivity of the results. The impact of the agricultural land allocation is analyzed to show the influence of the biomass availability on the methanol plants position and production. The impact of load hours is analyzed to investigate the consequences of a methanol plant closure. The impact of transport and the biomass costs are analyzed to address competitiveness issues between methanol plants. In the two last scenarios it is assumed that the biomass is only available in the south-east corner of Baden-Württemberg. All scenarios are briefly described in Table 4.

Table 4: Brief description of the different scenarios

Scenarios	Description
0	Reference scenario
I	The agricultural land allocation* equals 926 ha instead of 1,852 ha
II	The load hours for the methanol plant 3 equals 6,400 hours instead of 7,200 hours
III	The transport cost for the biomass increases by 80% for the methanol plant 2
IV	The cost of the biomass rises to 50 €/m³ for the methanol plant 1
V	Biomass available in the south-east part of the region (agricultural land allocation = 1,852 ha)
VI	Methanol plant sizes are set from scenario I and the biomass is only available in the south-east part of the country (scenario V)

*the land allocation represents the area reserved for energy production for 1% of the total possible methanol consumption in Baden-Württemberg.

3. RESULTS

From the initial set of possible locations, six were selected in the reference scenario. Table 5 lists production, transportation, and distribution costs of selected methanol plants from the reference scenario.

Table 5: Results of selected methanol plants (reference scenario)

Variables	Units	Plant number 1	2	3	4	5	6
Plant							
Longitude	° East	9.2	7.9	8.7	8.2	9.2	9.3
Latitude	° North	48.8	48.0	49.4	48.3	48.3	47.8
Size (bio input)	$MW_{biomass}$	400	200	250	300	400	300
Efficiency		0.45	0.45	0.45	0.45	0.45	0.45
Load hours	hours	7,200	7,200	7,200	7,200	7,200	7,200
Methanol sold	m^3/year	292,514	125,638	181,337	191,775	273,910	217,851
Input of wood	t/hour	80	34	49	52	75	59
Agriculture area	ha	64,200	23,300	41,600	36,100	52,700	39,400
Gas stations delivered		489	210	304	321	457	364
Population		1,585,309	643,000	907,806	987,490	1,068,149	883,780
Costs							
Biomass transports	€/$GJ_{methnanol}$	3.34	3.17	3.34	3.25	3.25	3.18
Methanol transports	€/$GJ_{methnanol}$	0.60	0.56	0.64	0.69	0.85	1.04
Production costs	€/$GJ_{methnanol}$	11.43	26.59	18.43	17.43	12.20	15.34
Annual costs*	€/$GJ_{methnanol}$	6.74	15.68	10.86	10.27	7.19	9.04
Operating costs**	€/$GJ_{methnanol}$	4.69	10.91	7.56	7.15	5.01	6.30
Gas station costs	€/$GJ_{methnanol}$	0.24	0.24	0.24	0.24	0.24	0.24
Total cost	€/$GJ_{methnanol}$	19.78	34.78	26.83	25.92	20.74	23.92

* The annual costs represent the costs for the reimbursement of the plant over the economical lifetime of 20 years.

** The operating costs represent the costs for the maintenance of the methanol plant, such as operator labor, maintenance costs, insurance and local taxes, etc.

A sensitivity analysis is performed for the methanol plants that were selected in the reference scenario. The sensitivity scenario assumptions outlined in Table 4 are analyzed, and the results from the different scenarios are found in Table 6. Figure 3 lists the average total costs for each scenario, sorted in increasing order.

Table 6: Results of optimal plant sizes and costs among scenarios

	Scenarios	Units	Plant number 1	2	3	4	5	6
Size (biomass input)	0	$MW_{biomass}$	400	200	250	300	400	300
	I		400	200	250	250	400	350
	II		400	200	250	300	400	300
	III		400	-	300	350	400	350
	IV		150	200	400	300	400	350
	V		350	-	-	-	400	400
	VI		400	-	-	-	400	350
Biomass transport	0	€/$GJ_{methanol}$	3.34	3.17	3.34	3.25	3.25	3.18
	I		2.56	2.43	2.57	2.49	2.49	2.41
	II		3.32	3.25	3.17	3.31	3.33	3.23
	III		3.42	-	3.50	3.44	3.43	3.37
	IV		2.45	3.48	3.61	3.53	3.31	3.49
	V		5.21	-	-	-	4.10	3.74
	VI		5.10	-	-	-	3.69	3.00
Total cost	0	€/$GJ_{methanol}$	19.78	34.78	26.83	25.92	20.74	23.92
	I		19.29	33.08	27.03	29.57	20.27	21.81
	II		19.75	34.29	29.46	25.59	20.26	23.78
	III		19.69	-	24.74	21.44	19.91	23.26
	IV		43.38	32.34	21.00	23.32	19.90	21.94
	V		23.38	-	-	-	19.57	19.58
	VI		20.74	-	-	-	19.63	20.40

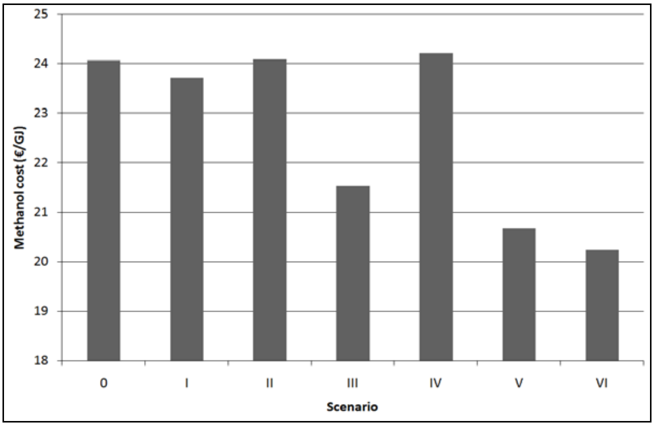

Figure 3: Average total costs in €/GJ$_{methanol}$ per scenario

4. DISCUSSION

A change in spatial agricultural land allocation for biomass production from 1,852 ha to 926 ha (scenario I) decreases biomass transport costs by about 23% (Table 6). The total cost of methanol including production, transports and distribution varies significantly for the plants 4 and 6: their optimal size would change in this case leading to an increase of the average costs by 14% (plant 4) and decline of 9% (plant 6) respectively. Although the potential production of poplar in Baden-Württemberg is well spread over the region and varies between 750 t/ha/year and 1,150 t/ha/year; changes in biomass availability have substantial influence on the competitiveness between methanol plants.

When, for instance, methanol plant 3 stops production for one month (scenario II) then the total costs increase by 10%. Further analyses have shown that a methanol plant would no longer be competitive if a shutdown is longer than 3 months.

An increase in biomass transportation costs by 80% for the methanol plant 2 (scenario III) would make this plant no longer competitive. Indeed the cost of the biomass transportation represents 17% of the total methanol production costs. Further analyses have shown that an increase of the biomass transportation costs by 40% would increase the total costs of plant 2 by 30% with an optimal plant size of 150 MW; over 40%, the plant 2 would no longer be competitive.

Increasing the biomass production costs from 40 to 50 €/m^3 for plant 1 (scenario IV) changes the plant sizes significantly; the plant 1 is then optimally smaller and the plants 3 and 6 are larger. The average production costs changes then consequently, but the mean production costs in the region are then stabilized from the other production plants (+0.6% from the base scenario).

In scenario V, the methanol plants located closer to the biomass supply areas will still be in operation and have larger plant sizes. The size of the plants would be higher than 350 MW, leading to a significant decrease of the average methanol costs (-14%) in the region.

Scenario VI uses the sizes of the methanol plants from scenario I, and assumes that the biomass supply is only available in the south-east corner of Baden-Württemberg. The same plants as in scenario IV are still in operation, and the average methanol costs in the region would decrease by 16% compared to scenario 0.

Ranking the scenarios according to total costs (Figure 3), scenarios VI and V reveal the lowest costs, where methanol is produced close to the feedstock, but the demand is not fully supplied due to limited feedstock availability in the south-east part of the region. Scenario IV gives the highest production costs, but the average costs are still close to the costs of the reference scenario (+0.6%); the increase of the feedstock costs would indeed reshape the optimal size of the plants which will offset this increase.

Even though the current paper has applied the model to a small region in Germany, the model itself can be applied to any region. However, the size of the region determines the spatial resolution of the data such that the number of integer variables can be solved with currently available optimization algorithms. Furthermore, the model results can be transferred to similar regions like Baden-Württemberg, which are quite densely populated. Therefore, feedstock costs, biomass transportation costs and biomass availability appear as the most important factors when optimizing the locations and sizes of plants in such regions. Moreover, the production of methanol shows large scale effects, which require well established infrastructures between biomass supplies and final product demands. Finally, the model can be expanded to optimize other bio-energy chains e.g. bio-ethanol or wood pellets.

5. CONCLUSIONS

A mixed integer programming model was developed and applied to find the optimal locations and sizes of the methanol production plants in a region. The major conclusions of the analysis are that shutting down a methanol plant for maintenance work has a big impact on the competitiveness of a plant. A closure of one month would increase the total cost by more than 10 percent, and a closure of more than 3 months would mean that the methanol plant is no longer competitive.

The feedstock costs have also a high impact on the optimal model solution; an increase by 25% will change the optimal size of the plants significantly. An increase in the biomass transportation costs by 80% for one plant would make this plant no longer competitive. In addition, the availability of biomass has also a substantial impact on the total costs: decreasing the agricultural land allocation from 1,852 ha to 926 ha decreases the biomass transport cost by 23%.

Biomass production and transportation costs as well as biomass availability appear to be most important factors in the optimal location of a methanol plant in a densely populated region.

6. REFERENCES

AMF-EA Engineering. Methanol Refueling Station Costs. Prepared for American Methanol Foundation. Prepared by EA Engineering, Science and Technology, Inc. Silver Spring. 1999.

Börjesson P, Gustavson L. Regional Production and Utilization of Biomass in Sweden. Energy 1996; 21; 9; 747-764.

Craig K, Mann M. Cost and Performance Analysis of Biomass-Based Integrated Gasification Combined-Cycle (BIGCC) Power Systems. National Renewable Energy Laboratory A national laboratory of the U.S. Department of Energy Managed by Midwest Research Institute; 1996.

Hamelinck C, Faaij A. Future Prospects for Production of Methanol and Hydrogen from Biomass. Utrecht University, Copernicus Institute, Science Technology and Society, Utrecht; 2001.

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

Ogden J, Steinbugler M, Kreutz T. A Comparison of Hydrogen, Methanol and Gasoline as Fuels for Fuel Cell Vehicles: Implications for Vehicle Design and Infrastructure Development. Journal of Power Sources 1999; 79; 143-168.

Parsons E, Shelton W, Lyons J. Advanced Fossil Power Systems Comparison Study. Final Report, prepared for: National Energy Technology Laboratory; 2002.

PPRC. The Pacific Northwest Pollution Prevention Resource Center. URL: http://www.pprc.org/pubs/altfuels.cfm; 2005.

Schmid E, Balkovic J, Moltchanova E, Skalsky R, Poltarska K, Müller B, Bujnovsky R. Bio-bysical Process Modelling for EU25 - Concept, Data, Methods and Results. Final Research Report for the EU-FP6 Research Project INSEA, International Institute of Applied System Analysis (IIASA), Laxenburg; 2006.

Sørensen Å. Economies of Scale in Biomass Gasification Systems. Interim Report IR-05-030, IIASA, Laxenburg; 2005.

Tijmensen M, Hooidonk G. 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; 2000.

Williams J. The EPIC Model. In Computer Models of Watershed Hydrology (eds. V.P. Singh). Water Resources Publication, Highland Ranch, Colorado; 1995. p. 909-1000.

Wolsey L. Integer Programming. John Wiley and Sons; 1998.

Article III

Optimal location of wood gasification plants for methanol production with heat recovery

INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. 2008; **32**:1080–1091
Published online 9 July 2008 in Wiley InterScience
(www.interscience.wiley.com). DOI: 10.1002/er.1446

Optimal location of wood gasification plants for methanol production with heat recovery

Sylvain Leduc[1,2,*,†], Dagmar Schwab[3], Erik Dotzauer[4], Erwin Schmid[3] and Michael Obersteiner[2]

[1]*Division of Energy Engineering, Luleå University of Technology, 97187 Luleå, Sweden*
[2]*International Institute for Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria*
[3]*Institute of Sustainable Economic Development, University of Natural Resources and Applied Life Sciences, Feistmantelstrasse 4, 1180 Vienna, Austria*
[4]*Department of Public Technology, Mälardalen University, 72123 Västerås, Sweden*

SUMMARY

Second generation biofuels from wood gasification are thought to become competitive in the face of effective climate and energy security policies. Cost competitiveness crucially depends on the optimization of the entire supply chain—field-wheel involving optimal location, scaling and logistics.

In this study, a linear mixed integer programming model has been developed to determine the optimal geographic locations and sizes of methanol plants and gas stations in Austria. Optimal locations and sizes are found by the minimization of costs with respect to biomass and methanol production and transport, investments for the production plants and the gas stations. Hence, the model covers competition in all levels of a biofuel production chain including supply of biomass, biofuel and heat, and demand for bio- and fossil fuels.

The results show that Austria could be self-sufficient in the production of methanol for biofuels like M5, M10 or M20, using up to 8% of the arable land share. The plants are optimally located close to the potential supply of biomass (i.e. poplar) in Eastern Austria, and produce methanol around $0.4\,€\,l^{-1}$. Moreover, heat production could lower the methanol cost by 12%. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: biofuel for vehicles; gasification; heat recovery; facility location; mixed integer programming; fossil fuel

1. INTRODUCTION

1.1. Background

The European energy policy is increasingly driven by considerations of climate change impacts and energy security issues. Therefore, the European Council has proposed that 15% of total energy consumption should be produced from renewable resources in 2015; for the European Parliament the share of renewable resources on total energy consumption should be even 25% in 2020. However, the EU-25 share of renewable resources on gross domestic energy consumption was about 6.3% in 2004 [1]. Consequently, the

*Correspondence to: Sylvain Leduc, International Institute for Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria.
†E-mail: leduc@iiasa.ac.at

Received 15 October 2007
Revised 14 January 2008
Accepted 18 March 2008

European Commission has published a renewable energy road map that supports an obligatory share of 20% in 2020. The road map emphasizes the importance of a regulatory and legal framework to encourage investments and outlines several measures that help to reach this target level [2]. So far, substantial progress in renewable energy has been made only in the electricity sector; the transport and the heat/cooling sectors are lagging behind their intermediate targets. Particularly, biofuels will need additional support to attain the EU target of 10% on total gasoline and diesel consumption in 2020. In 2007 all Member States were required to report national target levels of biofuels for 2010. Austria is currently aiming at a 10%-target level for biofuels in 2010 and one at 20% in 2020. In this study we investigate the potential of the realizations of these target levels, by analyzing a national methanol production chain for Austria.

1.2. Research objective

The energy chain of methanol production—harvesting, biomass transport, methanol production, methanol transport, methanol distribution—is analyzed (Figure 1). The cost of methanol is calculated and compared with one of the possible by-products, heat. The competition with fossil fuel is also taken into account as a competitor to biofuel.

In this study, the optimal geographical locations of the plants in Austria are determined by a mixed integer linear programming model [3]. The plants produce methanol and heat. The model minimizes the total costs of the energy chain described below by considering regional biomass supply, biomass production costs and demography in Austria.

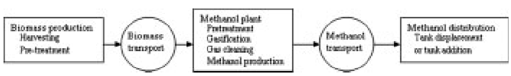

Figure 1. Methanol energy chain.

2. METHODOLOGY

2.1. The methanol production chain

2.1.1. Biomass supply. Biomass production of a short-rotational poplar coppice system has been modeled by Schmid *et al*. [4] using the latest version of the bio-physical process model EPIC† [5]. The poplar coppice system is fertilized with nitrogen only in the first 2 years of each rotation period. Biomass is harvested every 6 years over a simulation period of 30 years. It is assumed that poplar coppice can only be planted on agricultural lands with decent slopes ($<5\%$) to keep harvesting costs low. Biomass production costs typically depend on the choice of biomass crops, management system, land type or basic climate conditions. In this paper we do not use a biomass costing calculator but rather assumed, for reasons of comparability, a regional biomass price of 30 € m^{-3} including extraction and pretreatment.

2.1.2. Biomass transportation. The biomass transportation cost (in € TJ^{-1}) is described by Börjesson and Gustavson [6], and is represented by Equations (1) and (2), for truck transportations and tractor-trailer, respectively:

$$C_{\mathrm{Truck}} = 344 + 7.77d \tag{1}$$

$$C_{\mathrm{Tractor}} = 226 + 12.78d \tag{2}$$

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

2.1.3. Methanol production. Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following 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 [7]. A gas

†The EPIC model version EPIC3060 with the program code from 02/03/2006 is used for this analysis.

DOI: 10.1002/er

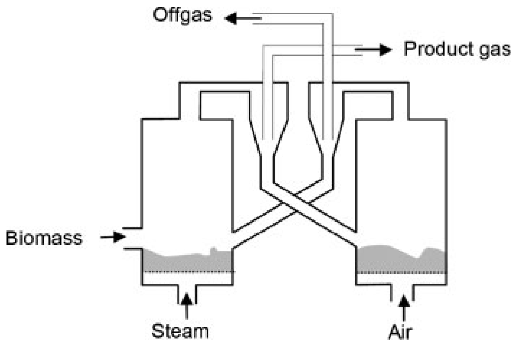

Figure 2. The indirectly heated, twin bed gasifier of Battelle Columbus Laboratory.

turbine or boiler is optional to employ the unconverted gas equipments for heat production (or a steam turbine for electricity co-production).

According to Hamelinck and Faaij [7], only circulating 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 analyzed two gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. In this paper an atmospheric indirectly fired gasifier of Battelle Columbus Laboratory [8] type is used. This gasifier is indirectly heated by a heat transfer mechanism as shown in Figure 2. Ash, char and sand are entrained in the product gas, separated using a cyclone and sent to a second bed where the char is burned in air to reheat the sand. The heat is transferred between the two beds by circulating the hot sand back to the gasification bed. This allows one to provide heat by burning some of the feed, but without the need to use oxygen because combustion and gasification occur in separate vessels. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production. Figure 3 presents the production chain of methanol [7].

The investment costs for different units of the base methanol plant (430 $\mathrm{MW_{biomass}}$) are listed in Table I. Scale effects strongly influence the unit cost per plant capacity, which decrease with larger plants or equipments (such as boilers, turbines, etc.). For example, a methanol plant of 100 MW can be expected to be cheaper per GJ of methanol produced than a 10 MW plant, even though both plants are based on the same technology. This difference can be adjusted using the scaling function:

$$\frac{\mathrm{Cost}_a}{\mathrm{Cost}_b} = \left(\frac{\mathrm{Size}_a}{\mathrm{Size}_b}\right)^R \tag{3}$$

where R is the scaling factor, Cost_a and Cost_b are the costs of equipments for the biofuel plants (*a*) and (*b*), respectively, and Size_a and Size_b are the sizes of the biofuel plants (*a*) and (*b*), respectively. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding investment costs from the separate units, the total investment cost for the new size is determined, and production cost for the current methanol plant size can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [7]. The uncertainty range of such estimates is up to $\pm 30\%$ [7]. Table I lists the scaling factors based on a 430 $\mathrm{MW_{biomass}}$ methanol plant.

The total capital requirement (TCR) for a process plant can be calculated from the process plant costs, as listed in Table II. The TCR provides an annual cost (AC) that is calculated using the following equation:

$$\mathrm{AC} = \frac{\mathrm{IR}}{1 - 1/(1+\mathrm{IR})^{t_e}}\mathrm{TCR} \tag{4}$$

where IR is the interest rate and t_e the economical lifetime or pay down period. The annual operating and maintenance costs are calculated as the sum of the elements listed in Table III. In this study the production of heat as a by-product is considered.

2.1.4. Methanol transportation. Depending on the quantity, infrastructure and distance, methanol can be transported by truck, train or ship. The costs of methanol transportation are calculated using figures from Börjesson and Gustavson [6]. The transportation cost by truck (in € $\mathrm{TJ}^{-1}_{\mathrm{methanol}}$) is a function of actual transportation distance, d, (in km):

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

DOI: 10.1002/er

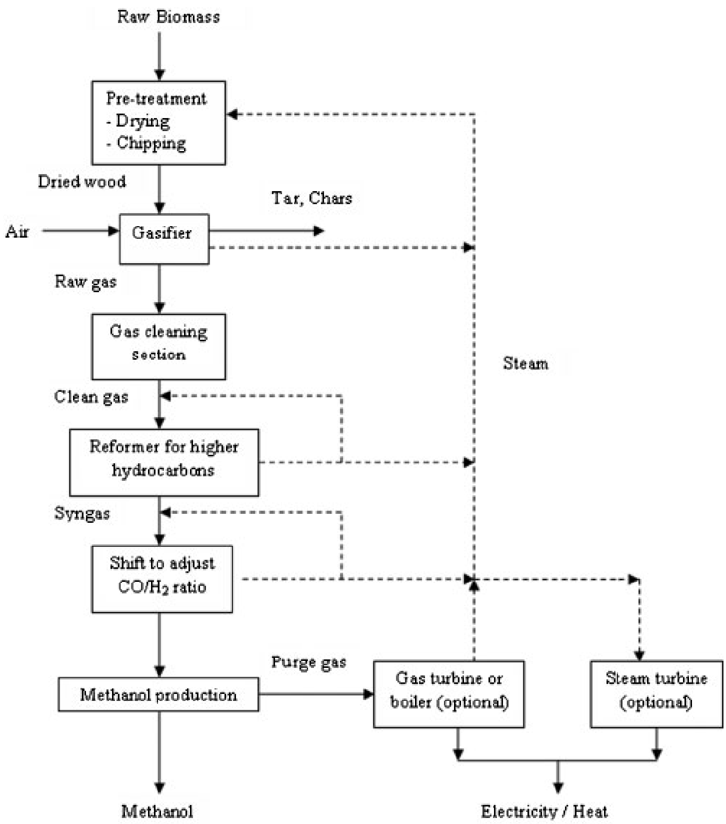

Figure 3. Process flow diagram of methanol production.

Table I. Base scale factors for a 430 $MW_{biomass}$ methanol plant [7].

Gasification system	R	Cost (M€)
Total pretreatment	0.79	31.4
Gasifier	0.65	25
Tar cracker	0.7	7.6
Cyclones	0.7	5.6
Heat exchanger	0.6	9.2
Baghouse filter	0.65	3.4
Condensing scrubber	0.7	5.6
Compressor	0.85	13.9
Steam reformer	0.6	37.8
Make-up compressor	0.7	14.3
Liquid phase methanol	0.72	3.6
Recycle compressor	0.7	0.3
Refining	0.7	15.7
Process plant cost (PPC)		173.4

The calculated cost might differ from the actual transportation cost, as the cost may be reduced due to discounts or special agreements [6]. In the calculations for transportation cost, these costs are scale-independent.

2.1.5. Methanol distribution. It is assumed that all the gas stations that are considered are able to distribute methanol. As methanol today is not widely used in the transportation sector, changes to gas stations would be required. One can consider a station that has three underground storage tanks of three grades of gasoline, two pump islands and four dispensers capable of refueling eight vehicles simultaneously. At an average fill-up of 51 l requiring 6 min, a station

DOI: 10.1002/er

Table II. Total capital requirement for a process plant [9,10].

Capital required	Description
Total plant cost (TPC)	
Engineering fee	10% of PPC
Process contingency	2.345% of PPC
General plant facilities	10% of PPC
Project contingency	15% of (PPC+general plant facilities)
Total plant investment (TPI)	
Adjustment for interest and inflation	0.34% of PPC
Total capital requirement (TCR)	
Prepaid royalties	0.5% of PPC
Start-up costs	2.7% of TPI
Spare parts	0.5% of TPC
Working capital	3% of TPI
Land, 200 acres	200 acres at 6500 € Acre^{-1}

Table III. Annual operating and maintenance costs [9,10].

Operating and maintenance (O&M)	Description
Wood	30 € m^{-3}
Operator labor	3% of TPI
Supervision and clerical labor	30% of O&M labor
Maintenance costs	2.2% of TPC
Insurance and local taxes	2% of TPC
Operating royalties	1% of wood cost
Miscellaneous operating costs	10% of O&M labor

such as the one illustrated may service between 200 and 400 vehicles per day and have a gasoline throughput of 321 760–643 520 l month^{-1} [11]. Two scenarios can be analyzed, one is to add a methanol capacity to an existing station, and the second one is to consider that methanol would displace a fraction of existing gasoline storage capacity.

The costs for handling a gas station of methanol with a capacity of 124 918 l month^{-1} are between 0.2031 and 0.2412 € $\text{GJ}^{-1}_{\text{methanol}}$ regarding the chosen scenario. The costs are assumed to be independent of the methanol plant size [11].

2.2. Model

This section formulates the problem as a facility location problem (FLP). Solving the problem will result in the optimal locations and sizes of the plants and gas stations. The model is defined as a mixed integer linear optimization problem. To simplify the presentation, the defined model considers one time period (year), but it can easily be generalized to be multi-periodic.

The parameter S is the number of biomass supply regions, P is the number of plants, G is the number of gas stations and D is the number of demand regions. The corresponding sets are: $\tilde{S} = \{1, \ldots, S\}$, $\tilde{P} = \{1, \ldots, P\}$, $\tilde{G} = \{1, \ldots, G\}$ and $\tilde{D} = \{1, \ldots, D\}$. Besides biofuel, a plant may be constructed to produce one or several additional commodities. Let C be the number of additional commodities and define $\tilde{C} = \{1, \ldots, C\}$ as the corresponding set. Heat is the only commodity considered in this study.

The following variables are defined: $b_{i,j}$ is the amount of biomass delivered from supply region i to plant j, $x^{\text{biofuel}}_{j,k}$ is the amount of biofuel delivered from plant j to gas station k and $x^{\text{biofuel}}_{k,l}$ is the amount of biofuel sold at gas station k to costumers from demand region l. The variable x^c_j represents the amount of commodity c that is produced at plant j. Heat is then a so-called by-product. The variable x^{fossil}_l is the amount of fossil fuel sold to costumers from demand region l. The variables $b_{i,j}$, $x^{\text{biofuel}}_{j,k}$, $x^{\text{biofuel}}_{k,l}$, x^c_j and x^{fossil}_l are non-negative. The binary variables u_j and u_k, respectively, indicate whether the plant j and the gas station k are in operation. If u_j (u_k) is equal to one, then the plant (station) is in operation, otherwise u_j (u_k) is zero.

The cost for producing biomass in supply region i is c_i. The biomass delivered from region i is restricted by

$$\sum_{j=1}^{P} b_{i,j} \leqslant \bar{b}_i, \quad i \in \tilde{S} \tag{6}$$

where $\bar{b}_i$ is the available biomass (defined here as a certain percentage of all available biomass in Austria). The cost for transporting biomass from supply region i to plant j is $t_{i,j}$.

Plant j is described by the following parameters and equations. The cost for building a plant with maximal biofuel capacity $\bar{x}^{\text{biofuel}}_j$ is e_j and the cost for producing in the plant is c_j. The biofuel production is thus restricted by

$$\sum_{k=1}^{G} x_{j,k}^{\text{biofuel}} \leqslant \bar{x}_j^{\text{biofuel}} u_j, \quad j \in \tilde{P} \tag{7}$$

The efficiency of producing methanol is a_j^{biofuel} giving

$$a_j^{\text{biofuel}} \sum_{i=1}^{S} b_{i,j} = \sum_{k=1}^{G} x_{j,k}^{\text{biofuel}}, \; j \in \tilde{P} \tag{8}$$

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

The corresponding equations for commodity c, e.g. heat, are

$$x_j^c \leqslant \bar{x}_j^c u_j, \quad j \in \tilde{P} \tag{9}$$

where $\bar{x}_j^c$ is the capacity, and

$$a_j^c \sum_{i=1}^{S} b_{i,j} = x_j^c, \quad j \in \tilde{P} \tag{10}$$

where a_j^c is the efficiency. The produced biofuel in plant j is transported to gas station k for the cost $t_{j,k}$. The value of producing commodity c is given by the price p_j^c.

The cost for setting up a gas station k with the capacity $\bar{x}_k^{\text{biofuel}}$ is e_k. The cost for handling biofuel at the station is c_k. Similar to the plant model, the gas station is also modeled using capacity and mass flow equations; i.e.

$$\sum_{l=1}^{D} x_{k,l}^{\text{biofuel}} \leqslant \bar{x}_k^{\text{biofuel}} u_k, \quad k \in \tilde{G} \tag{11}$$

and

$$\sum_{j=1}^{P} x_{j,k}^{\text{biofuel}} = \sum_{l=1}^{D} x_{k,l}^{\text{biofuel}}, \quad k \in \tilde{G} \tag{12}$$

must hold.

The demand for car fuel in region l is modeled by

$$\sum_{k=1}^{G} x_{k,l}^{\text{biofuel}} + x_l^{\text{fossil}} = d_l, \quad l \in \tilde{D} \tag{13}$$

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

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

$$\begin{aligned} f(b,x,u) = {} & \sum_{i=1}^{S} \sum_{j=1}^{P} (c_i + t_{i,j}) b_{i,j} + \sum_{j=1}^{P} e_j u_j \\ & + \sum_{j=1}^{P} \sum_{k=1}^{G} (c_j + t_{j,k}) x_{j,k}^{\text{biofuel}} \\ & + \sum_{j=1}^{P} c_j x_j^c - \sum_{j=1}^{P} p_j^c x_j^c + \sum_{k=1}^{G} e_k u_k \\ & + \sum_{k=1}^{G} \sum_{l=1}^{D} (c_k + t_{k,l}) x_{k,l}^{\text{biofuel}} \\ & + \sum_{l=1}^{D} p_l^{\text{fossil}} x_l^{\text{fossil}} \end{aligned} \tag{14}$$

The different summands in the objective function are:

(1) Cost of biomass production (parameter) plus the transportation cost (parameter) times the amount of biomass that is actually taken (variable).
(2) Plant setup cost (parameter) times the 'decision' (variable) of building a plant.
(3) Plant production cost (parameter) plus transportation cost of biofuel from the plant to the gas stations (parameter) times the amount of methanol being produced at the plant (variable).
(4) Plant production cost (parameter) times the amount of heat produced (variable).
(5) Minus the price of heat (parameter) times the amount of heat produced (variable).
(6) Plus the setup cost of gas stations (parameter) times the 'decision' (variable) of setting up a gas station.
(7) Gas station handling cost (parameter) plus transport cost from the gas station to the living area (parameter) times the amount of biofuel taken from the gas station (variable).
(8) Price of fossil fuel (parameter) times the amount of fossil fuel taken (variable).

DOI: 10.1002/er

Table IV. Parameters for the plants [12].

Parameters	Units	Value
Conversion methanol	%	60
Conversion heat	%	10
Load hours	h	7200
Interest rate	%	10
Economical lifetime	Years	25

Finally, define the FLP as a linear mixed integer program:

$$\begin{aligned}
&\min_{b,x,u}\,[f(b,x,u)]\\
&\text{s.t.}\\
&(6)-(14)\\
&\quad b_{i,j}, x_{j,k}^{\text{biofuel}}, x_j^c, x_{k,l}^{\text{biofuel}}, x_l^{\text{fossil}} \geqslant 0,\\
&\quad i \in \tilde{S}, j \in \tilde{P}, c \in \tilde{C}, k \in \tilde{G}, l \in \tilde{D}\\
&u_j \in \{0,1\}, u_k \in \{0,1\},\;\; j \in \tilde{P}, k \in \tilde{G}.
\end{aligned} \tag{15}$$

2.3. Input data and scenarios

Different positions of plants in Austria are used in the model. The possible plants studied are geographically distributed every 0.33° in longitude and latitude all over the country. The optimal geographical position will be selected for three scenarios. For each scenario, one considers alternatively the production of one kind of biofuel blend, M5, M10 and M20. The plants are defined by the parameters described in Table IV.

The price for heat is assumed to be $0.054\,€\,\text{kWh}^{-1}$ [13]. Once the plants are selected for each scenario, the competition with fossil fuel is conducted, and the influence of the production of heat and the raw material prices are analyzed. Finally, the consequence of the use of methanol blend on the carbon emissions is emphasized.

3. RESULTS AND DISCUSSION

3.1. Blend

In Austria, fossil fuel should be replaced by 10 and 20% biofuels by the years 2010 and 2020, respectively. To achieve these targets, different methanol–gasoline blends were studied: M5, M10 and M20. For each of these scenarios, the model finds the number of plants needed to fulfill the demand, their size and their location. The optimal locations of the methanol plants for the three scenarios of blends are presented in Table V together with their characteristics and different transport and production costs.

Austria had about 1 380 480 ha of arable lands in 2005. Producing M5, M10 or M20 would require 2.07, 4.08 or 8.19% of the arable lands respectively. Under these conditions, Austria would be self-sufficient in the production of methanol blend using poplar biomass. For the production of M10, two methanol plants were the optimal situation ahead of one bigger methanol plant. The same can be noticed for the production of M20, where three methanol plants were selected (Figure 4).

Concerning the transport costs, one can notice that for biomass they increase slightly as the capacities of the plants increase, since more raw materials are needed. At the same time the transport costs of the fuel decrease (from 2.04 to $1.31\,€\,\text{GJ}^{-1}$). The distances for delivering the biofuel remain high (over 460 km for each scenario), since the far west of the country has to be delivered. For every scenario, setting up a methanol plant closer to the biomass supply has been a better choice than building it closer to the fuel demand.

Meanwhile, the total cost of methanol decreases as the capacity of the plant increases. The cheaper methanol is found for two plants from the M20 scenario. For this scenario, one can notice that the third plant produces the most expensive fuel of the three scenarios; this plant also has the lowest capacity.

3.2. Geography and cost

The methanol cost depending on the geographical position of the plant for the M5 scenario is shown in Figure 5. These costs are calculated by assuming a virtual plant at each grid point alternatively. The calculations were also carried out for each result of the other scenarios presented in Table V, which gave similar maps.

Table V. Results of the optimal location of the methanol plant in Austria for different methanol blends.

	Units	M5	M10	M10	M20	M20	M20
Longitude		13.99	13.99	15.97	13.99	16.63	15.97
Latitude		48	48	48.33	48	48.33	48.33
Capacity	$t_{biomass}\,day^{-1}$	846	928	765	1429	1231	725
Methanol production	$m^3\,year^{-1}$	143 891	287 781			575 562	
Area of arable land	ha	26 400	54 300			110 600	
Arable land share	%	2.1	4.1			8.2	
Biomass transports							
Mean	€ GJ^{-1}	1.60	1.62	1.56	1.73	1.61	1.55
Max	€ GJ^{-1}	1.80	1.83	1.71	2.05	1.78	1.70
Max distance	Km	25.3	26.9	21.3	37.3	24.5	20.6
Production costs	€ GJ^{-1}	16.58	15.13	18.33	12.41	14.42	19.36
Fuel transports							
Mean	€ GJ^{-1}	0.91	0.88	0.58	0.95	0.75	0.68
Max	€ GJ^{-1}	2.04	2.04	1.31	2.04	1.76	1.52
Max distance	Km	461	461	285	461	394	336
Fuel cost							
Min	€ GJ^{-1}	22.33	20.91	24.04	18.30	20.19	25.07
Max	€ GJ^{-1}	24.18	22.72	25.16	20.15	21.75	26.40
Mean	€ GJ^{-1}	23.05	21.54	24.44	19.06	20.74	25.56
Max	€ l^{-1}	0.38	0.36	0.40	0.32	0.33	0.42
Extra products (heat)	GWh $year^{-1}$	126	138	114	213	183	108

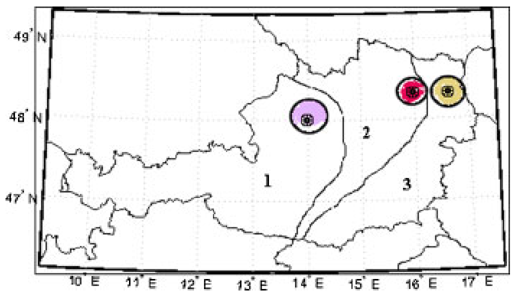

Figure 4. Geographical results for the production of M20 in Austria: the dots inside the circles represent the arable land that could possibly deliver the raw material to the plants (represented by the stars). The areas 1–3 represent the three zones where each plant would deliver methanol.

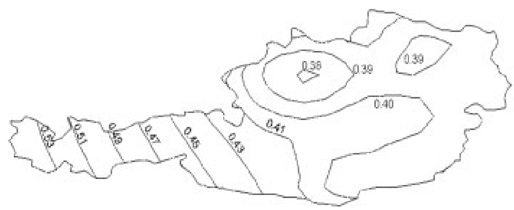

Figure 5. Cost of methanol (in € l^{-1}) regarding the position of a 846 $t_{biomass}\,day^{-1}$ plant. A methanol–gasoline blend M5 is considered.

Figure 5 presents the areas for different costs of methanol regarding the location of the plant, for the M5 blend. The lowest production cost would then be obtained with the plant located in the north of the country, where the total methanol cost is around 0.38 € l^{-1}. This area corresponds to the area selected by the model (Table V). The figure shows that a change in the position of the plant could vary the cost by 2.5% (from the 0.38 to the 0.39 € l^{-1} area). Thus, changes in positions within a cost area will influence the methanol cost less than 2.5%.

3.3. Biofuel versus gasoline

Gasoline has an energy density of 32 MJ l^{-1}. Pure methanol has an energy density of 15.7 MJ l^{-1}. A higher amount of methanol is then needed to drive the same distance as with gasoline. Hence, the

DOI: 10.1002/er

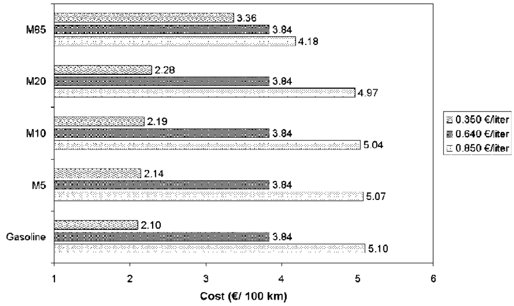

Figure 6. Costs of different methanol blends in €/100 km, for three gasoline prices (0.35, 0.64 and 0.85 € l^{-1}) and a methanol cost of 0.3 € l^{-1}.

methanol and gasoline costs are important for the choice of fuel by the costumer.

Figure 6 presents the cost in €/100 km for gasoline and methanol blends (M5, M10, M20 and M85). The gasoline consumption of a personal car is here assumed to be 5 l/100 km. This figure compares the cost of pure conventional gasoline with biofuel, i.e. methanol blends.

The break even point is for a cost of gasoline of 0.640 € l^{-1}, where all the fuels have the same cost (3.84 €/100 km). The break even line between gasoline and the different methanol blends is reached when the ratio of the methanol cost over the gasoline cost equals the ratio of the methanol energy density over the gasoline energy density. In other words, as soon as the cost of gasoline is over 0.640 € l^{-1} (assuming the methanol cost is 0.3 € l^{-1}), driving with a higher blend of methanol would be more attractive than driving with gasoline.

3.4. Methanol production with heat recovery

From the production of methanol, one can consider the production of heat as a by-product. Producing heat has the advantage for the methanol plant to have extra income. Heat can be sold to a heating network or to some nearby factories. The influence of heat sale on the methanol cost is presented in Table VI.

Considering the heat production in the methanol plant with an efficiency of 10%, the

Table VI. Consideration of heat in the methanol cost for different blends.

	Units	M5	M10	M20
Initial cost	€ l^{-1}	0.393	0.375	0.352
Heat	GWh $year^{-1}$	126	138	168
Adapted cost	€ l^{-1}	0.345	0.327	0.304

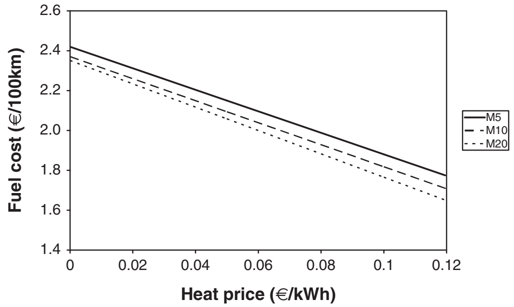

Figure 7. Impact of heat prices on the cost of methanol for three methanol blends.

fuel cost would decrease about 12%. How fuel costs are influenced with respect to heat prices for different methanol blends is shown in Figure 7.

As the heat price increases, the plant would earn extra incomes, and thus the fuel costs decrease. For instance, an increase of the heat price by 30% would reduce the costs of M5 by 16%, M10 by 18% and M20 by 20%. In order to sell the most competitive methanol as possible, production with heat recovery would help the plant reducing its costs. Selling excess heat would be one mean to reach this goal. The location of the methanol plant should then be decided regarding the heat demand in the area either from private consumers or from industrial needs.

3.5. Biomass cost influence

The cost of biomass is the parameter that has the greatest influence on the final products. A sensitivity analysis on biomass production costs reveals the impact and the economic viability of a plant. In this analysis, biomass costs vary between 30 and 120 € m^{-3} (Figure 8).

DOI: 10.1002/er

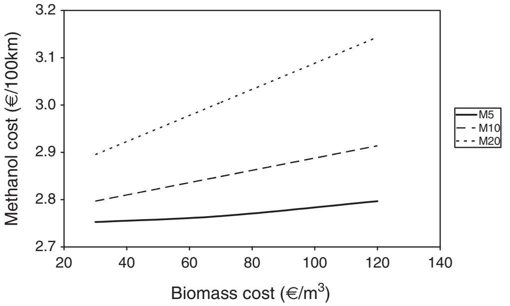

Figure 8. Influence of biomass production costs on the methanol cost for three methanol blends.

One should notice that an increase of 50% in biomass production costs will raise the cost of M5, M10 and M20 by 0.5, 2 and 4%, respectively. The production of M20 would be the most sensible as it requires more biomass. For these three blends, the costs of biomass production and biomass transport represent 24, 37 and 49% of the total methanol cost.

3.6. Carbon emissions

Different CO_2 emissions (as well as elemental carbon) per fuel are presented in Table VII. From this table, one can notice that the emissions of carbon or CO_2 would decrease by 2.5, 5.2 and 11% if one uses M5, M10 or M20, respectively. To achieve the goal set by the European Parliament, a blend of gasoline with 33% methanol would be necessary to decrease the carbon emissions (from cars only) by 25%. It was totalized in 2005, 5.6 million cars in Austria [14]. Figure 9 shows how emissions reduction and carbon price are depending on each other regarding the methanol blends.

In the figure one assumes that all the cars run with a methanol blend. Considering M20, this would decrease the CO_2 emissions by 1.7 Mt year^{-1}, which is equivalent to 2% of the total Austrian carbon emissions in 2003 [15]. The total saving on the use of M20 would amount to 9 M€ year^{-1} in carbon cost. The carbon emissions and emission cost would be lower for higher methanol blends; i.e. if one considers M85, the emissions would be decreased to 4 Mt year^{-1} of CO_2 and the cost reduction becomes 60 M€ year^{-1}.

Table VII. Emissions from different fuels and difference between gasoline and the methanol blends expressed in carbon prices (a carbon price of 20 € t^{-1} is assumed).

Fuel	CO_2 emissions (kg/100 km)	Carbon emissions (kg/100 km)	Carbon cost (€/100 km)
Gasoline	18.57	5.07	—
M5	18.10	4.94	−0.003
M10	17.61	4.80	−0.005
M20	16.54	4.51	−0.011

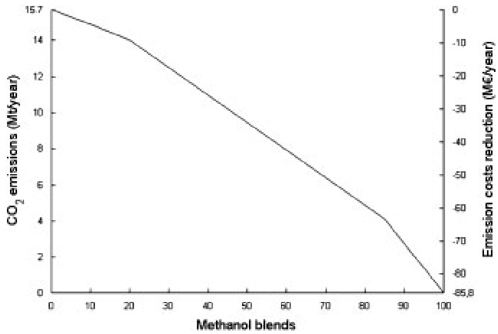

Figure 9. CO_2 emissions and emission price reduction in regard to the methanol blends.

4. CONCLUSIONS

This article presents a mixed integer linear programming model that determines the optimal sizes and locations of biomass-based methanol plants with heat recovery. The supply in raw material is characterized by the location and the yield of poplar coppice, and the demand in car fuel is characterized by the location of the gas stations in the studied country. Owing to new EU goals, biofuel will probably be introduced in large-scale all over Europe. It is thus important to optimize the investment and operation costs, which include the whole energy chain from biomass supply to delivery of methanol at the gas stations. The model presented in the current paper was found to be a useful tool in this planning process.

Three scenarios for optimal locations of methanol plants in Austria have been studied. For each scenario, different blends of methanol were analyzed. Producing methanol blends M5, M10 or M20 from poplar biomass would require about 2, 4 or 8% of total arable lands in Austria, respectively. Consequently, Austria has the potential in supplying domestic biomass to attain the national biofuel targets of 10 and 20% in 2010 and 2020.

By-production of heat decreases the biofuel cost by 12%. This would have a great impact concerning the cost of blends to become more competitive with fossil fuel. An increase of the heat price by 30% would decrease the cost of M20 by 20%. The Austrian carbon emissions are considered. With the use of the biofuel M20, the Austrian total emissions could decrease by 2%, and would lower the cost on fossil fuel emissions by 9 M€ year^{-1}.

An extension of the model would be to study the production of power and analyze the price and the demand of each product.

NOMENCLATURE

a_j^{biofuel} = efficiency for producing biofuel at the plant j
a_j^c = efficiency for producing commodity c at the plant j
AC = annual cost (€ year^{-1})
$\bar{b}_i$ = available biomass at the supply region i (t)
$b_{i,j}$ = amount of biomass delivered from supply region i to plant j (t)
c_i = cost for producing biomass in the supply region i (€ t^{-1})
c_j = cost for producing biofuel at the plant j (€ GJ^{-1})
c_k = cost for handling biofuel at the gas station k (€ GJ^{-1})
C = number of additional commodities
$\tilde{C}$ = set of additional commodities
C_{Tractor} = transportation cost by tractor (€ GJ^{-1})
C_{Truck} = transportation cost by truck (€ GJ^{-1})
Cost_a = cost of equipment for the plant a (€)
Cost_b = cost of equipment for the plant b (€)
d = actual distance (km)
d_l = demand of car fuel in the region l (GJ)
D = number of demand regions
$\tilde{D}$ = set of demand regions
e_j = cost for setting up plant j (€)
e_k = cost for setting up gas station k (€)
G = number of gas stations
$\tilde{G}$ = set of gas stations
IR = interest rate
p_j^c = price of the commodity c produced at the plant j (€ GJ^{-1})
p_l^{fossil} = price of fossil fuel in the region l (€ GJ^{-1})
P = number of plants
$\tilde{P}$ = set of plants
R = scaling factor
S = number of biomass supply regions
$\tilde{S}$ = set of biomass supply regions
Size_a = size of the biofuel plant a ($\text{MW}_{\text{biomass}}$)
Size_b = size of the biofuel plant b ($\text{MW}_{\text{biomass}}$)
t_{e} = economical lifetime (years)
$t_{i,j}$ = cost for transporting biomass from supply region i to plant j (€ t^{-1})
$t_{j,k}$ = cost for transporting biofuel from plant j to gas station k (€ GJ^{-1})
$t_{k,l}$ = transportation cost from gas station k to region l (€ GJ^{-1})
TCR = total capital requirement (€)
u_j = binary variables, indicate if the plant j is in operation
u_k = binary variables, indicate if the gas station k is in operation
$\bar{x}_j^{\text{biofuel}}$ = capacity of the plant j (GJ)
$\bar{x}_k^{\text{biofuel}}$ = capacity of the gas station k (GJ)
$\bar{x}_j^c$ = capacity of commodity c at the plant j (GJ)
x_j^c = amount of commodity c that is produced at plant j (GJ)
$x_{j,k}^{\text{biofuel}}$ = amount of biofuel delivered from plant j to gas station k (GJ)
$x_{k,l}^{\text{biofuel}}$ = amount of biofuel sold at gas station k to costumers from demand region l (GJ)

DOI: 10.1002/er

x_l^{fossil} = amount of fossil fuel sold to costumers from demand region l (GJ)

Subscripts

i = biomass supply number
j = plant number
k = gas station number
l = demand region number

Superscript

c = commodity number

ACKNOWLEDGEMENTS

This study was sponsored by the GEO-BENE project coordinated at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

REFERENCES

1. EUROSTAT. Data of various years available online at http://epp.eurostat.ec.europa.eu (accessed on 26 February 2007).
2. COM 2006. *Renewable Energy Road Map—Renewable Energies in the 21st Century*: *Building a More Sustainable Future*. Communication from the Commission to the Council and the European Parliament, 2007. COM(2006) 848 final.
3. Wolsey LA. *Integer Programming*. Wiley: New York, 1998.
4. Schmid E, Balkovic J, Moltchanova E, Skalsky R, Poltarska K, Müller B, Bujnovsky R. Bio-physical process modeling for EU25—concept, data, methods and results. *Final Research Report for the EU-FP6 Research Project INSEA*, International Institute of Applied System Analysis (IIASA), Laxenburg, Austria, 2006.
5. Williams JR. The EPIC model. In *Computer Models of Watershed Hydrology*, Singh VP (ed.). Water Resources Publication: Highland Ranch, CO, U.S.A., 1995; 909–1000.
6. Börjesson P, Gustavson L. Regional production and utilization of biomass in Sweden. *Energy* 1996; **21**(9):747–764.
7. Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. *Journal of Power Sources* 2002; **111**:1–22.
8. Katofsky RE. *The Production of Fluid Fuels from Biomass*. Center for Energy and Environmental Studies/Princeton University: Princeton, 1993.
9. Craig KR, Mann MK. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems. *Report from National Renewable Energy Laboratory*, Golden, CO, 1996. NREL/TP-430-21657.
10. Parsons EL, Shelton WW, Lyons JL. Advanced fossil power systems comparison study. *Final Report*, prepared for National Energy Technology Laboratory, Morgantown, U.S.A., 2002.
11. AMF-EA Engineering. *Methanol Refueling Station Costs*. Prepared for American Methanol Foundation by EA Engineering, Science and Technology, Inc., Silver Spring, U.S.A., 1999.
12. Hansson J. Combined heat/power plants versus the co-generation of heat and alternative transportation fuels—an energy-economy model based evaluation of cost-efficiency for the EU. *Thesis for Master of Science in Environmental Science with an Emphasis on Problem Solving*, Chalmers University of Technology, Sweden, 2003.
13. Ecoheatcool and Euroheat & Power. Ecoheatcool work package 1. The European heat market. *Final Report*, 2006.
14. Statistik Austria. http://www.statistik.at (accessed on 03 March 2007).
15. UNEP/GRID—Arendal, United Nations Environment Programme. http://www.grida.no (accessed on 05 March 2007).

DOI: 10.1002/er

Article IV

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

Applied Energy xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

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

S. Leduc [a,b,*], J. Lundgren [a,b], O. Franklin [a], E. Dotzauer [c]

[a] International Institute for Applied System Analysis (IIASA), A-2361 Laxenburg, Austria
[b] Division of Energy Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden
[c] Mälardalen University, SE-721 23 Västerås, Sweden

A R T I C L E I N F O

Article history:
Received 16 May 2008
Received in revised form 10 February 2009
Accepted 10 February 2009
Available online xxxx

Keywords:
Plant location
Methanol
Forestry-based biomass
Gasification
Heat
Mixed integer programming

A B S T R A C T

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

Contents

* Corresponding author. Address: International Institute for Applied System Analysis (IIASA), A-2361 Laxenburg, Austria. Tel.: +43 2236 807 267; fax: +43 2236 807 599.
E-mail address: leduc@iiasa.ac.at (S. Leduc).

0306-2619/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2009.02.009

1. Introduction

The greenhouse gas emissions from the transport sector represent a large share of the current total anthropogenic emissions, of which road transport is expected to be the largest by 2050 [1]. An increased utilization of bioenergy constitutes one of the key alternatives to replace fossil fuels and mitigate greenhouse gas emissions. At present, different routes for biomass based heat and power production are established in a variety of markets, but only a small amount of liquid biofuels is produced.

Substituting fossil fuels in the transportation sector does not only serve the purpose to mitigate the climate impact, but also to decrease the oil dependency and thereby increase the energy supply security. The global transport sector is today highly dependent on fossil fuels and the introduction of biofuels is an important measure to reduce the CO_2 emissions in this sector. The European Commission has set a target that renewable energies should constitute 5.75% of the sold volume of transport fuels in Europe by the year 2010 [2] and 10% by the year 2020 [3].

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

The costs for the feedstock, the feedstock transportation, the methanol production and the methanol transportation represent approximately 26%, 16%, 46% and 12% of the total production cost respectively; if only truck transportation is considered for a 100 $MW_{biomass}$ plant [5]. These cost shares may differ significantly depending on where the methanol plant is located relative to the feedstock and the gas stations. It is therefore of great importance to build the plants at proper locations and in appropriate sizes to minimize the transportation cost and thereby also reduce the total production cost.

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

2. Methodology

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

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

2.1. Automotive fuel demand

The future development of the automotive fuel demand is strongly depending on demographic changes, changes in car travel

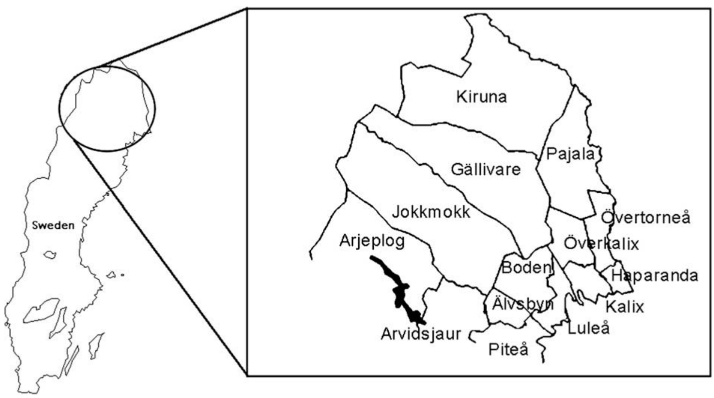

Fig. 1. Maps over the county of Norrbotten subdivided in different municipalities.

habits, infrastructure as well as the technological development of the cars, in particular the fuel efficiencies of the engines. The total transportation fuel demand (E_{fuel}) has been assessed according to Eq. (1):

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

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

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

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

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

According to the European Commission, renewable sources are to account for 20% of the total energy consumption within the EU, of which biofuels should account for at least 10% of the motor fuel consumption by the year 2020 [7]. Partly due to the abundant resources of biomass in the county of Norrbotten, an even more challenging target of 20% biofuels was set in the BAU scenarios. Assuming that the same required growth rate to reach that target continues, the biofuel demand in the year 2025 becomes 27%. Regarding the development of the gasoline and diesel share, the BAU scenarios assume that the present trends continue, which leads to that the gasoline- and fossil diesel shares amount to 51% and 22%, respectively. The Green scenarios assume that biofuels constitutes as much as 75% of the total demand. Regarding gasoline and diesel, the shares in the year 2025 is assumed to be 8% and 17%, respectively.

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

Fig. 2 describes the total fuel demand as well as the assumed evolution of the fuel shares (gasoline, diesel and biofuel) from the year 2004 to 2025. As seen in the figure, the two reference

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

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

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

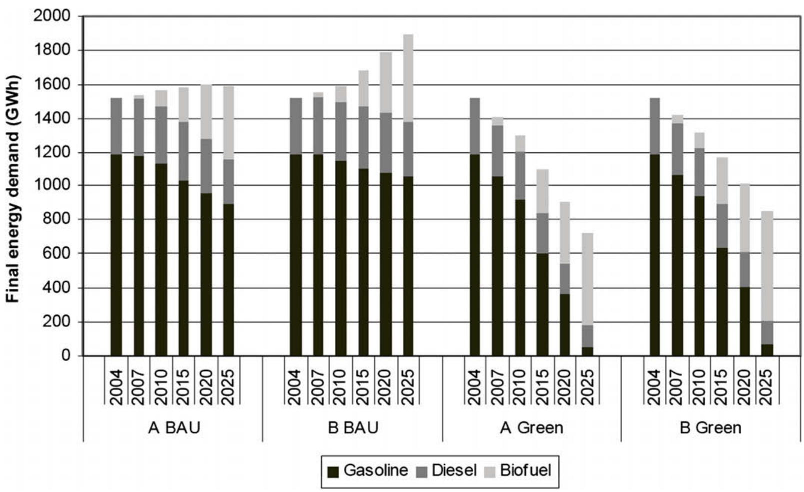

Fig. 2. Total fuel demand for private transport by car in Norrbotten until the year 2025 according to the four scenarios.

scenarios (BAU) show an increasing motor fuel demand, while the alternative ones (Green) show a significant reduction. Based on the assumed shares, the biofuel demand will be in the range of 430–640 GWh (1.55–2.30 PJ) per year in the year 2025 in the county of Norrbotten.

2.2. Methanol production chain

2.2.1. Potential biomass supply

The estimation of the future potential biomass production is based on data from a forest inventory [8], which comprises about 12,000 forest plot measurements arranged in clusters of around nine circular plots (about 0.007 ha each). For each plot, biomass and biomass-growth per hectare of the three most abundant tree species (Norway spruce, Scots pine, and birch) and other deciduous trees are reported. Each plot is representative of a surrounding forest area, which varies in size between plots and is not geographically explicitly defined. These forest inventory data were converted to a geographically explicit grid using the following method: the whole study area was divided into equally sized grid-cells, 10×10 km. For each inventory plot and tree species, the representative forest area was assumed to be circular and centered in the location of the plot. The circular forest areas of the plots were then laid over the grid-cells and distributed to the grid-cells covered according to the area covering each grid-cell.

Biomass productivity was estimated for each grid-cell and tree species using the plot data assigned to each cell (2–50 plots per cell), where each data point (plot) was weighted by the forest area it covers in the grid-cell. By fitting the set of biomass, age and biomass-growth data points for each grid-cell to species specific biomass growth functions [9], site productivity and the mean biomass production over time was estimated. In this estimation it was assumed that the forest management (for example thinning intensity) is not changed, and that forest stands are harvested at an age that maximizes harvested biomass over time. The biomass growth functions used in the estimation relate growth to biomass, age, stand density and site productivity and have been parameterized for all included species using an extensive set of yield table data [9]. In this paper a regional biomass price of 35 €/m^3 (0.02 €/kWh) was assumed to be constant for the complete time period, (a sensitivity analysis on the price is performed in Section 4.3). This is the average value of the wood price in northern Sweden from 2002 to 2007 [10].

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

2.2.2. Biomass transportation

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

$$C_{\mathrm{Truck}} = 344 + 7.77d \quad (2)$$

$$C_{\mathrm{Tractor}} = 226 + 12.78d \quad (3)$$

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

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

The actual distance (in km) to the methanol plant, d, is defined as the direct distance multiplied by the estimated ratio of actual road length to direct distance (this ratio is estimated to an average value of 1.4 for Norrbotten). These values correspond to the transportation costs if the biomass is extracted from the surrounding areas.

2.2.3. Methanol production

Methanol can be produced from biomass via different gasification technologies. The methanol production facilities typically consist of the following steps: fuel pre-treatment, gasification, gas cleaning, reforming of higher hydrocarbons, shift to obtain appropriate H_2:CO ratios, and gas separation for methanol synthesis and purification [12]. A boiler is optional to employ the unconverted gas for heat production (or a turbine for electricity co-production). According to Hamelinck and Faaij [12], only circulating fluidized bed gasifiers are feasible for large-scale fuel gas production. This conclusion is based on an analysis of throughput, cost, complexity and efficiency issues. They have analyzed two types of circulating fluidized bed gasifiers for methanol production: a pressurized direct oxygen fired gasifier and an atmospheric indirectly fired gasifier. The latter type is selected in this study. In this gasifier, ash, char and sand are entrained in the product gas, separated using a cyclone, and sent to a second bed where the char is burned in air to reheat the sand. The heat is transferred between the two beds by circulating the hot sand back to the gasification bed. This allows one to provide heat by burning a part of the fuel, but without oxygen supply as combustion and gasification occur in separate vessels. The gasifier is fired by air and there is no risk of nitrogen dilution or need for oxygen production [12]. In this study, it is assumed that the blending of methanol with gasoline to suitable mixtures, e.g. M85 containing an 85% share of methanol, is performed on site immediately after the methanol production process.

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

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

where R is the scaling factor, $Cost_a$ and $Cost_b$ are the costs of equipments for the biofuel plant (a) and (b), respectively, and $Size_a$ and $Size_b$ are the sizes of the biofuel plant (a) and (b), respectively. Using this information it is possible to calculate costs for different processing steps of methanol plants with different sizes. By adding the costs of the separate units, the total investment cost for the new size is determined, and production cost for the current methanol plant size can be calculated. For biomass systems, R is usually between 0.6 and 0.8 [13]. The uncertainty range of such estimates is up to ±30% on investment costs [12].

2.2.4. Methanol transportation

The transport infrastructure in Norrbotten is mainly suitable for trucks all over the county. The costs of methanol transportation by truck are calculated using figures from Börjesson and Gustavson [11]. The transportation cost by truck (in €/TJ$_{\mathrm{methanol}}$) is described in Eq. (5):

$$C_{\mathrm{Truck}} = 138 + 3.05d \quad (5)$$

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

2.2.5. Methanol distribution

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

2.3. Model

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

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

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

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

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

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

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

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

The plant is modeled using an energy balance equation,

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

where η_j is the plant efficiency. The relations between the biofuel and the commodities produced are modeled using parameters ρ^{c}_{j}, giving

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

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

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

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

and

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

must hold.

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

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

where $d_{l,y}$ is the demand calculated from Eq. (1). The corresponding transportation cost is $t_{k,l,y}$, which shall be interpreted as the driving cost for people driving from region l to gas station k. The fossil fuel is assumed to be available for a price $p^{fossil}_{l,y}$.

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

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

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

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

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

and

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

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

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

Finally, define the Facility Location Problem as

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

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

3. Case study

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

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

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

The district heating demand is also considered in the model. Table 3 shows the current heat demand of each municipality in the county with their different heat price. From Table 4 one can find the change in the heat demand for the four scenarios, within the whole county. It is further assumed that the heat demand and price are fluctuating at the same rate all over the county and that existing district heating network can be used without any restrictions. Moreover, it is assumed that 10% of the total fuel input to the plant becomes residual heat that can be sold as district heating within a 30 km radius from the plant.

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

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

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

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

4. Results and discussion

4.1. Results without district heat production

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

4.2. Results with district heat production

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

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

4.3. Sensitivity analysis

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

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

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

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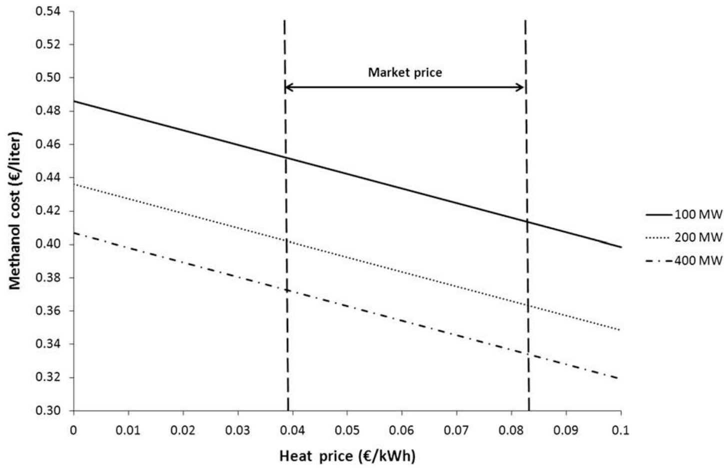

Fig. 3. Influence of the heat price on the methanol cost.

to be 0.01 €/kWh, and is presumed to increase until 2025 at the same rate as the heat price in the other municipalities of the county. The influence on the final methanol cost and the plant position from those parameters is analyzed for each plant size and each energy demand scenario. The scenarios studied in the sensitivity analysis are presented in Table 6.

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

Table 6
Parameters used in the sensitivity analysis.

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

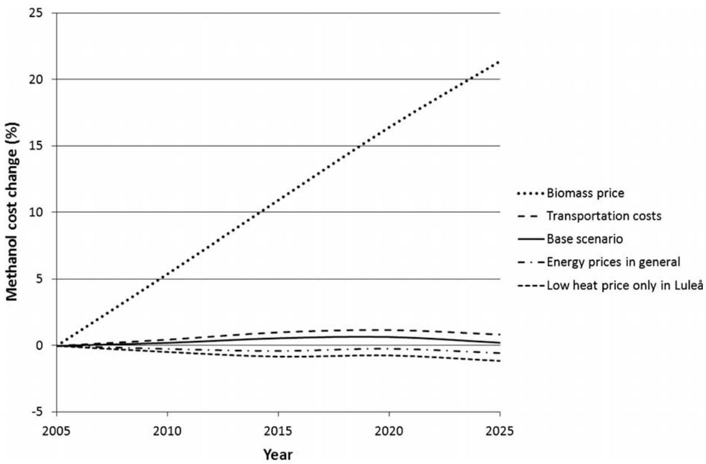

Fig. 4. Results from the sensitivity analysis: the change in percent of the methanol cost for the 100 MW plant and demand scenario A-BAU, from 2005 to 2025 in comparison with the 2005 level.

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

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

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

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

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

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

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

4.4. Influence on emissions

When the plant considers district heat production, the optimal position of the plant will be located closer to the heat demand, which implies changes in distances for the biomass and biofuel transportation. The emissions from the road transports are therefore affected. Table 8 presents the increase of emissions from the transportation of the feedstock and the produced biofuel if a plant is built in Luleå instead of in Boden. This change of position would increase the emissions of CO_2 by 2031 t/year. This represents approximately 0.7% of the total CO_2 emissions from the road traffic in Norrbotten [16]. Emissions of nitrogen oxides (NO_x), particulate matters (PM), hydrocarbons (HC) and carbon monoxide (CO) are also presented in the table.

5. Concluding discussion

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

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

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

References

[1] Fuglestvedt J, Berntsen T, Myhre G, Rypdal K, Skeie RB. Climate forcing from the transport sectors. Proc Natl Acad Sci USA 2008;105(2):454–8.
[2] Commission of the European Communities. Communication from the commission to the European parliament, the council, the economic and social committee and the committee of the regions on alternative fuels for road transportation and on a set of measures to promote the use of biofuels. COM; 2001. 547p.
[3] Commission of the European Communities. Communication from the Commission to the European Council and the European Parliament, an Energy Policy for Europe. Brussels; 2007.
[4] Bram S, De Ruyck J, Lavric D. Using biomass: a system perturbation analysis. Appl Energy 2009;86:194–201.
[5] Sørensen ÅL. Economies of scale in biomass gasification systems. IIASA, interim report; 2005, IR-05-030.
[6] Lundgren J, Pettersson T. FOCUS – Energy resources in Norrbotten [FOKUS – Norrbottens energiresurser]. Norrbottens energikontor AB (NENET); 2007 [in Swedish].
[7] Swedish Environmental Objectives Council. Sweden's environmental objectives – in an interdependent world. Progress report from the Swedish Environmental Objectives Council; 2007.
[8] The Swedish National Forest Inventory. Department of Forest Resource Management, Swedish University of Agricultural Sciences. <www.riksskogstaxeringen.slu.se> [01.10.07].
[9] Franklin O. Modeling forest production and carbon storage potentials in response to management in the European Union 2005–2050. In: Obersteiner et al, editor. INSEA EU FP 6; 2006. Project SSPI-CT-2003/503614.
[10] Statistical Yearbook of Forestry 2007. Official statistics of Sweden. Jönköping: Swedish Forest Agency; 2007.
[11] Börjesson P, Gustavson L. Regional production and utilization of biomass in Sweden. Energy 1996;21(9):747–64.
[12] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. Utrecht, Netherlands: Utrecht University, Copernicus Institute, Science Technology and Society; 2001.
[13] Tijmensen M, Hooidonk GV. Long term perspectives for production of fuels from biomass; integrated assessment and RD&D priorities – final results. Utrecht, Netherlands: Utrecht University, Copernicus Institute, Science Technology and Society; 2000.
[14] AMF-EA. Engineering. Methanol refueling station costs. Prepared for American methanol foundation. Prepared by EA engineering, science and technology, Inc. Silver Spring. US; 1999.
[15] Wolsey LA. Integer programming. John Wiley and Sons; 1998.
[16] Swedish Statistics. Annual energy balances by region, category, energy carrier and time. <www.h.scb.se/scb/mr/enbal/database/energi/Balanser/Balanser_lan.asp> [15.10.07].
[17] The Swedish Energy Agency, Energimyndigheten. Långsiktsprognos 2006 – Enligt det Nationella Systemet för Klimatrapportering. ER 2007:02; 2007 [in Swedish].
[18] Nils Holgersson. Avgiftsundersökningen, 2007. <www.nilsholgersson.nu/Arkiv.asp> [11.12.08].
[19] Swedish District Heating Association, Statistics 2004, February 2006. <www.svenskfjarrvarme.se> [10.10.07].

Please cite this article in press as: Leduc S et al. Location of a biomass based methanol production plant: A dynamic problem ... Appl Energy (2009), doi:10.1016/j.apenergy.2009.02.009

Article V

Optimal location of ethanol ligno-cellulosic biorefineries with poly-generation in Sweden

OPTIMAL LOCATION OF ETHANOL LIGNO-CELLULOSIC BIOREFINERIES WITH POLYGENERATION IN SWEDEN

S. Leduc[1, 2, *], F. Starfelt[3], E. Dotzauer[3], G. Kindermann[1], I. McCallum[1], M. Obersteiner[1], J. Lundgren[2]

[1] International Institute for Applied System Analysis, A-2361 Laxenburg, Austria
[2] Division of Energy Engineering, Luleå University of Technology, SE-97187 Luleå, Sweden
[3] School of Sustainable Development of Society and Technology, Mälardalen University, SE-72123 Västerås, Sweden

Abstract

The integration of ethanol production with combined heat and power plants is considered in this paper. An energy balance process model has been used to generate data for the production of ethanol, electricity, heat and biogas. The geographical position of such plants becomes of importance when using local biomass and delivering transportation fuel and heat. An optimization model has thus been used to determine the optimal locations for such plants in Sweden. The entire energy supply and demand chain from biomass outtake to gas stations filling is included in the optimization. Input parameters have been studied for their influence on both the final ethanol cost and the optimal locations of the plants. The results show that the biomass cost, biomass availability and district heating price are crucial for the positioning of the plant and the ethanol to be competitive against imported ethanol. The optimal location to set up polygeneration plants is demonstrated to be in areas where the biomass cost is competitive and in the vicinity of small to medium size cities. Carbon tax does not influence the ethanol cost, but solicits the production of ethanol in Sweden, and changes thus the geography of the plant locations.

Keywords: bio-ethanol; forestry; optimization; polygeneration; biorefinery

1. Introduction

In March 2007 EU heads of state and governments broadly endorsed the Commission's proposals of a common European energy and climate policy – known as the 20-20-20 Rule referring to 20% less greenhouse gas emissions compared to the 1990 level, a 20% renewable energy share of the total primary energy supply, 20% energy efficiency improvement and finally a 10% biofuel for inland transport target by the year 2020. These policies need to be translated to national action plans. Mainly by mixing gasoline with 5% ethanol, Sweden reached the previous EU goal of 2% biomass derived fuels (biofuels) in the transport sector in 2005. Ethanol will play an important role in reaching the up-coming goals of 5.75% and 10% renewable in the transportation sector by the years 2010 and 2020 respectively. It is important that the ethanol is produced from raw materials that do not compete with food production. The feedstock should preferably be locally produced as the international competition may increase import prices. Currently, ethanol is mainly imported into Sweden and the commercial ethanol production is limited to feedstock such

* Corresponding author. Fax.: +43 2236-807-599, email address: leduc@iiasa.ac.at.

as wheat and white liquor, but it has been shown that lignocellulosic biomass has a higher energy yield than conventional feedstock for ethanol production [1].

Lignocellulosic ethanol production is one promising technology for future sustainable fuel for the transport sector. Many previous studies have mainly focused on the ethanol process and aimed at reaching higher ethanol yields and efficiencies; see for example [2-5]. By applying integrated systems with simultaneous production of multiple products (polygeneration) instead of independent production plants, the total efficiency is increased. The idea of the biomass-based polygeneration process is to utilize the biomass efficiently and not only focus on the yield for one product, such as ethanol. By investigating the complete system of simultaneous production of electricity, heat, ethanol and biogas from woody biomass, the performance of the total system is considered.

Utilization of polygeneration processes in energy production is an efficient alternative to conventional energy systems. However, studies of energy systems have to consider biomass cultivation, harvesting, transportation, pre-treatment and distribution as well as the conversion process. Biomass costs are varying depending on where the biomass is grown and transportation of biomass as well as fuels have to be optimized. Thus, locations of such plants represent important factors for sustainable production.

This paper presents optimal locations for polygeneration systems with simultaneous production of electricity, district heating, ethanol and biogas in Sweden with the aim to reduce the total production cost and the environmental impact.

2. Methodology

A detailed process model is used to generate input data for an optimization model and optimal geographic locations for polygeneration plants in Sweden are found using a mixed integer linear programming model [6].

2.1. Ethanol production chain

2.1.1. Biomass Supply

The potential increment of wood in the current forests depends on the net primary production (NPP) of the region, the forest share of the grid (For) and the grid size (GSize). The wood increment per year and grid is calculated in (m^3/year/grid) by:

$$\text{IncrementGrid} = c \cdot \text{NPP} \cdot \text{For} \cdot \text{GSize} \tag{1}$$

c is a factor to convert km^2 to hectare, percentage to share, kg of carbon to m^3 of wood, takes harvesting losses into account and estimate the NPP allocation (stem, leave, root). 1 m^3 of spruce correspond to a mass of 430 kg and 1 kg wood consists of 44% carbon, so 1 m^3 of wood will have around 0.2 t_{carbon}. We assume that 30% of the harvesting losses and 50% of the NPP will be stored into the stem. By making this assumption the factor c has a value of 1,750. Annual NPP was calculated for the years 2000 to 2006, and an average value for this time period has been used. The average potential increment calculated for Sweden by using this method is 5.2 m^3/ha/year.

The potential biomass increment was calculated using the global datasets presented in Table 1.

Table 1
Datasets used for the calculation

Dataset	Value	Source
Net primary production (NPP)	0-25,184 kgC/ha/year	[7]
Forest share (For)	0-100 %	[8]
Grid size (GSize)	0-3,091 km^2	[9]

The wood cost was calculated according to Kindermann, 2006 [10], and includes costs of felling and transportation to the forest road. The wood cost is scaled between a minimum and maximum cost per m^3 depending on the population density, forest share and land cost level of the country. Fig. 1 shows a wood cost scenario calculated for Sweden.

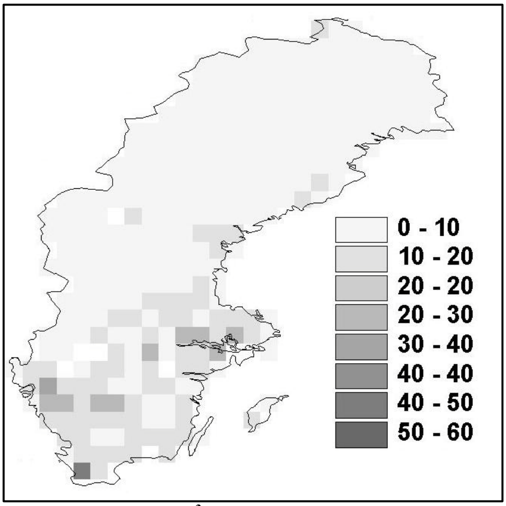

Fig. 1. Wood cost (€/m^3) in Sweden.

The average cost of biomass in Sweden is calculated to be 15.16 €/m^3. After adding taxes and other transaction costs, a biomass price between 25 and 37 €/m^3 was reached. The biomass price on the Swedish market at present amounts on average to 27 €/m^3 [11].

2.1.2. Biomass Transportation

Five sets of spatial data were utilized in the study (Table 2). For simplicity, all spatial features within the ports, waterways, roads and railroads datasets were considered equal i.e. no distinction was made between road types or port size etc. In addition, it was assumed that all features present within these datasets were navigable and existing on the ground. This is a fair assumption as these datasets contain fairly coarse-level data and would likely represent major features.

Initially, each dataset in Table 2 was converted to grid format. Each dataset was then converted to a Euclidean distance grid. Euclidean distance is calculated from the center of the source cells to the center of each of the surrounding cells. Then this distance was converted to actual distance on the earth surface, geographic coordinates were added to the cell center, and resultant database was created. A final grid resolution of 0.5° (~50km) was chosen.

Table 2
Description of spatial data utilized in the study

Dataset	Updated	Source
Country borders	2000	[12]
Global maritime ports database	2007	[13]
Waterways	2000	[12]
Roads	1993	[14]
Railroads	1993	[14]

Biomass and biofuel transportation costs (in €/TJ) are described by Börjesson and Gustavsson [15] These costs are presented in Table 3 for tractor-trailer, truck, train and boat transportation.

Table 3
Transport costs for logging residues and ethanol in €/TJ regarding different transport alternatives. The transport distance d is in km [15]

Fuel	Tractor	Truck	Train	Boat
Logging residues	226+12.78 d	344+7.77 d	727+1.08 d	836+0.44 d
Ethanol	-	423+0.66 d	138+3.05 d	462+0.15 d

2.1.3. Ethanol Production and Process Integration

Ethanol is traditionally produced from corn in the USA and from sugarcane in Brazil [16]. The major difference between using these two feedstocks for ethanol production is that after pre-treatment, corn must be hydrolyzed before the fermentation, while sugarcane can be fermented directly. After the fermentation, the ethanol is separated by distillation and further dehydrated to the applicable vehicle fuel.

Lignocellulosic biomass and straw can be used as feedstock for ethanol production after pre-treatment and hydrolysis to fermentable sugars. The lignin in the wood is loosened in the pre-treatment and separated after hydrolysis or fermentation depending on the configuration used. The cellulose and hemicellulose is pre-treated with acid, dilute acid or enzyme hydrolysis to sugars of which the 6-carbon (C-6) sugars, mainly glucose, can be fermented with regular baker's yeast. The 5-carbon (C-5) sugars, mainly xylose, requires specially selected or genetically modified micro-organisms for fermentation [17]. The separated lignin can be used as a high quality combustion fuel with a lower heating value of 22.8 MJ/kg at 4.4% moisture content [18].

Several steps in the ethanol process require energy inputs in different forms, and several by-products as output from the process have to be considered in order to reach an efficient system. Thus, the simultaneous production of heat and power in combined heat and power (CHP) plants are suitable for integration with an ethanol production process due to its similar temperatures, pressures and useful by-products. Steam at different pressures is needed for hydrolysis and distillation of ethanol. It is extracted from the steam turbine at appropriate pressures to gain electricity production. Condensed steam discharged from the ethanol production at lower temperatures can potentially be used for district heating production and in other parts of the ethanol production process.

District heating is currently accounting for about 40% of the total heat supply in Sweden [19]. Produced heat in the condensers is the limiting factor for increased electricity production in CHP plants, unless the heat is consumed in cooling towers or other cooling arrangements. Thus, it is also the limiting factor for the production of electricity, ethanol and biogas in a polygeneration system. Since the heat load is limited by the heat demand, it is profitable to reach high power-to-heat ratios.

2.2. Model

2.2.1. Process Model

A steady-state simulation model of a polygeneration system with lignocellulosic ethanol and CHP production has been developed [20], where it is shown that an integrated system can save up to 14% of fuel input compared to a stand-alone CHP and ethanol plant. The model is used to generate input data for the optimization model described in chapter 2.2.2.

The configuration is shown in Fig. 2.

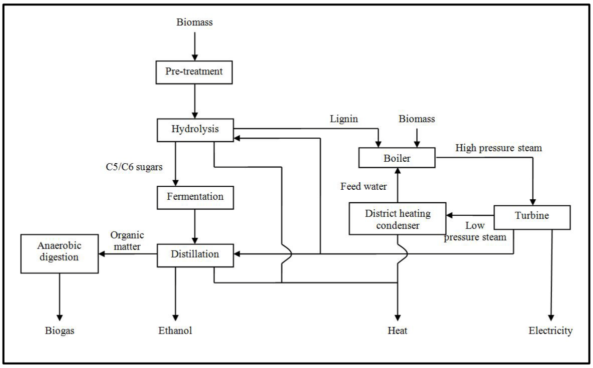

Fig. 2. Configuration scheme of the polygeneration process.

The model is based on biomass steam CHP technology with a grate-fired boiler and lignocellulosic ethanol production from lab and pilot scale plants. The model is validated with actual operation data from a CHP plant. In Fig. 2, pre-treatment indicates mechanical treatment of the input biomass, and the hydrolysis stage relates to hydrolysis of hemicellulose and cellulose with steam explosion and dilute acid. Steam is extracted from the turbine for hydrolysis and distillation of ethanol, and excess heat from the hydrolysis and distillation is utilized in the district heating system. By-products from the ethanol production, mainly lignin, are combusted in the grate-fired steam boiler.

The process model was simulated and the results in terms of yields of ethanol, electricity, heat and biogas produced from the feedstock were used as input data for the optimization model. Both C5 and C6 sugars are considered to be fermented to ethanol in the model. The dilute acid pre-treatment and separate hydrolysis and fermentation configurations are applied. A yield of 90% will be reached when the technology comes to a commercial stage; a higher yield was then assumed which integrates technology improvements. Two cases with different hydrolysis yields were simulated with the process model at 97% and 90% of theoretical yield of sugars from cellulose and hemicelluloses respectively. The lower yield brings less ethanol fuel and biogas production (although higher heat and electricity production) because the unconverted biomass is used for CHP production. The results are shown in Table 4 with different product yields of the polygeneration system.

Table 4
Energy yields for different products calculated from the process model

Hydrolysis yield cases	Fuel	Power	Biogas	Heat
0.97	0.292	0.127	0.183	0.234
0.90	0.258	0.145	0.161	0.277

Economic parameters have been collected to calculate installation and operation costs of the system. A summary of the equipment costs for a polygeneration system with 350 MW of biomass fuel input is shown in Table 5.

Scaling factors in Table 5 are used for up and down scaling of the plant size according to

$$\frac{Cost_a}{Cost_b} = \left(\frac{Size_a}{Size_b}\right)^R \qquad (2)$$

where R is the scaling factor and a and b represent the original plant and the up/down scaled plant respectively. The equipment cost for a circulating fluidized bed (CFB) combustor in Table 5 is used with reference to [21]. A grate-fired boiler has been considered for this study, which might imply less equipment cost than a CFB boiler.

Table 5
Equipment cost for the polygeneration system [21]

Component	Scaling factor	Investment cost (M€)
Pre-treatment		
Mechanical	0.67	4.44
Mill	0.70	0.91
Dilute acid	0.78	14.10
Steam explosion	0.78	1.41
Ion-exchange	0.33	2.39
Overliming	0.46	0.77
Hydrolysis + fermentation		
Seed fermentors	0.60	0.68
C5 fermentation	0.80	6.39
Hydrolyse-fermentation	0.80	6.39
Upgrading		
Distillation and purification	0.70	2.11
Molecular sieve	0.70	2.80
Residuals		
Solids separation	0.65	1.78
Anaerobic digestion	0.60	2.51
Power Island		
Boiler	0.73	53.95
Steam system + turbine	0.70	14.3

Operational costs for the polygeneration system are summarized in Table 6. Operational costs are mainly taken from [21].

Table 6
Operational costs for the polygeneration system [22, 23]

Capital required	Description
<u>Total Plant Cost (TPC)</u>	
Engineering fee	10% of Process plant cost (PPC)
Process contingency	2.345% of PPC
General plant facilities	10% PPC
Project contingency	15% of (PPC + General plant facilities)
<u>Total Plant Investment (TPI)</u>	
Adjustment for interest and inflation	0.34% PPC
<u>Total Capital Requirement (TCR)</u>	
Prepaid royalties	0.5% of PPC
Start-up costs	2.7% TPI
Spare parts	0.5% of TPC
Working capital	3% TPI
Land, 200 acres	200 Acres at 6,500 € per Acre

The income from district heating, electricity and biogas are summarized in Table 7. The power price includes electricity certificates as well as the market price.

Table 7
Income for sold products from the polygeneration process (€/MWh)

Heat price	Power price	Biogas price
69.3 [24]	71.4 [25]	18.12 [26]

Transportation costs for produced biogas or electricity are not considered in the model, thus they are assumed to only generate an income at the production site. Electricity is assumed to be sold to the grid and biogas sold at the plant (many city buses and garbage trucks currently run on biogas in Sweden).

2.2.2. Optimization Model

A mixed integer linear programming model [6] is used to optimize the supply and delivery of ethanol. A detailed description of the model is given in Leduc et al., 2008 [27].

In Fig. 3, the model is schematically depicted as a graph with nodes and arcs. A continuous variable is associated to each arc, representing transportation of biomass or ethanol. Binary variables are associated to the plant and gas station nodes, modeling when the current plant or gas station is in operation.

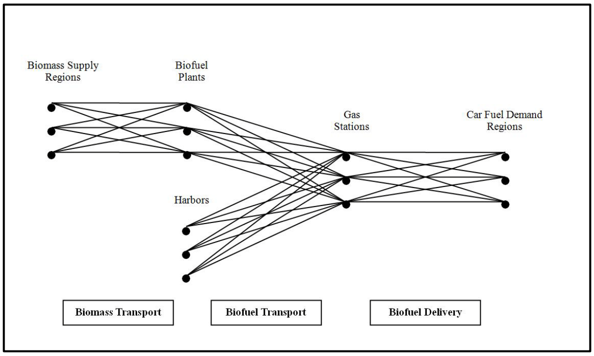

Fig. 3. Scheme of the model.

The supply of biomass is restricted in each supply region by the available amount that can be harvested. Plants and gas stations are modeled using energy balance equations, combined with capacity constraints for production or delivery. Depending on whether an ethanol plant is built to produce additional commodities, such as heat and/or power, constraints modeling these specific relations are included. An ethanol demand constraint is defined for each demand region.

The objective is to minimize the overall costs in order to fulfill the demand for ethanol. The cost function that is minimized includes the cost for supply of biomass, operation of production plants, investment in plants and gas stations, handling and delivery of ethanol at the gas stations, and transportation of biomass and ethanol. In this version of the model, the import cost of ethanol is also considered.

Evaluating the model by solving the optimization problem generates the optimal locations, sizes and configurations of production plants. The solution also includes the optimal amount of ethanol that shall be imported, and from which supply region the biomass shall be taken.

2.3. Imports

Gasoline in Sweden is mixed with 85% ethanol (E85). 71% of the 363,000 m^3 ethanol used per year in Sweden is imported [28], mostly from Brazil. This import is also considered in the model. Import from Brazil is transported by boat from Rio de Janeiro to the closest bigger harbor in Sweden, Gothenburg. This represents a distance of 10,536 km [29]. An import price of ethanol to Gothenburg is assumed to be 0.52 €/liter [30]. From here the ethanol can be transported further either by truck, train or boat to fulfill the demand at the most competitive cost. Mixing with gasoline in an intermediate refinery is not considered in this study.

2.4. Scenarios

Input data from the simulated scenarios are summarized in Table 8. About 100 TWh of vehicle fuel is used annually in Sweden, of which about 4% is biofuel [31]. The EU-goal of renewable fuels in the transport sector is 5.75% in 2010 and 10% in 2020 [32]. The biofuel plants studied produce ethanol and other products such as power, heat and biogas. Biogas is here assumed to be used at the plant for local transport (taxis, buses, trucks…) or for other purposes such as heating. It is then not considered in the calculations for the fulfillment of the EU-goals.

The parameters varied in the different scenarios are highlighted in bold letters. The base scenario (scenario 1) is calculated with the prices of 2007 for the biomass, electricity, heat and biogas in Sweden. The influence of the prices of the different products are studied except for the biogas, for which the price is fixed to 18.1 €/MWh [26]. A description on the parameter studied for each set of scenarios is stated in the last column of the table. The heat demand is calculated per person in the populated areas, assuming that the infrastructure for heating systems, such as district heating piping, already exists. Electricity is produced in the polygeneration plants and is distributed to the electricity grid. Connection costs or expansion of the grid to connect to the plants are not considered in the simulations. It is assumed that as much biomass as possible can be used around the new built plant. But taking care of the large amount of biomass used from the other forest industries such as the pulp and paper industry, 30% of the yearly growth of biomass is assumed to be available, which mainly represents forest residues (such as tops and branches) for energy purposes.

Table 8
List of scenarios

Scenarios	Carbon tax	Demand	Ethanol yield	Power yield	Biogas yield	Heat yield	Available biomass	Average biomass price	Ethanol Import price	Heat price	Power price	Max size	Description
	€/t_{CO2}	TWh					%	€/m^3	€/liter	€/MWh	€/MWh	MW_{bio}	
1	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	Base scenario
2	0	5.75	0.292	0.127	0.183	0.234	30	**30**	0.52	69.28	71.41	400	Influence on biomass cost
3	0	5.75	0.292	0.127	0.183	0.234	30	**35**	0.52	69.28	71.41	400	
4	0	5.75	0.292	0.127	0.183	0.234	30	**37**	0.52	69.28	71.41	400	
5	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	**50**	71.41	400	Decrease of heat price
6	0	5.75	0.292	0.127	0.183	0.234	30	**30**	0.52	**50**	71.41	400	
7	0	5.75	0.292	0.127	0.183	0.234	30	**35**	0.52	**50**	71.41	400	
8	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	**76.23**	71.41	400	Increase of heat price
9	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	**67.83**	400	Increase of power price
10	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	**74.97**	400	Decrease of power price
11	0	5.75	0.292	0.127	0.183	0.234	30	25	**0.397**	69.28	71.41	400	No tax on imports
12	0	5.75	0.292	0.127	0.183	0.234	30	**30**	**0.397**	69.28	71.41	400	
13	**100**	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	Carbon tax influence
14	**100**	5.75	0.292	0.127	0.183	0.234	30	**35**	0.52	69.28	71.41	400	
15	**100**	**0.59**	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	One plant is built
16	0	**0.59**	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	
17	0	**0.59**	0.292	0.127	0.183	0.234	30	**30**	0.52	69.28	71.41	400	
18	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	**280**	
19	0	5.75	0.292	0.127	0.183	0.234	**5**	25	0.52	69.28	71.41	400	Available biomass decrease
20	0	5.75	0.292	0.127	0.183	0.234	**5**	**30**	0.52	69.28	71.41	400	
21	0	5.75	0.292	0.127	0.183	0.234	**5**	**35**	0.52	69.28	71.41	400	
22	0	**10**	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	400	Demand increase to year 2020
23	0	**10**	0.292	0.127	0.183	0.234	30	**30**	0.52	69.28	71.41	400	
24	0	**10**	0.292	0.127	0.183	0.234	30	**35**	0.52	69.28	71.41	400	
25	0	**10**	0.292	0.127	0.183	0.234	30	**30**	**0.397**	69.28	71.41	400	2020 goal & no tax on imports
26	0	**10**	0.292	0.127	0.183	0.234	30	**35**	**0.397**	69.28	71.41	400	
27	0	5.75	0.292	0.127	0.183	0.234	30	25	0.52	69.28	71.41	**200**	Maximum size limited
28	0	5.75	**0.258**	**0.145**	**0.161**	**0.277**	30	25	0.52	69.28	71.41	400	Yields change

3. Results

The results from the scenarios are presented in Table 9. The table presents for each run the number of plants that would be selected and their position number, from 1 to 20. The minimum and the maximum costs of ethanol at the gas station are also indicated as well as the total annual amount of imported ethanol.

Table 9
Results for each scenario

Scenarios	Number of plants	Identification numbers of the selected plants (Fig. 4)	Cost min	Cost max	Import
			€/liter	€/liter	m^3/year
1	8	4, 8, 9, 10, 13, 14, 16, 20	0.0650	0.2517	0
2	8	4, 8, 9, 10, 13, 14, 16, 20	0.1164	0.3031	0
3	3	8, 13, 20	0.1577	0.4505	745,218
4	0	-	-	-	1,159,404
5	8	4, 8, 9, 10, 13, 14, 16, 20	0.1433	0.3205	0
6	8	4, 8, 9, 10, 13, 14, 16, 20	0.1947	0.3719	0
7	0	-	-	-	1,159,404
8	8	4, 8, 9, 10, 13, 14, 16, 20	0.0374	0.2302	0
9	8	4, 8, 9, 10, 13, 14, 16, 20	0.0726	0.2593	0
10	8	4, 8, 9, 10, 13, 14, 16, 20	0.0572	0.2439	0
11	8	4, 8, 9, 10, 13, 14, 16, 20	0.0650	0.2517	0
12	7	8, 9, 10, 13, 14, 16, 20	0.1116	0.3336	187,926
13	8	4, 8, 9, 10, 13, 14, 16, 20	0.0650	0.2517	0
14	6	8, 9, 10, 13, 16, 20	0.1600	0.4505	332,211
15	1	19	-	0.2181	0
16	1	19	-	0.2181	0
17	1	19	-	0.3502	15,276
18	1	9	-	0.0879	1,040,707
19	6	2, 3, 8, 10, 13, 16	0.1607	0.4266	536,925
20	4	4, 8, 13, 16	0.2356	0.4395	801,456
21	0	-	-	-	1,159,404
22	13	1, 2, 4, 6, 7, 8, 9, 10, 13, 14, 15, 16, 20	0.0596	0.2351	0
23	8	4, 8, 9, 10, 13, 14, 16, 20	0.1164	0.4047	0
24	3	8, 13, 20	0.1544	0.4275	745,218
25	7	8, 9, 10, 13, 14, 16, 20	0.0920	0.2973	187,926
26	0	-	-	-	2,016,355
27	14	4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15, 17, 18, 20	0.0684	0.1807	0
28	12	1, 2, 4, 7, 8, 9, 10, 13, 14, 15, 16, 20	-0.0174	0.1602	249,713

Fig. 4 presents the identification numbers of the plants selected. The numbers in brackets represent the number of appearance of the corresponding plant. For example, position 15 is selected as an optimal position for three scenarios (scenarios 22, 27 and 28).

Scenarios 1-4 are simulated with increasing biomass prices until it is more profitable to import the total ethanol demand from Brazil. Similar scenarios are simulated again with lower income from produced district heating (scenario 5-7) with a lower biomass cost increase to reach 100% import. A decrease of the heat price by 28% would increase the ethanol cost by 75%. An increase of the heat price is studied in scenario 8, where a decrease of the ethanol cost of 26% has been noticed when the heat price increases by 10%.

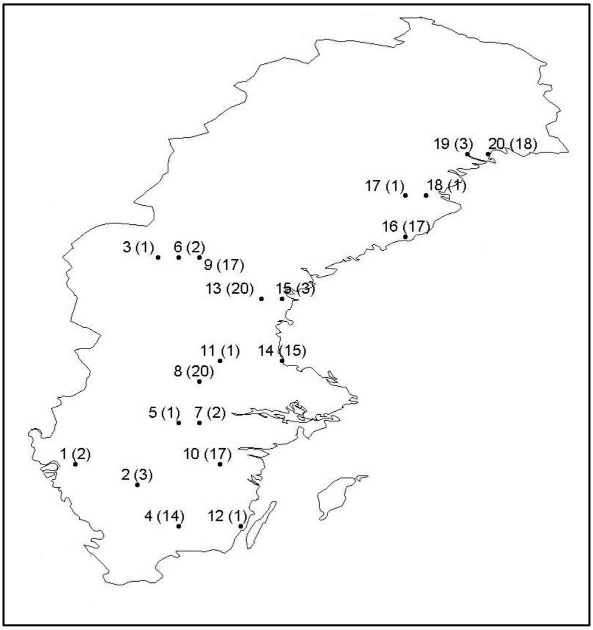

Fig. 4. Plant identification with their number of appearance in brackets.

The changes in ethanol production prices can be studied from scenarios 9 and 10 with changed power prices. A change of the power price by ± 5% would change the ethanol cost by ± 7.5%, without changing the positions of the plants.

Scenarios 11 and 12 are simulated without the existing taxes on the ethanol import. Comparing scenarios 12 and 2 one notices that ethanol would be imported for a biomass cost lower in scenario 12, and one plant less would be needed.

In scenario 13, a carbon tax of 100 €/tonne$_{CO_2}$ on transportation emissions is introduced. A carbon tax on transportation is used together with an increase in biomass costs in scenario 14, resulting in some imports. Comparing scenarios 3 and 14, one notices that three more plants would be needed in the case of a carbon tax, but the final ethanol cost remains unchanged.

Scenarios 15-17 are simulated with varying carbon tax, demand and biomass cost increase to see where the optimal position for the first biorefinery in Sweden should be built by setting the demand to fit the maximum size of one plant. The location chosen for all three scenarios is in the northern part of Sweden, at longitude 21.75 and latitude 65.75 where biomass costs are lower than average. Scenario 18 is placing one plant of 280 MW in Östersund, at longitude 15.25 and latitude 63.25.

By reducing the amount of available biomass to 5% of the yearly growth and varying the biomass cost increase, it is shown in scenarios 19-21 that the ethanol production cost increases. It increases by an average of 90% and imports would be needed for a biomass cost lower than for scenarios 1-4.

To meet the EU goal of 2020, scenarios 22-26 show that more plants have to be set up.

14 plants are required to meet the ethanol demand with a lower limit for maximum size plants of 200 MW$_{biomass}$ in scenario 27. Scenario 28 shows that with a decreased yield of ethanol and an increased yield of

heat and power, four more plants have to be set up to meet the ethanol demand. This scenario however, gives a lower ethanol production price by 80%.

Comparing the scenarios where the biomass cost have changed, one notices that an increase of the biomass price by 5 €/m^3 increases the ethanol cost by an average of 50%.

4. Discussion

Optimal geographic locations of polygeneration plants within Sweden have been presented. The factors that have the most influence on the plant location and ethanol cost are the biomass cost, the biomass availability and the plant efficiencies.

Concerning the by-products, electricity and biogas are assumed to be distributed without constraints; only heat distribution to residential areas would have an impact on the final cost and position of the plant. Thus, in order to generate an income from produced heat for district heating, the plant is best located in populated areas. However, the biomass prices are higher in populated areas which counter this statement. The optimization results show that the optimal locations for the simulated cases are in cities with a range of about 50,000 to 140,000 inhabitants. The optimal size for each plant depends on the heat demand in the region where the plant is located. The regions that were verified to be the most attractive locations include the following cities; Sundsvall, Borlänge, Umeå, Linköping, Östersund, Luleå, Gävle and Växjö.

Apart from the affect of the sold by-products on the ethanol price, the competitive import price has a large impact on whether it is profitable to produce ethanol in polygeneration plants in Sweden. Scenario 11 (ethanol import price of 0.397 €/liter) shows that ethanol production in Sweden with simultaneous electricity, heat and biogas production is still profitable even without import taxes on ethanol from Brazil. However, the operational cost, feedstock cost and other related factors are difficult to predict and it is shown in e.g. scenario 12 that it might be more profitable to import sugarcane-based ethanol than to produce it locally from wood.

Including a carbon tax on the transport and the imported products will not influence the ethanol cost. But as the biomass cost increases the geography of the location of the plants will change. Ethanol produced in Sweden is then solicited.

The ethanol yield reduction in scenario 28 gives the lowest ethanol production cost, which strongly points to the importance of utilizing the by-products of polygeneration rather than producing it separately. The low production cost is due to the income from the increased heat and power yield which clearly shows that the importance of research in this area is not towards optimizing ethanol yield, but instead towards optimizing the energy system as a whole and focusing on the best utilization method of biomass instead of only one product.

The results presented in this paper are especially important for energy policy development and shows that import taxes can promote the technology development needed to stimulate local ethanol production in countries like Sweden.

5. Conclusions

Polygeneration systems with simultaneous production of heat, power, ethanol and biogas utilize the biomass feedstock to a higher extent than in independent production plants. This paper has presented the optimal locations of biomass based ethanol plants with polygeneration in Sweden. With variations of different parameters in the optimization, locations that prove to be optimal were identified and the final ethanol cost calculated.

The biomass cost, biomass availability and the income for by-products such as heat, have a large impact on both the final ethanol costs and the optimal geographic locations. An increase of the biomass cost by 5 €/m^3 increases the ethanol cost by an average of 50%, a decrease of the biomass available by 25% would increase the ethanol cost by 90%, a heat price increase by about 10% decreases the ethanol cost by 25%. The carbon tax has on the other hand very little influence on the ethanol cost but a higher impact on the location of the plants, encouraging limitation on the import of ethanol.

The optimal location for a polygeneration plant would be in the vicinity of cities with a range of about 50,000 to 140,000 inhabitants. In a broader perspective it can be concluded that polygeneration production plants should not be positioned in too dense nor too sparse populated areas, and that Sweden has the opportunity to develop a sustainable ethanol production industry towards the EU goals.

The findings presented in this paper are essential for energy planning purposes on a national and international level.

6. References

[1] Sims REH, Hastings A, Schlamadinger B, Taylor G, Smith P. Energy crops: current status and future prospects. Global Change Biology 2006;12:2054.

[2] Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, et al. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. NREL/TP-510-32438, National Renewable Energy Lab., Golden, CO. (US); 2002.

[3] Sassner P, Galbe M, Zacchi G. Bioethanol production based on simultaneous saccharification and fermentation of steam-pretreated Salix at high dry-matter content. Enzyme and Microbial Technology 2006;39:756.

[4] Sun Y, Cheng J. Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresource Technology 2002;83:1.

[5] Öhgren K, Rudolf A, Galbe M, Zacchi G. Fuel ethanol production from steam-pretreated corn stover using SSF at higher dry matter content. Biomass & Bioenergy 2006;30:863.

[6] Wolsey L. Integer programming: Wiley-Interscience New York, NY, USA; 1998.

[7] Running S, Nemani R, Heinsch F, Zhao M, Reeves M, Hashimoto H. A continuous satellite-derived measure of global terrestrial primary production. BioScience 2004;54:547.

[8] JRC. The Global Land Cover Map for the Year 2000. 2003, p. GLC2000 database.

[9] Center for International Earth Science Information Network (CIESIN) CUaCIdATC, URL. 2005, p. Gridded Population of the World Version 3 (GPWv3): Land Area Grids. Palisades.

[10] Kindermann GE, Obersteiner M, Rametsteiner E, McCallum I. Predicting the deforestation-trend under different carbon-prices. Carbon Balance and Management 2006;1.

[11] STEM. Prisblad för biobränslen, torv m.m. Nr 1/2008. Swedish Energy Agency, Eskilstuna, Sweden; 2008.

[12] ESRI. 2008.

[13] General Dynamics Advanced Information Systems. 2008.

[14] Digital Chart of the World Data Server. 2008.

[15] Börjesson P, Gustavsson L. Regional production and utilization of biomass in Sweden. Energy 1996;21:747.

[16] Wheals A, Basso L, Alves D, Amorim H. Fuel ethanol after 25 years. Trends in Biotechnology 1999;17:482.

[17] Reith J, Veenkamp J, Van Ree R, De Laat W, Niessen J, De Jong E, et al. Co-production of bio-ethanol, electricity and heat from biomass wastes: potential and R&D issues. First European Conference on Agriculture & Renewable Energy. Amsterdam, the Netherlands; 2001, p. 6.

[18] Eriksson G, Kjellström B, Lundqvist B, Paulrud S. Combustion of wood hydrolysis residue in a 150kW powder burner. Fuel 2004;83:1635.

[19] Sahlin J, Knutsson D, Ekvall T. Effects of planned expansion of waste incineration in the Swedish district heating systems. Resources, Conservation and Recycling 2004;41:279.

[20] Starfelt F, Thorin E, Dotzauer E, Yan J. Performance Evaluation of Adding Ethanol Production into an Existing Combined Heat and Power Plant. Biomass & Bioenergy 2008.

[21] Hamelinck C, van Hooijdonk G, Faaij A. Prospects for Ethanol from Lignocellulosic Biomass: Techno-economic Performance as Development Progresses: Utrecht University, Copernicus Institute, Science Technology Society; 2003.

[22] Parsons EL, Shelton WW, Lyons JF. Advanced Fossil Power Systems Comparison Study. NETL USDOE Final Report 2002.

[23] Craig K, Mann M. Cost and Performance Analysis of Biomass-Based Integrated Gasification Combined-Cycle (BIGCC) Power Systems. NREL/TP-43021657 UC Category: 1311-DE96013105 1996.

[24] Nilsholgersson. The Rate Survey "Nils Holgersson" (In Swedish: Avgiftsundersökningen "Nils Holgersson") HSB, Hyresgästföreningen, Riksbyggen, Sabo, Fastighetsägarna; 2008.

[25] Nordpool. Nordpool electricity spot market. 2008.

[26] Kärrman E, Olofsson M, Persson B, Sander A, Aberg H. Food waste disposers – a technical solution for sustainable resource management? A pre-study in Gothenburg (In Swedish: Köksavfallskvarnar – en teknik för uthållig resursanvändning? En förstudie i Göteborg). VA-Forsk; 2001.

[27] Leduc S, Schwab D, Dotzauer E, Schmid E, Obersteiner M. Optimal Location of Wood Gasification Plants for Methanol Production with Heat Recovery. International Journal of Energy Research, IGEC-III special issue 2008.

[28] Lagerkvist Tolke C. Market Overview: Ethanol, a farming and industrial product (In Swedish; Marknadsöversikt: Etanol, en jordbruks- och industriprodukt). Swedish Board of Agriculture; 2006.

[29] MaritimeChain.com pte ltd Singapore; 2008.

[30] F.O. Licht's World Ethanol & Biofuels Report. 2007.

[31] Agency SE. Energy use in the tranport sector 2007 (In Swedish: Transportsektorns energianvändning 2007). Eskilstuna, Sweden: Swedish Energy Agency; 2008.

[32] EU. Communication from the Commission – An EU Strategy for Biofuels. In: SEC(2006), editor. 142: Commission of the European Communities; 2006.

Article VI

Potentials of bioenergy production within the Austrian forest market

Potentials of bioenergy production within the Austrian forest market

Johannes Schmidt[1], Sylvain Leduc[2,3], Erik Dotzauer[4], Georg Kindermann[2], Thomas Greigeritsch[1], Erwin Schmid[1]

[1] University of Natural Resources and Applied Life Sciences, Feistmantelstrasse 4, 1180 Vienna, Austria, [2] International Institute for Applied Systems Analysis, Schlossplatz 1, 2361 Laxenburg, Austria, [3]Division of Energy Engineering, Luleå University of Technology, 97187 Luleå, Sweden, [4] Mälardalen University, 72123 Västerås, Sweden

Abstract
Forest wood is a substantial and competitive biomass stock for bioenergy production in Austria. Besides increasing forest productivity and harvest efficiencies, waste products from the wood processing industry may be a cost competitive resource for the bioenergy production sector. The aim of this study is to optimize the supply chain of the biofuel industry based on cellulosic biomass by particularly considering the waste products from the wood processing industry. The optimal portfolio of combined heat and power and second generation ethanol plants is assessed for different CO_2 price scenarios.

The optimal location of plants is evaluated by minimizing the costs of the full supply chain. The model includes biomass harvesting, transport and processing as well as the distribution of the final commodities. Availability of forest wood is geographically explicitly estimated considering future production and demand potentials. Wood imports and sawmill co-products are also included. The model takes into account the wood demands of existing pulp-and-paper industries and bioenergy plants. Two technologies are considered: combined heat and power and second generation ethanol production. The distribution of ethanol and district heat to the consumers is explicitly integrated. Results indicate that an additional 2.5% of Austria's energy consumption may be produced from wood. Rising CO_2-prices increase the share of biofuel production and decrease the share of combined heat and power in the optimal portfolio of technologies.

Keywords: Biofuel, biomass, bioenergy, forest industries, supply chain

1. Introduction

Decreasing dependency on imported fossil oil and climate change mitigation are the main drivers of the European renewable energy policies. The goal of the European Union is to reach 20% of renewable energy consumption by 2020. The commission emphasizes that a significant increase in the use of biomass is necessary to reach these targets. Austria has already a high share of renewable energy consumption and wants to increase it from currently around 23% to 34% by 2020 (COM, 2008). About 43% of the Austrian territory is forest lands and wood is already an important feedstock for biomass based energy generation. In 2004, 37% of the renewable energy was produced from wood (Kopetz and Scheiber, 2006). To meet the 2020 targets, the Austrian biomass action plan estimates that forest harvests have to be increased in a sustainable manner by 10.7 million m^3 of wood until 2020 (BMFLUW, 2006). The efficient use of those additional biomass resources in the different bioenergy industries should be known in designing future energy systems. Optimal portfolios of bioenergy technologies for Austria have previously been assessed (Steininger and Voraberger, 2003) but they did not include the spatial distribution of feedstock potentials and demands. The spatial distribution plays an important role as the transport of biomass is a crucial factor in the total production costs (Eriksson and Björheden, 1989; Bjornstad, 2005). Also, costs of distribution of the final commodities, especially in the case of district heating, depend on the density of the demand in certain areas (Schiller and Siedentop, 2005; Konstantin, 2007). This paper therefore minimizes costs of wood based bioenergy industries along the whole supply chain by selecting optimal plant locations, feedstock production sites and demand sites. Combined heat and power (CHP) and second generation ethanol production in multi commodity plants (MCP) are assessed. Different scenarios for biomass price as well as prices of CO_2-emission are assumed.

2. Methodology

The article presents a spatially explicit optimization model of the supply chain of bioenergy industries considering that industries compete for wood resources. Figure 1 shows the general wood flow used by the model. It is based on the Austrian Wood Flow Account 2005 (Hagauer et al., 2007). Possible new bioenergy plants are either supplied by domestic biomass production, by imports or by sawmill co-products (SCP). The model considers the existing wood demand in energy industries and in the pulp-and-paper industry. Sawmills produce a significant amount of residuals that are an important feedstock for other wood based industries. The model assumes that the existing wood demand has to be fulfilled, allowing new plants to be built only if there is enough surplus of wood available. The model is spatially explicit and the transportation of wood from biomass supply to demand spots is considered. Also, the distribution of ethanol and heat to the consumers is included in the model.

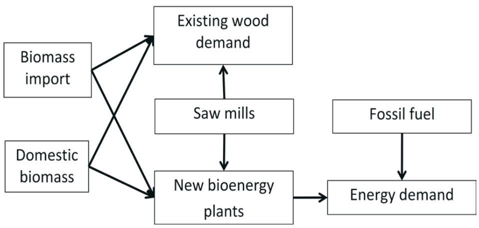

Figure 1: Supply chain of the forestry industry model.

The wood sources are forest wood, imports and SCP. Imports are assumed to be transported by trucks only, the amount of imports by country are taken from Ebner (2008). SCP production from all sawmills with a capacity above 50,000 m^3 / year is included (Eder (2002); Rebernig (2005)). According to the Austrian Wood Flow Accounts, about 34% of the total wood consumption of sawmills is assumed to be sold as SCP (Hagauer et al., 2007). Spatial distribution of forestry yields is estimated with increment curves from Assman's yield table (Assman, 1970) and a net primary production map from Running (1994). This is calibrated with the observations from the national forest inventory of Austria (Schadauer, 2004). Harvesting costs are a function of tree size (which depends on site quality and rotation time) and the slope steepness. The slope steepness is calculated using a 30x30m digital elevation map from the shuttle radar topography mission (NASA, 2008). The dimension of the harvested wood used for bioenergy has a diameter below 15 cm. The pulp-and-paper industry and energy industries are the main competitors for these resources. The model contains wood demand and positions of the pulp-and-paper mills. The wood demand was calibrated to the Austrian Wood Flow Accounts. Capacities and locations of biomass fired CHP and district heating (DH) plants are known from LKN (2008). The demand of DH and CHP plants for wood was estimated according to BMLFUW (2007). The fuel wood consumption of private households was modeled by the heat demand model presented by Schmidt (2008). It estimates the spatial distribution of fuel consumption for heating purposes in Austria. The three sinks of wood (pulp-and-paper, private households and CHP/DH) were aggregated in cells of 0.2 degrees. Two technologies for energy production from biomass were considered: CHP and MCP. Table 1 shows the efficiencies of converting biomass to various products for the two technologies. While the delivery of power and biogas is not modelled in detail - it is assumed that they can be sold to the market at a fixed price at the plant - the use of heat for district heating is handled spatially explicit as described in Schmidt (2008). The costs for delivering the fuel to the final consumers are also part of the model.

The model calculates the amount of green house gas (GHG) emissions offset by bioenergy use. The commodities produced in the plants substitute fossil fuels in transportation, in power generation according to the current mix of fuels in Austria and in heat generation. The emission factors are taken from Umweltbundesamt (2007). A mixed integer linear programming model is used to optimize the supply, processing and delivery of biomass and bioenergy. A detailed description of the model is given in Leduc et al. (2008), which is here extended by considering biomass based CHP production and

Technology	Ethanol	Heat	Power	Biogas
MCP (Leduc, 2008)	29.2	23.4	12.7	18.3
CHP (Dornburg and Faaij, 2001)	0	55	35	0

Table 1: Conversion efficiencies in %.

existing biomass demands in pulp-and-paper industries, sawmills and energy installations.

This study assesses how changes in the prices of biomass supply, in the demand of competing industries, and in CO_2-prices affect the total production potentials of bioenergy and the optimal mix of technologies by applying several scenarios. The baseline scenario assumes an increase in total wood harvesting, while demand and prices reflect the current wood market in Austria. Generally, an increase in the use of forest products is expected by 2020 (Schwarzbauer, 2005; Teräs, 2006). In scenarios S2 to S4 prices of imports, SCP and of forest wood are increased by 20%, respectively. The wood demand from the pulp-and-paper industry is increased by 25% in S5 and the supply of SCP is increased by 10% in S6. A high competitive scenario, S7, combines scenarios S2-S6. In scenarios S8-S32 the effect of increasing emission allowance prices on the optimal technological mix is assessed. Prices are increased from 0 to 250 €/t_{CO2}. Assumptions for prices of fossil power generation, of fossil transportation fuels and of natural gas are taken from the high price scenario developed by the EIA for 2020 (EIA, 2008). The reference costs for heating systems are taken from the high-price scenario in Kranzl and Haas (2008). Prices of emission allowances are assumed to be 20 € / t_{CO2} in S1-S7, which represents the mean price in 2005 at the European Energy Exchange spot market (EEX, 2008). In the baseline scenario, the demand for wood as well as the supply of wood imports and of SCP is calibrated to the Austrian Wood Flow Accounts. An increase in domestic wood harvests of seven million cubic meters is assumed, according to the forest model described above. The average costs for wood production and harvesting are 24 € / m^3. SCP prices are set to 26 € / m^3 (Kuneth, 2008) while imports are priced with 48 € /m^3 (Ebner, 2008). The capacity of both CHP plants and MCP is set to 200 MW. At 7200 working hours per year, one plant needs 576,000 m^3 of wood per year.

3. Results

The effect of changes in the forest market are analyzed at a low carbon price scenario (20 € / t_{CO2}). A summary of the results – the amount of energy produced, the number of plants built and the proportion of SCP to total biomass use – can be found in Table 2. Only CHP plants are built and imports are never used as feedstock for plants in the seven scenarios. In S2, no effects on the total output are observed as imports are not used at all in the baseline scenario. Prices of SCP have a significant impact on the total energy production as shown in S3. The increase in the price of domestic wood production in S4 yields an increase in the competition for SCP. A decline in bioenergy production is therefore observed. Increasing the demand of the pulp-and-paper industry also has significant effects (S5). Due to the additional demand the feedstock

	Scenario description	**Energy production (% of production in S1)**	**Number of plants built**	**Proportion SCP (% of total biomass use)**
S1	Baseline	100	5	64
S2	Imports prices plus 20%	100	5	64
S3	SCP prices plus 20%	40	2	24
S4	Forest wood prices plus 20%	80	4	68
S5	Pulp-and-paper industry demand plus by 25%	80	4	61
S6	Sawmills production plus 25%	120	6	60
S7	S2-S6 combined	20	1	53

Table 2: Results of scenarios S1-S7.

prices increase as cheap sources of wood are getting scarce and less plants are consequently built. S6 assumes that the production of sawmills increases. The additional supply allows that another plant is built. In S7, scenarios assumptions of S2-S6 are combined. In that case, there is not much potential for bioenergy production left, as only one plant can be built. Increases of biomass supply prices and of concurring wood demand is not offset by the additional supply of SCP. Generally the competition for SCP is most intensive. Increasing SCP use by concurring industries has a major effect on the total bioenergy production potentials in Austria. This is mainly due to the fact that small wood users like small district heating plants and single stove heating rely on the wood supply out of local forests in the model results. Still, for large bioenergy plants like the ones discussed in this paper, logistic is a major cost factor. Decentralized production of the feedstock implies high transportation costs making plant projects unprofitable.

Figure 2 depicts the diffussion of the technologies depending on the price of CO_2. For low CO_2-prices there is very little potential for bioenergy plants. Only one CHP-plant is built assuming that CO_2 emissions are cost-free. Increasing CO_2 prices cause more plants to be built. At a price level of 110 € / t_{CO2} the whole available biomass supply is used. Still, at this price level, only CHP plants are built. Increasing prices further allows MCP to go into solution. CHP plants are substitued by MCP with raising price levels because MCP saves more emissions per unit of generated energy. Reference technologies for heat and power, i.e. the mix of fuels currently consumed in heat and power generation, emit less GHG than the reference technology in transportation, i.e. fossil transportation fuels. Additionally the energy production per unit of biomass is higher for MCP than for CHP although the total theoretical efficiency is better for CHP (0.9 for CHP, 0.84 for MCP). This is due to the fact that CHP has a high proportion of heat production. Heating demand is subject to significant demand variations and the model assumes that the heat produced is used for district heating. It is not possible to use the co-produced heat for other useful purposes during low heat demand. MCP produces less heat per unit of biomass which reduces losses of heat due to demand constraints. The total emissions saved ranges from 200,000 t_{CO2} for the zero emission price scenario up to 2.5

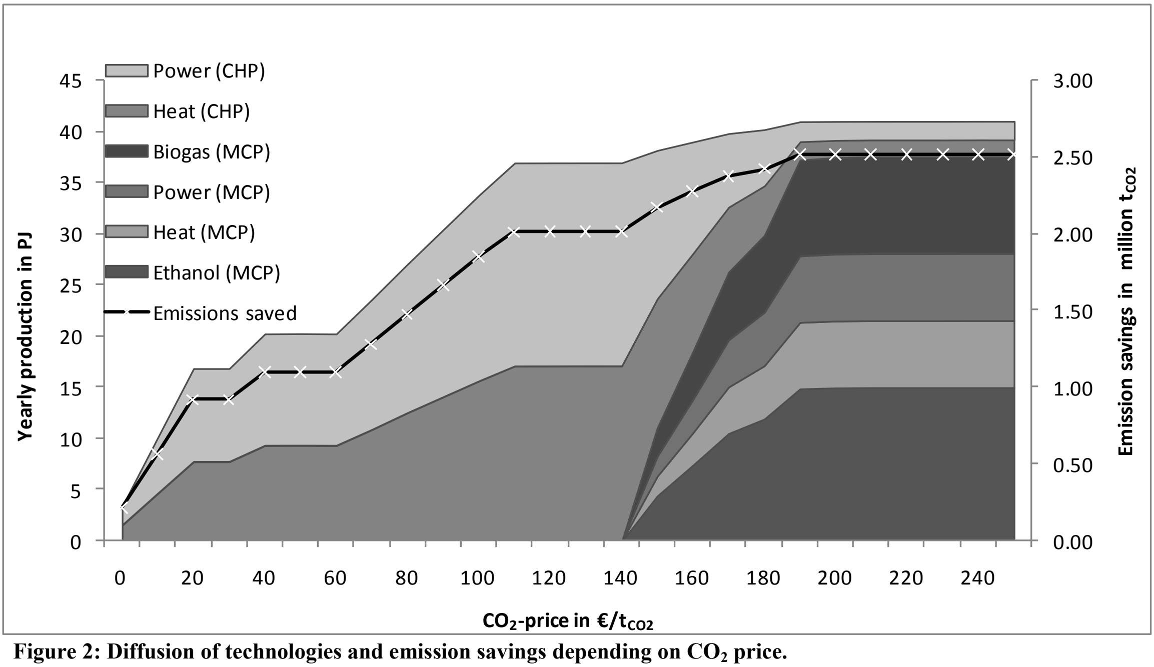

Figure 2: Diffusion of technologies and emission savings depending on CO_2 price.

million t_{CO2} for the high emission price scenarios as shown in Figure 2. The model results show that an additional 2.9% of the Austrian energy demand (2004 level) can be supplied by bioenergy at prices of 250 € / t_{CO2}.

4. Conclusion

The biomass action plan assumes that an additional amount of 10 million m^3 of wood is necessary to meet the renewable energy targets. This cannot be achieved by increasing the Austrian production only. The available, additional domestic wood harvests from forests sum up to 73% of that amount. At a price of emission allowances of 110 € / t_{CO2}, this potential is mobilized. However, lower prices have a significant impact on the amount of wood that is harvested. Also, bioenergy production is sensitive to prices of biomass and wood demand of concurring industries, as feedstock prices constitute a significant part of total production costs. Production of second generation biofuels, heat, power and biogas in MCP saves more emissions than power and heat generation in CHP. However, CHP is much cheaper and consequently MCP is only a profitable option at emission allowance prices of 150 € / t_{CO2}.

5. References

Assmann, E. (1970), *The principles of forest yield study. Pergamon*.

Bjornstad, E. (2005), 'An engineering economics approach to the estimation of forest fuel supply in North-Trondelag country, Norway', *Journal of Forest Economics* **10**, 161-188.

BMLFUW (2006), 'Nationaler Biomasseaktionsplan für Österreich', Lebensministerium BMLFUW.

BMLFUW (2007), 'Holzbedarf für energetische Verwertung', Lebensministerium BMFLUW.

COM (2008), *Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources*, Commission of the European Union.

Dornburg, V. & Faaij, A. P. (2001), 'Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies', *Biomass and Bioenergy* **21**, 91-108.

Ebner, G. (2008), 'Außenhandel nahm Nadelschnittholz-Mehrproduktion ab', *Holzkurier* **13**, 3.

Eder, R. (2002), 'Herausforderung 2002', *Holzkurier* **1**, 3.

EIA (2008), 'International Energy Outlook 2008', Technical report, Energy Information Administration.

Eriksson, L. O. Björheden, & Rolf, W. (1989), 'Optimal storing, transport and processing for a forest-fuel supplier', *European Journal of Operational Research* **43**, 26-33.

Hagauer, D.; Lang, B. & Nemestothy, K. (2007), 'Wood Flow Austria 2005', Austrian Energy Agency.

Konstantin, P. (2007), *Praxisbuch Energiewirtschaft*, Springer Berlin Heidelberg.

Kopetz, H. & Scheiber, E. (2006), 'Basisdaten Bioenergie Österreich 2006', Österreichischer Biomasse-Verband.

Kranzl, L. & Haas, R. (2008), 'Strategien zur optimalen Erschließung der Biomassepotenziale in Österreich bis zum Jahr 2050 mit dem Ziel einer maximalen Reduktion an Treibhausgasemissionen', Energy Economics Group, TU Vienna.

Kuneth, G. (2008), 'Monatliche Holzpreisstatistik Kärnten', Technical report, Landwirtschaftskammer Kärnten.

Leduc, S.; Starfelt, F.; Dotzauer, E.; Kindermann, G.; McCallum, I.; Obersteiner, M. & Lundgren, J. (2008), 'Optimal location of ethanol ligno-cellulosic biorefineries with polygeneration in Sweden', Submitted to Renewable Energy.

LKN (2008), 'Energieholzindex Österreich', Landwirtschaftskammer Niederösterreich.

Rebernig, C. (2005), Österreichisches Holz-Jahrbuch 2006, avBUCH im Österreichischen Agrarverlg.

Running, S. W. (1994), 'Terrestrial remote sensing science and algorithms planned for EOS/MODIS', International Journal of Remote Sensing **15**, 3587-3620.

Schadauer, K. (2004), 'Die österreichische Waldinventur 2000 / 02 - Vielfältige Information aus erster Hand', ÖWI.

Schiller, G. & Siedentop, S. (2005), 'Infrastrukturfolgekosten der Siedlungsentwicklung unter Schrumpfungsbedingungen', *DISP* **160**, 83-93.

Schmidt, J. (2008), 'Surplus Heat from Bioenergy Production for District Heating: an Austrian Case Study', Institute for Applied Systems Analysis.

Schwarzbauer, P. (2005), *Lignovisionen*, Wien, chapter Long-Term Supply and Demand Projections for Wood Products in Austria until 2020. A contribution to the UN-ECE/FAO 'European Forest Sector Outlook Study'.

Steininger, K. W. & Voraberger, H. (2003), 'Exploiting the Medium Term biomass Energy Potentials in Austria', *Environmental and Resource Economics* **24**, 359-377.

Teräs, T. J. (2006), 'Future Fibre Demand and Fibre Production in Central Europe', *International Paper World* **11**, 64-67.

Umweltbundesamt (2007), Austria's National Inventory Report, Umweltbundesamt.