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

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DOCTORAL THESIS

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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.

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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].

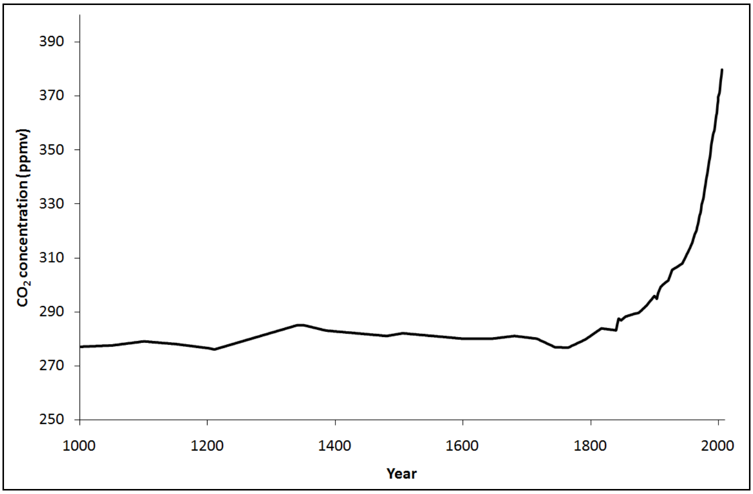

Figure 1: Atmospheric concentrations of carbon dioxide, 1000-2003 [8].

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.

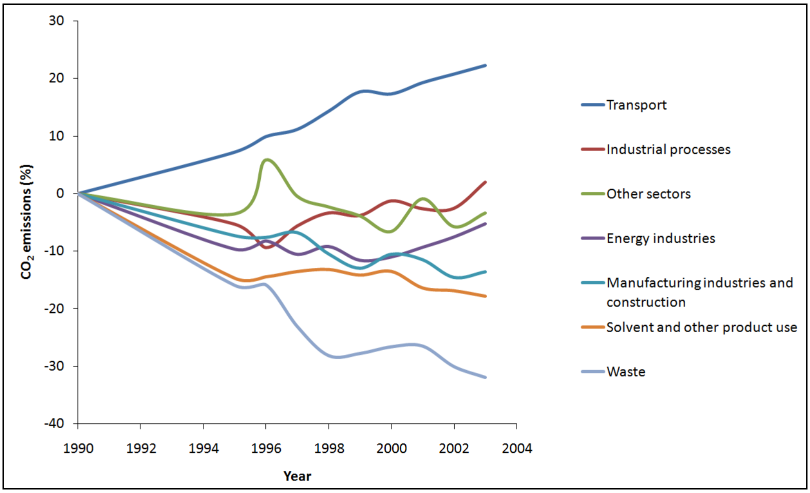

Figure 2: Evolution of the CO_2 emissions compared with 1990 for EU-25 [11].

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].

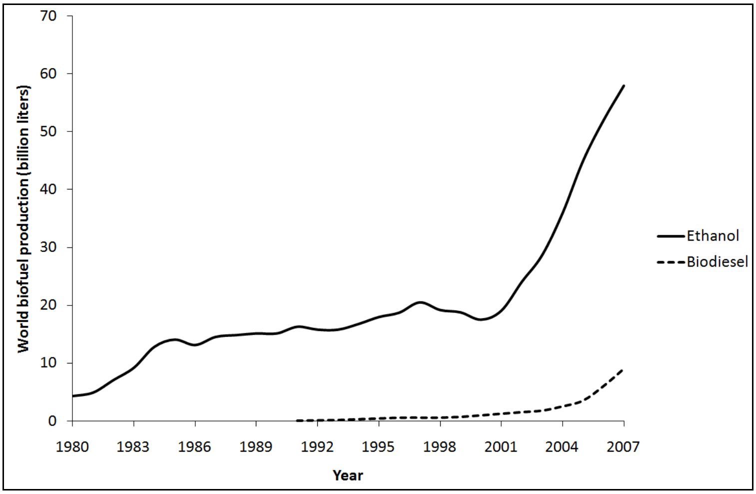

Figure 3: Global ethanol and biodiesel production, 1980-2007 [16, 17].

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.

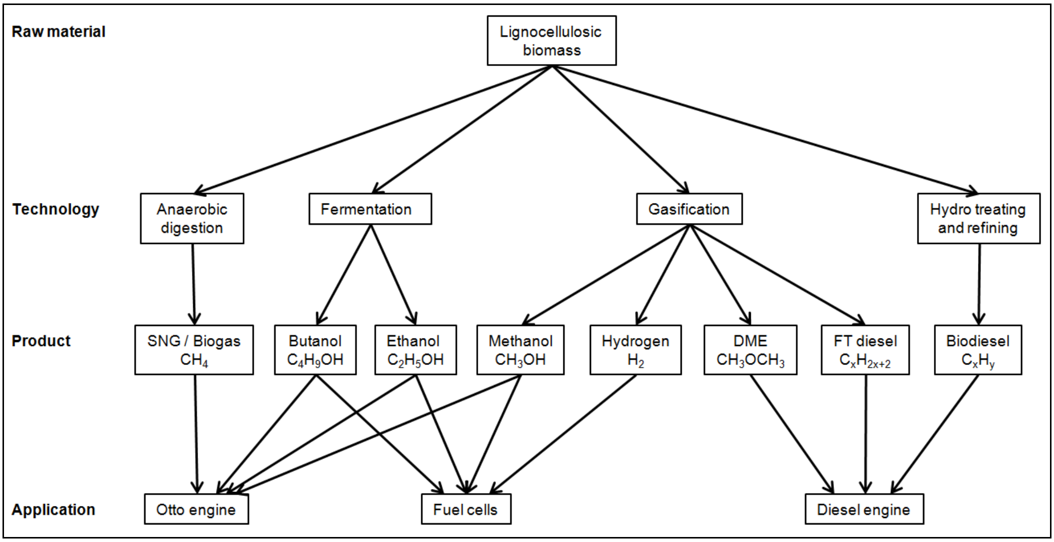

Figure 4: Outlook of different second generation biofuel production pathways.

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.

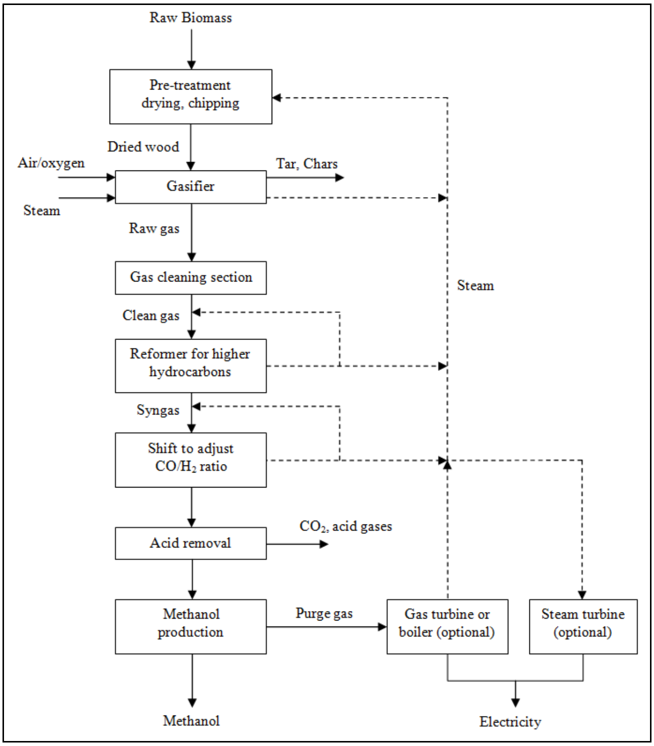

Figure 5: General process flow diagram for biomass based methanol production.

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.

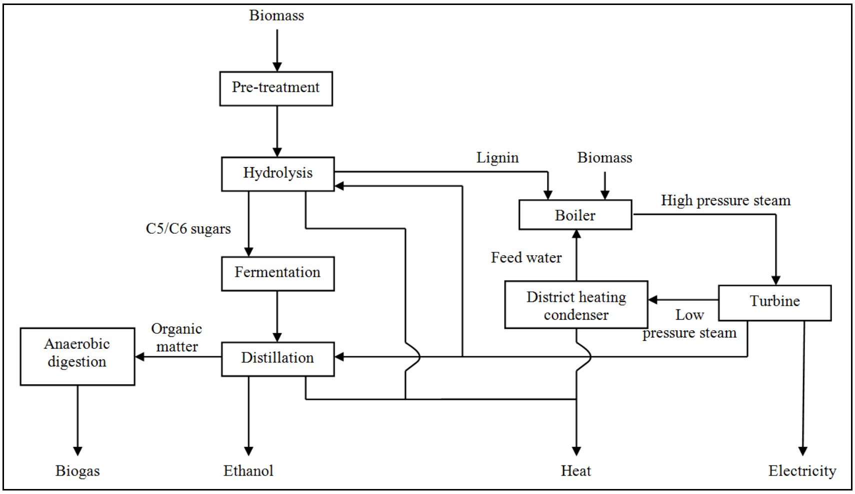

Figure 6: Configuration scheme of the poly-generation process.

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, $b_{i',j,t,y}^{import}$ is the amount of biomass delivered from the import point i' to the production plant j, $b_{m,j,t,y}^{sawmill}$ 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, $b_{i',f,t,y}^{import}$ is the amount of biomass delivered from the import point i' to the existing industry f and $b_{m,f,t,y}^{sawmill}$ is the amount of biomass delivered from the sawmill m to the existing industry f. $x_{j,k,t,y}^{biofuel}$ is the amount of biofuel delivered from the production plant j to the gas station k, $x_{i',k,t,y}^{import}$ is the amount of biofuel delivered from the import point i' to the gas station k and $x_{k,l,y}^{biofuel}$ 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

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

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

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

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 $\overline{b}^{sawmill}_{m,y}$. The biomass from the sawmill has a cost of $c^{sawmill}_{s,y}$. The biomass delivered from the sawmill m is then expressed by

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

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 ($\overline{b}^{import}_{i',y}$) and the sawmills ($\overline{b}^{sawmill}_{m,y}$). Different percentages of these values are considered and analyzed.

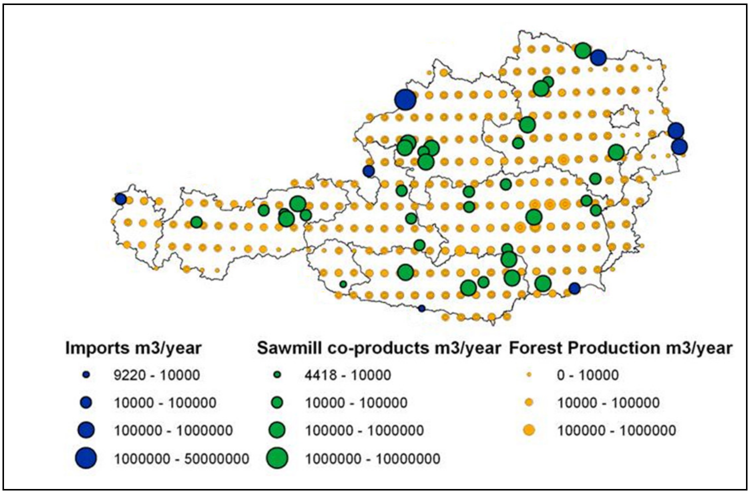

Figure 7: Biomass availability in Austria from the imports [67], sawmills [68] and forestry.

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.

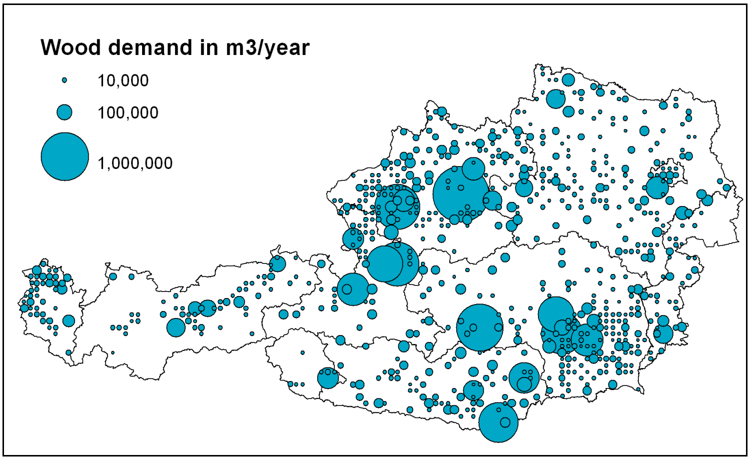

Figure 8: wood demand from the actual forest industries other than sawmills in Austria (the demand spots greater than 5,000 m^3/year are represented for reading simplicity).

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

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

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*.

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

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 $\left(Cost_a / Cost_b = (Size_a / Size_b)^{SF}\right)$ 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 $q_{j,c,y}^{D}$, 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 €/year	Cost €/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:

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

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

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

and

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

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.

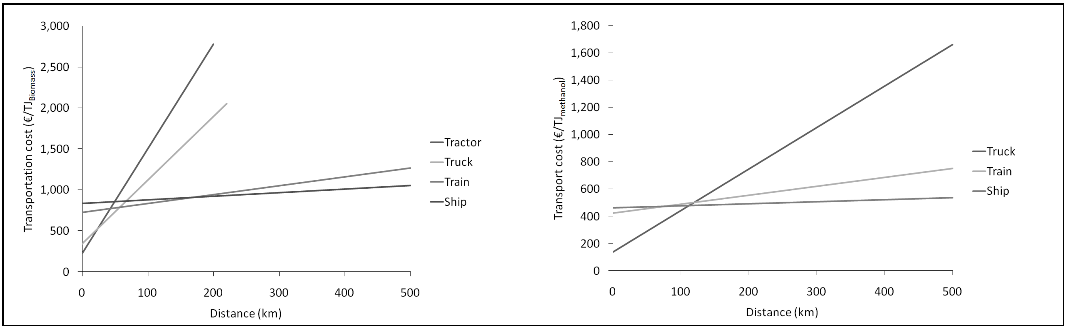

Figure 9: Transportation cost for biomass (left) and biofuel (right) by tractor, truck, train and ship [83].

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].

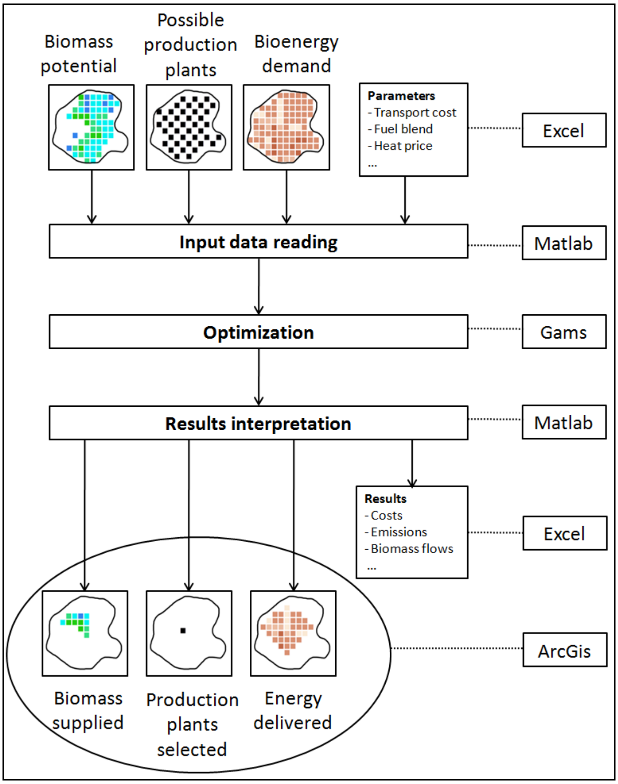

Figure 10: Overview of the modeling procedure together with the software used at each step.

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.

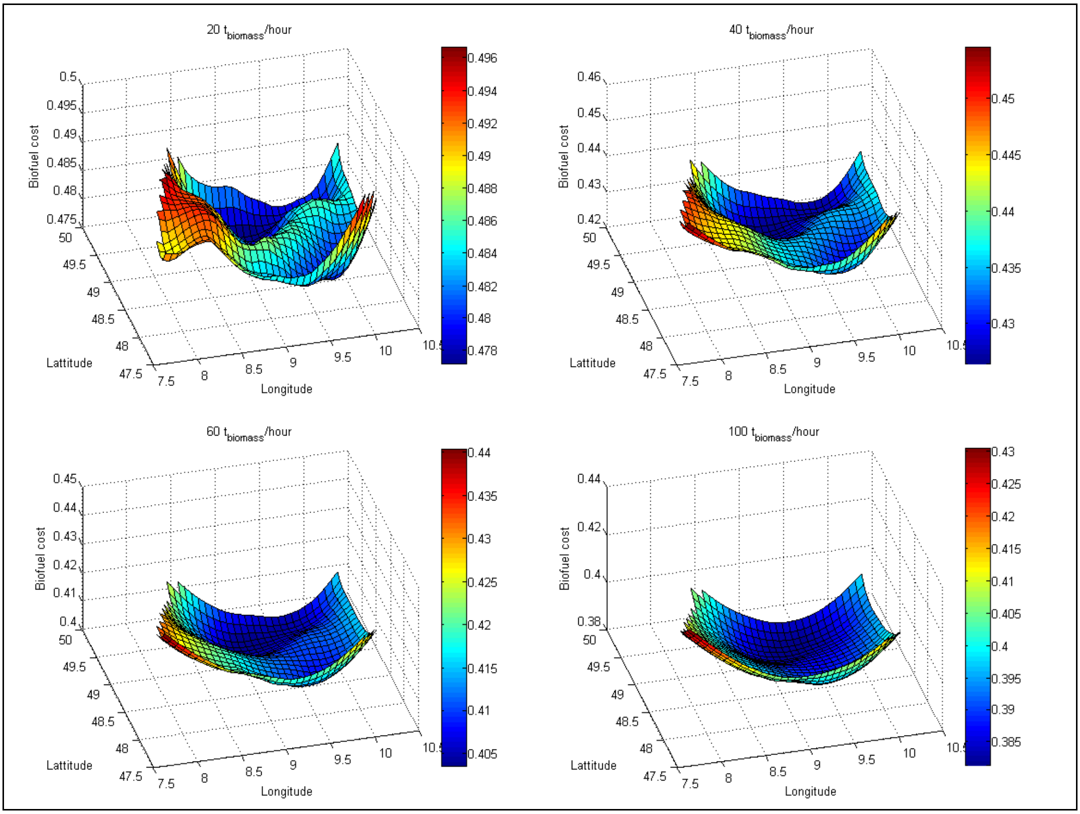

Figure 11: 3D representation of the economy of scale in the region of Baden-Württemberg for four production plant sizes. From left to right and top to down, the size of the production plants are 20, 40, 60 and 100 tons of biomass per hour. Each graph represent the methanol cost in €/l$_{methanol}$. Each 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.

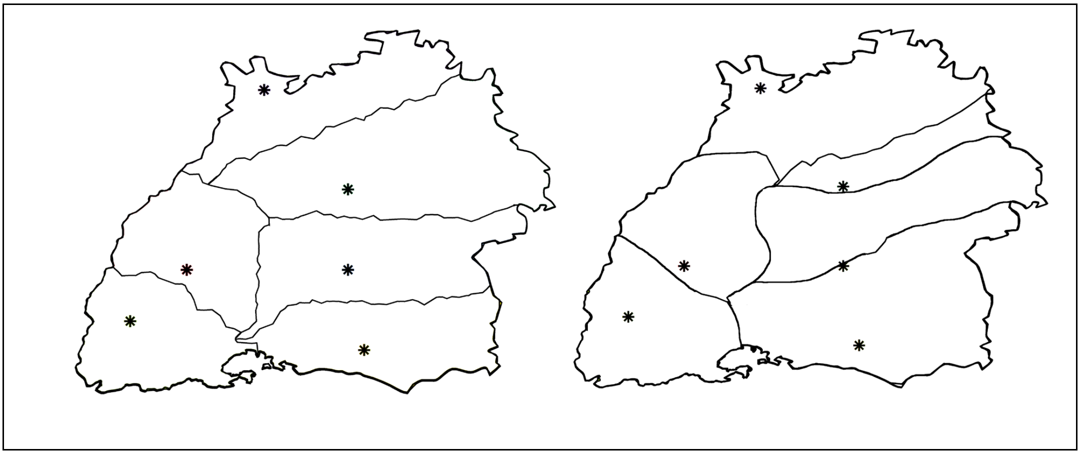

Figure 12: Baden-Württemberg. Left: Feedstock areas supplying each of the production plants symbolized by a star. Right: Biofuel distribution regions for each of the production plants.

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.

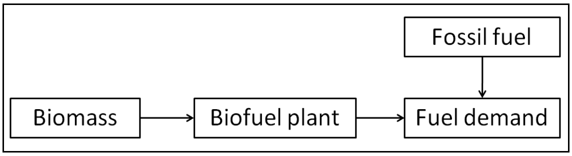

Figure 13: Supply chain of the model with fossil fuel.

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.

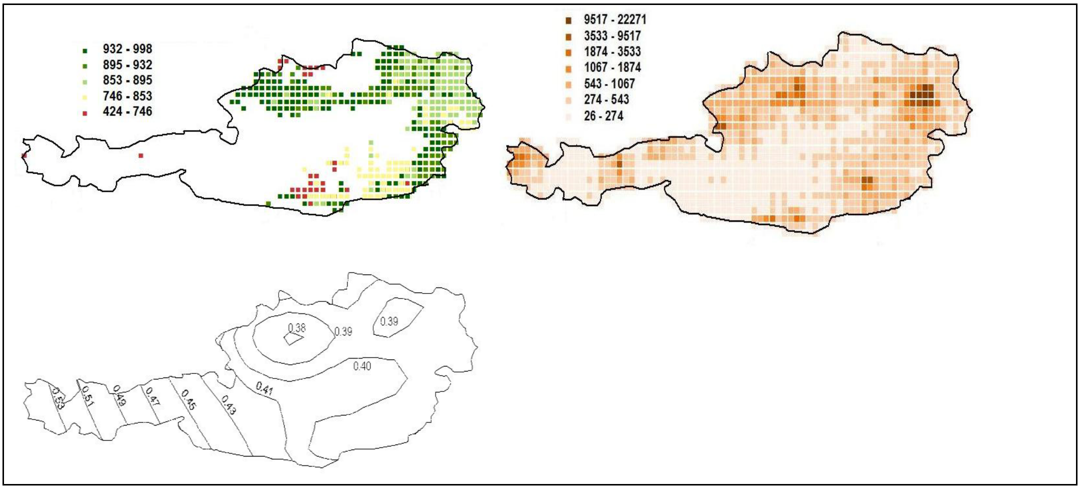

Figure 14: Austria. Top left: Potential production of poplar coppice in ton per grid cell per year. Top right: Number of inhabitants per grid cell. Bottom left: cost of methanol in €/$l_{methanol}$ regarding the position of a production plant of 846 $t_{biomass}$/day. The methanol-gasoline blend M5 is 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.

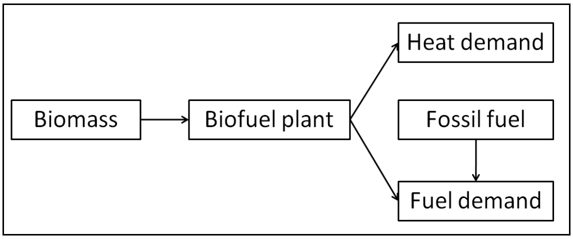

Figure 15: Supply chain of the model with heat demand.

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.

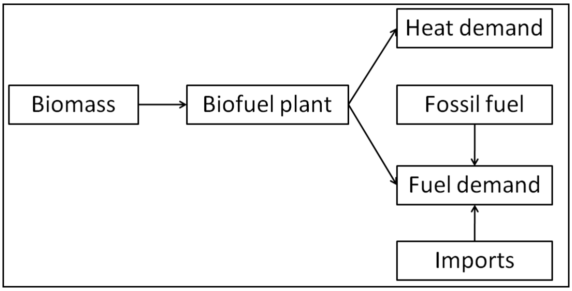

Figure 16: Supply chain of the model with biofuel imports.

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.

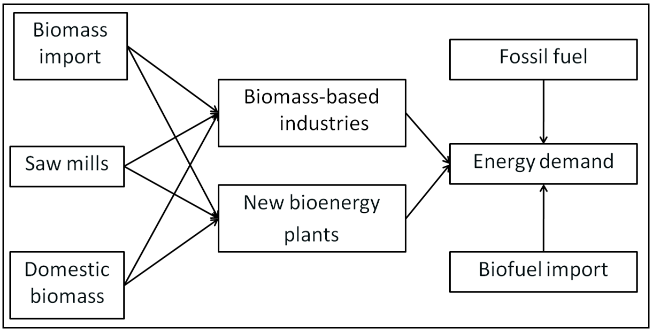

Figure 17: Latest version of the supply chain. The biomass is provided from a domestic production, the sawmill residues and the imports. The biomass-based industries and the potential bioenergy plants compete for the biomass and the energy demand. The energy demand comprises the transport fuel demand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

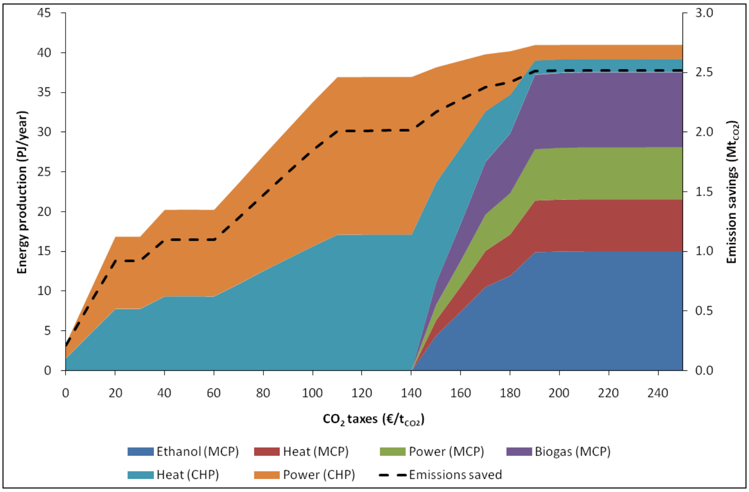

Figure 18: Diffusion of technologies and emission savings depending on CO_2 taxes (MCP stands for multi commodity plant).

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.

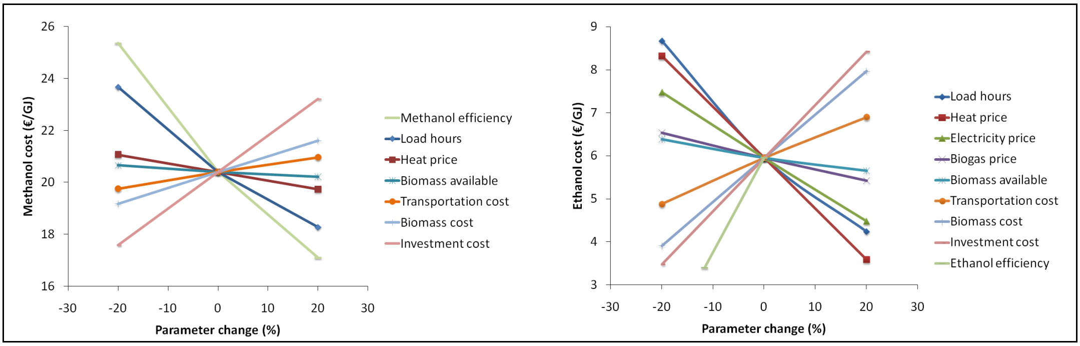

Figure 19: Sensitivity on the methanol (left) and ethanol (right) cost.

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.

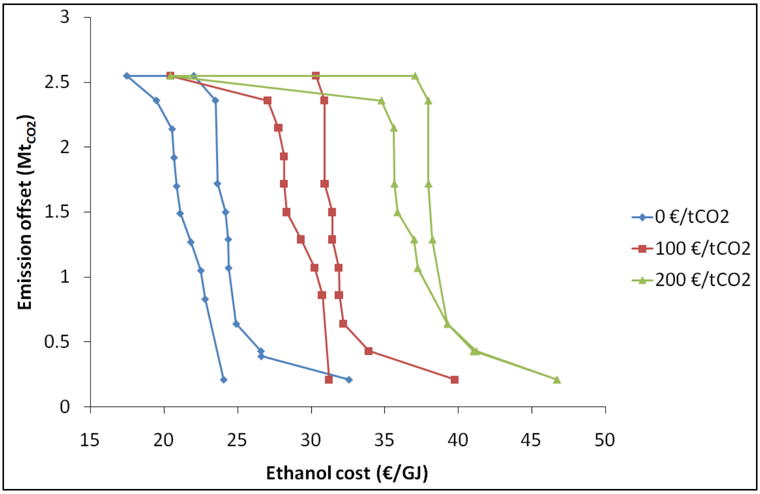

Figure 20: Outer boundaries for three carbon taxes. The values within the boundaries are possible values.

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.

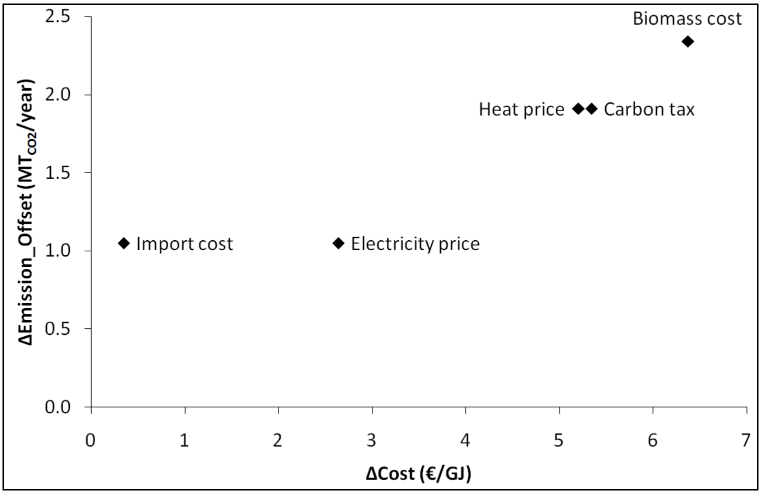

Figure 21: Parameter sensitivity.

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.

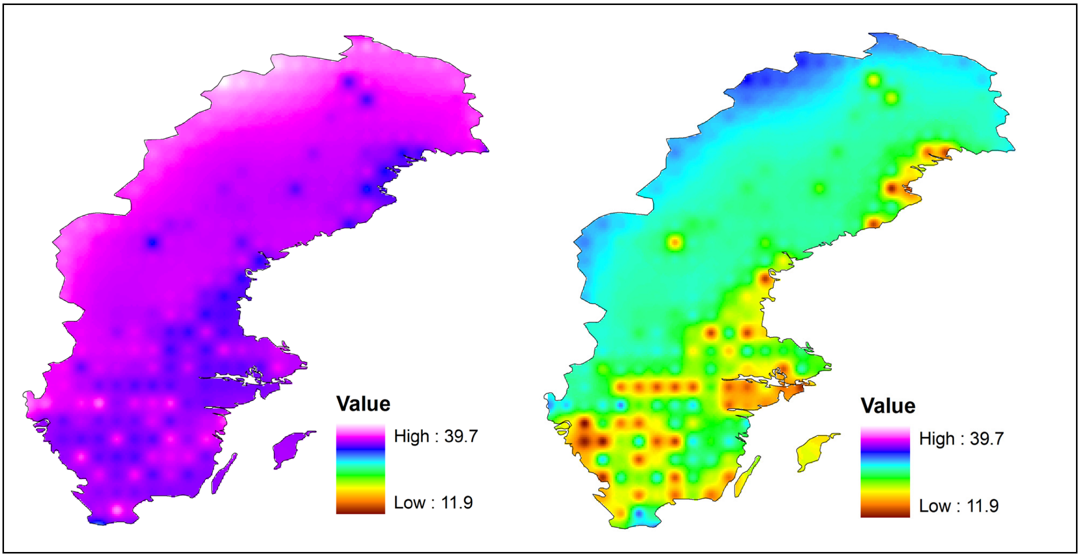

Figure 22: Methanol (left) and ethanol (right) cost in €/GJ for a 40 $t_{biomass}$/h plant in Sweden.

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.

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