Cost-effective CO_2 emission reduction and fossil fuel substitution through bioenergy production in Austria: a spatially explicit modeling approach

PhD thesis submitted in
partial fulfillment of the requirements for the degree

Doctor rer. nat. Bodenkultur

at the University of Natural Resources and Applied Life Sciences (BOKU), Vienna

prepared in the framework of the
Doctoral School Sustainable Development (dokNE) by

DI Johannes Schmidt

Supervisor:
Priv. Doz. Dr. Erwin Schmid — *Institute for Sustainable Economic Development, BOKU*

Co-advisors:
Dr. Sylvain Leduc — *International Institute of Applied Systems Analysis, Laxenburg,Austria*
Dr. Erik Dotzauer — *Mälardalen University, Västerås, Sweden*
ao. Univ. Prof. Dr. Marianne Penker — *Institute for Sustainable Economic Development, BOKU*

Reviewers:
o. Univ. Prof. Dr. Markus Hofreither — *Institute for Sustainable Economic Development, BOKU*
Ass. Professor Dr. Frank Pettersson — *Thermal and Flow Engineering Laboratory, Åbo Akademi University, Åbo, Finland*

Vienna, December 2009

This thesis has been prepared in the framework of the doctoral school Sustainable Development (DOKNE) at BOKU University of Natural Resources and Applied Life Sciences, Vienna, Austria. The doctoral school is funded by the Austrian Research Program on Sustainability "provision" as well as by the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and the states Lower Austria, Styria, and Vienna.

Acknowledgements

First of all, I would like to thank my advisor, Erwin Schmid for his feedback and the very valuable ideas that were crucial for writing this thesis. A lot of time and dedication went into advising and encouraging me and I'm very thankful for all of his contributions. Sylvain Leduc, who is the main author of the model that this thesis is based on, supervised my work at the Young Scientists Summer Program at the International Institute of Systems Analysis and later on co-authored all of my articles. I am very grateful to him for giving a first start to my modeling efforts and for investing very much time in advising me. Sylvain also appointed me to Erik Dotzauer who started helping in the model development from the very beginning, providing crucial inputs to the thesis and co-authoring all of the articles. I'm very thankful for all of his contributions, his ideas, his comments and his critique. Special thanks go to Dagmar Schwab who initially had the idea of combining Sylvain's model with my ideas. I am grateful to Georg Kindermann for providing the data on forest productivity to me.

A lot of appreciation goes to my colleagues from the Doctoral School "Sustainable Development". I would like to thank them for all the discussions, the fun and the troubles they shared with me. I owe a lot to the organizers of the Doctoral School, particularly Andreas Muhar, for providing a framework for my PhD studies that allowed the dedication of my entire working time to research. Many thanks go to the other researchers and employees at the Institute of Sustainable Economic Development for discussing my thesis and other ideas with me.

I owe a lot to my parents who supported me in my ongoing studies, always showed interest in my work and encouraged me to continue it – thank you for everything. To my brother Michael and my sisters Maria and Elisabet, thanks for being there! Special thanks go to Rudi, your Mohnpalatschinken often saved my days. I'm grateful to my grandfather who always was eager to learn about my work and supported me in my studies. Many thanks go to all my friends who've been there for me in the last three years. Very special thanks go to Herbert and Birgit for the good times we passed together. Rototom live!

Ulla, you shared my joy when I was successful, you calmed me when I wasn't and you've made me *not* think about my thesis. Thank you so much for everything.

Kurzfassung

Die Verringerung von CO_2-Emissionen und die Sicherstellung der Energieversorgung sind Hauptziele der österreichischen Energiepolitik. Forstholz stellt eine wichtige Ressource für erneuerbare Energieproduktion in Österreich dar. Neue Technologien zur Bioenergieproduktion bieten zusätzliche Möglichkeiten, mit Hilfe dieses Rohstoffes die energiepolitischen Ziele zu erreichen. Zu diesen technischen Möglichkeiten gehören Zweitgenerationstreibstoffe und Biomassegasifizierungskraftwerke zur Stromerzeugung mit optionaler CO_2-Abscheidung und Speicherung. Um Anreize für eine höhere Produktion von Bioenergie zu schaffen, wurden verschiedene Politikinstrumente, wie der CO_2-Emissionshandel, Einspeisetarife für Ökostrom, Beimischungsverpflichtungen für Biotreibstoffe und Subventionen für Pelletsöfen, eingeführt. Jedoch ist bislang nicht klar ersichtlich, wie hoch das Potential unterschiedlicher Bioenergietechnologien ist, CO_2-Emissionen zu verringern und fossile Treibstoffe zu substituieren und inwiefern die energiepolitischen Instrumente die kosteneffektive Erreichung diese Politikziele ermöglichen. Diese kumulative Dissertation behandelt die Problemstellung mit Hilfe eines räumlich expliziten Energiesystemmodells. Das Modell minimiert die Gesamtkosten von Bioenergiesystemen, die im Wettbewerb mit fossilen Energieträgern stehen. Dadurch lassen sich die Systemkosten sowie der Umfang an CO_2-Emissionen und fossilen Energieträgern, die eingespart werden können, abschätzen. Unsicherheiten in den Modellparametern werden explizit behandelt. In den drei wissenschaftlichen Artikeln, aus denen sich diese Dissertation zusammensetzt, wurden (i) eine Potentialanalyse für Kraftwärmekopplungsanlagen, (ii) ein Vergleich über die Wettbewerbsfähigkeit von neuen Technologien und (iii) eine Kosteneffektivitätsanalyse von verschiedenen Bioenergiepolitikinstrumenten durchgeführt. Der erste Artikel legt dar, dass zwar beträchtliche Potentiale für Biomasse betriebene Kraftwärmekopplungsanlagen vorhanden sind, dass aber die Abwärmenutzung der Kraftwerke sehr stark von der räumlichen Verteilung der Wärmenachfrage beschränkt wird. Der zweite Artikel zeigt, dass sich CO_2-Emissionen mit Hilfe von Strom- und Wärmeproduktion wesentlich effizienter reduzieren lassen als durch Biotreibstoffe. Die Ergebnisse des dritten Artikels belegen, dass Beimischungsverpflichtungen für Biotreibstoffe ein ineffektives Politikinstrument darstellen, während Steuern auf fossile CO_2-Emissionen das kosteneffektivste Politikinstrument zur Emissionsreduktion sind.

Abstract

Climate change mitigation and security of energy supply are main drivers of Austrian energy policies. Bioenergy production from forest wood is an important option for renewable energy generation in Austria. New conversion technologies are being developed to increase the options of utilizing wood in energy production. These options include second generation biofuel production and biomass integrated gasification combined cycle plants with optional carbon capture and storage. Several policy instruments including CO_2 emission trading, feed-in tariffs, biofuel blending obligations, and subsidies on pellet furnaces are implemented in the bioenergy sector. The capability of the new technologies to reduce CO_2 emissions and substitute fossil fuels as well as the effect of bioenergy policy instruments on the deployment of these technologies is not obvious yet. This cumulative thesis addresses these issues by developing and applying a spatially explicit energy system model. The model minimizes total costs of the bioenergy systems in competition with fossil fuels and allows estimating system costs, the amount of CO_2 emission reductions, and the substitution of fossil fuels. Uncertainties inherent to model input parameters are explicitly addressed in an uncertainty and sensitivity analysis. Three scientific articles present analyses on (i) the potentials of combined heat and power production, (ii) the competitiveness of new bioenergy technologies, and (iii) the capability of alternative energy policy instruments to attain policy targets cost-effectively. Results of the first article show that significant potential for biomass fired combined heat and power plants exists, however, the spatial distribution of heat demand limits the utilization of waste heat. The second article shows that the utilization of biomass for heat and power production is more efficient in reducing CO_2 emissions and substituting fossil fuels than the production of biofuels. The third article indicates that biofuel blending obligations are ineffective and produce negative CO_2 emission savings in comparison to a baseline scenario while carbon taxes are the most cost-effective policy instrument for CO_2 emission reductions.

List of appended papers

This thesis consists of the following articles:

Article 1

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. and Schmid, E. (2009): Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. *International Journal of Energy Research*, doi.10.1002/er.1623

Article 2

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. and Schmid, E. (2009): Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. *Applied Energy*, doi:10.1016/j.apenergy.2009.11.007

Article 3

Schmidt, J., Leduc, S., Dotzauer, E., and Schmid, E. (2009): Analyzing the cost-effectiveness of energy policy instruments in the bioenergy sector. Submitted to *Energy Policy*.

The following articles are related to the work and are also attached to the thesis:

Article A.1

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. and Schmid, E. (2009): Regional bioenergy supply and demand and some implications for rural development. In: Darnhofer, I., Grabner, A., Hambrusch, J., Kirner, L., Matscher, A., Oedl-Wieser, T., Peyerl, H., Pistrich, K.H., Pöchtrager, S., Reiter-Stelzl, J., Schermer, M., Sinabell, F. (eds.), Rollen der Landwirtschaft in benachteiligten Regionen, *19. Jahrestagung der österreichischen Gesellschaft für Agrarökonomie, Tagungsband 2009,* Innsbruck, Austria, 24. - 25. September 2009, 11-12.

Article A.2

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. and Schmid, E. (2009): Biofuel production in Austria considering the use of waste heat: a study on costs and potentials of greenhouse gas reduction In: H. Peyerl (eds). *Jahrbuch der österreichischen Gesellschaft für Agrarökonomie,* Band 18/3, Facultas, Wien, 117-126.

Article A.3

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

Abbreviations

BECS	Bioenergy with carbon capture and storage
BIGCC	Biomass integrated combined cycle
CCS	Carbon capture and storage
CHP	Combined heat and power
EU ETS	European emission trading scheme
GIS	Geographic information system
IPCC	Intergovernmental panel on climate change
MIP	Mixed integer programming

Contents

1 Introduction

1.1 Problem statement

This introduction is written while nations gather in Copenhagen to negotiate a follow-up treaty to the Kyoto protocol. The recently released Copenhagen Diagnosis Report [1] reveals that annual global CO_2 emissions from fossil fuel burning in 2008 were 40% above the levels of 1990 and thus close to the highest scenarios of CO_2 emissions from fossil fuels so far considered by the Intergovernmental Panel on Climate Change (IPCC). Observed reductions in solar activity are more than compensated by the drastic increase in CO_2 emissions and other greenhouse gases which may imply additional increases in global temperatures in the coming decades. Possible negative consequences to eco-systems and human societies can be found in the last IPCC report on the impacts of climate change [2]. At the same time, the extensive utilization of fossil fuels creates additional challenges for the society. The recent gas crisis in Europe, the dependency on fossil resources in politically unstable regions [3, 4] and the peak oil debate [5-7] cause discussions on how to fuel the world's growing needs for energy. A shift away from fossil fuels to renewable energy seems to be necessary, regardless of whether the supply of fossil fuels or the capability of the atmosphere to uptake the released carbon limits fossil fuel consumption [8]. Austria committed to CO_2 emissions reductions in the Kyoto protocol and to increasing shares of renewable energy production in the EU directive 2009/28/EG. However, Austria is still struggling to comply with the Kyoto targets and the EU directive. Newest estimates show that Austria is far from reaching the targets in the period 2008-2012 [9]. Achieving renewable energy targets by 2020 will also be a tremendous effort [10].

Reducing fossil fuel consumption can be achieved by various means. On the supply side, a switch to renewable energies and an increase in the efficiency of energy production are common solutions. Reducing energy demands by improving energy efficiency in energy consumption is also relevant. On the interface between supply and demand, a change in the mode of supplying and using an energy service, e.g. a switch from private to public transportation, will be important to reduce total fossil fuel consumption [11].

This thesis analyzes the supply side of the energy system and focuses on a traditionally important renewable energy source in Austria: biomass from forests. A large part of Austria (47%) is covered by forests and the forest cover is still increasing [12]. Bioenergy production experienced an increase of 90% between 1980 and 2007 [13], contributing to 11% of total Austrian gross energy consumption. Around 85% (year 2004) of the resources for bioenergy production come from forests, including fuel wood, bark, residuals of the pulp and paper industry, and saw mill co-products [14]. Most of the forest wood is used for heat generation in private households. Starting in the late nineties, power production from woody biomass emerged and grew significantly, fostered by the implementation of the renewable energy act in 2003 [13]. However, new technological developments will increase the competitiveness among and within processes as well as products from wood resources. Figure 1 presents an overview of existing and future conversion technologies from woody biomass feedstock. In this thesis, the following new production technologies are considered:

1. Biomass integrated combined cycle technology (BIGCC), a new power generation technology, yields more power from wood resources than currently installed technologies do. It allows combined heat and power (CHP) production. Carbon capture and storage (CCS) can be combined with BIGCC and thus produce negative CO2 emissions. This combination may develop into an important technology for the appropriate management of climate change risks [15].
2. Second generation biofuel production allows the utilization of woody biomass as feedstock in transportation fuel production.

However, these technologies are still under development and are expected to be commercially available in a few years. To promote the bioenergy sector, various highly debated policy interventions have been implemented in recent years, including

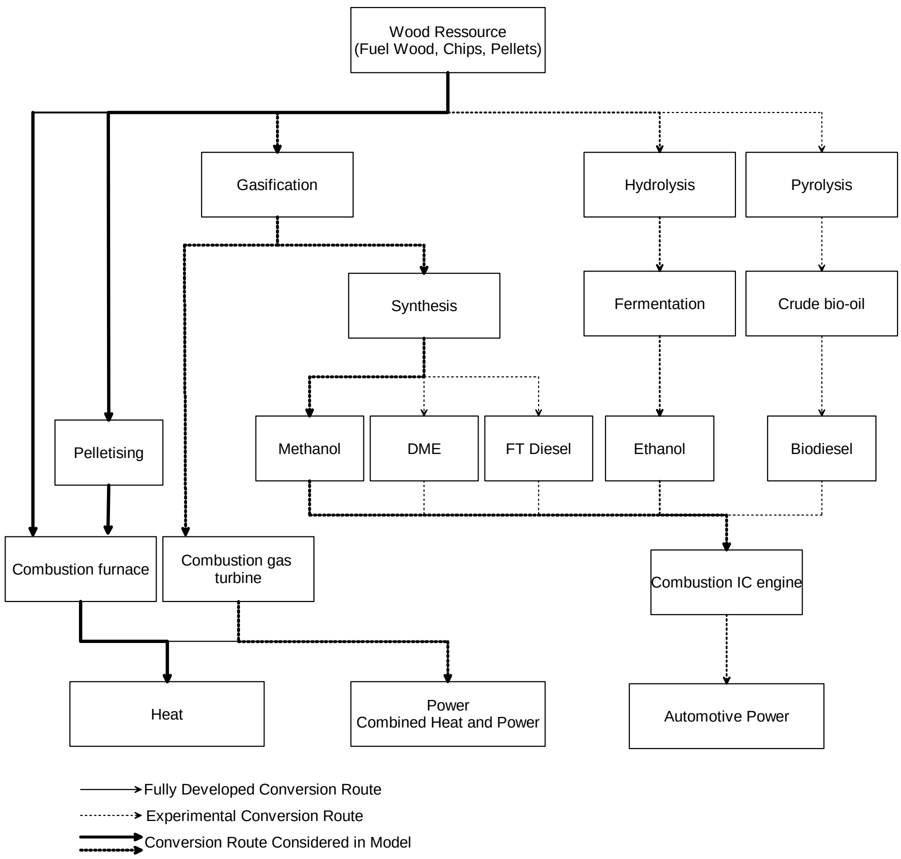

Figure 1: Most important biomass conversion routes [16, 17].

feed-in tariffs for power produced from biomass, subsidies on pellet heating systems, biofuel blending obligations and the European Emission Trading Scheme (EU ETS). The contributions of technologies to policy targets, i.e. the reduction of CO_2 emissions and the substitution of fossil fuels as well as the costs, ecological, and economic effects are crucial in designing efficient energy and environmental policies. A major goal of the thesis is to provide policy makers and stakeholders several analyses on the competitiveness of new technologies in the Austrian bioenergy supply chain and on the cost-effectiveness of alternative bioenergy policy instruments. The following policy relevant research questions are addressed in the thesis:

I. Which bioenergy technologies for woody biomass are cost-effective in reducing CO_2 emissions and substituting fossil fuels?

II. Which bioenergy policy instruments reach the targets of reducing CO_2 emissions and substituting fossil fuels cost-effectively? Which trade-offs have to be considered with respect to the two policy objectives?

Different methodologies for assessments of bioenergy technologies are available [16, 18-30]. However, they do not, or only partially, address some of the described questions, which are important in assessing bioenergy conversion technologies. Biomass transportation costs as well as energy distribution costs have significant impact on total costs of a bioenergy supply chain [31, 32]. In particular district heating may induce high infrastructure costs depending on the spatial densities of heat demand**.** As a consequence significant variations of production costs can be expected at different locations. A comparison of bioenergy technologies should therefore consider plant production costs at cost optimal locations and take into account demand restrictions imposed by the spatial distribution of demand. The thesis therefore also poses the following research questions:

III. Which restrictions are imposed on bioenergy utilization by the spatial structure of biomass supply and energy demand?

IV. Which plant locations are suitable and optimal for bioenergy production?

Modeling the competition of future bioenergy technologies involves uncertainty. Energy prices are volatile and long-term forecasts vary substantially [33]. Additionally, uncertainties are attached to the development of bioenergy technologies. Future production and investment costs and production efficiencies are not well known today. This problem is directly addressed in the thesis and formulated in the following research question:

V. How do uncertainties in relevant model parameters influence model results? Are results stable with regard to different assumptions on future parameter realizations?

These research questions are addressed in a cumulative thesis consisting of two published and one submitted article. Three additional conference articles (A.1-A.3) applying the model to selected research questions can also be found attached to the thesis. The first three articles present the model and apply it to an analysis of (a) the potential of biomass gasification power plants and least cost optimal locations in

Austria, (b) the relative cost competitiveness of pellet production, BIGCC with and without CCS and second generation biofuel production, and (c) the cost-effectiveness of bioenergy policy instruments in attaining emission reductions and fossil fuel substitution targets.

1.2 Methodology

Energy models can be characterized as top down and bottom up model approaches [34]. Bottom up or energy engineering models describe energy technologies in detail including costs and technical conversion efficiencies. They allow representing technical details evaluating new technologies, estimating the environmental impact of technologies (e.g. CO_2 emissions) and assessing the effect of policy instruments on the deployment of technologies. In bottom up optimization models, energy prices and demand quantities are given exogenously. However, these models usually do not allow estimating the effects of policy instruments on different upstream and downstream sectors or regions. Substitution effects are only captured limitedly. The latter is usually considered in top-down models by including estimated behavioral equations and elasticities based on historical data. A drawback of top-down models is the lack of technical details and that future technologies cannot be easily included in the assessment [34-36]. To address the research questions raised above, a bottom up energy system model approach seems to be more appropriate than a top-down one. They allow

(i) addressing of the competition of technologies and the measurement of CO_2 emissions and fossil fuel substitution (research question I)

(ii) estimating the effect of policies on the deployment of technologies and the consequences for CO_2 emissions and fossil fuel substitution (research question II)

(iii) the consideration of spatial factors and optimization of locations through detailed representation of the technical system (research question III-IV)

Uncertainty should be explicitly considered in the modeling process by deriving information on how the uncertainty in the model parameters affects the stability of results. The analysis of the influence of parameter uncertainty on model results is also relevant. Instead of assuming only one or few possible parameter values, the probability distributions of model results are therefore derived by assuming plausible distributions for input parameters. This approach allows comparing different scenarios under uncertainty by testing the scenario outputs statistically. Additionally, an extended sensitivity and uncertainty analysis is applied to model results by estimating a linear meta-model from the optimization model. The meta-model can be easily manipulated and is used to gain insights into the sensitivity of model results to variations of input parameters and into the contribution of model parameter uncertainty to the uncertainty of model results.

Numerous studies have assessed new woody biomass technologies with different methodologies. Table 1 reports recent work published in this subject of research. Assessments of single production technologies that derive production costs with either mixed integer programs (MIP), geographical information systems (GIS) or by

Table 1: Studies on bioenergy technologies based on woody biomass.

Solid Biomass Technologies	Methodology	Spatially Explicit	Reference
Ethanol through hydrolysis	MIP	Yes	[18]
Heat and CHP (steam engine)	GIS	Yes	[19]
Heat and CHP (steam engine)	MIP	Yes	[20]
CHP (steam engine)	MIP	Yes	[21]
Methanol through gasification	MIP	Yes	[37, 38]
Ethanol through hydrolysis	MIP	Yes	[39]
CCS with pulp and paper mills	Calculation of total costs and emission reductions	No	[22-24]
CCS with ethanol through hydrolysis	Calculation of total costs and emission reductions	No	[25]
Co-combustion, BIGCC, fuel wood, Fischer Tropsch biodiesel, ethanol through hydrolysis	System perturbation analysis (no economic analysis)	No	[16]
BIGCC, methanol and ethanol (production process not specified)	Linear program	No	[26]
Ethanol through hydrolysis, bio-oil, BIGCC	Comparative cost calculations	No	[27]
BIGCC, pellets	GIS	Yes	[28]
Ethanol through hydrolysis, ethanol through gasification	Comparative cost and emission reduction calculations	No	[29]
Ethanol through hydrolysis, methanol through gasification, DME, pellets, BIGCC	Comparative cost and emission reduction calculations	No	[30]

simple arithmetic calculations in most cases consider spatial factors. However, they often do not model the entire bioenergy supply chain. Especially costs of district heating are often neglected in these studies (see introduction of article 1). Assessments of the cost-competitiveness of different bioenergy technologies do not consider spatial factors yet (see introduction of article 2). Only one publication [28] addressed the spatial context in comparing biomass CHP to pellet production in a regional study using a GIS. However, the model does not include policy instruments and a cost minimization principle. None of the reviewed models explicitly addressed uncertainty in their assessments. An existing single technology, spatially explicit model developed by Leduc et al. [37-42] is used in this thesis. It is extended to allow analyzing the research questions. The original model is a static, spatially explicit MIP that minimizes costs of second generation biofuel production with regard to distances to biomass supply and fuel demands. The following model extensions were developed in this thesis:

- Spatially explicit estimation of energy demand to derive district heating infrastructure costs and transportation costs for the delivery of pellets and biofuels (article 1 and article 2)

- Monte-Carlo simulation and bootstrapping to address model parameter uncertainty (article 1 and article 2)
- Inclusion of additional conversion technologies including BIGCC, BECS and pellet production to allow for competition (article 2)
- Inclusion of energy policy instruments (article 3)
- Inclusion of biomass supply curves instead of constant biomass costs (article 3)

Model details are described in the three main research articles. However, the system boundaries of the model and the consequences for the interpretation of model results are not presented in detail. Therefore, the following sections focus on describing these boundaries and on discussing how the system boundaries affect the model and what, as a consequence, has to be considered when interpreting results.

1.2.1 Biomass feedstocks

Bioenergy can be produced from agricultural or forestry feedstocks. Different feedstocks are directed to different energy conversion chains. Energy crops from agriculture are mainly applied in power and transportation fuel production. Woody feedstocks consisting of lingo-cellulosic material go to power and heat production while transportation fuel production from lingo-cellulosic resources is still commercially limited [43]. The production of agricultural energy crops has increased mainly with soaring first generation biofuel production starting in the early 2000s and has caused a lot of discussions [44-48]. GHG emission savings of first generation biofuels are little or even negative, depending on

- soil texture, climate, cropping management practices [46]
- fertilization [49]
- crop and conversion chains chosen [50]
- direct and indirect land conversions caused by increased biofuel production [46, 51]

Direct and indirect changes from food to fuel production has caused increasing food prices with adverse effects on the urban poor in developing countries [45, 52, 53]. Woody biomass is considered to be an environmentally friendly and socially acceptable alternative option, because it is considered to be more efficient in reducing GHG emissions than agricultural energy crops are [50]. Sustainable forest management can provide additional resources of woody biomass [43]. In Austria, the potentials of unused forest resources are of major magnitude [12]. Such additional biomass supply is considered in all model analyses. However, imports of biomass or bioenergy products are not considered and therefore leakage effects are not addressed with respect to land use changes and GHG emissions in other regions (see section 1.2.7). Furthermore, the effects of management practices on the forest CO_2 cycle (see section 1.2.2) are not considered in the model as well.

1.2.2 Forest carbon cycle

The effect of feedstock production on CO2 balances is highly relevant in assessing the potentials of CO2 emission reductions through the substitution of fossil fuels by bioenergy products. Many bioenergy assessments [30, 54], including our model, assume a simple carbon model where re-growth of trees sequestrates the carbon that is previously released in bioenergy utilization. The amount of CO_2 emissions saved by substituting fossil fuels with bioenergy (e^{subst}) minus the amount of CO_2 emissions released in the production process (e^{prod} , e.g. through biomass transportation) is used as indicator for total emission reductions (e^{red}), i.e. $e^{red} = e^{subst} - e^{prod}$. However, harvests are disturbances to the forest CO_2 cycle and may induce changing levels of carbon in above ground reservoirs [55, 56] as well as in the soil [57]. Main results of assessments that compare fossil fuel substitution of wood products with carbon sequestration of unmanaged forests come to the conclusion that the contribution of the forest carbon cycle to total CO_2 emission reductions of bioenergy projects depends on

- timing of harvesting and carbon release [55]
- the observed time period and land use changes [56]
- how CO_2 sequestration of forests is allocated to bioenergy projects [56]
- type and magnitude of management practices (e.g. clear cut, harvesting, removals) [58]
- the likelihood of non-human disturbances like forest fires and fracture of trees due to winds and snow [59], and
- if carbon neutrality is reached in old grown forests which is contested by recent research [60]

A proper carbon cycle model considers carbon sequestration of forests and the release of carbon in biomass combustion by taking into account carbon sequestration of forests in a baseline scenario [56]. These assumptions yields the following equation

$$e^{red} = e^{subst} + e^{seq}_{manag} - e^{seq}_{nomanag} - e^{comb} - e^{prod}$$

where e^{seq}_{manag} is the amount of carbon sequestrated in the forest under management, $e^{seq}_{nomanag}$ is the carbon sequestration in the same unmanaged forest and e^{comb} is the amount of carbon released in biomass combustion. Different management practices can then be assessed using this model [61].

However, this thesis focuses on the comparison of different bioenergy technologies. Effects of forest management practices on the total carbon stock in the atmosphere are therefore of minor relevance because they do not change the relative efficiency of the bioenergy technologies to each other. Nevertheless, the absolute GHG emission reduction levels may be different, when CO_2 effects of forest management are included in the assessment.

1.2.3 Logistics

Biomass and bioenergy logistics are modeled quite simply. It is assumed that wood harvests are directly loaded to trucks at harvesting sites and transported to the bioenergy plant without any storage in between. The supply of wood is aggregated in grid cells. Transportation distances from harvesting sites to bioenergy plants are estimated by direct Euclidian distances between the center of a grid cell and potential plant sites. The distances are multiplied by a factor modeling additional distances imposed by the layout of the road network. The same procedure applies to commodity transportation: commodities are directly transported to consumers without considering distribution by retailers. Data on the actual road layout and retailing centers would refine results but are left for future analyses.

1.2.4 Conversion technologies

The current model includes a subset of available woody biomass conversion technologies. Bioenergy conversion technologies that are estimated to be most cost-effective in reducing CO_2 emissions in their sector are considered in the model analysis. An extensive argumentation of the chosen conversion technologies is given in article 2. Some important technical options such as co-firing of biomass in coal plants as an effective way of reducing CO_2 emissions [16] and fuel switching in existing district heating networks as low cost option in comparison to building new district heating infrastructures are however currently not included in the model. Limitations to biomass based CHP production imposed by the demand side may be loosened if existing district heating networks are included as heat sinks in the modeling process.

1.2.5 CO_2 emissions

The modeling of CO_2 emissions is presented in detail in article 2 and article 3. As stated there, the model tracks CO_2 emissions of all fossil fuels (including biomass transportation) but does not account for the carbon cycle involved in bioenergy production (see section 1.2.2). The baseline is assumed to be comparable to current emissions in the relevant sectors. Changes in the baseline due to changes in demand induced by economic growth or the introduction of low-carbon technologies other than bioenergy, e.g. photovoltaic, wind or building insulation are not considered. Depending on changes in the baseline scenario, the relative efficiency of technologies may be altered as well. For instance substituting fossil fuels in the power sector by renewable energies other than bioenergy (e.g. wind) decreases the effectiveness of bioenergy power generation relative to heat and fuel production. However, due to the high share of fossil fuels in all sectors, this model limitation is not very relevant, because renewable energy technologies will not entirely replace fossil fuels in the short term. Only heat generation by oil boilers in single-dwellings, as modeled in article 2 and 3, may be fully substituted by pellets. A consideration of new technologies in the private heating sector like heat pumps and building insulation may decrease the total pellet potential therefore.

1.2.6 Demand schedules

The model minimizes costs of supplying regions with energy from fossil fuels and bioenergy plants under different policy targets and demand quantities. The demand for energy is modeled by applying a spatially explicit bottom up estimation principle (see paper 1). The final demand quantity for energy is assumed to be constant. Economic drivers of energy demands like changes in relative prices, income and consumption levels [62] are not endogenously considered yet. However, it is assumed that energy consumers adapt their investment stock (i.e. heating boilers, district heating connections) according to changes in relative supply costs between the technologies.

1.2.7 Imports and exports of biomass and bioenergy products

Currently, only domestic biomass and bioenergy production as well as demands are considered. Imports and exports of biomass and bioenergy products like pellets, fuels and bio-oil as well as leakage effects of international bioenergy policies are not considered yet. Woody biomass is usually not transported far due to the low energy density of biomass which causes high transportation costs. Main Austrian trading partners in woody biomass are therefore neighboring countries and include Germany, the Czech Republic, Switzerland, Italy and Slovenia [63]. However, upgraded products like pellets, fuels and bio-oil can be traded easily due to their high energy density which facilitates the handling and storage of these products. International trade in pellets and biofuels is increasing, causing Canadian pellets to be burnt in Swedish power plants and Brazilian ethanol be used in German cars [64]. Considering trade of biomass resources and bioenergy commodities has significant effects on the competitiveness of the bioenergy sector through the existence of additional suppliers and consumers. Limiting the system boundary to a national context may neglect total GHG emissions caused by the introduction of bioenergy policies. Additional demand for bioenergy may trigger direct and indirect land use changes in regions distant from bioenergy consumption [51]. Land use change is a major contributor to GHG emissions, particularly due to deforestation of tropical rainforests [65]. Direct land use changes occur when land is converted to an intensive bioenergy production regime. Indirect land use changes are land use conversions triggered by increases in international demand of non-fuel products due to declining production in fuel producing countries [51]. For instance, an increase in maize production induced by US biofuel policies decreases land available for soja production. Other regions may take over the supply of these products which, as a consequence, may create additional land conversions there. Alongside to changes in the GHG emission balance, increased agricultural production and deforestation also provoke declines in biodiversity [47] and social conflicts in developing countries when small scale farmers or indigenous people are expelled from their lands by industrial production. The model presented in this thesis only accounts for domestic wood resources and energy demands. Integrating trading and effects of direct and indirect land use changes is beyond the scope of the model yet. However, a full assessment of policy induced effects would require including trade across the full supply chain.

1.3 Model implementation

1.3.1 Model design

The model is described in detail in all articles. This section summarizes the three most important model development steps and discusses the data and software design. The basic model builds on Leduc et al. [37-42]. It optimizes the locations of second generation biofuel plants at least costs. The model was extended by explicitly including district heating infrastructure costs and revenues from district heating. The preparation of a dataset on the spatial distribution of heating demand was important to allow this model extension. In article 1, the model is applied to assess BIGCC production potentials in Austria and to find optimal locations of BIGCC plants. Article 2 focuses on the competition of different bioenergy technologies, including bioenergy systems with carbon capture and storage (BECS), pellet

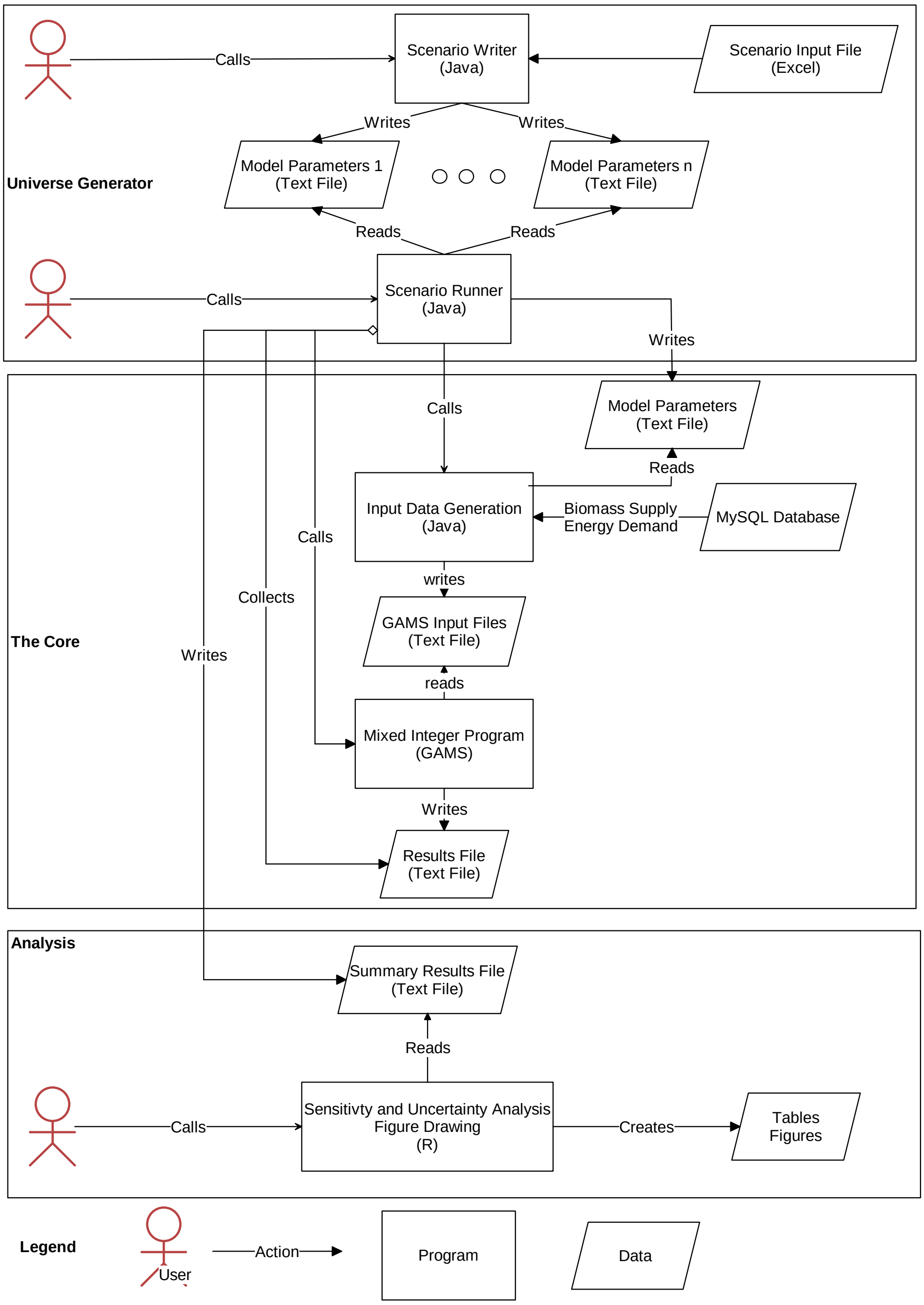

Figure 2: Software design.

production, and second generation biofuel production. The extension of the model to allow for the competition of various technologies was therefore a main focus of model development. Article 3 drops the assumption of constant biomass costs and introduces biomass supply curves instead. The model was applied to analyze the cost-effectiveness of alternative policy instruments in the bioenergy sector.

The assessment of model parameter uncertainties with respect to energy prices and technological details required additional methodological tools. Monte-Carlo simulations in combination with extended sensitivity and uncertainty analyses were used to allow estimating the effects of uncertainties on model outputs. Model parameters have been generated randomly, depending on assumed plausible distributions of the particular model parameter. The model is then solved for many different sets of randomly generated parameters. Model outputs yield distributions of results, which are further analyzed. A linear meta-model of the MIP has been built by applying linear regressions between model parameters and outputs. The resulting linear function has been used for sensitivity and uncertainty analyses.

1.3.2 Software design

This section gives a brief overview over the data and software design because these details are not presented in the articles. The model is split in three modules (see Figure 2): the first module handles the generation of multiple model "universes", i.e. the generation of input parameters for the model. It is written in Java [66]. The second module, the "Core", is responsible for the generation of input data for the MIP, including biomass supply and energy demand. It also contains the MIP which is executed in GAMS [67]. The data generation is done in Java because of its effective database interface and the object oriented paradigm that allows rapid development and fast execution of data based algorithms. In the "Analysis" part, the data is loaded from the output generated by GAMS and transformed into tables and figures. The sensitivity and uncertainty analysis as well as the statistical analysis on the output are performed in the statistical software package R [68].

The "Core" was initially developed as stand alone module and scenarios were generated manually. However, when the Monte-Carlo simulations were included, thousands of simulations, depending on statistical distributions of the model parameters, had to be generated and analyzed. Therefore, the "Universe Generator" was developed to allow the automatic creation of input parameter files. It consists of a "Scenario Writer" which creates text files that serve as inputs to the "Core". The "Scenario Runner" is responsible for providing the files to the "Core", invoking the input data generation and subsequently the MIP. This procedure is very flexible: the core can be run totally independently from the "Scenario Runner" for testing purposes. Also, generated scenarios as well as detailed model outputs of each run can be saved for further analysis. If a single scenario in a set of thousands of scenarios fails, the scenario can be simply invoked and tested again. The overhead produced by the Scenario Runner is less than 50 ms per scenario. The analysis part of the model is totally separated from the rest of the model. Statistical software packages are more appropriate for model output analysis, therefore an interface with the statistical software R, has been established. Data analysis needs a lot of human interaction because the purpose of data analysis determines the procedures applied to the data. A fully automatic link between the "Core" and the "Analysis" is therefore not possible and not necessary. A more detailed description of the three model parts follows next.

1.3.2.1 The universe generator

The “Scenario Writer” is a tool to read scenario data from an excel sheet. For each scenario, a corresponding parameter file, containing the individual settings for the scenario is generated and copied to a separate directory. The “Scenario Writer” is able to produce combinations of different scenarios. The “Scenario Runner” copies the model parameter files to the working directory of the “Core”, invokes the “Input Data Generation” and subsequently the GAMS solver. After termination of GAMS, the single model outputs are copied into one global output file. Statistics on the computation time are collected as well.

1.3.2.2 The core

The “Core” is responsible for the preparation of input data and also contains the MIP. The “Input Data Generation” program is written in Java. It reads the input parameter file and then connects to a MySQL database [69] to generate spatial explicit data on biomass supply, energy demand and district heating costs which are written to ASCII text files readable by GAMS. The MySQL Database contains data of the forest wood supply model, building stocks, and population (for energy demand calculation). The parameters in the input file control how the final biomass supply and the energy demand are defined from the raw stock data. This way, different supply and demand scenarios can be defined. The “Input Data Generation” program is also responsible for taking out spatial calculations, including the determination of transportation distances and aggregation of high resolution grids to grids of lower resolutions. All outputs are written to an ASCII text file format. The MIP executed in GAMS is described in detail in the three articles.

1.3.2.3 The analysis package

The output generated by the Universe Generator is read in by an R script. All calculations and estimations on model output, including the calculation of means and variances, the sensitivity and uncertainty analysis, statistical tests as well as the creation of figures and tables is done within R.

2 Discussion and comparison of research articles

This chapter briefly summarizes and discusses three co-authored research articles. It describes the contribution of the articles to the literature as well as the contribution of the thesis author to the articles. All input data besides the maximum sustainable yields (MSY) of Austrian forests were generated by the thesis author. The MSY was provided by Georg Kindermann. All model extensions including the district heating model, the competition of technologies and the biomass supply curves were accomplished by the thesis author but discussed in detail with the co-authors. Data and model output analyses, including sensitivity and uncertainty analysis as well as generation of output diagrams and tables were the responsibility of the thesis author as well. The author of this thesis also provided draft versions of the articles that were commented and augmented by the co-authors.

2.1 Article 1: Potential of biomass-fired combined heat and power plants and the spatial distribution of biomass supply and heat demand

This article is published in the "International Journal of Energy Research" and presents the basic MIP, details on the heating demand estimation, the district heating cost model, and the sensitivity and uncertainty analysis. An analysis of the potentials of biomass fired combined heat and power (CHP) plants with BIGCC technology was chosen as model application. The article thus addresses research questions III-V. The model builds on the spatially explicit second generation biofuel production model developed by Leduc et al. [37-42]. It is extended by explicitly considering the spatial distribution of heating demand and the effect of heating demand densities on district heating infrastructure costs. BIGCC produces considerably larger amounts of heat than biofuel plants and is therefore an appropriate choice for testing and presenting the district heating extension. CO_2 emissions reduced by the introduction of the plants are estimated. The article introduces Monte-Carlo simulation as measure for sensitivity and uncertainty analysis. Due to high uncertainties inherent to the problem of modeling future potentials – including uncertainties about technological developments, costs and fossil fuel prices – this approach is better in showing the dependency of model results on model parameter variances than simple point sensitivity analysis [70]. The article contributes to the literature by modeling the total bioenergy supply chain from biomass supply to heat demand. Particularly the integration of spatially explicit heating demand estimations and of district heating cost estimates based on heat demand densities is an enhancement to existing models (see introduction of article 1). Furthermore, the explicit consideration of model parameter uncertainties and the application of Monte-Carlo simulation have not been applied before in similar bioenergy models.

The main differences to the other articles are:

- Feedstock prices are exogenous within a simulation. However, prices are varied in the Monte-Carlo simulations.
- Only BIGCC is considered as production technologies.

- All stochastically modeled input parameters are distributed independently from each other.
- All stochastically modeled input parameters are normally distributed.
- Only a subset of input parameters is included in the sensitivity and uncertainty analysis.

The results indicate that BIGCC can contribute significantly to emission reductions in Austria. At price levels between 52 to 57 € MWh^{-1}, which are close to prices observed in the recent past, model results show considerable potentials for BIGCC production. Up to 10% of total Austrian power production can be substituted by BIGCC. However, total potentials are limited due to limitations in heating demand that may be supplied by district heating competitively. Most optimal locations can be found mainly close to the biggest Austrian cities Vienna, Linz, Graz and Salzburg, indicating that biomass transportation costs are less important than the proximity to very dense heating demand. Uncertainties in power and CO_2 emission prices have the biggest impact on model results.

2.2 Article 2: Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies

This article is published in the journal "Applied Energy" and analyzes the cost-competitiveness between bioenergy conversion technologies and contributes to research questions I and III-V. The model is expanded with respect to the first article in the following way:

- Five production technologies (BIGCC, BECS, ethanol, methanol, and pellets plants) are explicitly considered to allow the comparison of cost-effective bioenergy utilization in different sectors.
- Heating oil and transportation fuel demand are spatially explicitly estimated.
- A comprehensive sensitivity analysis of all relevant model parameters at different CO_2 prices is applied to the model.
- The distributions of model parameters are defined by Monte-Carlo simulations and by bootstrapping. Bootstrapping is applied to generate correlated input prices (energy and biomass).
- The optimal sizes of the bioenergy plants are determined by applying a meta-model approach.
- The model is validated by running it for existing bioenergy technologies, i.e. pellets plants and steam engine CHP plants.

The article describes the optimization model in detail and applies an extended model parameter sensitivity analysis. The analysis focuses on optimal locations of the different plant types and on optimal mixes of conversion technologies at different carbon prices. The article contributes to literature by comparing a range of new bioenergy technologies that have not been comparatively assessed before. Particularly BECS is a technology that has drawn little attention before. Spatially explicit modeling is new to comparative assessments of bioenergy technologies, to our knowledge none of the existing published models does consider spatial factors in such a detailed way as our model does (see introduction to article 2). We conclude from the analysis that second generation biofuel production (i.e. ethanol and methanol) are not competitive with any of the other conversion technologies. Pellet production is cheap and efficient in reducing CO_2 emissions and substituting fossil fuels, while BIGCC is competitive only at some locations. At a carbon price of around 50 € tCO_2^{-1}, BECS becomes competitive and partially substitutes pellet production.

The sensitivity and uncertainty analysis indicates that the elasticities between input parameters and outputs vary at different carbon price levels. The price of heating oil is the main contributor to model uncertainty at all levels. The amount of biomass supply and technical plant characteristics also significantly influence model results. An interesting finding is that biomass costs are positively correlated with CO_2 emission reductions, i.e. that an increase in biomass costs increases CO_2 emission reductions at low carbon prices. This is caused by a positive correlation of biomass costs and energy prices.

The validation procedure yields good results for CHP plants but only reasonable results with respect to pellet production. The latter can be explained by the fact that the optimal position of pellets plants depends less on the proximity to the consumers than in the CHP case. Distribution of pellets is inexpensive in comparison to district heating and therefore the proximity to wood resources seems to be more important. Wood resources are, however, not as concentrated as heating demands. Locations differ therefore less in their suitability for pellet production than for CHP production. This fact explains why the model does select only a subset of the locations actually found.

2.3 Article 3: Analyzing the cost-effectiveness of energy policy instruments in the bioenergy sector

The third scientific article is submitted to the journal "Energy Policy" and analyzes the cost-effectiveness of alternative policy instruments in the bioenergy sector. Carbon taxes, the EU ETS, feed-in tariffs for electricity generation, subsidies on pellets boilers, and biofuel blending obligations are analyzed and contribute to research question II. While the article focuses more on policy instruments and gives less attention to the methodology, the model was extended by biomass supply curves. The first two articles treated biomass supply and costs constant by allowing harvesting amounts close to the maximum sustainable yield (MSY). In article 3, biomass supply curves - based on supply elasticities found in the literature - are implemented in the model. Minor model modifications were necessary to allow the implementation of the policy instruments in the model. Results of the sensitivity and uncertainty analysis of previous articles are used to reduce the computational complexity. The article contributes to literature by assessing for the first time the effect of energy policy instruments on the deployment of new bioenergy technologies with a spatially explicit model. Existing studies assess the effect of policy instruments on second generation biofuel production, heat and power production but do not consider BECS. Spatial factors as determinant of production costs of different technologies are mostly not considered in published analyses (see introduction to article 3).

Model results indicate that biofuel blending obligations considering second generation biofuels are very costly and inefficient in reducing CO_2 emission and in substituting fossil fuels. Taxes on CO_2 emissions are cost-effective with regard to both policy objectives. However, at high carbon prices BECS is introduced to the technological portfolio and the fossil fuel substitution declines. The EU ETS is less effective because not all fossil fuels are included in the trading scheme. Subsidies on pellets furnaces are also cost-effective. However, the level of the policy instrument is limited due to restrictions in demand. BIGCC is a costly technology and therefore, direct feed-in tariffs rate worse than taxes or pellet subsidies. However, they are rated better than the biofuel instrument. The cost-effectiveness of all policy instruments are evaluated at three different energy price levels which are most influential to model results as shown in previous articles. The ordering of the cost-effectiveness of policy instruments is robust to changes in the energy price levels.

2.4 Comparison of model results between articles

A comparison between article 1 and the other two articles is not easily possible, because only BIGCC is included as conversion technology and CO_2 prices of up to only 35 € tCO_2^{-1} are considered in article 1. Nevertheless, when observing the CO_2 emission reduction and biomass consumption in article 1 at different power price levels, it can be observed that CO_2 emission reduction per unit of consumed biomass is lower than in the other two articles due to the fact that only BIGCC is considered. The results show that the assessment of a single conversion technology only allows conclusions about that technology and about technological restrictions (e.g. heat

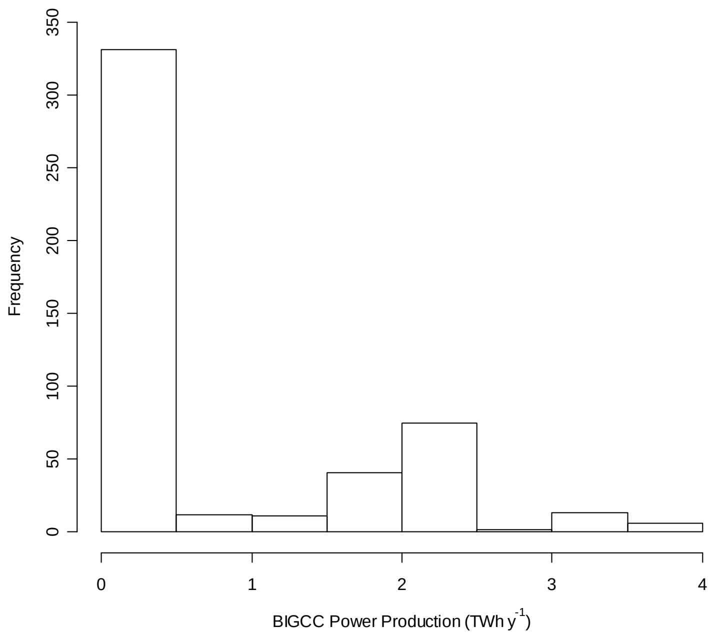

Figure 3: Distribution of BIGCC power production in article 2 (50 € tCO_2^{-1}).

demand restricts supply). The total potentials are overestimated, because conversion technologies competing for the same feedstocks are not considered. Model results of article 2 and article 3 can be easily compared because both articles analyze the consequences of a CO_2 tax on the optimal technological mix. Table 1 provides a comparison between these results. Absolute values in CO_2 emission substitution and fossil fuel substitution differ significantly between article 2 and 3. However, it is not surprising, because the introduction of the supply curve in article 3 causes an increase in marginal biomass supply costs which leads to reduced bioenergy production. Lower CO_2 emission reductions and fossil fuel substitution are the consequences. The technological mix between the two articles differs mainly with respect to the amount of BIGCC that goes into solution. Input parameters are modeled stochastically in article 2 while mean values of the distributions are assumed in article 3. The model parameter sets in article 2 contain parameter combinations that include low investment costs of BIGCC plants and high conversion efficiencies. In such settings, BIGCC is partially competitive to pellet production. A histogram (see Figure 3) showing the distribution of BIGCC production in article 2 at a carbon price of 50 € tCO_2^{-1} confirms that 66% of all Monte-Carlo runs produce a BIGCC power output of 0 TWh y^{-1}. Monte-Carlo simulations were only used in the first two articles. Monte-Carlo simulations are computationally demanding, but allow an extended sensitivity and uncertainty analysis and provide output distributions rather than point realizations. A good example is the difference of the technological mixes produced by the model in article 2 and article 3. Using the mean value of input parameters, BIGCC is not selected, but as article 2 shows, the consideration of a wide range of possible parameter inputs produces a certain probability for the technology to be included in the optimal portfolios.

2.5 Additional research articles

Articles A.1-A.3 provide additional analyses to selected research questions. Article A.1 analyzes optimal locations of different bioenergy technologies and implications

Table 2: Comparison of paper results.

Article	**CO_2 Price** (€ tCO_2^{-1})	**Mix of Technologies** (% BIGCC /% BECS /% Pellets)	**CO_2 Emission Reductions** ($MtCO_2y^{-1}$)	**Fossil fuel Substitution** (TWh y^{-1})	**Biomass used** (TWh y^{-1})
1[a]	PPI[b]: III	-/100/-	3.94	-	13.30
1[a]	PPI[b]: V	-/100/-	4.90	-	17.06
2[a]	0	10/0/90	2.71	10.24	9.60
2[a]	50	12/6/82	4.31	15.10	14.45
2[a]	100	1/38/61	5.65	14.32	15
3	0	0/0/100	1.80	6.76	6.37
3	50	0/0/100	3.00	11.25	10.62
3	100	-/39/61	5.11	12.95	13.69

[a]...Mean of the distribution of results

[b]...See Article 1 for description of p(ower) p(rice) i(ntervals)

for rural development are derived. Clearly, pellet production is to be favored over BIGCC production because pellet plants are optimally located in less favored rural regions while BIGCC is optimally placed close to urban centers. Article A.2. compares methanol and ethanol production from forest wood and short rotation poplar grown on agricultural land. It specifically focuses on the value of the waste heat produced in the plant. The district heating extension of the optimization model is first applied in this article. The results indicate that waste heat utilization has a significant impact on final production costs of biofuels. Furthermore, ethanol production is more cost-effective than methanol production. Article A.3 focuses on the competition between BIGCC and ethanol production under consideration of additional supply of woody biomass from sawmills and of additional demand for biomass from existing biomass fired combined heat and power plants in Austria. The results show that sawmill co-products are a cheap source of woody biomass. At high prices of CO_2, ethanol production is more cost-effective than BIGCC. However, articles A.2 and A.3 were written in early stages of model development and very optimistic assumptions concerning the efficiencies of ethanol production from woody biomass are made. These assumptions rely on a single unpublished research article on second generation biofuel production. They have been more realistically adjusted in the latter articles. Therefore, results and conclusions of articles A.2. and A.3 are different from the results of article 2 and article 3.

3 Summary and Outlook

This thesis presents a spatially explicit energy system model that allows the assessment of the competitiveness of bioenergy conversion technologies and of the cost-effectiveness of alternative bioenergy policy instruments. Uncertainty is explicitly addressed. The implementation of spatial factors in the model is necessary, because spatial variability in production costs is high between locations. The applied methodology allows the assessment of new technologies that are currently not available on the markets. Although certainly restricted due to the chosen system boundaries (see sections 1.2.1-1.2.7), the model allows insights into the relative effectiveness of bioenergy conversion technologies for reducing CO_2 emissions and substituting fossil fuels. The uncertainties inherent in a model that assesses new bioenergy technologies at uncertain fossil fuel prices are explicitly addressed with Monte-Carlo simulations. The procedure is computationally demanding but provides insights into possible outcomes and model parameter sensitivities and uncertainties.

With regard to total CO_2 emission reductions various factors are not considered by the model, yet (see section 1.2 for details):

- Effects of forest management on the forest carbon cycle;
- Effects of policy instruments on direct and indirect land use changes in other regions, i.e. leakage effects from imports and exports;
- Assumptions on CO_2 emissions in a baseline scenario.

The consideration of the first two issues will likely produce lower reduction levels, however, the assumptions on the CO_2 emission baseline may increase or decrease CO_2 emission reductions.

Future research shall enhance the model by additionally including important economic and technical options, for instance co-firing and fuel switching in district heating networks as well as consider the effects of the forest carbon cycle on CO_2 emission savings. A dynamic model version will be necessary to better account for the time preferences inherent in forest management and investment analysis. The application of the model to new regions and countries is an additional important research opportunity, because different energy demand structures and different baseline CO_2 emission conditions alter the results with regard to optimal conversion technologies. A drawback of the chosen uncertainty approach is that it does not provide the user with optimal decisions under uncertainty. One research option is therefore to develop a stochastic programming version [71] of the model. Model linkages to biomass production models and full economy models to analyze rural development impacts of bioenergy production are a further relevant direction of research.

The research questions are extensively answered in the three articles. With regard to research questions I and II, which deal with the optimality of bioenergy technologies and policy instruments, clear conclusions can be drawn from article 2 and article 3. Model results in both articles indicate that heat and, to some extent BIGCC and BECS, is the most cost-effective conversion route for woody biomass with regard to

CO_2 emission reductions. Utilizing large amounts of biomass resources for biofuel production is not recommended, because the costs are high and CO_2 emission reductions and fossil fuel substitutions are low. The better insulation of buildings and the installation of other low carbon heating technologies (e.g. heat pumps) may alter the competitiveness of biomass resources in the heating sector and may shift some of the resources from pellet to BIGCC production. A carbon tax on all fossil fuels is the most cost-effective policy instrument to reduce CO_2 emissions in the bio-energy sector. The EU ETS does not include all fossil fuels in the trading of CO_2 emission permits and is therefore less effective. A trade-off between both policy objectives – substitution of fossil fuels and CO_2 emission reductions –arises if CCS is available. A subsidy on pellets provides similar effects to a carbon tax, but is limited due to demand restrictions. Biofuel blending obligations are not cost-effective in reaching the two policy goals. The bioenergy technologies analyzed in this thesis will not be available before 2012 and are therefore not able to contribute to Kyoto targets. Nevertheless, Figure 4 shows model results on possible contributions of Austrian bioenergy production to the Kyoto GHG emission reduction targets and to the renewable energy targets in the EU directive 2009/28/EG. At a price of 150 € tCO_2^{-1} and with BECS available, 43% of the necessary CO_2 emission reductions (based on 2007 emission levels) can be attained by bioenergy production. Almost the same contribution (42%) to the renewable energy targets can be observed with a carbon tax. If BECS is not available, the contribution to Kyoto drops to 29% while 46% of the renewable energy targets are attainable by bioenergy. It has to be noticed that the results refer to the energy consumption level of 2007 and a substantial increase in the production of fuel wood in Austrian forests is necessary.

With regard to research question III, which addresses the existence of restrictions imposed by the spatial structure of demand, the model results of article I indicate that the amount of waste heat that BIGCC plants produce, need large heat demand sinks that are limited in Austria. Mainly cities like Vienna, Linz, Salzburg, Graz and Klagenfurt provide heat demand densities that are large enough for such plants. However, article 2 reports that pellet and second generation biofuel production can be found closer to wood resources as the distribution of products to consumers is cheaper than biomass transportation and waste heat production is low. The demand for power and fuel does not restrict bioenergy projects. Forest wood resource availability is clearly the limiting production factor. When assuming that pellets are mainly used for replacing heating oil as fuel in single dwellings, total pellet production potentials are restricted by the demand side, i.e. there is more potential for pellet production than potential for the substitution of heating oil. With regard to research question V, which deals with the uncertainty of the model parameters, the following conclusions can be derived: the sensitivity analyses in article 1 as well as the results of article 2 and article 3 indicate that energy prices and CO_2 prices mainly contribute to the uncertainty about cost-efficient technology mixes. Parameters related to the technologies, e.g. investment costs and conversion efficiencies, rank as the second most important. Particularly parameters related to CCS are highly uncertain and therefore strongly influence the technological portfolio with regard to BECS. Fossil fuel prices and prices of CO_2 emission permits in the EU ETS have proven to be very volatile in the recent past. While the volatility of fossil fuels can hardly be influenced locally, an introduction of a fixed carbon tax instead of emission

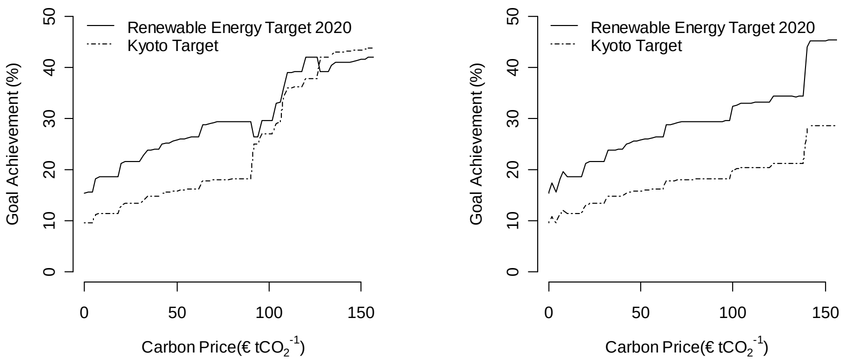

Figure 4: Contribution of bioenergy to Kyoto and renewable energy targets with BECS (left) and without BECS (right).

trading may reduce the uncertainty in relation to CO_2 prices and lead to more stable portfolios of low carbon technologies [72]. Further research in this direction will be needed. Model results are stable with regard to second generation biofuel production: although a very wide range of parameter combinations was considered in article 2, second generation biofuel production was never selected as production technology under different CO_2 pricing scenarios. Pellet production is selected in most scenarios, but the competitiveness in scenarios without any policy intervention depends on input parameter variations. Likewise, the introduction of BIGCC into the technological portfolio depends on the variations in input parameters. In Article 3, the effects of three different energy price scenarios are analyzed. Although the absolute contributions differ among energy prices, the ranking of the policy instruments with regard to their ability to reach policy goals does not change.

4 References

[1] Allison I, Bindoff NL, Bindschadler RA, Cox PM, de Noblet N, England MH, Francis JE, Gruber N, Haywood AM, Karoly DJ, Kaser G, Le Quéré C, Lenton TM, Mann ME, McNeil BI, Pitman AJ, Rahmstorf S, Rignot E, Schellnhuber HJ, Schneider SH, Sherwood SC, Somerville RCJ, Steffen K, Steig EJ, Visbeck M, Weaver AJ. The Copenhagen Diagnosis. Sydney, Australia: The University of New South Wales Climate Change Research Centre (CCRC), 2009.

[2] Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambrigde: Cambridge University Press, 2007.

[3] Bilgin M. Geopolitics of European natural gas demand: Supplies from Russia, Caspian and the Middle East. Energy Policy 2009;37(11):4482-4492.

[4] Jun E, Kim W, Chang SH. The analysis of security cost for different energy sources. Appl. Energy 2009;86(10):1894-1901.

[5] Ben WE, Daniel MM. Before the peak: impacts of oil shortages on the developing world. International Social Science Journal 2005;57(s1):71-78.

[6] de Almeida P, Silva PD. The peak of oil production--Timings and market recognition. Energy Policy 2009;37(4):1267-1276.

[7] Bardi U. Peak oil: The four stages of a new idea. Energy 2009;34(3):323-326.

[8] Verbruggen A, Al Archochi M. Peak oil and climate change policy. In: Haas R, Redl C, Auer H, Glatz M, editors. 10th IAEE European Conference. Vienna: International Association for Energy Economics, 2009.

[9] European Environment Agency. Greenhouse gas emission trends and projections in Europe 2009. Tracking progress towards Kyoto targets. Copenhagen: European Environment Agency EEA, 2009.

[10] Nakicenovic N, Haas R, Schleicher SP, Klettner C, Kletzan D, Köppl A, Türk A. Assessment of Austrian contribution toward EU 2020 Target Sharing. Vienna: Austrian Institute of Economic Research WIFO, 2008.

[11] Eliott D. Sustainable Energy - Opportunities and Limitations. New York: Palgrav MacMillan, 2007.

[12] Schadauer K. The Austrian forest inventory 2000/02 - Main results (Die Österreichische Waldinventur 2000/02 – Hauptergebnisse). Vienna: Bundesamt für Wald, 2004. See also: http://bfw.ac.at/040/pdf/1818_pi3.pdf

[13] Kranzl L, Haas R. Strategien zur optimalen Erschließung der Biomassepotenziale in Österreich bis zum Jahr 2050 mit dem Ziel einer maximalen Reduktion an Treibhausgasemissionen (Strategies for the optimal development of biomass potentials in Austria until the year 2050 aiming at a maximal reduction of green house gas emissions). Vienna: Energy Economics Group, University of Technology Vienna, 2008.

[14] Kopetz H, Scheiber E. Basis Data Bioenergy Austria (Basisdaten Bioenergie Österreich). Österreichischer Biomasse-Verband, 2006.

[15] Obersteiner M, Azar C, Kauppi P, Möllersten K, Moreira J, Nilsson S, Read P, Raiahi K, Schlamadinger B, Yamagata Y. Managing climate risk. Science 2001;294(5543):786-787.

[16] Bram S, De Ruyck J, Lavric D. Using biomass: A system perturbation analysis. Appl. Energy 2009;86(2):194-201.

[17] Sims REH. Bioenergy - a renewable carbon sink. Renewable Energy 2001;22(1-3):31-37.

[18] Dunnett A, Adjiman C, Shah N. A spatially explicit whole-system model of the lignocellulosic bioethanol supply chain: an assessment of decentralised processing potential. Biotechnol. Biofuels 2008;1(1):13.

[19] Bernotat K, Sandberg T. Biomass fired small-scale CHP in Sweden and the Baltic States: a case study on the potential of clustered dwellings. Biomass Bioenergy 2004;27(6):521-530.

[20] Freppaz D, Minciardi R, Robba M, Rovatti M, Sacile R, Taramasso A. Optimizing forest biomass exploitation for energy supply at a regional level. Biomass Bioenergy 2004;26(1):15-25.

[21] Rentizelas AA, Tatsiopoulos IP, Tolis A. An optimization model for multi-biomass tri-generation energy supply. Biomass Bioenergy 2008;33(2):223-233.

[22] Möllersten K, Gao L, Yan J. CO2 Capture in Pulp and Paper Mills: CO2 Balances and Preliminary Cost Assessment. Mitigation and Adaptation Strategies for Global Change 2006;11(5-6):1129-1150.

[23] Möllersten K, Gao L, Yan J, Obersteiner M. Efficient energy systems with CO2 capture and storage from renewable biomass in pulp and paper mills. Renewable Energy 2004;29(9):1583-1598.

[24] Möllersten K, Yan J, Westermark M. Potential and cost-effectiveness of CO2 reductions through energy measures in Swedish pulp and paper mills. Energy 2003;28(7):691-710.

[25] Möllersten K, Yan J, R. Moreira J. Potential market niches for biomass energy with CO2 capture and storage--Opportunities for energy supply with negative CO2 emissions. Biomass Bioenergy 2003;25(3):273-285.

[26] Grahn M, Azar C, Lindgren K, Berndes G, Gielen D. Biomass for heat or as transportation fuel? A comparison between two model-based studies. Biomass Bioenergy 2007;31(11-12):747-758.

[27] Kumar A. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. Bioresour. Technol. 2009;100(1):387-399.

[28] Alfonso D, Perpiñá C, Pérez-Navarro A, Peñalvo E, Vargas C, Cárdenas R. Methodology for optimization of distributed biomass resources evaluation, management and final energy use. Biomass Bioenergy 2009;33(8):1070-1079.

[29] Piccolo C, Bezzo F. A techno-economic comparison between two technologies for bioethanol production from lignocellulose. Biomass Bioenergy 2009;33(3):478-491.

[30] Wahlund B, Yan J, Westermark M. Increasing biomass utilization in energy systems: A comparative study of CO2 reduction and cost for different bioenergy processing options. Biomass Bioenergy 2004;26(6):531-544.

[31] Eriksson LO, Björheden RW. Optimal storing, transport and processing for a forest-fuel supplier. European Journal of Operational Research 1989;43(1):26-33.

[32] Grohnheit PE, Mortensen BOG. Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies. Energy Policy 2003;31(9):817-826.

[33] Matthes FC, Graichen V, Harthan RO, Horn M, Krey V, Markewitz P, Martinsen D, Repenning J. Energy prices and climate protection (Energiepreise und Klimaschutz). Dessau: Umweltbundesamt, 2008. See also: http://www.umweltdaten.de/publikationen/fpdf-l/3494.pdf

[34] Catenazzi G. Advances in techno-economic energy modeling. Costs, dynamics and hybrid aspects. Zürich: Swiss Federal Institute of Technology (ETH), 2009. Phd Thesis.

[35] Jacobsen HK. Integrating the bottom-up and top-down approach to energy-economy modelling: the case of Denmark. Energy Economics 1998;20(4):17.

[36] Worrell E, Ramesohl S, Boyd G. Towards increased policy relevance in energy modeling. ACEEE Summer Study on Energy Efficiency in Industry 2003. Sustainability and Industry: Increasing Energy Efficiency and Reducing Emissions, vol. 2, 2003.

[37] Leduc S, Schwab D, Dotzauer E, Schmid E, Obersteiner M. Optimal location of wood gasification plants for methanol production with heat recovery. Int. J. Energy Res. 2008;32(12):1080-1091.

[38] Leduc S, Schmid E, Obersteiner M, Riahi K. Methanol production by gasification using a geographically explicit model. Biomass Bioenergy 2009;33(5):745-751.

[39] Leduc S, Starfelt F, Dotzauer E, Kindermann G, McCallum I, Obersteiner M, Lundgren J. Optimal location of ethanol ligno-cellulosic biorefineries with polygeneration in Sweden. Energy 2009;doi:10.1016/j.energy.2009.07.018.

[40] Leduc S. Development of an Optimization Model for the Location of Biofuel Production Plants. Luleå University, 2009. Phd Thesis.

[41] Leduc S, Lundgren J, Franklin O, Schmid E, Dotzauer E. Location of a biomass based methanol production plant: a dynamic problem in northern sweden. Appl. Energy 2009;87(1):68-75.

[42] Leduc S, Natarajan K, Dotzauer E, McCallum I, Obersteiner M. Optimizing biodiesel production in India. Appl. Energy 2009;86(Supplement 1):S125-S131.

[43] Kullander S. Energy from biomass. The European Physical Journal - Special Topics 2009;176(1):115-125.

[44] Eggers J, Tröltzsch K, Falcucci A, Maiorano L, Verburg PH, Framstad E, Louette G, Maes D, Nagy S, Ozinga W, Delbaere B. Is biofuel policy harming biodiversity in Europe? GCB Bioenergy 2009;1(1):18-34.

[45] Gomez LD, Steele-King CG, McQueen-Mason SJ. Sustainable liquid biofuels from biomass: the writing's on the walls. New Phytologist 2008;178(3):473-485.

[46] Kim H, Kim S, Dale BE. Biofuels, Land Use Change, and Greenhouse Gase Emissions: some Unexplored Variables. Environmental Science & Technology 2009;43(3):961-967.

[47] Koh LP, Ghazoul J. Biofuels, biodiversity, and people: Understanding the conflicts and finding opportunities. Biological Conservation 2008;141(10):2450-2460.

[48] Lehrer N. (Bio)fueling farm policy: the biofuels boom and the 2008 farm bill. Agriculture and Human Values 2009;doi: 10.1007/s10460-009-9247-0.

[49] Crutzen PJ, Mosier AR, Smith KA, Winiwarter W. N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. Atmos. Chem. Phys. 2008;8(2):389-395.

[50] Zah R, Böni H, Gauch M, Hischier R, Lehmann M, Wäger P. Life cycle assessment of energy products: ecological assessment of biofuels. (Ökobilanz von Energieprodukten: Ökologische Bewertung von Biotreibstoffen). Bern: Empa, 2007.

[51] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T. Use of U.S. croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. Science 2008;319(5867):1238-1240.

[52] Müller A, Schmidhuber j, Hoogeveen J, Steduto P. Some insights in the effect of growing bio-energy demand on global food security and natural resources. Conference: Linkages between Energy and Water Management for Agriculture in Developing Countries. Hyderabad India, 2007.

[53] Rathmann R, Szklo A, Schaeffer R. Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate. Renewable Energy;35(1):14-22.

[54] Berndes G, Hansson J. Bioenergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. Energy Policy 2007;35(12):5965-5979.
[55] Kirschbaum MUF. To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels. Biomass Bioenergy;24(4-5):297-310.
[56] Reijnders L, Huijbregts MAJ. Choices in calculating life cycle emissions of carbon containing gases associated with forest derived biofuels. J. Cleaner Prod. 2003;11(5):527-532.
[57] Peng Y, Thomas SC, Tian D. Forest management and soil respiration: Implications for carbon sequestration. Envrionmental Reviews 2008;16(-):93-111.
[58] Jandl R, Rasmussen K, Tomé M, Johnson DW. Newsletter 4: Issue 4. Forest Management and Carbon Sequestration. The role of forests in Carbon Cycles, Sequestration, and Storage: IUFRO – The Global Network for Forest Science Cooperation, 2006.
[59] Gough CM, Vogel CS, Schmid HP, Curtis PS. Controls on Annual Forest Carbon Storage: Lessons from the Past and Predictions for the Future. BioScience 2008;58(7):609-622.
[60] Luyssaert S, Schulze ED, Borner A, Knohl A, Hessenmoller D, Law BE, Ciais P, Grace J. Old-growth forests as global carbon sinks. Nature 2008;455(7210):213-215.
[61] Böttcher H, Freibauer A, Obersteiner M, Schulze E-D. Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model Ecol. Modell 2008;213(1):45-62.
[62] Schmoranz I. The energy demand of private households (Die Energienachfrage privater Haushalte). Heidelberg: Physica Verlag, 1994.
[63] Hillring B. World trade in forest products and wood fuel. Biomass Bioenergy 2006;30(10):815-825.
[64] Junginger M, Bolkesjø T, Bradley D, Dolzan P, Faaij A, Heinimö J, Hektor B, Leistad Ø, Ling E, Perry M, Piacente E, Rosillo-Calle F, Ryckmans Y, Schouwenberg P-P, Solberg B, Trømborg E, Walter AdS, Wit Md. Developments in international bioenergy trade. Biomass Bioenergy 2008;32(8):717-729.
[65] Kindermann G, Obersteiner M, Sohngen B, Sathaye J, Andrasko K, Rametsteiner E, Schlamadinger B, Wunder S, Beach R. Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America 2008;105(30):10302-10307.
[66] Sun Microsystems. Java. 2009.
[67] GAMS Development Corporation. General Algebraic Modeling System. 2009.
[68] The R Foundation for Statistical Computing. R. 2007.
[69] Sun Microsystems. MySQL. 2009.
[70] Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, Saisana M, Tarantola S. Global Sensitivity Analysis: The Primer. Chichester: John Wiley & Sons Ltd., 2008.
[71] Sen S, Higle JL. An Introductory Tutorial on Stochastic Linear Programming Models. INTERFACES 1999;29(2):33-61.
[72] Green R. Carbon tax or carbon permits: the impact on generators' risks. The Energy Journal 2008;29(3):67-90.

Article 1

Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand

INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com). DOI: 10.1002/er.1623

Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand

Johannes Schmidt[1,*,†], Sylvain Leduc[2], Erik Dotzauer[3], Georg Kindermann[2] and Erwin Schmid[4]

[1]*Doctoral School Sustainable Development, University of Natural Resources and Applied Life Sciences, Peter Jordan Straße 82, A-1190 Vienna, Austria*
[2]*International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria*
[3]*Mälardalen University, P.O. Box 883, SE-72123 Västerås, Sweden*
[4]*Institute for Sustainable Economic Development, University of Natural Resources and Applied Life Sciences, Feistmantelstraße 4, A-1180 Vienna, Austria*

SUMMARY

Combined heat and power (CHP) plants fired by forest wood can significantly contribute to attaining the target of increasing the share of renewable energy production. However, the spatial distribution of biomass supply and of heat demand limits the potentials of CHP production. This article assesses CHP potentials using a mixed integer programming model that optimizes locations of bioenergy plants. Investment costs of district heating infrastructure are modeled as a function of heat demand densities, which can differ substantially. Gasification of biomass in a combined cycle process is assumed as production technology. Some model parameters have a broad range according to a literature review. Monte-Carlo simulations have therefore been performed to account for model parameter uncertainty in our analysis. The model is applied to assess CHP potentials in Austria. Optimal locations of plants are clustered around big cities in the east of the country. At current power prices, biomass-based CHP production allows producing around 3% of the total energy demand in Austria. Yet, the heat utilization decreases when CHP production increases due to limited heat demand that is suitable for district heating. Production potentials are most sensitive to biomass costs and power prices. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: combined heat and power; district heating; bioenergy; biomass; mixed integer programming; Monte-Carlo simulation

1. INTRODUCTION

Decreasing dependency on imported fossil oil and climate change mitigation are the main motives for European renewable energy policies. The European Commission set the target to reach 20% of renewable energy consumption by 2020 [1]. The Commission emphasizes that a significant increase

*Correspondence to: Johannes Schmidt, Doctoral School Sustainable Development, University of Natural Ressources and Applied Life Sciences, Peter-Jordan Straße 82, A-1190 Vienna, Austria.
†E-mail: johannes.schmidt@boku.ac.at

Contract/grant sponsor: Austrian Research Program 'provision'
Contract/grant sponsor: Federal Ministry of Agriculture, Forestry, Environment and Water Management
Contract/grant sponsor: Federal States Vienna, Lower Austria and Styria

Received 8 April 2009
Revised 7 August 2009
Accepted 11 August 2009

Copyright © 2009 John Wiley & Sons, Ltd.

in the utilization of biomass is necessary to reach this target. The Austrian government aims at increasing the share of renewable energy production from currently around 23–34% by 2020 [1]. Wood is an important feedstock for biomass-based energy production in Austria. Over the last five years substantial subsidies have stimulated the installation of additional heat plants and power plants fired by biomass [2,3]. However, a further increase in power production is necessary to achieve the energy production targets. Such increases are possible because the annual growth in wood stocks is currently not fully explored [4]. Combined heat and power (CHP) production is a favorable form of power production because heat that would otherwise be lost can be used in district heating. However, the geo-spatial distribution of biomass supply and heat demand has significant impacts on total system costs [5,6] and is therefore a factor that limits CHP potentials. Temporal distribution of heat demand also matters [7]. There are numerous geo-spatial explicit bioenergy models available, which can be used to assess costs and optimal locations of bioenergy systems. They are based on geographic information systems and/or linear programming methodology and mainly assess CHP and biofuel technologies. Several models concentrate on single parts of the supply chain—either on the biomass supply logistics and energy production [8–10] or on the energy distribution [11,12]—without considering the whole bioenergy system. Models that do consider the whole supply chain either do not regard district heating costs at all [9,10,13] or do not take into account spatial factors in estimating costs for district heating infrastructure [14]. In this article, technical and least cost potentials for CHP production are assessed by including the spatially explicit estimation of heat demand into an approved full supply chain model of bioenergy production [15,16]. The model optimizes the locations of bioenergy plants considering the spatial distribution of biomass supply and costs resulting from biomass transportation. Technical and economic restrictions implied by the spatial distribution of heat demand are considered in the assessment of potentials. Model parameters, which are based on a literature review, can vary substantially. Monte-Carlo simulations are therefore performed to account for model parameter uncertainties. Furthermore, an extended sensitivity analysis allows identifying the parameters that have the strongest influence on the total potentials. Parameter influence on model output is expressed by elasticity estimations. The median absolute percentage error (MdAPE) is calculated to measure the contribution of parameters to model uncertainty.

The article is structured as follows: after presenting the optimization model in Section 2.1, the estimation of input parameters biomass supply, transportation and conversion technology, heat demand and district heating costs is discussed in Sections 2.2–2.6. The handling of parameter uncertainty is described in Section 2.7. Following the results in Section 3, the sensitivity analysis is presented in Section 4. The discussion and conclusions conclude the article in Section 5.

2. DATA AND METHODS

A mixed linear integer programming (MIP) model is built to optimize the locations of biomass-fired CHP plants. It includes the production and transportation of biomass, the conversion of biomass to power and heat in the CHP plant and the distribution of heat to district heating consumers (Figure 1). An average year of operation is simulated; therefore, investment costs are accounted as annuities in the model. However, this average year is divided into heating seasons to

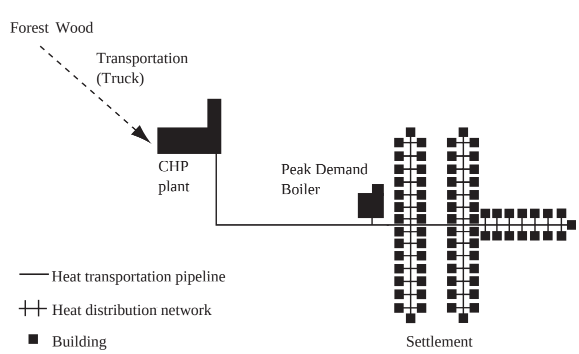

Figure 1. Model of biomass-fired CHP plant.

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

capture restrictions in heat consumption due to seasonal variations in temperature.

2.1. The model

Austria is divided into 150 biomass supply regions (i). Possible plant locations (j) are deterministically spread at a vertical and horizontal distance of 0.41° over Austria. Biomass is harvested and transported (variable $b_{i,j}$) from the supply regions to the plants. Investments into plants are modeled by the binary variable u_j^{plant}. The plants produce power (variable p_j^{chp}) and heat (variable q_j^{chp}). Power demand (parameter p^{D}) is satisfied by p_j^{chp} and power production with fossil fuels (variable p^{fp}). Heat consumption is modeled by seasons (t). Heat is transported to the boundaries of the settlements (h) with transportation pipelines (binary variable $u_{j,\text{h,ps}}^{\text{pipe}}$) of varying sizes (ps). District heating distribution networks (binary variable $u_{\text{h,ns}}^{\text{dnet}}$) of different extensions (ns) distribute the heat within the settlements. Heat transported from CHP plants to the settlements (variable $q_{j,\text{h,ps},t}^{\text{dh}}$) and heat from peak boilers (variable $q_{\text{h},t}^{\text{peak}}$) supply the district heating network. Peak boilers are used as backup for the CHP plants and as additional heat source in times of high heat demand (Figure 1). District heating competes with local heat production (variable $q_{\text{h},t}^{\text{local}}$) by small boilers inside of the buildings.

Biomass utilization in the plants is restricted by

$$\sum_j b_{i,j} \leqslant \bar{b}_i \tag{1}$$

where parameter $\bar{b}_i$ denotes the total amount of biomass available in supply region i. The production of the CHP plant is restricted by the size of the installed equipment:

$$q_j^{\text{chp}} \leqslant \bar{q}_j u_j^{\text{plant}} \tag{2}$$

where parameter $\bar{q}_j$ is the total annual heat production capacity of plant j. Heat and power production is determined by the biomass input and conversion efficiency (parameter η_j^{chp}) in

$$\eta_j^{\text{chp}} \sum_i b_{i,j} = p_j^{\text{chp}} + q_j^{\text{chp}} \tag{3}$$

Parameter α_j is introduced to model the relationship of power and heat production, which is given by

$$p_j^{\text{chp}} = \alpha_j q_j^{\text{chp}} \tag{4}$$

Power demand (parameter p^{D}) is satisfied by power production of the CHP plants, p_j^{chp}, and by power generation with fossil fuels modeled with variable p^{fp}:

$$\sum_j p_j^{\text{chp}} + p^{\text{fp}} = p^{\text{D}} \tag{5}$$

Heat production, q_j^{chp}, limits the amount of heat available for district heating. The power and heat production is modeled on an annual time period. Variations in heat demand in winter and summer are however considered. Seasonal supply of heat in the plant is restricted by

$$\sum_{\text{h,ps}} q_{j,\text{h,ps},t}^{\text{dh}} \leqslant \Delta t_t q_j^{\text{chp}} \tag{6}$$

where parameter Δt_t denotes the relative length of a season.

The production of heat has to meet the demand (parameter $q_{\text{h},t}^{\text{D}}$) in each period, which is guaranteed by

$$\eta_{\text{h},t}^{\text{dh}} \left(\left(\sum_{j,\text{ps}} \eta_{j,\text{h,ps},t}^{\text{trans}} q_{j,\text{h,ps},t}^{\text{dh}} \right) + q_{\text{h},t}^{\text{peak}} \right) + \eta_{\text{h},t}^{\text{local}} q_{\text{h},t}^{\text{local}} = q_{\text{h},t}^{\text{D}} \tag{7}$$

where parameter $\eta_{j,\text{h,ps},t}^{\text{trans}}$ denotes the heat losses in the pipe system from the plant to the settlement. The heat losses in the transportation pipeline are different for each combination of plant and settlement as the distances of the plants to the settlements vary. Losses in the heat distribution network within the settlement are modeled by parameter $\eta_{\text{h},t}^{\text{dh}}$. Parameter $\eta_{\text{h},t}^{\text{local}}$ is introduced to describe conversion efficiencies of local heating systems.

The sum of heat produced by the CHP plant and by the peak demand boiler has to match the district heating demand (parameter $q_{\text{h,ns},t}^{\text{D}}$) in settlement h. This is modeled by

$$\eta_{\text{h},t}^{\text{dh}} \left(\left(\sum_{j,\text{ps}} \eta_{j,\text{h,ps},t}^{\text{trans}} q_{j,\text{h,ps},t}^{\text{dh}} \right) + q_{\text{h},t}^{\text{peak}} \right) = \sum_{\text{ns}} q_{\text{h,ns},t}^{\text{D}} u_{\text{h,ns}}^{\text{dnet}} \tag{8}$$

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

The existence of a transportation pipeline, in case a settlement is supplied by a CHP plant, is ensured by

$$q^{\mathrm{dh}}_{j,\mathrm{h},\mathrm{ps},t} \leqslant \bar{q}^{\mathrm{pipe}}_{\mathrm{ps},t}\, u^{\mathrm{pipe}}_{j,\mathrm{h},\mathrm{ps}} \tag{9}$$

where parameter $\bar{q}^{\mathrm{pipe}}_{\mathrm{ps},t}$ denotes the capacity of the pipeline.

Only one district heating network may be built in each settlement which is ensured by

$$\sum_{\mathrm{ns}} u^{\mathrm{dnet}}_{\mathrm{h,ns}} \leqslant 1 \tag{10}$$

The total cost of the supply chain in the objective function $f(b,p,q,u)$ is given by:

5. Costs for producing peak heat (parameter c^{peak}_t) times the amount of peak heat produced.
6. Costs for producing local heat including investment and fuel costs (parameter c^{local}_t) times the amount of local heat produced.
7. Costs for producing power with fossil fuel (parameter c^{fp}) times the amount of power produced.
8. CO_2 emissions of biomass transportation (emission factor $e^t_{i,j}$), emissions of fossil power production (emission factor e^{fp}), emissions of local heating systems (emission factor $e^{\mathrm{local}}_{\mathrm{h}}$) and emissions of peak heat production (emission factor e^{peak}) are multiplied by the CO_2 price (parameter c^{em}).

$$\begin{aligned} f(b,p,q,u) = {} & \sum_{i,j} (c^{\mathrm{sup}}_i + c^{\mathrm{trans}}_{i,j} + c^{\mathrm{prod}}_j) b_{i,j} + \sum_j c^{\mathrm{plant}}_j u^{\mathrm{plant}}_j \\ & + \sum_{j,\mathrm{h},\mathrm{ps}} c^{\mathrm{pipe}}_{j,\mathrm{h},\mathrm{ps}} u^{\mathrm{pipe}}_{j,\mathrm{h},\mathrm{ps}} + \sum_{\mathrm{h,ns}} c^{\mathrm{dnet}}_{\mathrm{h,ns}} u^{\mathrm{dnet}}_{\mathrm{h,ns}} \\ & + \sum_{\mathrm{h},t} c^{\mathrm{peak}}_t q^{\mathrm{peak}}_{\mathrm{h},t} + \sum_{\mathrm{h},t} c^{\mathrm{local}}_t q^{\mathrm{local}}_{\mathrm{h},t} + c^{\mathrm{fp}} p^{\mathrm{fp}} \\ & + c^{em} \left(\sum_{i,j} e^t_{i,j} b_{i,j} + e^{\mathrm{fp}} p^{\mathrm{fp}} + \sum_{\mathrm{h},t} e^{\mathrm{local}}_{\mathrm{h}} q^{\mathrm{local}}_{\mathrm{h},t} + \sum_{\mathrm{h},t} e^{\mathrm{peak}} q^{\mathrm{peak}}_{\mathrm{h},t} \right) \end{aligned} \tag{11}$$

The different summands in the objective function are:

1. Biomass supply costs (parameter c^{sup}_i), transportation costs (parameter $c^{\mathrm{trans}}_{i,j}$) and bioenergy production costs (parameter c^{prod}_j) times the amount of biomass used.
2. Annualized costs of investing in a plant (parameter c^{plant}_j) times the binary variable for the plant selection.
3. Annualized costs of building a pipeline from the plant to the settlement (parameter $c^{\mathrm{pipe}}_{j,\mathrm{h},\mathrm{ps}}$) times the binary variable for the pipeline selection.
4. Annualized costs for installing a district heating network in the settlement (parameter $c^{\mathrm{dnet}}_{\mathrm{h,ns}}$) times the binary variable for district heating network selection.

The MIP is finally defined as:

$$\begin{aligned} & \min \quad [f(b,p,q,u)] \\ & \text{s.t.} \quad (1)-(10) \\ & 0 \leqslant b_{i,j}, p^{\mathrm{chp}}_j, p^{\mathrm{fp}}, q^{\mathrm{chp}}_j, q^{\mathrm{peak}}_{\mathrm{h},t}, q^{\mathrm{dh}}_{j,\mathrm{h},\mathrm{ps},t}, q^{\mathrm{local}}_{\mathrm{h},t} \\ & u^{\mathrm{dnet}}_{\mathrm{h,ns}}, u^{\mathrm{pipe}}_{j,\mathrm{h},\mathrm{ps}}, u^{\mathrm{plant}}_j \in \{0,1\} \end{aligned} \tag{12}$$

2.2. Biomass supply

Domestic forest wood is considered as feedstock for biomass-based heat and power production. Spatial distribution of forestry yields is estimated with increment curves from Assman's yield table [17], assuming sustainable forest

Copyright © 2009 John Wiley & Sons, Ltd.

management, and a net primary production (NPP) map from Running [18]. This is calibrated with the observations from the national forest inventory of Austria [4]. The forest cover is taken from the Corine Land Cover data set [19]. An equation system describes the forest increment and mortality per hectare and year depending on yield level, age and stand density. An NPP map was used to estimate the yield level. The observed increment data from the Austrian national inventory was used to calibrate the transformation from NPP to yield level. The diameter of the harvested wood, which is used in the CHP plants, is below 15 cm. The total potential is reduced by the wood demand of (i) private households, (ii) existing bioenergy plants and (iii) the pulp and paper industry. Biomass costs are taken from local market statistics.

2.3. Transportation and conversion technology

Biomass transportation costs and CO_2 emissions are considered by calculating Euclidean distances between biomass supply sites and plant locations. The transportation distance is estimated using a ratio of actual road length to direct distance [16]. Trucks have to travel once each direction; therefore, those distances are doubled.

Combustion and gasification are major technologies for producing power and heat from biomass. Gasification has higher technical efficiencies and is projected to be economically more competitive than combustion although few plants have already been built [20,21]. The study assesses pressurized biofuel-integrated gasification combined cycle plants (BIGCC). The biomass is gasified with pressurized air. The resulting gas is burnt in a gas turbine, using combined cycle CHP technique [20]. Table I lists economical and technical plant parameters for the model. The likely plant size was determined in a pre-analysis. The model was run with 1000 stochastically determined input parameter sets, varying the plant size between 50 and 300 $MW_{biomass}$. A response surface of the input parameters on the total power production potential (similar to Section 4) was estimated and the maximum of the response surface with regard to the plant size was calculated. A plant size of 130 $MW_{biomass}$ was found to maximize the total CHP production.

Table I. Technical and economical parameters of gasification plant [20].

Investment costs	78 M€
Fixed O&M costs	2.50% of investment
Variable O&M costs	3.276 € $MWh_{biomass}^{-1}$
Plant size	130 $MW_{biomass}$
Minimum load	30.00%
CHP conversion efficiency	90.00%
Alpha factor	91.50%
Full load hours	7200 h $year^{-1}$
Lifetime	25 years

2.4. Emissions

The model tracks emissions in biomass transportation as well as emissions of reference technologies, which may be replaced by the biomass CHP plants. Fossil-fueled-based power production is chosen as the reference system in the power sector. Biomass-based power production is able to provide baseload power similar to fossil fuels. Average emissions of the Austrian fossil fuel mix are calculated by weighting the emission factors for gas, oil and coal with the proportion that the fuel has in Austrian power production [22]. The emissions of the reference system for district heating are determined by weighting the fuels currently in use of the specific settlement with the corresponding emission factors. All emission factors are taken from the Austrian Inventory Report [23].

2.5. Heat demand estimation

This section briefly presents the estimation of the spatial distribution of heating demand, which is a necessary input parameter to the optimization model. The heating demand of private dwellings and the demand of commercial and industrial facilities is computed for all Austrian settlements. The geographical position and size of each settlement are known with a spatial resolution of 1 km^2. The methodology was used before on an aggregated national and regional scale [24–26] as well as on spatially explicit scales [11,27].

2.5.1. Private dwellings heating demand model. A bottom-up approach is applied to estimate the

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

heat demand of private dwellings. The age and type of dwelling areas and the spatial distribution of the areas are known. These data are combined with typical energy coefficients for those buildings. The dwellings data are based on the Austrian Buildings- and Dwellings Census [28]. The final energy demand denoted by $q_{\mathrm{h}}^{\mathrm{Dd}}$ is estimated for each settlement h. It describes the amount of energy necessary to heat the dwelling stock. The calculation is given in Equation (13). Buildings already connected to a district heating network are not included in the calculation:

$$q_{\mathrm{h}}^{\mathrm{Dd}} = \sum_{\mathrm{bt}} \sum_{\mathrm{ba}} \mathrm{EC}_{\mathrm{bt,ba}} A_{\mathrm{h,bt,ba}} \chi_{\mathrm{bt}}^{\mathrm{dh}} \frac{\mathrm{HDD_h}}{\mathrm{HDD^{ref}}} \quad (13)$$

The dwelling areas (parameter $A_{\mathrm{h,bt,ba}}$) differentiated by building type (bt) and building age (ba) are combined with energy coefficients (parameter $\mathrm{EC}_{\mathrm{bt,ba}}$). The coefficients represent average heating demand values for buildings of a specific type and age. The coefficients are calculated by assuming a constant amount of heating degree days (parameter $\mathrm{HDD^{ref}}$) and a constant indoor temperature of 20°C, 24 h a day [27]. Behavior of consumers who generally decrease the temperature throughout the night or when nobody is in the dwelling is considered by introducing a usage factor (parameter $\chi_{\mathrm{bt}}^{\mathrm{dh}}$) into Equation (13). Users of district heating systems choose higher indoor temperatures than users of single stoves with solid fuels due to easier handling of the former one. In addition, different indoor temperatures are selected in single- and multi-dwelling buildings [29]. Climatic influences are regarded by correcting the heat demand using parameter $\mathrm{HDD_h}$ that denotes local heating degree days.

2.5.2. Commercial and industrial heat demand model. A different calculation procedure is used for commercial and industrial heat demand. No data on the type of commercial activity are available in conjunction with commercial and industrial building areas. However, the number of employees (parameter $\mathrm{EM}_{\mathrm{h,es}}$) per economic sector is known in all settlements. Primary energy consumption for space heating, warm water and process heat per employee and per economic sector (parameter $\mathrm{ECE}_{\mathrm{es}}$) can be calculated from the Austrian analysis of useful energy [30]. The accuracy of the data is limited because the economic sectors do not differentiate between industrial production subsectors. An overall, average factor is therefore used. Equation (14) shows the calculations of the final energy demand, denoted by $q_{\mathrm{h}}^{\mathrm{Dc}}$:

$$q_{\mathrm{h}}^{\mathrm{Dc}} = \sum_{\mathrm{es}} \mathrm{EM}_{\mathrm{h,es}} \mathrm{ECE}_{\mathrm{es}} \frac{\mathrm{HDD_h}}{\mathrm{HDDC^{ref}}} \eta^{\mathrm{com}} \quad (14)$$

Local heating degree days (parameter $\mathrm{HDD_h}$) are used to correct for spatial climatic variations. Parameter $\mathrm{HDDC^{ref}}$ is chosen in a way that the sum of the climatically corrected heating demand for all settlements equals the heating demand without climatic correction. Parameter η^{com} denotes the average efficiency of heating systems used in commercial buildings.

2.5.3. Total heat demand model. The combination of private and commercial heating demand and the determination of seasonal heating demand are shown in Equation (15). Parameter $\Delta s_{\mathrm{h},t}$ denotes the proportion of the heat demand that is consumed in season t in settlement h and is calculated as the proportion of heating degree days in the season and of total heating degree days per year. Parameter con denotes—as a percentage—the amount of dwellings that are connected to the district heating network within a settlement. Generally, not all dwellings within a settlement are connected to district heating. The parameter con is a factor applied equally to all district heating cells:

$$q_{\mathrm{h},t}^{\mathrm{D}} = \Delta s_{\mathrm{h},t} \mathrm{con}(q_{\mathrm{h}}^{\mathrm{Dd}} + q_{\mathrm{h}}^{\mathrm{Dc}}) \quad (15)$$

2.6. District heating costs

Investment costs of the transportation pipeline, of the heat distribution pipeline network, of the peak heat boiler and of heat exchangers are considered in the model. Costs for building pipelines $c_{j,\mathrm{h,ps}}^{\mathrm{pipe}}$ of different sizes are calculated as average costs from typical cost structures in the industry [31]. While the transportation pipeline delivers heat from the plant to the boundaries of the settlement, the heat distribution network delivers the heat within the settlement. The costs of the heat distribution network $c_{\mathrm{h,ns}}^{\mathrm{dnet}}$ are the most expensive part of the

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

district heating system due to the large extension of such networks [32,33]. The geometry and the density of a settlement are important determinants of the costs of the distribution network. The spatial distribution of the heat consumers and the road system determine the length of the heat distribution network and therefore the construction costs [34]. When information on the structure of settlements is available, a classification of settlements could be used to estimate district heating distribution costs [35]. However, such data are not obtainable for Austria. Therefore, a relation between heat demand density and the costs for distributing heat is assumed. Generally, for supply systems relying on pipe networks, decreasing costs per unit can be expected with increasing demand density due to shorter pipes per consumer [12]. A direct estimation of costs depending on the heat demand density can be found in [32]. It is used in this study. Figure 2 compares this estimation to a cost calculation in a real world project [33]. Additionally to the district heating network, costs for gas-fired peak demand boilers and for heat exchangers necessary to exchange heat of the district heating network with the pipe system inside of buildings are considered.

Local heating systems, whose costs are denoted by parameter c_t^{local}, concur with district heating. The costs of such systems are determined from

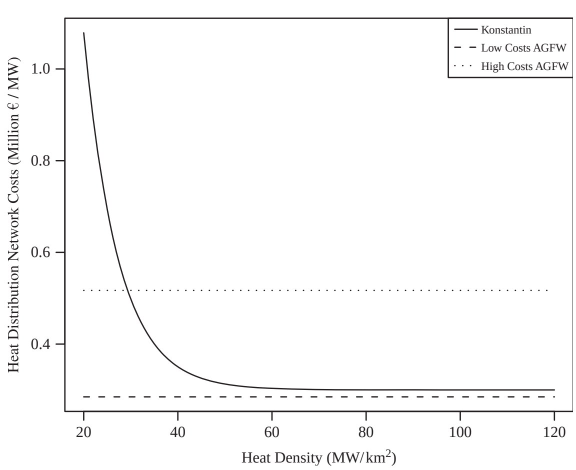

Figure 2. Comparison of district heating network costs in Konstantin [32] and AGFW [33].

literature [36]. In addition, heat prices charged by district heating utilities in Austria are used as indicators for local heating costs. This is feasible as district heating utilities charge a heat price just below the price of an alternative heating technology under the assumption that alternate cost pricing is applied [37,38].

2.7. Model parameter uncertainty

The values of some parameters are highly uncertain because they specify volatile prices or economical and technical characteristics of yet unavailable technology. Other parameters cannot be estimated more accurately, because the information is not available at all. Analyzing the influence of variances in the model parameters on the model output is therefore a relevant part of this article. The precise value of the parameters is usually not known; however, a plausible range of values can be determined from historical data sets, from literature reviews and from expert opinion. A range of parameter values was defined for 9 of the 25 model parameters (index l) (Table II). The remaining parameters are not stochastically modeled because they are either determined by results of pre-analysis (plant capacity $\bar{q}_j$, see Section 2.3), or they are known with high accuracy ($\eta^{\mathrm{trans}}_{j,\mathrm{h,ps},t}, \bar{q}^{\mathrm{pipe}}_{\mathrm{ps},t}, \alpha_j, \eta_j^{\mathrm{chp}}$, emission factors) or are non-restricting constraints (p^{D}) or are determined by another stochastically modeled parameter (the value of con determines $q^{\mathrm{D}}_{\mathrm{h},t}$ and $q^{\mathrm{D}}_{\mathrm{h,ns},t}$, see Equation (15)) or are known to have little influence on model output from previous sensitivity analysis ($\eta^{\mathrm{dh}}_{\mathrm{h},t}\eta^{\mathrm{local}}_{\mathrm{h},t}, c_j^{\mathrm{prod}}, c^{\mathrm{pipe}}_{j,\mathrm{h,ps}}$). A plausible range of parameters values is not sufficient to estimate a probability distribution of the input parameters. Therefore, the parameters are assumed to be normally distributed. The mean μ and the standard deviation σ of the distribution $N(\mu, \sigma)$ are determined by the upper limit up_l and lower limit lo_l of the plausible parameter range, that is, $\mu = (\mathrm{up}_l + \mathrm{lo}_l)/2$ and $\sigma = (\mu - \mathrm{lo}_l)/1.96$ as proposed in [42]. It is assumed that there is no covariance between the parameters, that is, they are independently drawn. This assumption may not hold for energy and biomass prices. However, as all parameters are normally distributed, combinations

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

Table II. Ranges of model input parameters.

Parameter	Lower bound lo_l	Upper bound up_l	References
Annualized district heating costs $c^{dnet}_{h,ns}$ (% *of standard calculation*)	50	150	[32,33]
Biomass supply b_i (% *of standard calculation*)	95	105	Expert opinion
Biomass costs c^{sup}_i (€ GJ^{-1})	4.34	5.83	[39]
Plant setup costs c^{plant}_j (M€)	52	130	[20,21]
Transportation costs $c^{trans}_{i,j}$ (% *of standard costs*)	85	115	[16], Expert opinion
Price local heat c^{local}_t (€ MWh^{-1})	62	80	[36], district heating prices
Carbon price c^{em} (€/t_{CO_2})	6	30	Prices at European Energy Exchange 2005–2008 [40]
Connection rate con (%)	61	74	Expert opinion
Power price c^{fp} (€ MWh^{-1})	30	79	[41] and Prices at European Energy Exchange 2006–2008, [40]

of extreme values are minor. In addition, the price ranges of consideration are narrow and reflect annual price variations on the markets for the years 2004–2007. Consequently, the price variations can be seen to specify annual price volatilities on the energy markets, which are assumed to be independent from each other. Monte-Carlo simulations for 1000 independent draws of parameter sets are used in the model. Solving the model for each parameter set yields a probability distribution of the model outputs that are used for further analysis.

3. RESULTS

3.1. Optimal locations

Possible plant locations are deterministically spread at a vertical and horizontal distance of 0.41° over Austria. In total, 89 possible positions are evaluated by counting the number of times a location was selected in the 1000 Monte-Carlo simulations (Figure 3). In this manner an indication of favorable locations considering all parameter variations can be given. Locations selected by the model are compared with locations of real biomass-fired CHP plants. However, CHP plants of a capacity of 130 $MW_{biomass}$, which is the plant size assumed in the model, are currently not being built in Austria. Therefore, the biggest Austrian CHP plants (capacities of 20–66 $MW_{biomass}$) are chosen as reference. Figure 3 shows optimal locations selected by the model and the locations of the four real CHP plants. The locations of real installations and positions favored by the model correspond. Plants are mainly located around bigger cities due to the high heat densities in these regions. More plants are located in the east of the country because the highest yield potentials of forest wood and the biggest cities in Austria, Vienna, Linz and Graz, are located there. Therefore, biomass transportation costs and heat demand distribution costs are low.

3.2. Power and heat production potentials

Potentials of CHP production are measured with variable $p^{tot} = \sum_j p^{chp}$—representing the total power production in CHP plants—and variable $q^{tot} = (\sum_{h,t} q_{h,t}/\eta^{local}_{h,t} - q^{local}_{h,t})$—representing the total local heat production substituted by district heating. The model results represent not single values but rather probability distributions due to the Monte-Carlo simulations. The distributions of p^{tot} and q^{tot} show high variances. The power price, which has a broad plausible range of values and a strong influence on output, mainly contributes to the variance. This is confirmed by the sensitivity analysis (Section 4) and by Figure 4 that shows a plot of the power price against p^{tot} and q^{tot}. The total production potential is mainly influenced by the number of plants that are built. As plants are modeled as integer variables, an additional plant increases the total production potential significantly. Although power production is modeled with a continuous variable, the annual production

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

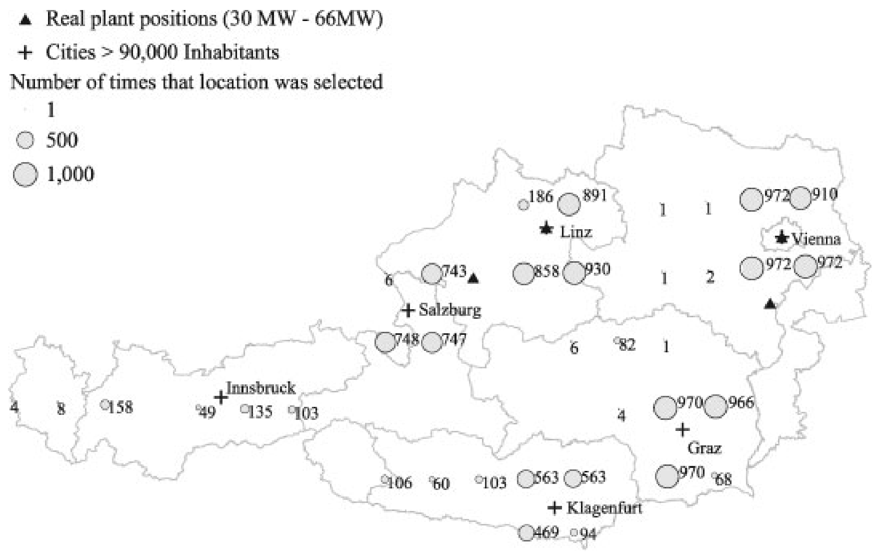

Figure 3. Number of times plant locations were selected in 1000 model runs.

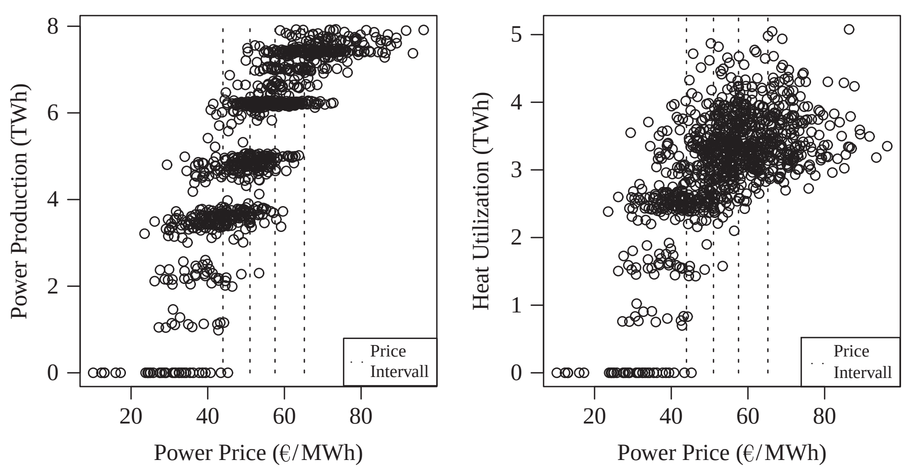

Figure 4. Power production potentials and heat utilization depending on power price.

per plant does not vary substantially as a high level of production is necessary to make the plants profitable. The separated clusters in Figure 4 therefore represent the different number of plants built in the scenarios.

The model results are examined by dividing the sample of results in five groups of equal sample size to facilitate the interpretation. The groups are determined by five different intervals (I1,…,I5) of power prices (Table III and Figure 4).

Table III. Power price intervals for analysis of production potentials (€ MWh^{-1}).

Interval	Power price lower bound	Power price upper bound
I1	—	43.51
I2	43.52	51.69
I3	51.70	57.11
I4	57.12	64.50
I5	64.51	—

Copyright © 2009 John Wiley & Sons, Ltd.

Consequently, the variance of model results is reduced within each interval, which provides a better picture of bioenergy production potentials. The power and heat production potentials of each interval are shown in Figure 5. The bars represent the mean of the distribution. Boxplots indicate the range of the results. At current power prices, which are comparable to the prices of interval I3, the mean (1st and 3rd quartile) of the power production is at 5.72 TWh (4.91–6.24 TWh). This accounts for 9.53% (8.19–10.40%) of total Austrian power consumption while heat and power production together sum up to 3.02% (2.67–3.30%) of total Austrian energy consumption. The mean (1st and 3rd quartile) of the lowest price interval I1 corresponds to 4.62% (3.55–6.08%) of Austrian power consumption. At prices of above 65 € $\text{MWh}^{-1}_{\text{power}}$ (I5), almost the total available forest biomass is utilized in CHP production and a maximum of 12.06% (12.18–12.61%) of power consumption can be supplied by CHP plants in Austria. The variance of model results decreases as power prices get higher because cost variations become less influential.

In CHP plants, the production of heat is higher than power production due to higher conversion efficiencies. However, the amount of heat used for district heating is lower due to spatial and temporal demand restrictions. Figure 6 shows that the proportion of produced to utilized heat declines when power production is increased. The reasons for decreasing heat utilization are twofold: first, different district heating settlements vary in their infrastructure costs. Therefore, some settlements are not selected because of high district heating infrastructure costs. Second, the total heat demand in some settlements is low. Big plants as assumed in the model produce excess heat in areas with low population densities.

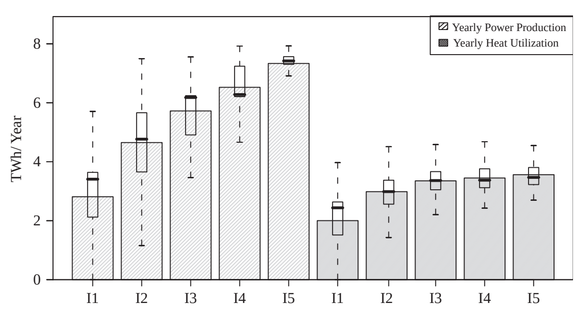

Figure 5. Power production and heat utilization at different price intervals I1–I5 (for intervals, see Table III). The bars represent the mean of the distribution of the results.

4. SENSITIVITY ANALYSIS

A sensitivity analysis is applied to test which model parameters have a strong influence on model outputs and which contribute most to the uncertainty of model results. Sensitivity elasticities describe the relative change of the output to relative changes in the input [43]. Elasticities can be defined for all possible combinations of input parameters and output variables. Variable p^{tot} is used for further descriptions. The elasticities of variable q^{tot} are calculated likewise. The elasticity is defined as

$$p^{\text{tot}}_{\text{par}_l} = \frac{\partial p^{\text{tot}}}{\partial \text{par}_l} \frac{\text{par}_l}{p^{\text{tot}}} \tag{16}$$

where $p^{\text{tot}}_{\text{par}_l}$ is the elasticity between p^{tot} and par_l. The derivative $\partial p^{\text{tot}}/\partial \text{par}_l$ cannot be derived analytically from the optimization model. However, it is possible to estimate a response surface by applying a linear regression model of the output on the input parameters and thereby approximating a continuous function [44]

$$p^{\text{tot}} = \beta_0 + \sum_{l=1}^{10} \beta_l \text{par}_l + e \tag{17}$$

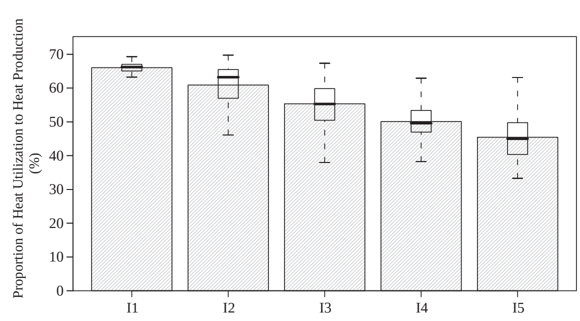

Figure 6. Proportion of heat utilization to heat production.

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

where coefficent β_0 is the intercept, coefficients β_l are the regression coefficients and e is an error term. The parameter vectors par_l which represent the input to the Monte-Carlo simulation and the corresponding result vectors p^{tot}, both consisting of n elements, are used in the regression analysis. The regression is not able to capture the whole dynamics of the noncontinuous relationship between the variables that result from the MIP. However, the ordinary least-square estimator exhibits a fit of $R^2 = 0.86$. The signs of the coefficients have the expected direction for all parameters. The response surface is used to numerically compute the elasticities:

$$p^{\text{tot}}_{\text{par}_l} = \frac{\partial p^{\text{tot}}}{\partial \text{par}_l} \frac{\text{par}_l}{p^{\text{tot}}} = \beta_l \frac{\text{par}_l}{p^{\text{tot}}} \qquad (18)$$

When no power is produced at all, the elasticity is not defined, as the denominator of the fraction in Equation (18) is 0 in such a case. Undefined elasticities are excluded from further calculations. The mean of each elasticity distribution and for all observed parameter/output combinations are reported in Table IV. Moreover, Figure 7 shows boxplots to illustrate the probability distribution of the elasticities. The elasticity indicates how much the model output changes in percent, if a model input parameter changes by 1%. Parameters power price c^{fp} and biomass supply costs c_i^{sup} are elastic with regard to the power output, that is, the absolute value of the parameters is greater than one. Transportation costs have the smallest influence on the total power output. Output variable q^{tot} is mainly influenced by the connection rate con. The power price is less important. The impact of the connection rate on heat production potentials is explained by the direct correlation of heating demand and connection rate, that is, the heating demand is a function of the connection rate. Increasing the heating demand allows the supply of more heat to the settlements by decreasing infrastructure costs. Transportation costs show little effect on the total heat production potential.

Elasticities are a measure for the relative impact of a relative change in the input parameters on the output. However, if the uncertainty of the distribution of a parameter is low, a high elasticity does not imply that the parameter contributes a lot to the uncertainty of the model. To estimate the contribution of a parameter to model uncertainty, the MdAPE [45] is calculated as error measure from the response surface following [42]. The results are reported in Table IV. The power price—which has high elasticities—also contributes most to model uncertainty with regard to both output variables. However, while the CO_2 price c^{em} has a low elasticity, it contributes a lot to the uncertainty of the model. The same is the case for district heating infrastructure costs $c^{\text{dnet}}_{\text{h,ns}}$. They show a high contribution to uncertainty with regard to the heat output. Both parameters c^{em} and $c^{\text{dnet}}_{\text{h,ns}}$ show a wide plausible range of values, which explains the high contribution to model uncertainty.

Table IV. Results of sensitivity analysis: mean of elasticities and MdAPE.

Parameter	Mean of elasticity		MdAPE	
	$p^{\text{tot}}_{\text{par}_l}$	$q^{\text{tot}}_{\text{par}_l}$	p^{tot} (%)	q^{tot} (%)
Biomass supply costs (c_i^{sup})	−1.10	−0.54	6.76	3.66
CHP plant investment costs (c_j^{plant})	−0.49	−0.35	4.00	3.04
District heating infrastructure costs ($c^{\text{dnet}}_{\text{h,ns}}$)	−0.23	−0.52	4.87	11.48
Transportation costs ($c_{i,j}^{\text{trans}}$)	−0.16	−0.09	1.09	0.65
CO_2 price (c^{em})	0.30	0.19	8.65	6.10
Connection rate (con)	0.54	1.14	2.23	5.14
Local heating costs (c_t^{local})	0.62	0.87	3.36	5.13
Biomass supply (b_i)	0.82	0.23	1.66	0.49
Costs of fossil power production (c^{fp})	1.34	0.76	24.12	15.10

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

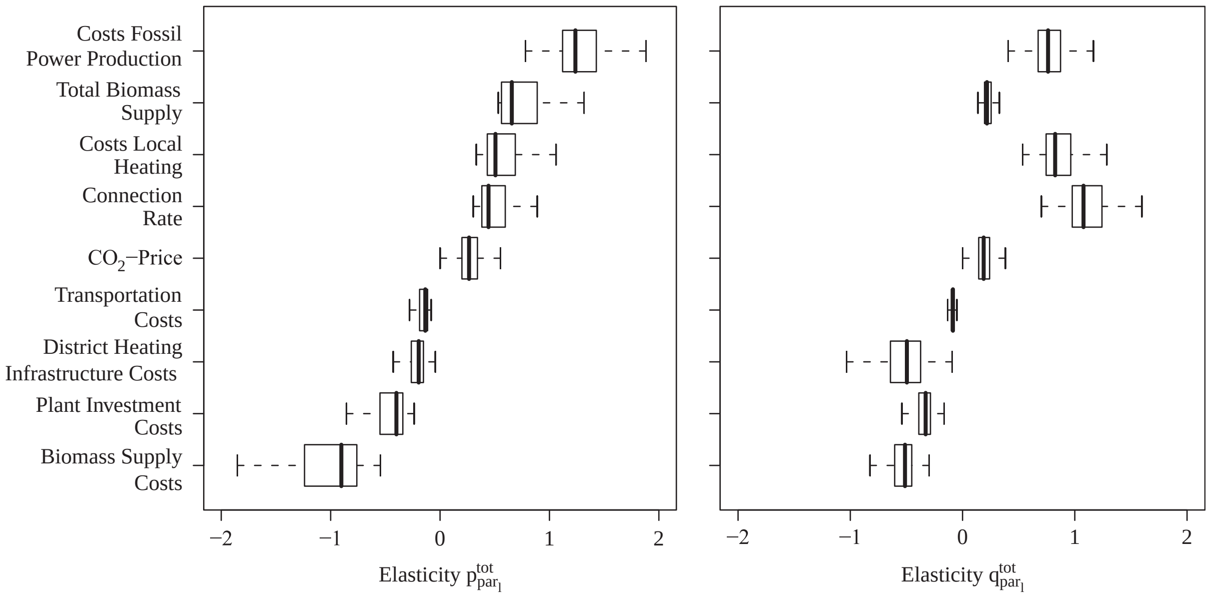

Figure 7. Boxplots of elasticities between power production (p^{tot}) as well as heat substitution (q^{tot}) and nine stochastically modeled parameters par_l.

5. DISCUSSION AND CONCLUSIONS

There is a considerable potential for CHP production at price levels between 52 and 57 € MWh^{-1}_{power}. These prices are close to current market prices. About 83% of the total available biomass-fired CHP production can be mobilized according to our model analysis. Although feed in tariffs guaranteed for biomass-based power production are currently even higher than 57 € MWh^{-1}_{power}, the biomass-based CHP production levels have not been achieved. However, it has to be regarded that the potentials of BIGCC technologies that are currently not available on the market are assessed in this article. Additionally, the sensitivity analysis shows that the market price of biomass has significant impact on the total production potential. However, market feedbacks on the biomass price due to increased biomass consumption are not modeled yet. Others [46] estimate costs of biomass-based CHP production to be around 54 € MWh^{-1}_{power}. Low biomass costs and constant district heating distribution costs of densely populated urban areas are assumed in [20,21]. They estimate very low power costs of biomass-based CHP production ranging between 32 and 42 € MWh^{-1}_{power}. These results may be justifiable for favorable locations. Yet, a national cost assessment of CHP potentials has to consider the spatial distributions of heating demand and biomass supply. The methodology presented in this article allows assessing least cost options of CHP systems accounting for the spatial distribution of heating demand in national contexts. The analysis shows that the spatial and temporal distributions of heat demands have a significant impact on CHP production. The seasonal variation in heat demand decreases the overall utilization potential of heat, that is, the plants produce a lot of excess heat in summer. The spatial variation in heat demand limits the amount of plants that are able to use heat for district heating. There are only a limited number of settlements where heat demand densities are high enough to allow building district heating networks. However, the accuracy of the current industrial heat demand model is low and the restriction on CHP production potentials due to the lack of heat demand may be partly removed if the accuracy could be increased—and if potential new industrial CHP consumers are added. The model does not yet evaluate the partial substitution of fossil fuels by co-firing in fossil

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

CHP plants or by totally switching from fossil fuels to biomass in already existing district heating networks. More research in this direction is necessary. Lower heat demand densities due to better insulation of buildings [25] and warmer winter temperatures due to climate change [27] may decrease district heating potentials in the future.

Optimal locations for plants are mainly concentrated around bigger cities because heat distribution in district heating networks is cheap there. The distance to the biomass supply and resulting biomass transportation costs are less important for the choice of the optimal location. The east of Austria is better suited for CHP production due to sufficient forest wood supply and higher heat demand densities of bigger cities. The existing CHP plants around Vienna and Linz confirm this result.

About 3.0% of total Austrian energy consumption could be supplied by biomass-fired CHP plants at current market prices. The Austrian renewable energy targets require a production increase of 11%, assuming that consumption stays at current levels until 2020. Biomass-based CHP production can account for 27% of that necessary increase at current market prices. Utilizing the total available biomass from Austrian forests allows producing up to 3.6% of the total energy consumption. However, high levels of CHP production would reduce the total conversion efficiency because less of the produced heat can be used for district heating.

Energy prices are highly volatile, for example, power prices have increased by 100% between 2003 and 2008. Therefore, impacts of price variations should be explicitly assessed in model analysis. The power and emission prices as well as district heating costs have the most impact on model output. While power and emission prices reflect stochastic processes in the energy system and market, the uncertainty of the parameter describing district heating costs could be reduced by further research. Another future research direction should be the assessment of bioenergy technologies that compete with CHP. Heat generation in single home heating systems is the main competitor to CHP production, whereas other technologies like second-generation biofuel production may become sound alternatives of wood use in the future [47]. Future application of the model to assess the competition of different technologies should therefore be an important research opportunity.

NOMENCLATURE

Variables

$\bar{b}_i$	= biomass supply
$b_{i,j}$	= biomass transportation
p^{fp}	= power production with fossil fuels
p_j^{chp}	= power production in the CHP plant
$p_{\mathrm{par}_l}^{\mathrm{tot}}$	= elasticity between power production and input parameters
p^{tot}	= total CHP power production
$q_{\mathrm{h},t}^{\mathrm{local}}$	= local heat production
$q_{\mathrm{h},t}^{\mathrm{peak}}$	= peak heat production
q_j^{chp}	= heat production in the CHP plant
$q_{j,\mathrm{h,ps},t}^{\mathrm{dh}}$	= heat transportation from plant to district heating network
$q_{\mathrm{par}_l}^{\mathrm{tot}}$	= elasticity between heat substitution and input parameters
q^{tot}	= total fossil heat generation substituted by CHP production
$u_{\mathrm{h,ns}}^{\mathrm{dnet}}$	= binary variable for investment in district heating network
$u_{j,\mathrm{h,ps}}^{\mathrm{pipe}}$	= binary variable for investment in transportation pipeline
u_j^{plant}	= binary variable for plant investment

Parameters

$A_{\mathrm{h,bt,ba}}$	= dwelling area
c^{fp}	= costs of power generation with fossil fuels
c_i^{sup}	= costs of biomass supply
$c_{i,j}^{\mathrm{trans}}$	= costs of biomass transportation
c_j^{plant}	= costs of plant investment
c_j^{prod}	= costs of CHP production
$c_{j,\mathrm{h,ps}}^{\mathrm{pipe}}$	= costs of transportation pipeline investment
$c_{\mathrm{h,ns}}^{\mathrm{dnet}}$	= costs of district heating network investment
c_t^{local}	= costs of local heat production
c_t^{peak}	= costs of peak heat production

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

c^{em} = CO_2 price
con = district heating connection rate
e = error term
e^{fp} = CO_2 emission factor of power generation with fossil fuels
e_h^{local} = CO_2 emission factor of local heat production
$e_{i,j}^t$ = CO_2 emission factor of biomass transportation
e^{peak} = CO_2 emission factor of peak heat production
$EC_{bt,ba}$ = heat consumption coefficient
ECE_{es} = heat consumption per employee
$EM_{h,es}$ = number of employees
HDD_h = spatial explicit heating degree days
HDD^{ref} = reference heating degree days for private demand
$HDDC^{ref}$ = reference heating degree days for commercial heating demand
lo_l = lower bound of plausible range of parameters
n = number of runs in Monte-Carlo Simulation
p^D = power demand
par_l = input parameter vector
q_h^{Dd} = private heating demand
q_h^{Dc} = commercial heating demand
$q_{h,t}^D$ = heat demand
$q_{h,ns,t}^D$ = heat demand in district heating networks of different size
$\bar{q}_j$ = heat production capacity of CHP plant
$\bar{q}_{ps,t}^{pipe}$ = capacity of heat transportation pipeline
up_l = upper bound of plausible range of parameters
α_j = alpha value of CHP plant
β_0, β_l = regression coefficients
η_j^{chp} = conversion efficiency in CHP plant
$\eta_{j,h,ps,t}^{trans}$ = transportation efficiency of heat pipeline
$\eta_{h,t}^{dh}$ = efficiency of distributing heat in district heating network
$\eta_{h,t}^{local}$ = local heat conversion efficiency
η^{com} = heat conversion efficiency in commercial buildings
Δt_t = relative length of a season
χ_{bt}^{dh} = heating system usage factor
$\Delta s_{h,t}$ = proportional heat consumption in season

Subscripts

ba = building age
bt = building type
es = economic sector
h = settlements
i = biomass supply sites
j = plant locations
l = model input parameter
ns = district heating network size
ps = pipeline size
t = season

ACKNOWLEDGEMENTS

The article has been prepared in the framework of the doctoral school Sustainable Development (DOKNE) at BOKU University of Natural Resources and Applied Life Sciences, Vienna, Austria. The doctoral school is funded by the Austrian Research Program on Sustainability 'provision' as well as by the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and the states Lower Austria, Styria, and Vienna. The Austrian 'Fachverband Gas Wärme' (Professional Association of Gas and Heat Utilities) provided data for this study. We are very grateful to comments to early versions of the article from Dagmar Schwab, Martin Schönhart, Ulrich Morawetz and Georg Benke. Comments received from three anonymous referees are gratefully acknowledged.

REFERENCES

1. Commission of the European Union. *Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources*. Commission of the European Union: Brussels, 2008. See also: http://ec.europa.eu/energy/climate_actions/doc/2008_res_directive_en.pdf.
2. Madlener R. Innovation diffusion, public policy, and local initiative: the case of wood-fuelled district heating systems in Austria. *Energy Policy* 2007; **35**(3):1992–2008.
3. E-Control. *Development of Approved Green Power Plants According to Decisions of Provincial Governments* (*Entwicklung der anerkannten Ökostromanlagen laut Bescheiden der Landesregierungen*). E-Control: Vienna, 2009. See also: http://www.e-control.at/portal/page/portal/ECONTROL_HOME/OKO/ZAHLEN_DATEN_FAKTEN/Anlagenstatistik/ANERKANNTEOEKOANLAGEN.

Copyright © 2009 John Wiley & Sons, Ltd.

4. Schadauer K. *The Austrian Forest Inventory 2000/02—Main Results* (*Die Österreichische Waldinventur 2000/02—Hauptergebnisse*). Vienna: Bundesamt für Wald, 2004. See also: http://bfw.ac.at/040/pdf/1818_pi3.pdf.
5. Eriksson LO, Björheden RW. Optimal storing, transport and processing for a forest-fuel supplier. *European Journal of Operational Research* 1989; **43**(1):26–33.
6. Grohnheit PE, Mortensen BOG. Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies. *Energy Policy* 2003; **31**(9):817–826.
7. Gustafsson S-I. Municipal thermal and electricity loads—a case study in Linköping. *Applied Thermal Engineering* 1998; **18**(5):257–263.
8. Perpina C, Alfonso D, Pérez-Navarro A, Penalvo E, Vargas C, Cárdenas R. Methodology based on Geographic Information Systems for biomass logistics and transport optimisation. *Renewable Energy* 2009; **34**(3): 555–565.
9. Panichelli L, Edgard G. GIS-based approach for defining bioenergy facilities location: a case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass and Bioenergy* 2008; **32**(4):289–300.
10. Dunnet AJ, Adjiman CS, Shah N. A spatially explicit whole-system model of the lignocellulosic bioethanol supply chain: an assessment of decentralized processing potential. *Biotechnology for Biofuels* 2008; **1**(1):13.
11. Bernotat K, Sandberg T. Biomass fired small-scale CHP in Sweden and the Baltic States: a case study on the potential of clustered dwellings. *Biomass and Bioenergy* 2004; **27**(6):521–530.
12. Ivezic D, Zivkovic M, Tanskovic T, Dajic N. An economic model for the appraisal and selection of energy supply system. *Applied Thermal Engineering* 2008; **29**(8–9): 1440–1446.
13. Freppaz D, Minciardi R, Robba M, Rovatti M, Sacile R, Taramasso A. Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass and Bioenergy* 2004; **26**(1):15–25.
14. Rentizelas AA, Tatsiopoulos IP, Tolis A. An optimization model for multi-biomass tri-generation energy supply. *Biomass and Bioenergy* 2008; **33**(2):223–233.
15. Leduc S, Schmid E, Obersteiner M, Riahi K. Methanol production by gasification using a geographically explicit model. *Biomass and Bioenergy* 2009; DOI:10.1016/j.biombioe.2008.12.008(-).
16. 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.
17. Assmann E. *The Principles of Forest Yield Study*. Pergamon: Oxford, 1970.
18. Running SW. Terrestrial remote sensing science and algorithms planned for EOS/MODIS. *International Journal of Remote Sensing* 1994; **15**(17):3587–3620.
19. European Environment Agency. *Corine Land Cover*. European Environment Agency, 2008. See also: http://www.eea.europa.eu/publications/COR0-landcover.
20. Marbe G, Harvey S, Berntsson T. Biofuel gasification combined heat and power—new implementation opportunities resulting from combined supply of process steam and district heating. *Energy* 2004; **29**(8):1117–1137.
21. Dornburg V, Faaij APC. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. *Biomass and Bioenergy* 2001; **21**(2):91–108.
22. E-Control. *Time Series of Power Production* (*Jahresreihen: Gesamte Elektrizitätsversorgung Aufbringung*). E-Control: Vienna, 2009. See also: http://www2.e-control.at/portal/page/portal/ECONTROL_HOME/STROM/ZAHLENDATENFAKTEN/ENERGIESTATISTIK/JAHRESREIHEN.
23. Umweltbundesamt. *Austria's National Inventory Report*, Umweltbundesamt Österreich, 2008.
24. Hens H, Verbeeck G, Verdonck B. Impact of energy efficiency measures on the CO_2 emissions in the residential sector, a large scale analysis. *Energy and Buildings* 2001; **33**(3):275–281.
25. Winkelmüller S. Optimization of demand and supply structures of municipal energy systems using the example of Vienna (Optimierung der Nachfrage- und Erzeugungsstruktur kommunaler Energiesysteme am Beispiel von Wien). *Ph.D. Thesis*, Mathematisch Naturwissenschaftliche Fakultät—Universität Augsburg, Augsburg, 2006.
26. Suzuki Y, Pak PS, Ito K. Total planning of combined district heating, cooling and power generation systems for a new town—Part I. *International Journal of Energy Research* 1984; **8**(1):61–75.
27. Prettenthaler F, Gobiet A, Habsburg-Lothringen C, Steinacker R, Töglhofer C, Türk A. *Effects of Climate Change on Heating- and Cooling Demand in Austria* (*Auswirkungen des Klimawandels auf Heiz- und Kühlenergiebedarf in Österreich*). StartClim, Vienna, 7. See also: http://www.austroclim.at/fileadmin/user_upload/reports/StCl06F.pdf.
28. Statistik Austria. *Buildings- and Dwellings Census 2001: Main Results* (*Gebäude- und Wohnungszählung 2001: Hauptergebnisse*). Statistik Austria: Vienna, 2004. See also: http://www.statistik.at/web_de/dynamic/statistiken/wohnen_und_gebaeude/bestand_an_gebaeuden_und_wohnungen/publdetail?id = 179&listid = 179&detail = 117.
29. Haas R, Auer H, Biermayr P. The impact of consumer behavior on residential energy demand for space heating. *Energy and Buildings* 1998; **27**(2):195–205.
30. Statistik Austria. *Analysis of Useful Energy 1998* (*Nutzenergieanalyse 1998*). Statistik Austria: Vienna, 2000.
31. Gesellschaft für Energiemanagement mbH. *Catalogue of Indicators. Preperation of Investments in the Energy Industry* (*Kennziffernkatalog. Investitionsvorbereitung in der Energiewirtschaft*). Gesellschaft für Energiemanagement mbH: Berlin, 1999.
32. Konstantin P. *Handbook Energy Industry* (*Praxisbuch Energiewirtschaft*). Springer: Berlin, Heidelberg, 2007.
33. Arbeitsgemeinschaft Fernwärme e.V. *Strategies and Technologies of a Pluralistic District Heating Supply in a Liberalized Energy Market Considering Combined Heat and Power and Renewable Energies* (*Strategien und Technologien einer pluralistischen Fern- und Nahwärmeversorgung in einem liberalisierten Energiemarkt unter besonderer Berücksichtigung der Kraft-Wärme-Kopplung und erneuerbarer Energien*). Arbeitsgemenschaft Fernwärme e.V.: Frankfurt, 2000. See also: http://www.isi.fhg.de/e/publikation/waerme/band1-lang.pdf.
34. Kristjansson H, Bohm B. Pipe network cost models for system analysis. *The 11th International Symposium on District Heating and Cooling*, Reykjavik, 2008.

Copyright © 2009 John Wiley & Sons, Ltd.

35. Blesl M. Spatially highly resolved modelling of grid-bound energy supply systems to cover the demand for low temperature heat (Räumlich hoch aufgelöste Modellierung leitungsgebundener Energieversorgungssysteme zur Deckung des Niedertemperaturwärmebedarfs). *Ph.D. Thesis*, Universität Stuttgart, Stuttgart, 2002.
36. Styles D, Jones MB. Current and future financial competitiveness of electricity and heat from energy crops: a case study from Ireland. *Energy Policy* 2007; **35**(8): 4355–4367.
37. Sjödin J, Henning D. Calculating the marginal costs of a district-heating utility. *Applied Energy* 2004; **78**(1):1–18.
38. Rolfsman B, Guastafsson S-I. Energy conservation conflicts in district heating systems. *International Journal of Energy Research* 2002; **27**(1):31–43.
39. Landwirtschaftskammer Niederösterreich. *Energy Wood Index Austria* (*Energieholzindex Österreich*). Landwirtschaftskammer Niederösterreich: St. Pölten, 2008.
40. European Energy Exchange. *Market Data*. European Energy Exchange, 2009. See also: http://www.eex.com/en/Download/Market%20Data.
41. Matthes FC, Graichen V, Harthan RO, Horn M, Krey V, Markewitz P, Martinsen D, Repenning J. *Energy Prices and Climate Protection* (*Energiepreise und Klimaschutz*). Umweltbundesamt: Dessau, 2008. See also: http://www.umweltdaten.de/publikationen/fpdf-l/3494.pdf.
42. Salhofer K, Schmid E, Streicher G. Testing for the efficiency of a policy intended to meet objectives: general model and application. *Journal of Agriculture and Resource Economics* 2006; **31**(2):151–172.
43. Zhao X, Griffiths WE, Griffith GR, Mullen JD. Probability distributions for economic surplus changes: the case of technical change in the Australian wool industry. *Australian Journal of Agriculture and Resoure Economics* 2000; **44**(1): 83–106.
44. Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, Saisana M, Tarantola S. *Global Sensitivity Analysis*: *The Primer*. Wiley: Chichester, 2008.
45. Armstrong JS, Collopy F. Error measures for generalizing about forecasting methods: empirical comparisons. *International Journal of Forecasting* 1992; **8**(1): 69–80.
46. Kumar A, Cameron JB, Flynn PC. Biomass power cost and optimum plant size in western Canada. *Biomass and Bionergy* 2003; **24**(6):445–464.
47. Bram S, De Ruyck J, Lavric D. Using biomass: a system perturbation analysis. *Applied Energy* 2009; **86**(2): 194–201.

Copyright © 2009 John Wiley & Sons, Ltd.

DOI: 10.1002/er

Article 2

Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies

Applied Energy xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies

Johannes Schmidt [a,*], Sylvain Leduc [b], Erik Dotzauer [c], Georg Kindermann [b], Erwin Schmid [d]

[a] Doctoral School Sustainable Development, University of Natural Resources and Applied Life Sciences, Peter Jordan Straße 82, A-1190 Vienna, Austria
[b] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria
[c] Mälardalen University, P.O. Box 883, SE-72123 Västerås, Sweden
[d] Institute for Sustainable Economic Development, University of Natural Resources and Applied Life Sciences, Feistmantelstraße 4, A-1180 Vienna, Austria

ARTICLE INFO

Article history:
Received 4 August 2009
Received in revised form 2 November 2009
Accepted 4 November 2009
Available online xxxx

Keywords:
Bioenergy
CO_2 mitigation
Pellets
Biofuels
Combined heat and power
Bioenergy system with carbon capture and storage
Mixed integer program
Monte-Carlo simulation

ABSTRACT

Bioenergy is regarded as cost-effective option to reduce CO_2 emissions from fossil fuel combustion. Among newly developed biomass conversion technologies are biomass integrated gas combined cycle plants (BIGCC) as well as ethanol and methanol production based on woody biomass feedstock. Furthermore, bioenergy systems with carbon capture and storage (BECS) may allow negative CO_2 emissions in the future. It is still not clear which woody biomass conversion technology reduces fossil CO_2 emissions at least costs. This article presents a spatial explicit optimization model that assesses new biomass conversion technologies for fuel, heat and power production and compares them with woody pellets for heat production in Austria. The spatial distributions of biomass supply and energy demand have significant impact on the total supply costs of alternative bioenergy systems and are therefore included in the modeling process. Many model parameters that describe new bioenergy technologies are uncertain, because some of the technologies are not commercially developed yet. Monte-Carlo simulations are used to analyze model parameter uncertainty. Model results show that heat production with pellets is to be preferred over BIGCC at low carbon prices while BECS is cost-effective to reduce CO_2 emissions at higher carbon prices. Fuel production – methanol as well as ethanol – reduces less CO_2 emissions and is therefore less cost-effective in reducing CO_2 emissions.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

The Austrian government has committed to reduce greenhouse gas (GHG) emissions by 13% below the level of 1990 in the period 2008–2012 [1]. The private heating sector, the transport sector and the power and heat production sector contributed to 56% of total anthropogenic GHG emissions in Austria in 2006 [2]. In 2006, Austria was far away from reaching emission reduction targets. Bioenergy is seen as an economic viable and politically favorable option to reduce CO_2 emissions in Austria. Particularly wood is an important feedstock for biomass based energy production. Over the last 5 years, substantial subsidies have stimulated the installation of additional heat and power plants fired by biomass in Austria [3,4]. Further increases are possible because the annual growth in wood stocks is currently not fully exploited [5]. There are several technologies available to produce bioenergy from woody biomass (Fig. 1). The commodities produced by plants of different type replace fossil fuels in several sectors. CO_2 reduction potentials are therefore varying between conversion technologies. It is still not obvious which conversion chain saves most CO_2 emissions. In addition, the systems' costs of a conversion chain influence the competitiveness with respect to fossil commodities.

This article assesses the use of forest biomass to reduce CO_2 emissions in three sectors including heat, power and transportation fuels. In each sector, at least one conversion technology is chosen for the assessment. The selection of technologies for the modeling process depends on their techno-economic performance in comparison to other bioenergy technologies in the sector. In the heating sector, pellets heating systems are chosen. Burning pellets in single stoves to heat dwellings is highly efficient [6]. Pellets are also convenient to handle for the user due to their high energy density and low storage space requirements in comparison to other wood fuels [7]. We model pellets production in a bioenergy combine that integrates pellets production with combined heat and power production [8] and burning of the pellets in single dwelling heaters. A biomass integrated combined cycle (BIGCC) production technology with optional combination with carbon capture and

* Corresponding author. Tel.: +43 6502151579; fax: +43 1476543692.
E-mail address: johannes.schmidt@boku.ac.at (J. Schmidt).

0306-2619/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2009.11.007

ARTICLE IN PRESS

Nomenclature

Variables

- $b_{i,j,l}$ biomass transported to plants (MW $h_{biomass}$)
- $esav$ total emission reductions (tCO_2)
- q_j^{bio} heat production in the plant (MW h)
- $q_{j,h,ps,t}^{dh}$ heat transportation from plant to district heating network (MW h)
- $q_{h,t}^{local}$ local heat production (MW h)
- $q_{h,t}^{peak}$ peak heat production (MW h)
- $totem$ total CO_2 emissions (tCO_2)
- $u_{h,ns}^{dnet}$ binary variable for investment in district heating network (–)
- $u_{j,h,ps}^{pipe}$ binary variable for investment in transportation pipeline (–)
- $u_{j,l}^{plant}$ binary variable for plant investment (–)
- $z_{j,c}^{bio}$ amount of energy commodity produced in a plant (MW h)
- $z_{j,k,c}^{bio}$ amount of energy commodity transported to consumers (MW h)
- $z_{k,c}^{fossil}$ amount of fossil fuel used to satisfy demand (MW h)

Parameters

- β_0, β_m regression coefficients (–)
- $\eta_{c,d}^{bio}$ efficiency of converting a bioenergy commodity to useful energy (–)
- $\eta_{j,l,c}^{conv}$ conversion efficiency in bioenergy plants (–)
- $\eta_{h,t}^{dh}$ efficiency of distributing heat in district heating network (–)
- $\eta_{c,d}^{fossil}$ efficiency of converting fossil fuel to useful energy (–)
- $\eta_{j,l}^{heat}$ heat efficiency in bioenergy plants (–)
- $\eta_{h,t}^{local}$ local heat conversion efficiency (–)
- $\eta_{j,h,ps,t}^{trans}$ transportation efficiency of heat pipeline (–)
- $\bar{b}_i^{sup}$ biomass supply capacity (MW h y^{-1})
- $\bar{b}_{j,l}$ production capacity of plant (MW h y^{-1})
- c^{ccs} costs of carbon capture and storage (€ tCO_2^{-1})
- $c_{h,ns}^{dnet}$ annualized costs of investment in district heating network (€ y^{-1})
- c^{em} CO_2 price (€ tCO_2^{-1})
- c_c^{fossil} price of fossil fuel (€ MW h^{-1})
- c_c^{inv} investment cost necessary at consumer (€ MW h^{-1})
- c_t^{local} costs of local heat production (€ MW h^{-1})
- c_i^{sup} costs of biomass supply (€ MW $h_{biomass}^{-1}$)
- $c_{j,h,ps}^{pipe}$ annualized costs of investment in transportation pipeline (€ y^{-1})
- c_t^{peak} costs of peak heat production (€ MW h^{-1})
- $c_{j,l}^{plant}$ annualized costs of plant investment (€ y^{-1})
- $c_{j,l}^{prod}$ variable costs of bioenergy production (€ MW $h_{biomass}^{-1}$)
- $c_{i,j,l}^{transb}$ costs of biomass transportation from i to j (€ MW $h_{biomass}^{-1}$)
- $c_{j,k,c}^{transc}$ costs of transporting commodity from j to k (€ MW h^{-1})
- $cplant_l^{ref}$ reference plant investment costs (€)
- $d_{k,d}$ energy demand (MW h y^{-1})
- e error term (–)
- e_l^{ccs} carbon capture rate in plant (tCO_2 MW $h_{biomass}^{-1}$)
- e_c^{fossil} CO_2 emission factor of fossil fuels (tCO_2 MW h^{-1})
- e_h^{local} CO_2 emission factor of local heat production (tCO_2 MW h^{-1})
- $e_{h,t}^{peak}$ CO_2 emission factor of peak heat production (tCO_2 MW h^{-1})
- $e_{i,j}^{trans}$ CO_2 emission factor of biomass transportation from i to j (tCO_2 MW $h_{biomass}^{-1}$)
- $e_{j,k,c}^{trans}$ CO_2 emission factor of commodity transportation (tCO_2 MW h^{-1})
- lo_m lower bound of plausible range of parameters (depending on parameter)
- n number of runs in Monte-Carlo simulation (–)
- OM operation and management costs (% of investment costs)
- par_m input parameter vector (depending on parameter)
- $q_{h,t}^D$ heat demand in settlement (MW h $season^{-1}$)
- $q_{h,ns,t}^D$ heat demand in district heating network (MW h $season^{-1}$)
- $q_{ps,t}^{pipe}$ capacity of heat transportation pipeline (MW h $season^{-1}$)
- s annuity factor (–)
- sf scaling factor (–)
- $size_{j,l}$ plant size ($MW_{biomass}$)
- $size_l^{ref}$ reference plant size ($MW_{biomass}$)
- Δt_t relative length of a season (–)
- up_m upper bound of plausible range of parameters (depending on parameter)

Subscripts

- c energy commodity (–)
- d energy demand for useful energy (–)
- h settlement (–)
- i biomass supply site (–)
- j plant location (–)
- k demand region (–)
- l technology (–)
- m input parameter (–)
- ns district heating network size (–)
- ps pipeline size (–)
- t season (–)

storage (CCS) is chosen for the power production sector. Such plants produce power more efficiently than steam engines [9,10]. Carbon capture and storage is an emerging low carbon technology and one of the view options that allows achieving negative CO_2 emissions [11] which may be necessary to manage climate risk appropriately [12]. It is therefore also included in our analysis. Forest wood is currently not used as feedstock for fuel production in the transportation sector. However, so called second generation technology allows converting woody biomass into fuels. Biofuels as ethanol, Fischer Tropsch (FT) diesel, DME or methanol can be produced by such technologies [13]. Hydrolysis and subsequent fermentation is identified to be the best available ethanol process technology according to the techno-economic efficiency [14]. Gasification of biomass allows producing FT diesel, DME and methanol [15]. However, from those conversion technologies, the methanol process is identified as the least cost option for CO_2 reductions [16,17]. We selected therefore ethanol production through hydrolysis and methanol production through gasification as CO_2 reduction options in the transportation sector. Biomass transportation costs as well as energy distribution costs have significant impact on the final cost of a bioenergy supply chain [18,19]. Particularly, district heating (DH) may induce high infrastructure costs depending on the spatial densities of heat demand. The spatial variability of energy demand is high in Austria [20], which significantly impacts distribution costs. The different technologies and plants considered in the analysis produce a wide set of commodities which have to be transported by various means (e.g. pipelines, truck transportation) to consumers. The relative competitiveness of a

ARTICLE IN PRESS

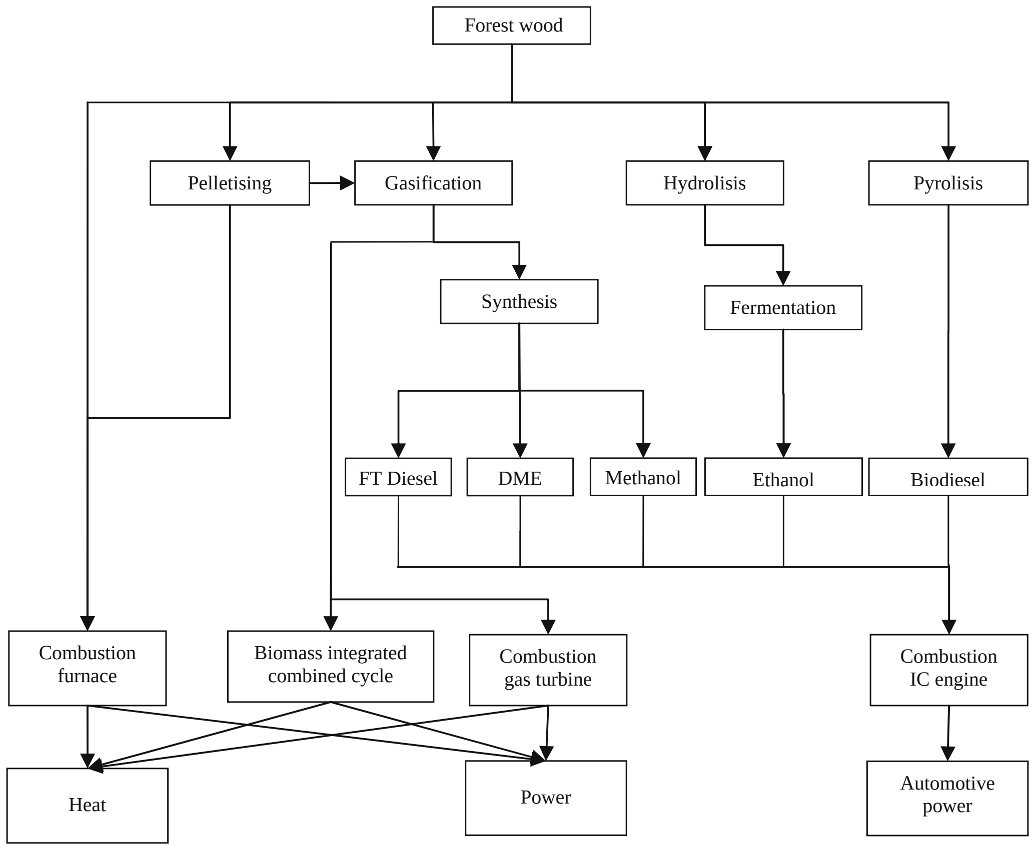

Fig. 1. Energy conversion routes for forest wood [15,63].

conversion technology also depends on the spatial distribution of consumers and costs arising from distribution of final products. Consequently, spatially explicit modeling is necessary in assessing the competiveness and CO_2 reduction potentials of alternative conversion technologies.

There are several studies that have assessed the techno-economic performance of emerging bioenergy technologies based on woody biomass [14,15,17,20–31]. Table 1 lists which technologies were assessed by which methodologies and if spatial explicit modeling has been used in the studies. Only a few models consider spatial factors in their analysis. Most of them are limited to assessing a single technology. For instance, [30] has applied a GIS analysis to compare BIGCC and pellets production. A large set of technologies has been assessed by the two models presented in [28]. Both are global energy models and do not consider specific details of the technologies as well as spatial factors therefore. Bioenergy systems with carbon capture and storage (BECS) are not included in their analysis. A detailed technical study on new bioenergy technologies can be found in [17]. A wide range of technologies, including DME, methanol and ethanol production as well as pellets production in stand alone plants and in energy combines and BIGCC are assessed within that study. Demand restrictions are only discussed but formally not considered in modeling CO_2 emission reductions and costs of technologies. Spatial factors of any kind are not explicitly included in the assessment and BECS is not considered. However, spatial factors are fundamental in analyzing and comparing different conversion technologies. We apply a spatially explicit mixed integer programming (MIP) model to assess different conversion technologies by optimizing the supply chains as well as the location of bioenergy facilities at least cost. It is therefore possible to assess the relative competitiveness of alternative technologies and to seek least cost plant locations in Austria. Many of the technological input parameters are highly uncertain, because some of the technologies are currently not available on the market. Additionally, prices of fossils fuels are highly volatile. They, however, determine mainly the competitiveness of the bioenergy technologies. Monte-Carlo simulations are used to account for model parameter uncertainties. An extended sensitivity analysis allows identifying the model parameters which have the highest impact on results and contribute most to uncertainty.

The article is structured as follows: system boundaries, technologies and other model parameters are briefly discussed in Sections 2.1–2.6. The optimization model and the use of Monte-Carlo simulations to deal with model parameter uncertainty are presented in Sections 2.7–2.9. Section 3 reports on results including optimal locations, scenario and sensitivity outcomes. Section 4 closes the article with a discussion of results and conclusions. The appendix contains details on the model, determination of optimal plant sizes, sensitivity analysis and model validation.

2. Methods and materials

2.1. System boundaries, assumptions and limitations

We apply a static, spatially explicit MIP model to assess the relative competitiveness of bioenergy conversion technologies in Austria. The model includes the full supply chain of bioenergy production from wood harvests to final energy distribution. Bioenergy conversion technologies in the transportation, heating and electricity sectors are modeled explicitly. Forest wood serves as feedstock. Biomass supply and energy demand are limited to domestic Austria only, therefore, imports and exports of biomass and bioenergy products are not accounted for. It is assumed that newly built bio-

Please cite this article in press as: Schmidt J et al. Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. Appl Energy (2009), doi:10.1016/j.apenergy.2009.11.007

Table 1
List of publications on new bioenergy technologies for woody biomass.

Paper	Technologies considered	Methodology	Spatially explicit
[20]	BIGCC	MIP	Yes
[21,22]	Methanol	MIP	Yes
[23]	Methanol	Calculation of production potentials and CO_2 emission reductions (no economic assessment)	No
[31]	Ethanol	MIP	Yes
[24,25,26]	CCS with pulp and paper mills	Calculation of total costs and emission reductions	No
[27]	CCS with ethanol	Calculation of total costs and emission reductions	No
[15]	Co-combustion, BIGCC, fuel wood, Fischer Tropsch biodiesel, ethanol	System perburtation analysis (no economic analysis)	No
[28]	BIGCC, methanol, ethanol	Linear program	No
[29]	Ethanol, bio-oil, BIGCC	Comparative cost calculations	No
[30]	BIGCC, pellets	GIS	Yes
[14]	Ethanol through hydrolysis, ethanol through gasification	Comparative cost calculations	No
[17]	Ethanol, methanol, DME, pellets, BIGCC	Comparative cost and emission reduction calculations	No

energy plants replace fossil fuels in each of the sectors. The CO_2 emission baseline for each sector consists of the technologies and fuels currently in use in Austria. The model does not consider effects of wood harvests on the forest CO_2 cycle but assumes that wood production is organized CO_2 neutral, i.e. forests sequestrate amounts of the CO_2 released by burning of previously harvested biomass. However, CO_2 emissions from biomass transportation are considered in the model. A stochastic approach is used to model varying prices and demand levels. The next sections report details on bioenergy technologies, model input parameters, CO_2 emission baseline assumptions, the optimization model and how we assess uncertainty. The model input parameters including technical plant characteristics are reported in Table 2. Details on the validation of the model can be found in Appendix A.

2.2. Technologies

2.2.1. Biofuel integrated gasification combined cycle (BIGCC)

In biomass combined heat and power (CHP) plants, a steam engine is operated with evaporated water that is produced by burning biomass. The technology is well known and plants of varying sizes are installed in Austria [4]. However, the power to heat ratio is low: the total conversion efficiency for power reaches about 30% [10]. Gasification of biomass in an integrated combined cycle plant allows reaching efficiencies that are significantly higher than in plants with steam engines. The power efficiency goes up to 43%. However, no commercial plants have been installed yet [9]. Installation costs are high and plants have to be sized bigger than steam engines to be economically competitive [9]. In this article, a pressurized BIGCC plant is assessed as it is expected to have the best power to heat ratio of all gasification technologies [9,10].

2.2.2. Bioenergy system with carbon capture and storage (BECS)

CCS allows decreasing the release rate of CO_2 of fossil fuelled power plants. CO_2 is captured either before or after combustion and then transported to permanent storages. BECS combines this technology with biomass fired CHP plants. This way, CO_2 is removed from the atmosphere: CO_2 is sequestrated in tree growth and released in the energy production process where it is captured and permanently stored. A transfer of atmospheric CO_2 to the permanent storage is therefore possible [11,32,33].

The captured CO_2 is transported by pipelines or ships to the final deposits which may be oil, gas or coal fields, deep saline aquifers or oceans. Costs for CCS arise mainly from transportation and compression of the CO_2. Gas and oil fields are low cost storages because the injected CO_2 can be used to increase the total depletion of the fields. Risks are associated with all possible deposits: CO_2 may leak slowly or suddenly from the deposits [34,35] and thus either decrease the utility of CCS or even pose a risk to life. In the case of CO_2 storage in deep oceans, marine eco-systems may be affected negatively [36]. This article assesses BECS in combination with BIGCC.

2.2.3. Transportation fuel production

Second generation transportation fuel production from woody biomass increases per hectare yields of fuel in comparison to first generation fuels which are mainly produced from agricultural crop grains [37]. However, second generations biofuels are not yet fully available on a commercial level. Two conversion technologies are considered in this article: (i) enzymatic hydrolysis of biomass with subsequent fermentation to ethanol and (ii) gasification of biomass with subsequent reforming to methanol.

2.2.3.1. Ethanol from ligno cellulose. The fuel characteristics of ethanol are very similar to fossil gasoline. Up to 10% of ethanol can be blended with fossil gasoline without the need to modify car engines [37]. In the production process, biomass is first pre-treated for the hydrolysis of (hemi)cellulose. The sugars from hydrolysis are fermented to ethanol. Lignin is a residual of the process and is burnt in a CHP plant to produce heat and power for the ethanol production process. Depending on the quantity of lignin contained in the biomass, surplus production of power is possible. A detailed description of the process can be found in Piccolo [14] and Hamelinck [38]. The theoretical conversion efficiency for ethanol is limited to about 52%, current pre-commercial installations are however far from reaching these fuel yields. Costs for raw materials and plant investments are high and depend on the processing technology [14,38].

2.2.3.2. Methanol through gasification. Methanol can be used as transportation fuel by blending it with gasoline. Mixtures of up to 85% methanol and 15% gasoline are possible, requiring minor modifications of car engines [22]. In the production process, the biomass is first gasified. Subsequently, the gas is cleaned and higher hydrocarbons are created through gas reformation. Shift reactions and gas separation then produce the methanol. Production in very large facilities is necessary to make the production process competitive [21]. Theoretical conversion efficiencies reach up to 70%, which are, however, not reached in current pre-commercial installations [39]. District heating networks can be fed with surplus heat from the production process [21].

2.2.4. Pellets

Wood pellets are made of dry wood stock and are small, cylindrical objects [7]. They have an average higher heating value (HHV) of 18.5 GJ t^{-1} [40]. Transport as well as storage of pellets is cheaper

Table 2
List and ranges of model parameters as well as method of data generation.

Nmb	Parameter name		Variable name	Unit	Minimum lo_m	Maximum up_m	Method[a]	Sources
Prices								
1	Power		c_c^{fossil}	€ MW h^{-1}	29.09	73.80	B	[56]
2	Heating oil		c_c^{fossil}	€ MW h^{-1}	22.18	66.74	B	[55]
3	Gasoline		c_c^{fossil}	€ MW h^{-1}	27.34	44.70	B	[55]
–	CO_2 price		c_c^{fossil}	€ tCO_2^{-1}	Scenarios: 0, 25, 50, 75, 100 € tCO_2^{-1}			–
Investment costs for plants (100 MW size)								
4	BIGCC		$c_{j,l}^{plant}$	Million €	62.61	70.22	ND	[9,10,33]
5	BECS[b]		$c_{j,l}^{plant}$	Million €	4.48	11.15	ND	[32,33,64]
6	Ethanol		$c_{j,l}^{plant}$	Million €	83.75	107.56	ND	[14,38]
7	Methanol		$c_{j,l}^{plant}$	Million €	82.73	111.93	ND	[39]
8	Pellets[c]		$c_{j,l}^{plant}$	Million €	9.22	10.77	ND	[41,65]
Variable production costs[d]								
9	BIGCC		$c_{j,l}^{prod}$	€ MW $h_{biomass}^{-1}$	1.85	6.43	ND	[9,10,33]
10	BECS[e]		$c_{j,l}^{prod}$	€ MW $h_{biomass}^{-1}$	1.85	6.43	ND	[9,10,33]
11	Ethanol		$c_{j,l}^{prod}$	€ MW $h_{biomass}^{-1}$	6.16	10.00	ND	[14,38]
12	Methanol		$c_{j,l}^{prod}$	€ MW $h_{biomass}^{-1}$	1.77	2.40	ND	[39]
13	Pellets		$c_{j,l}^{prod}$	€ MW $h_{biomass}^{-1}$	0.94	2.60	ND	[41,65]
Efficiency								
	Commodity	Plant type	$\eta_{j,l,c}^{conv}$	–				
14	Power	BIGCC	$\eta_{j,l,c}^{conv}$	–	0.34	0.43	ND	[9,10,33]
15		BECS	$\eta_{j,l,c}^{conv}$	–	0.25	0.33	ND	[32,33,64]
16		Ethanol	$\eta_{j,l,c}^{conv}$	–	0.01	0.04	ND	[14,38]
17		Pellets	$\eta_{j,l,c}^{conv}$	–	0.04	0.06	ND	[41,65]
18	Heat	BIGCC	$\eta_{j,l,c}^{conv}$	–	0.43	0.47	ND	[9,10,33]
19		BECS	$\eta_{j,l,c}^{conv}$	–	0.33	0.55	ND	[32,33,64]
20		Methanol	$\eta_{j,l,c}^{conv}$	–	0.05	0.10	ND	[21,51]
21		Pellets	$\eta_{j,l,c}^{conv}$	–	0.02	0.02	ND	[41,65]
22	Ethanol	Ethanol	$\eta_{j,l,c}^{conv}$	–	0.35	0.39	ND	[14,38]
23	Methanol	Methanol	$\eta_{j,l,c}^{conv}$	–	0.54	0.60	ND	[39]
24	Pellets	Pellets		–	0.79	0.84	ND	[41,65]
Other parameters								
25	Costs carbon capture and storage		c^{ccs}	€ tCO_2^{-1}	13.06	41.62	ND	[32,33,64]
26	Connection rate district heating		–	Factor	0.61	0.74	ND	Estimate
27	Transportation costs		$c_{i,j,l}^{transb}$	€ MW $h_{biomass}^{-1}$ km^{-1}	0.03	0.04	ND	[21,66]
28	Local heating costs		c_t^{local}	€ MW h_{heat}^{-1}	72.00	88.00	ND	[20,67]
29	Emission savings BECS		e_l^{ccs}	tMW $h_{biomass}^{-1}$	0.19	0.40	ND	[32,33,64]
30	Biomass supply costs		c_i^{sup}	€ MW h^{-1}	20.08	26.79	B	[47]
31	Amount of biomass supply		–	Factor	0.95	1.05	ND	Estimate
32	DH infrastructure costs		$c_{h,ns}^{dnet}$	Factor	0.50	1.50	ND	[68,69]
33	Efficiency of distributing heat in DH network		$\eta_{h,t}^{dh}$	Factor	0.94	0.99	ND	Estimate
34	CO_2 emissions fossil power		$e_{c,ff}^{f}$	tCO_2MW h_{power}^{-1}	0.54	0.58	ND	[70]

[a] (B)oostrapping, (N)ormal (D)istribution.
[b] Additional to standard CHP costs.
[c] Without CHP unit.
[d] Not including biomass costs.
[e] Without carbon capture and storage costs.

compared to sawdust or traditional fuel wood because of the better HHV. Pellets can be manipulated with compressed air which facilitates the handling of pellets in comparison to other wood based energy products [7]. Pellets can be used either in power or heating plants or in small local boilers to directly heat buildings. Boilers with condensing heating technology allow increasing the energy efficiency significantly above that of traditional fuel wood furnaces. In this study, the use of pellets in heating boilers for single dwellings is assessed.

The production process of pellets starts with the drying of the wood which requires large amounts of heat. The wood is ground and then pressed through a die resulting in the final pellets. This process consumes significant amounts of electricity [41]. The electricity as well as the heat necessary for drying can be produced in a separate CHP unit. A part of the feedstock is burnt in the CHP. Surplus power (heat) can be sent to the power grid (a district heating network) [8]. Such a combined power, heat and pellets production is assessed in the model, assuming that a BIGCC is used for power and heat production.

2.3. Plant investment costs

As the optimization model considers one year of operation, plant investment costs are annualized. Investment costs depend on the plant size. A standard scaling function with a scaling factor ^{sf} of 0.7 [9,39,42] is used to model economies of scale. The annual plant costs $c_{j,l}^{plant}$ for a plant of technology l at location j

include annualized investment costs and operation and management costs. The costs are given by

$$c_{j,l}^{plant} = (s + OM)\left(\frac{size_{j,l}}{size_l^{ref}}\right)^{sf} cplant_l^{ref}, \qquad (1)$$

where s is the annuity factor assuming a lifetime of 25 years and an interest rate of 10%. Parameter OM denotes annual operating and management costs in percent of investment costs. In the scaling function, parameter $size_{j,l}$ is used to model the size of the plant. The reference size for a plant of type l at location j is denoted by $size_l^{ref}$. Parameter $cplant_l^{ref}$ are reference costs of a plant with technology l. There is an upper limit on the size of plants because the equipment cannot be scaled infinitely. Maximum plant sizes are 250 MW for all plant types [9,38]. All economical and technological parameters – which are listed in Table 2 – are chosen to reflect expected technological developments within the next 10 years.

2.4. Forest wood supply

In this analysis domestic forest wood is regarded as feedstock to bioenergy production. Forests cover about 47% of land in Austria. On average, wood harvests are currently lower than the amount that can be sustainably harvested [5]. If forests are managed at the maximum sustainable yield, additional fuel wood is available to supply new bioenergy projects. The spatial distribution of forestry yields is estimated with increment curves from Assman's yield table [43], assuming sustainable forest management, and a net primary production (NPP) map from Running [44]. It is calibrated with the observations from the national forest inventory of Austria [5]. The forest land cover is taken from the Corine Land Cover dataset [45]. An equation system describes the forest increment and mortality per hectare and year depending on yield level, age, and stand density. An NPP map was used to estimate the yield level. The observed increment data from the Austrian national inventory was used to calibrate the transformation from NPP to yield level. The diameter of the harvested wood, which is used in the CHP plants, is below 15 cm. Wood that is additionally available for new bioenergy plants is determined by reducing the total harvest potential by current wood harvests as stated in official statistics [46]. Wood prices have been determined from the energy wood index [47] that reports prices of fuel wood every quarter of a year.

2.5. CO_2 emissions

The model tracks CO_2 emissions from bioenergy production as well as CO_2 emissions from fossil fuel combustions. CO_2 emissions from biomass transportation are also included into the model while it is assumed that CO_2 emissions created from burning biomass are offset by tree growth. This assumption is consistent with the current version of the UNFCC reporting guidelines for the Kyoto protocol that assumes that woody biomass use in energy applications is CO_2 emission neutral [48]. The optimal mix of biomass technologies depends on technologies and products that are chosen as competitors to bioenergy production. We assume that bioenergy power production competes with the current fossil fuel based power production i.e. with the mix of fossil fuels currently used for power production in Austria. This assumption is made because biomass based power production is able to produce base and peak load power similar to fossil fuels. Ethanol and methanol are competing with gasoline as a direct substitute. Pellets replace fossil heating oil in single dwelling buildings because oil boilers are most appropriate to be substituted by wood pellets boilers [7]. District heating substitutes fuels currently used in the settlements. The CO_2 emission factor for a settlement is determined by weighting CO_2 emission factors of fuels with the amount of the respective fuel that is used in the settlement.

Table 3
CO_2 emission reductions in tCO_2 $MW\,h_{biomass}^{-1}$ relative to heating oil (pellets), to the Austrian fossil fuel mix in power production (BIGCC and BECS) and fossil gasoline (ethanol and methanol). Lower (upper) bounds assume the lower (upper) bound of conversion efficiencies given in Table 1 and 0% (100%) usage rate of surplus heat for district heating. Sources: Table 1, [2], own calculations.

	Pellets	BIGCC	BECS	Ethanol	Methanol
Lower bound	0.26	0.23	0.33	0.10	0.14
Upper bound	0.28	0.37	0.76	0.12	0.19

Estimations of CO_2 emission reductions per $TWh_{biomass}$ for the different technologies – regarding the chosen reference technologies – are listed in Table 3. Those values are given for illustration only and show theoretical lower and upper bounds of CO_2 emission reductions. The figures in row "Upper bound" represent conversion efficiencies (and rates of carbon storage for BECS) that are equal to the upper bound of the parameters in Table 2. The use of surplus heat for district heating is assumed to reach 100%. The figures in row "Lower bound" represent the lowest possible conversion efficiency assuming a surplus heat utilization of 0%. The table shows that ethanol production reduces fewer CO_2 emissions than any other technology, regardless if upper or lower bounds are considered.

2.6. Energy demand

Heating demand is estimated spatially explicit with a bottom up model that combines average consumption values with private dwelling areas and with the number of employees for commercial buildings and industrial applications. Heating demand is differentiated by fuels. The bottom up model is validated with national consumption values for heating fuels. Heating demand is estimated in cells of 1 km^2 size for whole Austria. The costs of the district heating infrastructure are determined by applying an exponential cost function that depends on heat demand density. Cells where the costs for district heating infrastructure of consumed heat are higher than the costs of the competing fossil heating technology are not included in the optimization model. Therefore, the model complexity can be reduced without loosing accuracy of results, because cells where the district heating infrastructure alone is more costly than total heat generation costs of competing technologies will not be selected in the optimization model. The demand for heat in non-district heating areas is determined by dwellings that are currently heated by oil boilers. Pellets use is restricted to single-dwellings buildings [7]. The detailed description of the heating demand model can be found in [20]. Transportation fuel consumption is estimated based on the spatial distribution of the population, which is combined with the average gasoline consumption per capita in the year 2006 [49].

2.7. The optimization model

A MIP model, that builds on previous work published in [20–22,31,50–52] is used to minimize the costs for supplying demand regions (index k) with different forms of energy products (index d) from either biomass plants or fossil fuels. Biomass is transported from supply regions (index i) to possible plant locations (index j) where different conversion technologies (index l) may be employed to produce different commodities (index c). Ethanol, methanol and pellets are transported to the demand regions by truck. Power is directly distributed to the power grid, while heat is delivered to the settlements (index h) using pipelines of different sizes (index ps). District heating networks of different sizes (index ns)

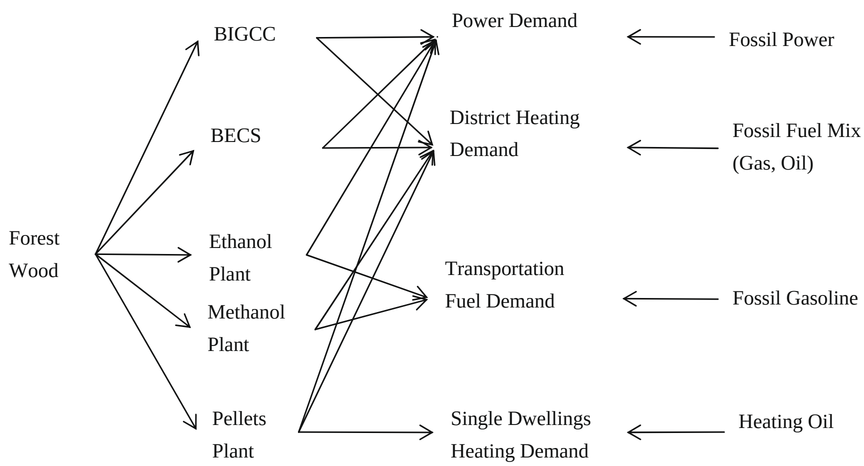

Fig. 2. Diagram of the mixed integer programming model.

have to be built in the settlements to allow heat distribution. Bioenergy competes with fossil fuels. Fig. 2 shows the overall scheme of the model. It is static and models 1 year of operation. All investment costs are annualized assuming an interest rate of 10% and 25 years of economical lifetime. Heating seasons (index t) are used to differentiate between seasonal heating demands.

The total costs in the objective function $f(b,z,q,u)$ are minimized:

$$f(b,z,q,u) = \sum_{i,j,l}\left(c_i^{sup} + c_{i,j,l}^{transb} + c_{j,l}^{prod} + e_l^{ccs}c^{ccs}\right)b_{i,j,l} + \sum_{j,l} c_{j,l}^{plant}u_{j,l}^{plant} + \sum_{j,k,c}\left(c_{j,k,c}^{transc} + c_c^{inv}\right)z_{j,k,c}^{bio} + \sum_{k,c} c_c^{fossil}z_{k,c}^{fossil} + \sum_{j,h,ps} c_{j,h,ps}^{pipe}u_{j,h,ps}^{pipe} + \sum_{h,ns} c_{h,ns}^{dnet}u_{h,ns}^{dnet} + \sum_{h,t} c_t^{peak}q_{h,t}^{peak} + \sum_{h,t} c_t^{local}q_{h,t}^{local} + c^{em}totem \quad (2)$$

where

$$totem = \sum_{i,j,l} e_{i,j}^{trans}b_{i,j,l} + \sum_{j,k,c} e_{j,k,c}^{trans}z_{j,k,c} + \sum_{k,c} e_c^{fossil}z_{k,c}^{fossil} + \sum_{h,t} e_h^{local}q_{h,t}^{local} + \sum_{h,t} e_{h,t}^{peak}q_{h,t}^{peak} - \sum_{i,j,l} e_l^{ccs}b_{i,j,l} \quad (3)$$

The different summands in the objective function represent:

1. Biomass supply costs (parameter c_i^{sup}), biomass transportation costs (parameter $c_{i,j,l}^{transb}$), bioenergy production costs (parameter $c_{j,l}^{prod}$) and carbon capture and storage costs (parameter c^{ccs} times the amount of CO_2 emissions captured by unit of biomass e_l^{ccs}) times the amount of biomass (variable $b_{i,j,l}$).
2. Annualized costs of plant investments (parameter $c_{j,l}^{plant}$) times the binary variable for plant selection ($u_{j,l}^{plant}$).
3. Costs for transporting energy commodities to demand regions (parameter $c_{j,k,c}^{transc}$) plus investment costs (parameter c_c^{inv}) times the amount of commodities (variable $z_{j,k,c}^{bio}$). Costs for power transportation and investment are zero as it is assumed that the power can be sold directly to the power grid. For ethanol, methanol and pellets, transportation costs from plants to demand regions by truck are considered. Investment costs c_c^{inv} are zero for biofuels, because no additional investments are necessary to operate cars with ethanol or methanol. For pellets, the investment costs represent the average difference between a pellets boiler and an oil boiler per unit of useful energy produced.
4. Costs for fossil fuels (parameter c_c^{fossil}) times the amount of fossil fuels used in a demand region (variable $z_{k,c}^{fossil}$).
5. Annualized costs of building a pipeline from the plant to the settlement (parameter $c_{j,h,ps}^{pipe}$) times the binary variable for pipeline selection ($u_{j,h,ps}^{pipe}$).
6. Annualized costs for installing a district heating network in the settlement (parameter $c_{h,ns}^{dnet}$) times the binary variable for district heating network selection ($u_{h,ns}^{dnet}$).
7. Costs for producing peak heat (parameter c_t^{peak}) for district heating times the amount of peak heat (variable $q_{h,t}^{peak}$) produced.
8. Costs for producing local heat including investment and fuel costs (parameter c_t^{local}) times the amount of local heat (variable $q_{h,t}^{local}$) produced.
9. Total CO_2 emissions ($totem$) which consist of: (i) CO_2 emissions of biomass transportation (CO_2 emission factor $e_{i,j}^{trans}$), (ii) CO_2 emissions of commodity transportation (CO_2 emission factor $e_{j,k,c}^{trans}$), (iii) CO_2 emissions of fossil energy production (CO_2 emission factor e_c^{fossil}), (iv) CO_2 emissions of local heating systems (CO_2 emission factor e_h^{local}), (v) CO_2 emissions of peak heat production (CO_2 emission factor $e_{h,t}^{peak}$), and (vi) CO_2 emission savings by BECS in bioenergy production (CO_2 emission factor e_l^{ccs}). Total CO_2 emissions ($totem$) are multiplied by the CO_2 price (parameter c^{em}).

The objective function in Eq. (2) is minimized subject to the following constraints. Biomass utilization (variable $b_{i,j,l}$) in the plants is restricted by

$$\sum_{j,l} b_{i,j,l} \leqslant \bar{b}_i^{sup}, \quad (4)$$

where parameter $\bar{b}_i^{sup}$ denotes the total amount of biomass available in supply region i.

The plant size constraints the production by

$$\sum_i b_{i,j,l} \leqslant \bar{b}_{j,l}u_{j,l}^{plant}, \quad (5)$$

where parameter $\bar{b}_{j,l}$ is the production capacity of plant j using technology l. The commodity production (variable $z_{j,c}^{bio}$) is determined by the biomass input and conversion efficiency (parameter $\eta_{j,l,c}^{conv}$) shown in the following equation:

$$\sum_{i,l} \eta_{j,l,c}^{conv}b_{i,j,l} = z_{j,c}^{bio}. \quad (6)$$

District heat production is modeled with variable q_j^{bio} because it is distributed differently than the other commodities:

$$\sum_{i,l} \eta^{heat}_{j,l} b_{i,j,l} = q^{bio}_j, \tag{7}$$

where $\eta^{heat}_{j,l}$ is the conversion efficiency for heat. Distribution of commodities to demand regions k is restricted by

$$\sum_k z^{bio}_{j,k,c} \leqslant z^{bio}_{j,c}, \tag{8}$$

where variable $z^{bio}_{j,k,c}$ denotes the amount of a commodity c transported from plant location j to demand region k.

Energy demands (parameter $d_{k,d}$) are satisfied by different commodities from bioenergy production (variable $z^{bio}_{j,k,c}$) and by fossil fuels (variable $z^{fossil}_{k,c}$):

$$\sum_{j,c} \eta^{bio}_{c,d} z^{bio}_{j,k,c} + \sum_c \eta^{fossil}_{c,d} z^{fossil}_{k,c} = d_{k,d}. \tag{9}$$

In the equation, parameter $\eta^{bio}_{c,d}$ ($\eta^{fossil}_{c,d}$) describes the efficiency of converting bioenergy commodities (a fossil fuel) to forms of useful energy.

The part of the model handling the usage of surplus heat for district heating and the district heating infrastructure can be found in Appendix B.

The MIP is finally defined as:

$$\begin{aligned} &\min[f(b,z,q,u)] \\ &s.t. \\ &(2)-(9), (B.1)-(B.5) \\ &0 \leqslant b_{i,j,l}, z^{bio}_{j,c}, z^{bio}_{j,k,c}, z^{fossil}_{k,c}, q^{bio}_j, q^{peak}_{h,t}, q^{dh}_{j,h,ps,t}, q^{local}_{h,t} \\ &u^{dnet}_{h,ns}, u^{pipe}_{j,h,ps}, u^{plant}_{j,l} \in \{0,1\}. \end{aligned} \tag{10}$$

2.8. A pre-selection of plant size and plant locations

As the model size grows exponentially with the number of possible plant locations (index j), the model is limited with respect to its spatial resolution. The plant size has also significant effect on total costs [21]. Therefore, a three-step approach is performed to pre-select likely plant locations and plant sizes in Austria:

(1) A set of likely locations is identified which is suitable for bioenergy production using results of previous studies [20,21]. The model is solved separately for each technology with alternative plant sizes ranging from 50 $MW_{biomass}$ to 250 $MW_{biomass}$, varying plant investment costs according to the scaling function in Section 2.3. As some of the parameters are uncertain, the model is run 1000 times with varying parameter values (see Section 2.9). Then a surface response function is estimated and the first derivate of that function is taken to determine the optimal plant size (see Appendix C for details).
(2) The model is again run 1000 times separately for each technology, using the previously determined plant size. If a location has been selected it is used for the subsequent analysis. This reduces the total number of possible locations from 60 to around 15, depending on the technology.
(3) The pre-selected locations are used in the complete model with all technologies.

2.9. Sensitivity and uncertainty analysis

We assess technologies which are currently not available on the market. Uncertainties related to investment and operation costs are therefore high. Additionally, energy prices are also volatile. Uncertainties in model parameters are considered by applying Monte-Carlo simulations, following the approach in [53]. Probability distributions (i.e. normal) are assumed for uncertain input parameters (index m). Then, n different input parameter sets are built and the simulation is run n times, thus providing n different results. The results are statistically analyzed to test the influence of model parameters on output (sensitivity) and determine which parameters contribute most to model uncertainty (uncertainty analysis).

A literature review provides upper (up_m) and lower (lo_m) bounds for investment and production costs as well as for technological parameters of bioenergy plants, transportation costs, district heating infrastructure costs, biomass availability, biomass costs, and CO_2 emission factors. It is assumed that the parameters are randomly distributed, following a normal distribution with parameters $\mu = (up_m + lo_m)/2$ and $\sigma = (\mu - lo_m)/1.96$. Input parameters are randomly drawn from the distribution, values lower than lo_m or higher than up_m are removed. A different method is used to capture volatile energy prices because these are generally correlated [54]. Energy prices are determined by using a database of prices for heating oil, gasoline [55], power prices [56] and fire wood [47] between January 2003 and December 2008. A bootstrapping process [57] is applied to determine the values of the different parameters for the Monte-Carlo simulation. Prices are determined by randomly choosing one of the 24 quarters in the statistical database. The prices of fossil fuels, biomass and power are set to the value of that quarter. Table 2 shows all stochastically modeled parameters and the corresponding range of values. All prices and costs are given in $€_{2008}$.

3. Results

3.1. Optimal plant sizes and optimal locations

The optimal sizes of BIGCC, methanol and ethanol plants are found to be 250 MW which is the maximum allowed in the model. The impact of economies of scale is therefore more important to total production costs than biomass transportation costs. A size of 180 MW is found to be optimal for pellets plants. Regarding the optimal plant locations, the model results (Fig. 3) show clearly that BIGCC plants are clustered around bigger cities while fuel and pellets plants are more evenly distributed over the country. Cities like Vienna and Graz are main locations for BIGCC and BECS plants. A reason is that heat production of BIGCC is ten times higher than of pellets and fuel plants. Proximity to main heat consumers such as big cities is therefore important for BIGCC and BECS plants. Consequently, biomass needs to be transported over longer distances. The transportation of fuels and pellets by truck does not influence the choice of locations much. Therefore, pellets and fuel plants are positioned closer to biomass resources.

3.2. Technological mixes and CO_2 emission reductions

CO_2 emission reductions and technological mixes depend mainly on the CO_2 price. This section presents least cost technological mixes and CO_2 emissions for five different CO_2 prices (0, 25, 50, 75, 100 € tCO_2^{-1}). The upper limit of 100 € tCO_2^{-1} is chosen because the European Emission Trading Scheme introduces a penalty of that amount for participants that have not bought sufficient number of allowances on the market. This penalty can therefore be considered as upper limit on the CO_2 price. Fig. 4 presents the technological mix under the influence of alternative CO_2 prices. Table 4 reports the share of biomass utilization of the technologies with confidence intervals. Pellets production is the predominant technology in each scenario while fuel production is not selected in any of the CO_2 price scenarios. Fuel conversion technologies are inferior with regard to cost-efficient CO_2 emission reductions

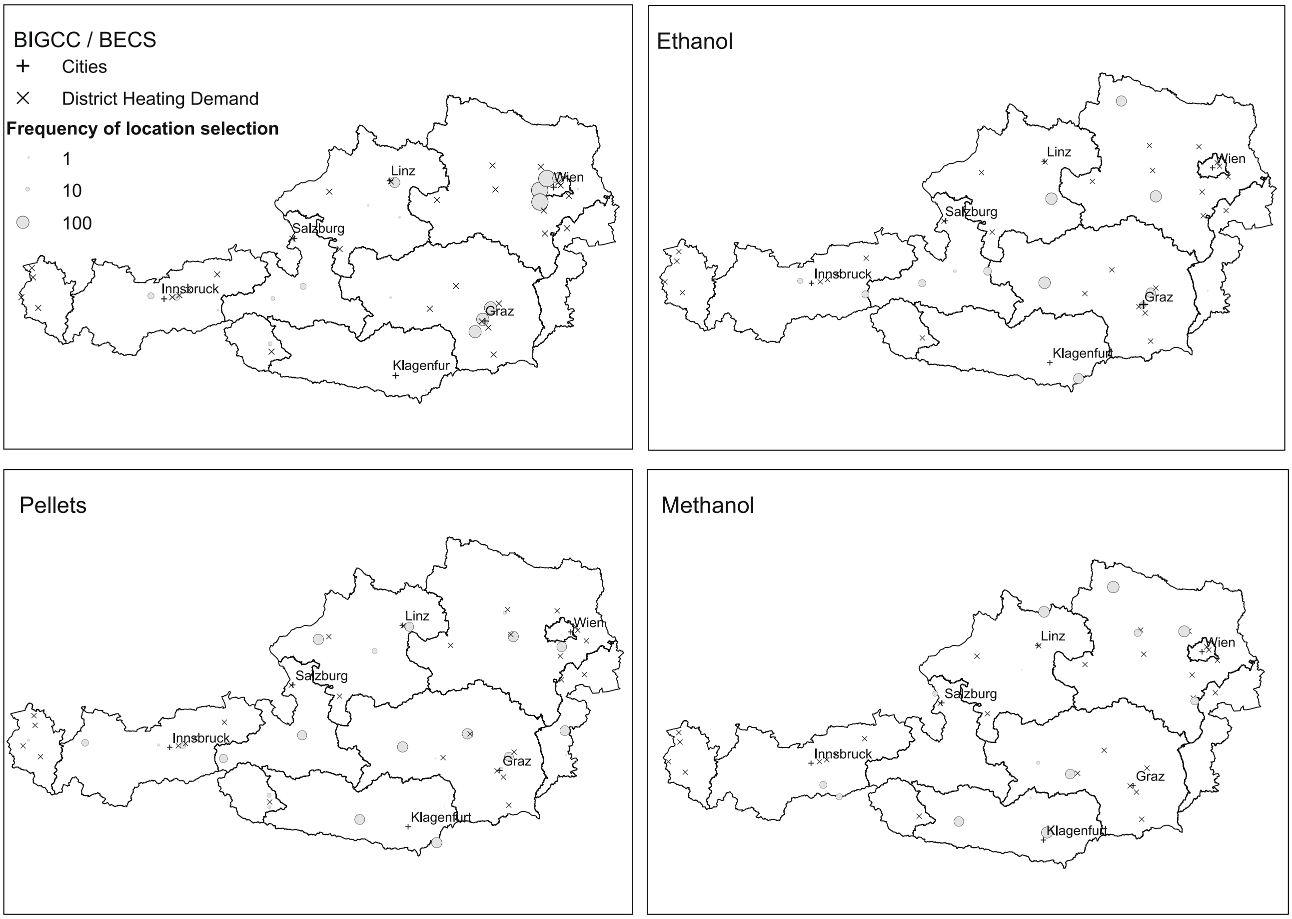

Fig. 3. Optimal locations of bioenergy plants.

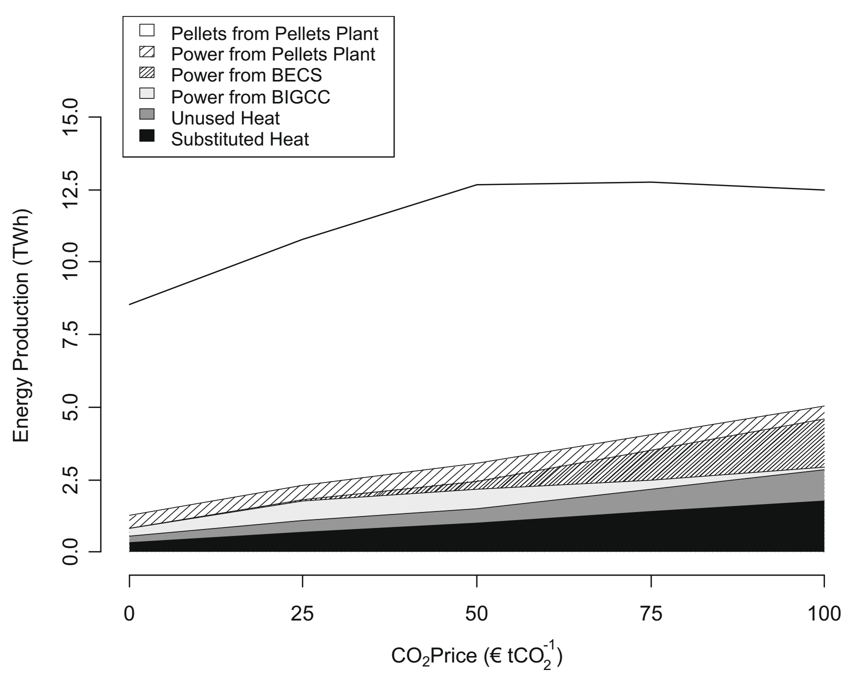

Fig. 4. Energy production and technology mixes for alternative CO_2 prices.

because conversion efficiencies and CO_2 emissions savings are low relative to the other technologies and investment costs are comparably high. BIGCC is economically viable for lower CO_2 prices. Locations with large and concentrated amounts of heat demand make

Table 4
Mean and confidence intervals of biomass utilization per technology at different CO_2 prices in percent. Note: *L* and *U* denote the lower and upper bound of the 99% confidence interval of the mean.

CO_2 price (€ tCO_2^{-1})	BIGCC biomass use (% of total biomass)			BECS biomass use (% of total biomass)			Pellets biomass use (% of total biomass)		
	Mean	*L*	*U*	Mean	*L*	*U*	Mean	*L*	*U*
0	10	5	14	0	0	0	90	81	99
25	21	14	28	1	0	2	77	70	85
50	12	8	15	6	3	9	82	78	86
75	5	2	7	23	19	28	72	67	76
100	1	0	2	38	32	44	61	55	67

BIGCC competitive to pellets production. BECS utilization starts at around 50 € tCO_2^{-1} and is increasing with the CO_2 price. At 100 € tCO_2^{-1}, about 38% of biomass is used for BECS. At low CO_2 prices, only part of the available biomass (64% for 0 € tCO_2^{-1} and 81% for 25 € tCO_2^{-1}) is utilized for bioenergy production. At 50 € tCO_2^{-1}, almost all available forest biomass (96.30%) is used to produce bioenergy.

CO_2 emission reductions (*esav*) in each of the scenarios are determined by the following equation:

$$esav = \left(\sum_{k,c,d} e_c^{fossil} z_{k,c}^{fossil} d_{k,d} \frac{1}{\eta_d^{fossil}} + \sum_{h,t} e_h^{local} q_{h,t}^{D} \frac{1}{\eta_{h,t}^{local}} \right) - totem \qquad (11)$$

Fig. 5 shows the CO_2 emission reductions and the amount of fossil fuels that are substituted in the five scenarios. At a CO_2 price of 0 € tCO_2^{-1}, annual CO_2 emission reductions of 2.71 $MtCO_2\ y^{-1}$ are achieved. This amounts to around 3% of total Austrian CO_2 emissions. At a price of 100 € tCO_2^{-1}, this sum goes up to 5.64 $MtCO_2\ y^{-1}$ (6.27% of total CO_2 emissions in Austria). A significant contribution to Austrian climate targets can thus be achieved through using bioenergy. However, there is a tradeoff between fossil fuel substitution and CO_2 emission savings: at high CO_2 prices – when BECS utilization is increased – less fossil fuels are substituted due to the lower conversion efficiencies of BECS (Fig. 5).

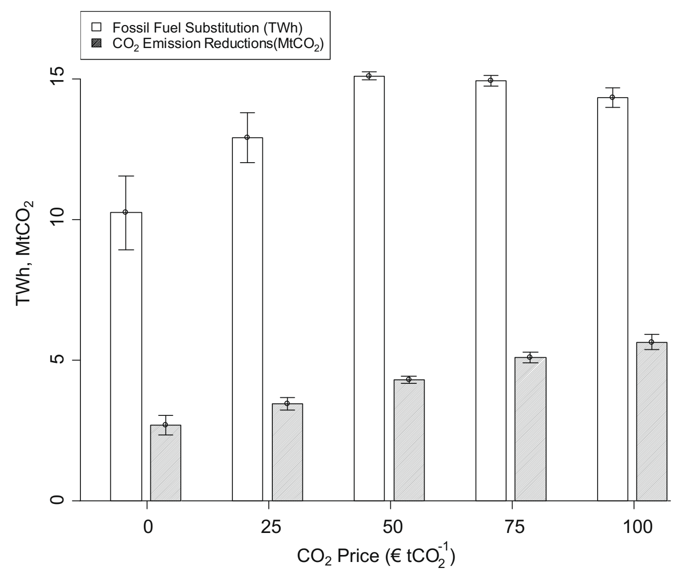

Fig. 5. Mean of CO_2 emission reductions (grey bars, in $MtCO_2$) and fossil fuel substitution (white bars, in TWh) at alternative CO_2 prices. Note: the intervals indicate the 99% confidence interval of the mean.

3.3. Sensitivity and uncertainty analysis

The sensitivity of model results to changes in input parameters and the contribution of single parameters to model uncertainty are discussed in this section. Each of the five CO_2 price scenarios is analyzed separately. Elasticities are estimated to measure the percentage change of model outputs on percentage change of model input parameters. The estimation process involves determining a response surface by means of linear regression and subsequent numerical calculation of the elasticities. The procedure is outlined in Appendix D. If the uncertainty of the distribution of a parameter is low, a high elasticity does not necessarily imply that the parameter contributes a lot to the uncertainty of the model. To estimate the contribution of a parameter to model uncertainty, an error measure is calculated from the response surface following [53]. The mean absolute percentage error (MAPE) was calculated in [53] as error measure. MAPE was criticized as it puts high penalties on errors if the actual value is very low [58]. The median absolute percentage error (MdAPE) protects against such outliers [59] and is therefore used in this study.

The results of the sensitivity and uncertainty analysis of two scenarios are discussed in detail as they are of special interest: the first one, 25 € tCO_2^{-1} represents a price that is close to the mean market price at the European Energy Exchange. The second one, 75 € tCO_2^{-1}, is the lowest CO_2 price that allows BECS production. The means of elasticities from Monte-Carlo simulations are plotted against the uncertainty of the parameter measured as MdAPE in Fig. 6. Only model parameters that are significant in the regression analysis on the 90% level are shown. The numbers in the figure are a reference to column 1 in Table 2 where all stochastically modeled parameters are listed. At 25 € tCO_2^{-1}, the efficiency of converting wood to pellets (24) is elastic and positively related to CO_2 emission reductions. The availability of biomass (31), biomass costs (30), the oil price (2), the efficiency of BIGCC plants (14) and the power price (1) are inelastic and positively related with CO_2 emission reductions. A negative, inelastic relationship exists between the costs of district heating infrastructure (32) and variable costs for BIGCC plants (9). While most of the results are as expected, it is not immediately intuitively clear that biomass costs are positively correlated with CO_2 emission reductions, i.e. that an increase in biomass costs causes an increase in bioenergy production. This is a result of the bootstrapping mechanism. Increases in biomass costs are positively correlated with increases in power and fossil fuel costs in the price data. However, relative biomass cost increases are lower than increases in energy prices. This allows for additional production of bioenergy because higher energy prices more than compensate the increase in feedstock prices. The oil price (2) and biomass costs (30) contribute most to model uncertainty.

BECS parameters, i.e. efficiency of power and heat production in BECS plants (15 and 19), the costs (25) and the efficiency (29) of carbon capture and storage are relevant parameters in the 75 € tCO_2^{-1} scenario. There are also minor changes regarding pellets parameters. The efficiency of pellets production (24) is not significant in this scenario while the variable costs (13) and the efficiency of power production (17) in pellets plants are significant. However, the elasticity as well as uncertainty of the parameters is very low. It

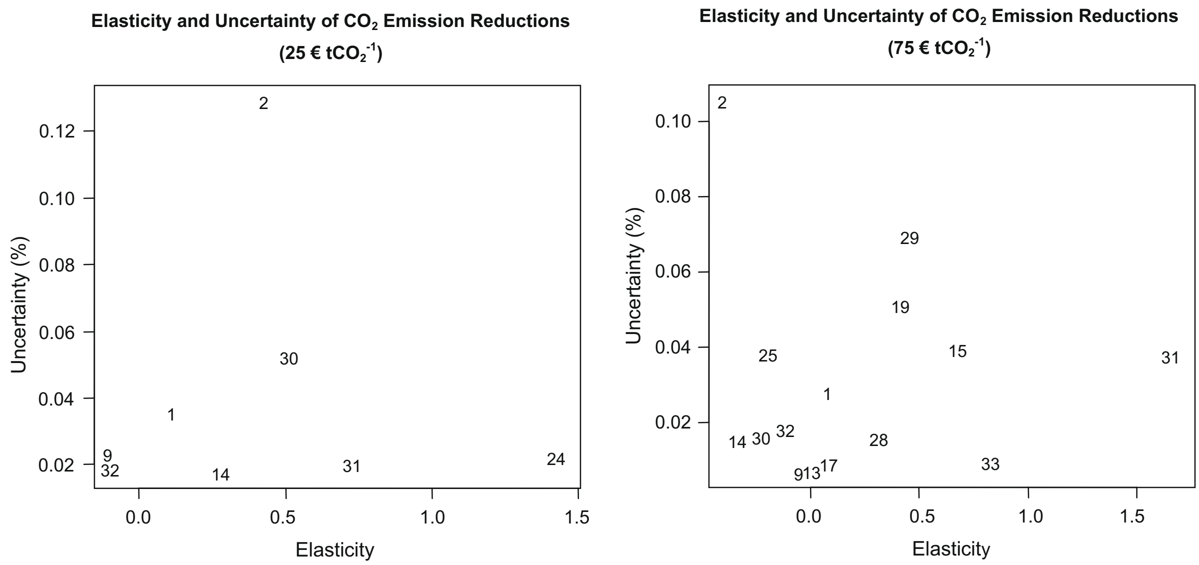

Fig. 6. Plots of parameter elasticities against parameter uncertainties corresponding to CO_2 emission reductions. Left: CO_2 price of 25 € tCO_2^{-1}, Right: 75 € tCO_2^{-1}. Note: The numbers indicate the number of the parameter in Table 2.

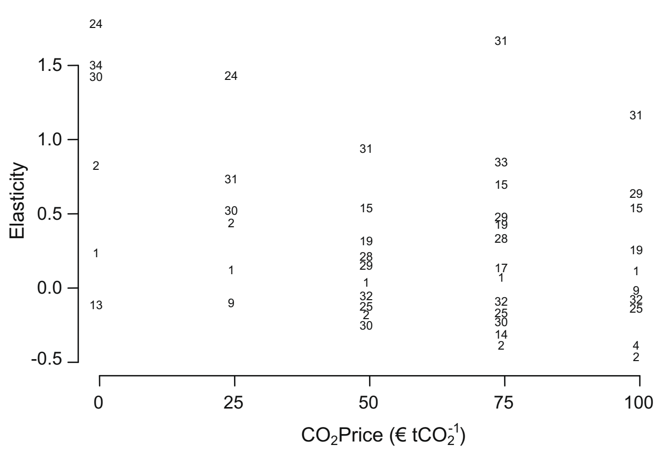

Fig. 7. Elasticities between input parameters and CO_2 emission reductions for five CO_2 prices. Note: the numbers indicate the number of the parameter in Table 2.

is of interest that the sign of the elasticity of the efficiency of power production in BIGCC plants (14) changes. While it is positive in the first scenario, it is negative in the second one. High power efficiencies in BIGCC plants decrease the utilization of BECS, which saves more CO_2 emissions than the former. The costs of biomass (30) also change the sign and are negative in the 75 € tCO_2^{-1} price scenario. While the relative difference between biomass costs and energy prices is relevant in the low CO_2 emission-price scenario, the relative difference between biomass costs and the CO_2 price is more relevant in the high emission-price scenario. CO_2 price and biomass costs are not correlated, therefore the sign of the elasticity of biomass costs (30) changes. Uncertainty of model results is mainly influenced by the oil price (2) and BECS plant parameters, i.e. the efficiency (29) and costs of carbon capture and storage (25), and the efficiency of power (15) and of heat production (19). The elasticities of all five CO_2 price scenarios are shown in Fig. 7. The figure shows that elasticities decrease with increasing CO_2 price, because the higher CO_2 price stabilizes results. However, when BECS becomes selected at 75 € tCO_2^{-1}, the elasticities increase because the introduction of the technology adds uncertainty to the model.

4. Discussion and conclusions

The model results show clearly that ethanol and methanol from forest wood is not an economically and technically sound option to reduce CO_2 emissions in Austria. For countries similar to Austria this result may be valid, if heat demand is high and considerable amounts of fossil fuels can be replaced by either pellets or district heating. Pellets production is preferred to BECS production at low CO_2 prices. National statistics confirm the trend of biomass based power and heat production: the number of dwellings heated by biomass increased by 13% from 2003/2004 to 2007/2008, which has resulted in an estimated increase of around 2 $TWh_{biomass}$ [60]. Furthermore, biomass based power production has increased by about 1 TWh in the same period [4]. It should be noticed that both, biomass based power production and pellets boilers, are currently subsidized. The model results are very much in line with findings of other research. Fuel production is rated worst with respect to costs and CO_2 emission reductions [15,17,28]. The model results clearly show that spatial restrictions in heat demand have significant impact on the competiveness of BIGCC. The results also show that BECS is an economically viable option to reduce CO_2 emissions. However, there is a tradeoff between fossil fuel substitution and CO_2 emission savings. Less fossil fuels are replaced by BECS due to the lower efficiency. Additionally, serious concerns are related to carbon capture and storage: it is not clear by now if CO_2 storages are environmentally safe. All results on potentials of the technologies to reduce CO_2 emissions depend on the assumed CO_2 emission baseline. Outside of the bioenergy sector, various new CO_2 emission reduction technologies like photovoltaic and wind for the power sector, insulation and solar heating for the heating sector and electric vehicles in the transportation sector are either already used or emerging. Assuming different baseline CO_2 emissions in the bioenergy scenarios – e.g. a fossil fuel free power sector – changes the relative techno-economic efficiency of bioenergy technologies for climate change mitigation. Interpretations of the results of this paper have to regard this model boundary.

The spatial distribution of biomass supply and energy demand is important for total costs and CO_2 emission savings. The locations of pellets plants are scattered over Austria while BIGCC plants are located closely to big cities due to the high heating demand

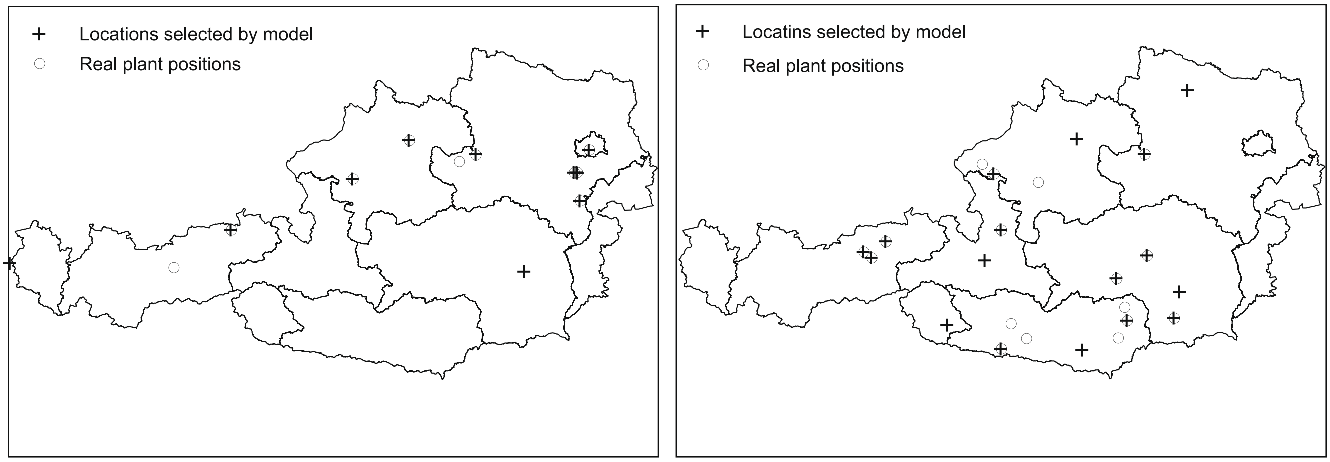

Fig. 8. Results of model validation for CHP plants (left) and for pellets plants (right).

densities and amounts. Biomass transportation costs are therefore higher for BIGCC plants. The total production costs can significantly decrease with respect to economies of scale of bioenergy plants. Plants of smaller size do not show the same competitiveness like plants of the size discussed in our analysis. Both elasticities and uncertainties related to energy prices are high. Energy prices are the main factor in determining the competiveness of bioenergy plants, particularly at low CO_2 prices. However, technical plant parameters, i.e. conversion efficiencies and carbon capture and storage rates influence model results significantly.

Model results indicate that pellets production and subsequent combustion for heating dwellings is a low cost technology to reduce CO_2 emissions. The technology is available on the markets and substitution of existing heating oil fuelled boilers would be favorable. There is also some potential for big scale BIGCC plants. However, there are little suitable locations for such plants. BECS is a high cost option for reducing CO_2 emission and risks associated with the permanent storage of the CO_2 have to be considered as well. Total CO_2 emission reduction potentials are, however, higher than for any of the other technologies.

Acknowledgements

The article has been prepared in the framework of the doctoral school Sustainable Development (DOKNE) at BOKU University of Natural Resources and Applied Life Sciences, Vienna, Austria. The doctoral school is funded by the Austrian Research Program on Sustainability "provision" as well as by the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and the states Lower Austria, Styria, and Vienna. This article has been also supported by the FP7 Project: Climate Change – Terrestrial Adaptation & Mitigation in Europe (ccTAME) funded by the European Commission. Comments received from two anonymous referees are gratefully acknowledged.

Appendix A. Model validation

The validation of models that assess emerging technologies is a difficult task because there is no real world data available which can be used for comparison with model results. No commercial installations of BIGCC, BECS, methanol and ethanol production are currently operating. Regarding parameters and costs of future technologies, we relied therefore on expert opinion, on peer reviews and on existing publications to validate the model. Publications applying our model on methanol [21,22,51], ethanol [31], biodiesel [52] and BIGCC [20] production are available. Regarding the validation of the model with respect to the selection of optimal plant locations, we opted for validating the model with existing pellets facilities and additionally CHP steam engine plants. Although CHP steam engine plants have different technical and economical properties than BIGCC, it is expected that the choice of the location is similar to BIGCC because feedstock supply and heat demand are important for both types of plants. Facilities installed since 2002 (for CHP) and since 1998 (for pellets) serve as basis for model validation [61]. The year 2002 is chosen because the green electricity law was implemented in Austria in that year while first large scale pellets plants started operations in 1998. The green electricity law guarantees feed-in tariffs to power produced from biomass and triggered a substantial increase in the number of CHP plants installed. Large scale pellets production started earlier in Austria but also experienced a boost due to subsidies given by state governments for the installation of pellets heating systems. For the validation process, only facilities that are larger than 20 $MW_{biomass}$ are considered. We do not assume that the model performs well for plants of lower capacity due to the limited spatial resolution of the model. Investment costs and plant characteristics – size and efficiencies – were taken from data provided publically by the operating companies on their websites. Eleven CHP and 17 pellets plants of a capacity above 20 $MW_{biomass}$ were built in the period. Model parameters were set to values corresponding to the year of 2004. Additional to the 28 existing locations, 36 additional locations were added to the model to test if the model selects the right locations. The model was forced to choose 11 locations for CHP plants and 17 locations for pellets plants among the 64 possible locations. The results of the validation process are shown in Fig. 8. For the CHP case, the model selected 9 of 11 positions correctly. Only two locations are chosen differently, and both are plants of lower capacity (27 $MW_{biomass}$ and 31 $MW_{biomass}$). In the pellets case, the model selected 11 out of 17 locations correctly. An explanation is that the optimal position of pellets plants depends less on the proximity to the consumers than in the CHP case. Distribution of pellets is inexpensive in comparison to district heating and therefore the proximity to wood resources is of more importance. Wood resources are, however, not as concentrated as heating demand. Locations differ therefore less in their suitability for pellets production than for CHP production which explains why the model does select only a subset of the locations found in reality. Considering this, the model performs well in the selection of plant locations.

Please cite this article in press as: Schmidt J et al. Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. Appl Energy (2009), doi:10.1016/j.apenergy.2009.11.007

Appendix B. District heating model

Heat production limits the amount of heat available for district heating. The commodity production is modeled on an annual time period. However, variations in heat demand in winter and summer are considered in the model. Seasonal supply of heat in the plant is restricted by

$$\sum_{h,ps} q^{dh}_{j,h,ps,t} \leqslant \Delta t_t q^{bio}_j, \tag{B.1}$$

where parameter Δt_t denotes the relative length of a season.

The production of heat has to meet the demand (parameter $q^D_{h,t}$) in each period, which is guaranteed by

$$\eta^{dh}_{h,t}\left(\left(\sum_{j,ps}\eta^{trans}_{j,h,ps,t}q^{dh}_{j,h,ps,t}\right)+q^{peak}_{h,t}\right)+\eta^{local}_{h,t}q^{local}_{h,t}=q^D_{h,t}, \tag{B.2}$$

where parameter $\eta^{trans}_{j,h,ps,t}$ denotes the heat losses in the pipe system from the plant to the settlement. Losses in the heat distribution network within the settlement are modeled by parameter $\eta^{dh}_{h,t}$. Parameter $\eta^{local}_{h,t}$ is introduced to describe conversion efficiencies of local heating systems.

The sum of heat produced by the bioenergy plant and by the peak demand boiler has to match the district heating demand (parameter $q^D_{h,ns,t}$) in settlement h. This is modeled by

$$\eta^{dh}_{h,t}\left(\left(\sum_{j,ps}\eta^{trans}_{j,h,ps,t}q^{dh}_{j,h,ps,t}\right)+q^{peak}_{h,t}\right)=\sum_{ns}q^D_{h,ns,t}u^{dnet}_{h,ns}. \tag{B.3}$$

The existence of a transportation pipeline, in case a settlement is supplied by a bioenergy plant, is ensured by

$$q^{dh}_{j,h,ps,t} \leqslant \bar{q}^{pipe}_{ps,t}u^{pipe}_{j,h,ps}, \tag{B.4}$$

where parameter $\bar{q}^{pipe}_{ps,t}$ denotes the capacity of the pipeline.

Only one district heating network can be built in every settlement, which is ensured by

$$\sum_{ns} u^{dnet}_{h,ns} \leqslant 1. \tag{B.5}$$

Appendix C. Determination of optimal plant size

The optimal plant size with regard to the biggest CO_2 emissions savings is determined by first running the model with 1000 stochastically determined input parameters for each technology separately. The plant size is varied between 50 $MW_{biomass}$ and 250 $MW_{biomass}$. From the results, a response surface is estimated by regressing the total CO_2 emission savings on all input parameter variations par_m, assuming that the plant size has a quadratic effect on model output as biomass transportation distance and economies of scale in bioenergy production have opposite effects:

$$esav = \beta_0 + \sum_m \beta_m par_m + \beta_{m+1} size^2 + e \tag{C.1}$$

The β_0 is the intercept, β_m are the regression coefficients, β_{m+1} is the regression coefficient of the quadratic term of the plant size, and e is an error term. The optimal size of the plants with regard to CO_2 emission savings is determined by calculating the root of the first derivate ($\partial esav/\partial size$). However, for biofuel plants and CHP plants, the root of the derivate is bigger than the maximally allowed plant size (250 $MW_{biomass}$). Therefore, the plant size is set to 250 $MW_{biomass}$. The optimal size for pellets plants is 180 $MW_{biomass}$.

Appendix D. Sensitivity analysis

Elasticities can be estimated for all combinations of input parameters and output variables. Variable *esav* is used for further descriptions of elasticity estimations. The elasticity is defined as:

$$esav_{par_m} = \frac{\partial esav}{\partial par_m}\frac{par_m}{esav}, \tag{D.1}$$

where $esav_{par_m}$ is the elasticity between *esav* and parameter par_m. The derivative $\frac{\partial esav}{\partial par_m}$ cannot be derived analytically from the optimization model. However, it is possible to estimate a response surface by applying a linear regression model of the output on the input parameters and thereby approximating a continuous function [62],

$$esav = \beta_0 + \sum_m \beta_m par_m + e, \tag{D.2}$$

where coefficient β_0 is the intercept, coefficients β_m are the regression coefficients and e is an error term. The size of the plant is fixed and is therefore not included in this estimation. The parameter vectors par_m, which represent the input to the Monte-Carlo simulation, and the corresponding result vectors $esav$ are used in the regression analysis. The regression is not able to capture the whole dynamics of the non-continuous relationship between the variables which result from the MIP. However, the ordinary least square estimators exhibit fits of $R^2 > 0.5$ for all combinations of input parameters and outputs. The signs of the coefficients have the expected direction for all parameters. The response surface is used to numerically compute the elasticities:

$$esav_{par_m} = \frac{\partial esav}{\partial par_m}\frac{par_m}{esav} = \beta_m\frac{par_m}{esav} \tag{D.3}$$

When no bioenergy is produced at all, the elasticity is not defined as the denominator of the fraction in Eq. (D.3) is zero. Undefined elasticities are excluded from further calculations. The procedure is applied separately to the five CO_2 price scenarios.

References

[1] European Council. Council decision of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto protocol to the United Nations framework convention on climate change and the joint fulfilment of commitments thereunder, vol. L 130; Official Journal 2002.
[2] Umweltbundesamt. Austria's national inventory report. Umweltbundesamt Österreich; 2008.
[3] Madlener R. Innovation diffusion, public policy, and local initiative: the case of wood-fuelled district heating systems in Austria. Energy Policy 2007;35: 1992–2008.
[4] E-Control. Development of approved green power plants according to decisions of provincial governments (Entwicklung der anerkannten Ökostromanlagen laut Bescheiden der Landesregierungen). Vienna: E-Control; 2009. <http://www.e-control.at/portal/page/portal/ECONTROL_ HOME/OKO/ZAHLEN_DATEN_FAKTEN/Anlagenstatistik/ANERKANNTEOEKOANLAGEN>.
[5] Schadauer K. The Austrian forest inventory 2000/02 – main results (Die Österreichische Waldinventur 2000/02 – Hauptergebnisse). Vienna: Bundesamt für Wald; 2004. <http://bfw.ac.at/040/pdf/1818_pi3.pdf>.
[6] Ammann H, Brecht I, Albisser Vögeli G. Comparison of wood-fired heating systems. Agrarforschung 2009;16:64–9.
[7] Gustavsson L, Mahapatra K, Madlener R. Energy systems in transition: perspectives for the diffusion of small-scale wood pellet heating technology. Int J Technol Manage 2005;29:327–47.
[8] Wahlund B, Yan J, Westermark M. A total energy system of fuel upgrading by drying biomass feedstock for cogeneration: a case study of Skelleftea bioenergy combine. Biomass Bioenergy 2002;23:271–81.
[9] Marbe G, Harvey S, Berntsson T. Biofuel gasification combined heat and power—new implementation opportunities resulting from combined supply of process steam and district heating. Energy 2004;29:1117–37.
[10] Dornburg V, Faaij APC. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass Bioenergy 2001;21: 91–108.
[11] Kraxner F, Nilsson S, Obersteiner M. Negative emissions from bioenergy use, carbon capture and sequestration (BECS) – the case of biomass production by sustainable forest management from semi-natural temperate forests. Biomass Bioenergy 2003;24:285–96.

[12] Obersteiner M, Azar Ch C, Kauppi P, Möllersten K, Moreira J, Nilsson S, Read P, Riahi K, Schlamadinger B, Yamagata Y, Yan J, van Ypersele J-P. Managing climate risk. Science 2001;294:786–7.

[13] Fatih Demirbas M. Biorefineries for biofuel upgrading: a critical review. Appl Energy 2009;86:S151–61.

[14] Piccolo C, Bezzo F. A techno-economic comparison between two technologies for bioethanol production from lignocellulose. Biomass Bioenergy 2009;33:478–91.

[15] Bram S, De Ruyck J, Lavric D. Using biomass: a system perturbation analysis. Appl Energy 2009;86:194–201.

[16] Faaij A. Modern biomass conversion technologies. Mitigat Adaptat Strategies Global Change 2006;11:335–67.

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

[18] Eriksson LO, Björheden RW. Optimal storing, transport and processing for a forest-fuel supplier. Eur J Operat Res 1989;43:26–33.

[19] Grohnheit PE, Mortensen BOG. Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies. Energy Policy 2003;31:817–26.

[20] Schmidt J, Leduc S, Dotzauer E, Kindermann G, Schmid E. Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. Int. J. Energy Res.; in press. doi:10.1002/er.1623.

[21] Leduc S, Schwab D, Dotzauer E, Schmid E, Obersteiner M. Optimal location of wood gasification plants for methanol production with heat recovery. Int J Energy Res 2008;32:1080–91.

[22] Leduc S, Schmid E, Obersteiner M, Riahi K. Methanol production by gasification using a geographically explicit model. Biomass Bioenergy 2009;33:745–51.

[23] Suntana AS, Vogt KA, Turnblom EC, Upadhye R. Bio-methanol potential in Indonesia: forest biomass as a source of bio-energy that reduces carbon emissions. Appl Energy 2009;86:S215–21.

[24] Möllersten K, Gao L, Yan J. CO_2 capture in pulp and paper mills: CO_2 balances and preliminary cost assessment. Mitigat Adaptat Strategies Global Change 2006;11:1129–50.

[25] Möllersten K, Gao L, Yan J, Obersteiner M. Efficient energy systems with CO_2 capture and storage from renewable biomass in pulp and paper mills. Renew Energy 2004;29:1583–98.

[26] Möllersten K, Yan J, Westermark M. Potential and cost-effectiveness of CO_2 reductions through energy measures in Swedish pulp and paper mills. Energy 2003;28:691–710.

[27] Möllersten K, Yan J, Moreira JR. Potential market niches for biomass energy with CO_2 capture and storage – opportunities for energy supply with negative CO_2 emissions. Biomass Bioenergy 2003;25:273–85.

[28] Grahn M, Azar C, Lindgren K, Berndes G, Gielen D. Biomass for heat or as transportation fuel? A comparison between two model-based studies. Biomass Bioenergy 2007;31:747–58.

[29] Kumar A. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. Bioresour Technol 2009;100:387–99.

[30] Alfonso D, Perpiñá C, Pérez-Navarro A, Peñalvo E, Vargas C, Cárdenas R. Methodology for optimization of distributed biomass resources evaluation, management and final energy use. Biomass Bioenergy 2009;33:1070–9.

[31] Leduc S, Starfelt F, Dotzauer E, Kindermann G, McCallum I, Obersteiner MJL. Optimal location of ethanol ligno-cellulosic biorefineries with polygeneration in Sweden. Energy; in press. doi:10.1016/j.energy.2009.07.018.

[32] Rhodes JS, Ketih DW. Engineering economic analysis of biomass IGCC with carbon capture and storage. Biomass Bioenergy 2005;29:440–50.

[33] Uddin NS, Barreto L. Biomass-fired cogeneration systems with CO_2 capture and storage. Biomass Bioenergy 2007;32:1006–19.

[34] van der Zwaan B, Gerlagh R. Economics of geological CO_2 storage and leakage. Climate Change 2009;93:285–309.

[35] Holloway S. Safety of the underground disposal of carbon dioxide. Energy Convers Manage 1997;38:241–5.

[36] Thistle D, Sedlacek L, Carman KR, Fleeger JW, Bewer PG, Barry JP. Simulated sequestration of industrial carbon dioxide at a deep-sea site: effects on species of harpacticoid copepods. J Exp Mar Biol Ecol 2006:330.

[37] Demirbas A. Present and future transportation fuels. Energy Sources Part A 2006;30:1473–83.

[38] Hamelinck CN, Hooijdonk GV, Faaij AP. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. Biomass Bioenergy 2005;28:384–410.

[39] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. J Power Sour 2001;111:1–22.

[40] Magelli F, Boucher K, Bi HT, Melin S, Bonoli A. An environmental impact assessment of exported wood pellets from Canada to Europe. Biomass Bioenergy 2009;33:434–41.

[41] Polagye BL, Hodgson KT, Malte PC. An economic analysis of bio-energy options using thinnings from overstocked forests. Biomass Bioenergy 2007;31:105–25.

[42] Andersson E, Harvey S, Berntsson T. Energy efficient upgrading of biofuel integrated with a pulp mill. Energy 2006;31:1384–94.

[43] Assmann E. The principles of forest yield study. Oxford: Pergamon; 1970.

[44] Running SW. Terrestrial remote sensing science and algorithms planned for EOS/MODIS. Int J Remote Sens 1994;15:3587–620.

[45] European Environment Agency. Corine land cover. European Environment Agency; 2008. <http://www.eea.europa.eu/publications/COR0-landcover>.

[46] Federal Ministry of Agriculture Forestry Environment and Water Management. Logging report 2001 – 2007 (Holzeinschlagsmeldung 2001–2007). Vienna: Federal Ministry of Agriculture, Forestry, Environment and Water Management; 2008. <http://duz.lebensministerium.at/duz/duz/category/1025>.

[47] Landwirtschaftskammer Niederösterreich. Energy wood index Austria (Energieholzindex Österreich). St. Pölten: Landwirtschaftskammer Niederösterreich; 2008.

[48] UNFCCC. Updated UNFCCC reporting guidelines on annual inventories following incorporation of the provisions of decision 14/CP.11. In: Advice Sbfsat, editor, vol. FCCC/SBSTA/2006/9: United Nations; 2006.

[49] Statistik Austria. Energy bilances 1970–2006 (Energiebilanzen 1970–2006). Statistik Austria; 2007.

[50] Leduc S. Development of an optimization model for the location of biofuel production plants. Phd Thesis, Luleå University; 2009.

[51] Leduc S, Lundgren J, Franklin O, Schmid E, Dotzauer E. Location of a biomass based methanol production plant: a dynamic problem in Northern Sweden. Appl Energy 2009;87:68–75.

[52] Leduc S, Natarajan K, Dotzauer E, McCallum I, Obersteiner M. Optimizing biodiesel production in India. Appl Energy 2009;86:S125–31.

[53] Salhofer K, Schmid E, Streicher G. Testing for the efficiency of a policy intended to meet objectives: general model and application. J Agri Resour Econom 2006;31:151–72.

[54] Batlle C, Barquín J. Fuel prices scenario generation based on a multivariate GARCH model for risk analysis in a wholesale electricity market. Int J Electr Power Energy Syst 2003;26:273–80.

[55] Energy Information Administration. Official energy statistics from the US government. Washington: Energy Information Administration; 2009. <http://www.eia.doe.gov/>.

[56] European Energy Exchange. Market data. European energy exchange; 2009. <http://www.eex.com/en/Download/Market%20Data>.

[57] Efron B. Bootstrap methods: another look at the jackknife. Ann Statist 1979;7:1–26.

[58] Makridakis S. Accuracy measures: theoretical and practical concerns. Int J Forecast 1993;9:527–9.

[59] Armstrong JS, Collopy F. Error measures for generalizing about forecasting methods: empirical comparisons. Int J Forecast 1992;8:69–80.

[60] Statistik Austria. Total use of energy sources (Gesamteinsatz aller Energieträger 2003/2004–2007/2008). Statistik Austria; 2009.

[61] Kopetz H, Scheiber E. Basis data bioenergy Austria (Basisdaten Bioenergie Österreich). Österreichischer Biomasse-Verband; 2006.

[62] Saltelli A, Ratto M, Andres T, Campolongo F, Cariboni J, Gatelli D, et al. Global sensitivity analysis: the primer. Chichester: John Wiley & Sons Ltd.; 2008.

[63] Sims REH. Bioenergy – a renewable carbon sink. Renew Energy 2001;22:31–7.

[64] Azar C, Lindgren K, Larson E, Möllersten K. Carbon capture and storage from fossil fuels and biomass – costs and potential role in stabilizing the atmosphere. Climate Change 2006;74:47–79.

[65] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass Bioenergy 2004;27:671–93.

[66] Gronalt M, Rauch P. Designing a regional forest fuel supply network. Biomass Bioenergy 2007;31:393–402.

[67] Styles D, Jones MB. Current and future financial competitiveness of electricity and heat from energy crops: a case study from Ireland. Energy Policy 2007;35:4355–67.

[68] Konstantin P. Handbook energy industry (Praxisbuch Energiewirtschaft). Berlin: Springer Berlin Heidelberg; 2007.

[69] Arbeitsgemeinschaft Fernwärme e.V. Strategies and technologies of a pluralistic district heating supply in a liberalized energy market considering combined heat and power and renewable energies (Strategien und Technologien einer pluralistischen Fern- und Nahwärmeversorgung in einem liberalisierten Energiemarkt unter besonderer Berücksichtigung der Kraft-Wärme-Kopplung und erneuerbarer Energien). Frankfurt: Arbeitsgemeinschaft Fernwärme e.V.; 2000. <http://www.isi.fhg.de/e/publikation/waerme/band1-lang.pdf>.

[70] E-Control. Production of electric energy in Austria, time series until 2006 (Aufbringung elektrischer Energie in Österreich, Jahresreihen bis 2006). E-control; 2008.

Please cite this article in press as: Schmidt J et al. Cost-effective CO_2 emission reduction through heat, power and biofuel production from woody biomass: A spatially explicit comparison of conversion technologies. Appl Energy (2009), doi:10.1016/j.apenergy.2009.11.007

Article 3

Analyzing the cost-effectiveness of energy policy instruments in the bioenergy sector

Analyzing the cost-effectiveness of energy policy instruments in the bioenergy sector

Johannes Schmidt [1*]; Sylvain Leduc[2] ; Erik Dotzauer[3]; Georg Kindermann[2]; Erwin Schmid[4];

Affiliations

[1] Doctoral School Sustainable Development, University of Natural Resources and Applied Life Sciences, Peter Jordan Straße 82, A-1190 Vienna, Austria.

[2] International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria.

[3] Mälardalen University, P.O. Box 883, SE-72123 Västerås, Sweden.

[4] Institute for Sustainable Economic Development, University of Natural Resources and Applied Life Sciences, Feistmantelstraße 4, A-1180 Vienna, Austria.

Abstract

Climate change mitigation and security of energy supply are main drivers of Austrian energy policies. Bioenergy production based on forest wood harvests is an important option for renewable energy generation in Austria. Several policy instruments such as CO_2 emission trading, feed-in tariffs, biofuel blending obligations, and subsidies for pellet furnaces are currently implemented in the bioenergy sector. New conversion technologies are being developed to increase the technological options of utilizing wood in energy production. These options include second generation biofuel production, bioenergy systems with carbon capture and storage (BECS), and biomass integrated gasification combined cycle plants (BIGCC). The effect of policy instruments on deployment of these technologies is not obvious. We address this question by applying a spatially explicit energy system model that minimizes the costs of bioenergy system considering competing fossil fuels and the effect of energy policy instruments. The model allows estimating bioenergy system costs, the amount of CO_2 emission reductions, and the substitution of fossil fuels generated by the instruments. Model results indicate that carbon taxes are the most cost-effective policy instrument for CO_2 emission reductions while biofuel blending obligations are costly and cause negative emission reductions and negative fossil substitution in comparison to a baseline scenario.

Keywords: bioenergy policy; optimization model; CO2 emission reduction

[*] Correspondence to: Johannes Schmidt, Doctoral School Sustainable Development, University of Natural Ressources and Applied Life Sciences, Peter-Jordan Straße 82, A-1190 Vienna, Austria. E-Mail: johannes.schmidt@boku.ac.at

Nomenclature

Variables	Unit	Description
$b_{i,j,l}$	$MWh_{biomass}$	Biomass transported to plants
$b_{i,o,u}$	-	Decision variable in seperable programming
p	€ MWh^{-1}	Price of wood supply
q	MWh	Quantity of wood supply
q_j^{bio}	MWh	Heat production in the plant
$q_{j,h,ps,t}^{dh}$	MWh	Heat transportation from plant to district heating network
$q_{h,t}^{local}$	MWh	Local heat production
$q_{h,t}^{peak}$	MWh	Peak heat production
totem	tCO_2	Total CO_2 emissions
$u_{h,ns}^{dnet}$	-	Binary variable for investment in district heating network
$u_{j,h,ps}^{pipe}$	-	Binary variable for investment in transportation pipeline
$u_{j,l}^{plant}$	-	Binary variable for plant investment
$z_{j,c}^{bio}$	MWh	Amount of energy commodity produced in a plant
$z_{j,k,c}^{bio}$	MWh	Amount of energy commodity transported to consumers
$z_{k,f}^{fossil}$	MWh	Amount of fossil fuel used to satisfy demand
Parameters		
$\varepsilon, \varepsilon_o$	-	Elasticity of biomass supply
Δt_t	-	Relative length of a season
$\eta_{c,d}^{bio}$	-	Efficiency of converting a bioenergy commodity to useful energy
$\eta_{j,l,c}^{conv}$	-	Conversion efficiency in bioenergy plants
$\eta_{h,t}^{dh}$	-	Efficiency of distributing heat in district heating network
$\eta_{f,d}^{fossil}$	-	Efficiency of converting fossil fuel to useful energy
$\eta_{j,l}^{heat}$	-	Heat efficiency in bioenergy plants
$\eta_{h,t}^{local}$	-	Local heat conversion efficiency
$\eta_{j,h,ps,t}^{trans}$	-	Transportation efficiency of heat pipeline
$\bar{b}_{i,o}$	MWh y^{-1}	Maximum sustainable yield (MSY) in supply cell
$\bar{b}_{j,l}$	MWh y^{-1}	Production capacity of plant
$\bar{b}_{s,o}$	MWh y^{-1}	MSY in federal state
C	-	Constant in wood supply function
c^{ccs}	€ tCO_2^{-1}	Costs of carbon capture and storage
c_f^{fossil}	€ MWh^{-1}	Price of fossil fuel

c_c^{inv}	€ MWh^{-1}	Investment cost necessary at consumer
$c_{j,l}^{plant}$	€ y^{-1}	Annualized costs of plant investment
$c_{j,l}^{prod}$	€ $MWh_{biomass}^{-1}$	Variable costs of bioenergy production
c_i^{sup}	€ $MWh_{biomass}^{-1}$	Costs of biomass supply
$c_{i,j,l}^{transb}$	€ $MWh_{biomass}^{-1}$	Costs of biomass transportation from *i* to *j*
$c_{j,k,c}^{transc}$	€ MWh^{-1}	Costs of transporting commodity from *j* to *k*
$c_{j,h,ps}^{pipe}$	€ y^{-1}	Annualized costs of investment in transportation pipeline
$c_{h,ns}^{dnet}$	€ y^{-1}	Annualized costs of investment in district heating network
c_t^{peak}	€ MWh^{-1}	Costs of peak heat production
c_t^{local}	€ MWh^{-1}	Costs of local heat production
c^{em}	€ tCO_2^{-1}	CO_2 price
$d_{k,d}$	MWh y^{-1}	Energy demand
e_l^{ccs}	tCO_2 $MWh_{biomass}^{-1}$	Carbon capture rate in plant
e_f^{fossil}	tCO_2 MWh^{-1}	CO_2 emission factor of fossil fuels
e_h^{local}	tCO_2 MWh^{-1}	CO_2 emission factor of local heat production
$e_{h,t}^{peak}$	tCO_2 MWh^{-1}	CO_2 emission factor of peak heat production
$e_{i,j}^{trans}$	tCO_2 $MWh_{biomass}^{-1}$	CO_2 emission factor of biomass transportation from *i* to *j*
$e_{j,k,c}^{trans}$	tCO_2 MWh^{-1}	CO_2 emission factor of commodity transportation
$f_{c,d}^{blend}$	-	Mandatory share of bioenergy commodity in final energy demand
$\hat{p}$	€ MWh^{-1}	Price of forest wood
q^*	MWh	Supply of wood harvests
q_u^*	-	Quantities for separable programming
$\hat{q}, \hat{q}_{i,o}, \hat{q}_{s,o}$	MWh y^{-1}	Observed quantities of wood harvests total, in supply cell, in federal state
$q_{h,t}^D$	MWh $season^{-1}$	Heat demand in settlement
$q_{h,ns,t}^D$	MWh $season^{-1}$	Heat demand in district heating network
$\bar{q}_{ps,t}^{pipe}$	MWh $season^{-1}$	Capacity of heat transportation pipeline
tx^s, tx_f^f	-	Binary parameters controlling which fossil fuels are priced
Subscripts		
c	-	Energy commodity
d	-	Energy demand for useful energy
f	-	Fossil fuels
h	-	Settlement
i	-	Biomass supply site
j	-	Plant location

k	-	Demand region
l	-	Technology
ns	-	District heating network size
o	-	Forest ownership
s	-	Federal state
ps	-	Pipeline size
t	-	Season
u	-	Index for separable programming

1. Introduction

Climate change mitigation and security of energy supply are main drivers of current European energy policies (Berndes and Hansson, 2007). Austria committed to a 13% reduction of green house gases with respect to the reference year of 1990 in the Kyoto commitment period of 2008-2012 (European Council, 2002) and to an increase of renewable energy production by 11 percentage points until 2020 according to the EU directive 2009/28/EG. Currently, Austria is far from reaching the Kyoto target (Umweltbundesamt, 2008) and significant efforts are necessary to meet the 2020 energy targets (Nakicenovic et al., 2008). The forestry sector represents an important source of Austrian renewable energy production. Further increases in forestry biomass utilization are still possible (Schadauer, 2004) and necessary to reach the climate and renewable energy targets. Several policy instruments are in place to facilitate the achievement of these targets. These policy instruments are implemented either for the whole energy sector or only for the bioenergy sector itself including:

- The EU Emission Trading Scheme (EU ETS), which was introduced in 2005. About 250 facilities which emit around one third of total CO_2 emissions were affected in Austria. CO_2 emission permits were allocated to installations for free in the start-up phase by applying a grandfathering principle, i.e. emissions are allocated relative to emissions of the facilities in the last years. These CO_2 emission permits can be traded on a market to attain efficient allocations. The second phase of the EU ETS runs from 2008 to 2012. The main differences to the first phase (from 2005 to 2008) are a slightly lower cap (reduction from 33.19 $MtCO_2$ to 32.8 $MtCO_2$) and the auctioning of 1.2% of the permits in the initial phase of the scheme (Lebensministerium, 2007; Paoletta and Taschini, 2006). A major drawback of the EU ETS is that only one third of total CO_2 emissions are currently covered by the system. Bioenergy projects are assumed to be carbon neutral and therefore do not have to acquire EU ETS permits for their operation.

- The EU directive 2003/30/EG obliges all member states to blend a share of 5.75% of biofuels with gasoline until 31st December 2010. Austria ratified this law in 2003. In 2009, the EU decided on directive 2009/28/EG, which demands among other targets a share of 10% of renewable energies in the transportation sector. In contrast to directive 2003/30/EG, this regulation does not dictate the utilization of biofuels. Electric cars which use renewably produced electricity or a shift to train transportation are measures that can also be applied. However, biofuels are one major technological option to reach the targets in the short term.

- Feed-in tariffs for different forms of renewable electricity production such as small water power plants, photovoltaic power, wind power and bioenergy power plants are defined in the Austrian renewable energy law. Installations receive feed-in tariffs for 12 years. However, there is a cap on the total costs for this scheme such that not all power producers may be able to get into this scheme. Feed-in tariffs are currently chosen to be close to production costs of specific technologies and therefore depend on the respective technology, e.g. feed-in tariffs for photovoltaic power are higher than for bioenergy plants.

- Subsidies are granted for pellet heating systems by federal states in Austria. House owners who install new pellet heating systems receive a subsidy on the investments, regardless if the system is installed in a new building or if the heating system of an existing building is replaced.

- A CO_2 tax on all fossil fuels is currently under political discussion in Europe. Such tax may cover CO_2 emissions inside as well as outside EU ETS, including fossil fuel consumption in private households. A CO_2 tax is currently not implemented in Austria but in several other European states, including France and Sweden.

These policy instruments have likely different effects on the production technologies chosen in the sector. Costs for reducing CO_2 emissions, the achievable reduction potentials, and the amount of fossil fuel substitution vary with the policy instrument (Berndes and Hansson, 2007).

This article assesses the effect of energy policy instruments on the deployment of bioenergy technologies, costs for reducing CO_2 emissions, and the potential of substituting fossil fuels. We particularly consider new conversion technologies, which are expected to become commercially available within the next ten years. Biomass integrated combined cycle (BIGCC) plants, bioenergy with carbon capture and storage (BECS), and second generation biofuels are included in our assessment. The applied methodology allows estimating costs of different policy instruments in attaining climate change and energy security targets by considering technologies that are currently not commercially available. Studies that compare the techno-economic performance of new bioenergy conversion technologies based on woody biomass and/or the effectiveness of policy instruments (Azar et al., 2003; Berndes and Hansson, 2007; Gielen et al., 2003; Wahlund et al., 2004) come to diverging results. While Wahlund et al. (2004), Berndes and Hansson (2007) and Azar et al. (2003) clearly prefer utilization of biomass for heat and combined heat and power (CHP) production over utilization for transportation fuel production, Gielen et al. (2003) conclude that transportation fuel production is a viable option. However, the studies differ in their regional resolution (worldwide – Europe wide – national), their technical detail and in their assumptions on the availability of other low carbon technologies in the respective sectors. BECS is not included in any of the available comparative assessments. Additionally, the competition between heat and CHP production depends on spatial factors. Biomass transportation costs as well as energy distribution costs have significant impact on the final cost of the bioenergy supply chain (Eriksson and Björheden, 1989; Grohnheit and Mortensen, 2003). Particularly district heating may induce high infrastructure costs depending on the spatial densities of heat demand. The spatial variability of energy demand is high in Austria and distribution costs vary (Schmidt et al., 2009b). Including spatial explicit modeling in the analysis therefore increases the significance of the results with regard to the competition of heating and CHP production. This article contributes by assessing the effect of several energy policy instruments on the deployment of new bioenergy technologies applying a spatial explicit energy system model. Especially BIGCC and BECS are significant technologies for reducing CO_2 emissions in the future.

The article is structured as follows: section 2 introduces the model and the data, the technologies included in the assessment and the policy scenarios. Section 3 presents the results including costs, emission reductions, and fossil fuel substitution of seven policy instrument scenarios. Section 4 summarizes the article with a discussion of the results and major conclusions. Details on biomass supply and district heating modeling can be found in Appendix A and Appendix B.

2. Methodology

2.1. A techno-economic spatially explicit model

We apply a spatially explicit, techno-economic mixed integer program (MIP) to assess the cost-effectiveness of different policy instruments in attaining policy objectives. The model minimizes the costs of supplying a defined area (e.g. region or country) with transportation fuels, heat and electricity from either bioenergy or fossil fuels. It is static and simulates one year of operation with several heating demand seasons. Our model considers domestic biomass supply and energy demand in Austria and does not currently allow imports and exports of biomass or bioenergy commodities. The model decides which (i.e. pellet, methanol, BIGCC or BECS) and where bioenergy plants shall be built and which demand regions are supplied with bioenergy and/or with fossil fuels. Each plant produces various energy commodities (Figure 1). They can replace fossil fuels in the private heating, the power generation, and the transportation sector. By assumption, pellets are burnt in furnaces of households, power is transmitted to the national grid, surplus heat is delivered to district heating networks and methanol replaces gasoline for transportation purposes. The objective function is minimized and consists of the costs of biomass supply (see Appendix A), biomass transportation, plant investment, district heating infrastructure, investments in pellet furnaces, carbon capture and storage (CCS), and commodity transportation (i.e. pellets, transportation fuels) to consumers. Biomass supply curves determine the costs of woody feedstocks that are regionally available, while prices of fossil fuels are given exogenously. Demands for energy commodities are assumed to be constant. The model assesses the relative effectiveness of policy instruments within the bioenergy sector and with respect to attaining two policy objectives i.e. reducing CO_2 emissions and substituting fossil fuels without considering additional low carbon technologies outside of the sector. We assess energy supply system costs associated with a shift from fossil fuels to bioenergy while transaction costs induced by the policy instruments are not considered in the analysis. Taxes currently applied to both fossil and bioenergy fuels are not included in the model as well. Table 2 reports the specific settings of model parameters.

2.2. Biomass conversion technologies

Fossil fuel consumption occurs mainly in three sectors: private heating, power generation, and transportation. In each sector, at least one conversion technology is chosen depending on the techno-economic performance in comparison to other bioenergy technologies available in the same sector. We have chosen pellet heating furnaces as technological option in the private heating sector. The combustion of pellets in furnaces to heat dwellings is highly effective in comparison to other wood heating technologies such as log furnaces (Ammann et al., 2009). Pellets are also convenient to handle for the user due to their high energy density and low storage space requirements (Gustavsson et al., 2005). Bioenergy-combine plants integrate pellet production with CHP production (Wahlund et al., 2002) and are regarded as production technology in the model. Biomass integrated combined cycle (BIGCC) plants produce power more efficiently than currently employed steam engines (Dornburg and Faaij, 2001; Marbe et al., 2004). They are therefore chosen as technological option in the power sector. Bioenergy with carbon capture and storage (BECS) is an emerging technology and one of the view options that allows achieving negative CO_2-emissions (Kraxner et al., 2003), which may be necessary to manage climate risk effectively (Obersteiner et al., 2001). BIGCC with CCS is therefore included as additional technological option in the assessment. In the transportation sector, so called second generation technologies allow converting forest biomass into fuels, which are currently not commercially viable. Nevertheless, various fuels such as ethanol, Fischer Tropsch (FT) diesel, DME or methanol can be produced by such technologies (Fatih Demirbas, 2009). Gasification of biomass is estimated to be the most competitive second generation technology (Semelsberger et al., 2006) and allows producing FT diesel, DME and methanol (Bram et al., 2009). Among these biomass conversion technologies, the methanol production process has been identified as the least cost option for CO_2 reductions (Faaij, 2006; Wahlund et al., 2004). Methanol production is therefore chosen as conversion technology for the transportation sector in this analysis.

2.3. CO_2 emissions and reference technologies

We assume that forest wood production is organized in a CO_2 neutral way, i.e. that forests sequestrate the CO_2 released by burning of previously harvested biomass. This assumption is consistent with the current version of the UNFCC reporting guidelines for the Kyoto Protocol that assumes that woody biomass use in energy applications is CO_2 emission neutral (UNFCCC, 2006). Transportation of biomass

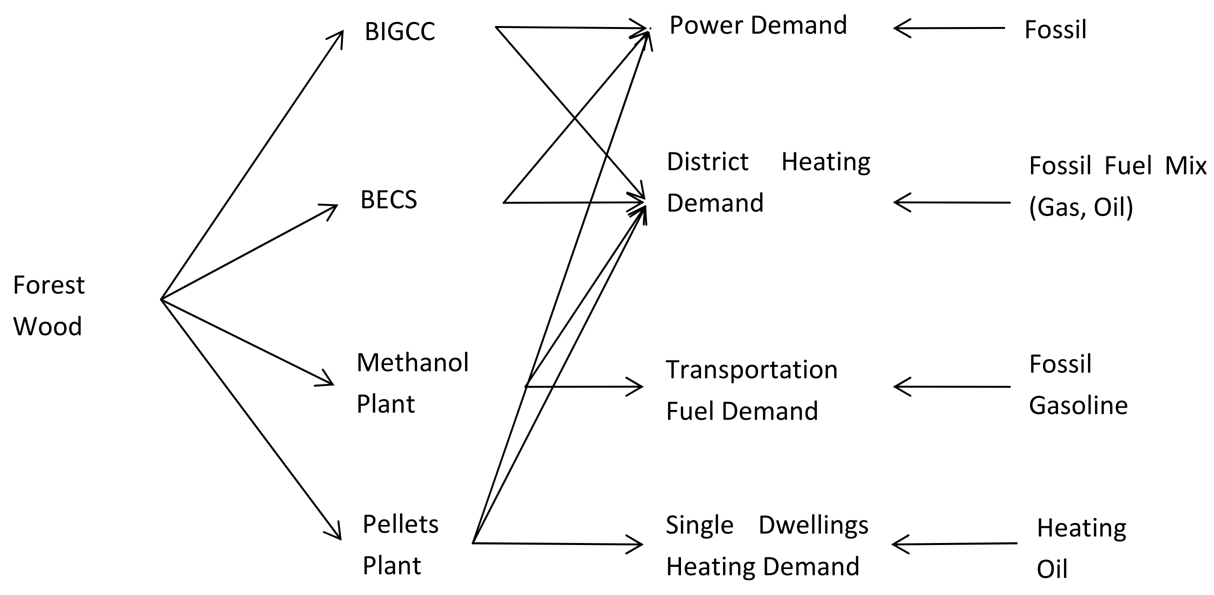

Figure 1: Diagram of the mixed integer programming model.

Table 1: Main model parameters.

Parameter name		Unit	Value	Sources
Investments Costs Plants (100 MW Size)				
BIGCC		Million €	66.42	(Dornburg and Faaij, 2001; Marbe et al., 2004; Uddin and Barreto, 2007)
BECS[a]		Million €	7.82	(Azar et al., 2006; Rhodes and Ketih, 2005; Uddin and Barreto, 2007)
Methanol		Million €	97.33	(Hamelinck and Faaij, 2001)
Pellets[b]		Million €	10.00	(Polagye et al., 2007; Thek and Obernberger, 2004)
Variable Production Costs[c]				
BIGCC		€ $MWh_{biomass}^{-1}$	4.14	(Dornburg and Faaij, 2001; Marbe et al., 2004; Uddin and Barreto, 2007)
BECS[d]		€ $MWh_{biomass}^{-1}$	4.14	(Dornburg and Faaij, 2001; Marbe et al., 2004; Uddin and Barreto, 2007)
Methanol		€ $MWh_{biomass}^{-1}$	2.09	(Hamelinck and Faaij, 2001)
Pellets		€ $MWh_{biomass}^{-1}$	1.77	(Polagye et al., 2007; Thek and Obernberger, 2004)
Efficiency				
Commodity	*Plant Type*			
Power	BIGCC		0.39	(Dornburg and Faaij, 2001; Marbe et al., 2004; Uddin and Barreto, 2007)
	BECS		0.29	(Azar et al., 2006; Rhodes and Ketih, 2005; Uddin and Barreto, 2007)
	Pellets		0.05	(Polagye et al., 2007; Thek and Obernberger, 2004)
Heat	BIGCC		0.45	(Dornburg and Faaij, 2001; Marbe et al., 2004; Uddin and Barreto, 2007)
	BECS		0.44	(Azar et al., 2006; Rhodes and Ketih, 2005; Uddin and Barreto, 2007)
	Methanol		0.08	(Leduc et al., 2009a; Leduc et al., 2008)
	Pellets		0.03	(Polagye et al., 2007; Thek and Obernberger, 2004)
Methanol	Methanol		0.57	(Hamelinck and Faaij, 2001)
Pellets	Pellets		0.82	(Polagye et al., 2007; Thek and Obernberger, 2004)
Other Parameters				
Costs CCS		€ tCO_2^{-1}	27.34	(Azar et al., 2006; Rhodes and Ketih, 2005; Uddin and Barreto, 2007)
Transportation Costs		€ $MWh_{biomass}^{-1}$ km^{-1}	0.04	(Gronalt and Rauch, 2007; Leduc et al., 2008)
Local Heating Costs		€ MWh_{heat}^{-1}	80.00	(Schmidt et al., 2009b; Styles and Jones, 2007)
Emission Savings BECS		tCO_2 $MWh_{biomass}^{-1}$	0.30	(Azar et al., 2006; Rhodes and Ketih, 2005; Uddin and Barreto, 2007)
Biomass Elasticity				(Schwarzbauer, 1997)
Small Property			0.40	
Large Property			0.50	
State Owned			0.70	

[a]additional to standard CHP costs, [b]without CHP unit, [c]not including biomass costs, [d]without carbon capture and storage

from the supply sites to the bioenergy plants produces CO_2 emissions which are included in the model. The model tracks CO_2 emissions from biomass transportation as well as CO_2 emissions produced by fossil fuels. Negative emission factors are applied to BECS to consider the effect of CCS. The choice of fossil reference technologies influences model results significantly. Emission reductions achieved by bioenergy technologies as well as the economic competitiveness depend on the reference technologies. We assume that bioenergy replaces fossil fuels which are currently (year 2009) in use in Austria. Model results refer CO_2 emission reductions and costs to a baseline scenario that comprises current fossil fuel consumption. BIGCC and BECS are, unlike other renewable energy technologies, able to produce base and peak load power similar to thermal power plants based on fossil fuels. In the model, power production therefore competes with the mix of fossil fuels currently consumed in power production in Austria. Methanol is blended with gasoline for utilization in transportation sector (Leduc et al., 2008) and is therefore regarded as direct substitute of gasoline. Wood pellet boilers most likely replace heating oil boilers because they are similar in operation and both need fuel storage space (Gustavsson et al., 2005). District heating replaces the mix of fuels that was previously consumed by local furnaces within the dwellings. The CO_2 emission factor of the heating fuel mix is determined by weighting CO_2 emission factors of single fuels with the amount of the fuel currently consumed in the settlement. CO_2 emission reductions for the different bioenergy technologies with regard to the reference technologies and costs of reference technologies can be found in Table 1 and Table 2.

Table 2: Emissions and costs of the reference technologies based on fossil fuels.

Bioenergy Product	**Fossil Reference Technology**	**Emissions of Reference Technology** ($tCO_2\ MWh^{-1}$)	**Costs of Reference Technology determined by**
Pellets	Heating oil furnaces	0.28	Fuel costs determined by heating oil price on international stock markets (Energy Information Administration, 2009). Investment costs for pellet furnaces are estimated to be higher than those of oil furnaces by 345€ kW^{-1}.
Power	Fossil fuel mix in Austrian power production. Average 2003-2007: - 40% Coal - 8% Oil - 52% Gas	0.57	Power Price at European Energy Exchange (European Energy Exchange, 2009).
District Heating	Heat produced in current local furnaces (Fuel mix in settlement)	0.10-0.35 (depending on settlement)	Heat prices charged by district heating utilities as indicator for local heating costs (Rolfsman and Guastafsson, 2002; Schmidt et al., 2009b; Sjödin and Henning, 2004).
Methanol	Gasoline	0.26	Gasoline price on international stock markets (Energy Information Administration, 2009).

2.4. Energy demand

Heating demand is estimated spatially explicit with a bottom up model that combines average consumption values with private dwelling areas and with the number of employees for commercial buildings and industrial applications. The bottom up model is validated with national consumption values for heating fuels. Heating demand is estimated in cells of 1 km^2 size. The costs of the district heating infrastructure are determined by applying an exponential cost function that depends on heat demand density. Cells where the costs for district heating infrastructure are higher than the costs of the competing fossil heating technology are excluded in the optimization model. Therefore, the model complexity can be reduced without loosing accuracy of results, because cells where the district heating infrastructure alone is more costly than total heat generation costs of competing technologies will not be selected in our scenario analyses. The demand for heat in non-district heating areas is determined by dwellings that are currently heated by oil boilers. Pellets use is restricted to those buildings (Gustavsson et al., 2005). A detailed description of the heating demand model can be found in (Schmidt et al., 2009b). Transportation fuel consumption is estimated based on the spatial distribution of the population, which is combined with the average gasoline consumption per capita in the year 2006 (Statistik Austria, 2007).

2.5. Optimization model

A MIP model, that builds on previous work published in (Leduc, 2009; Leduc et al., 2009a; Leduc et al., 2009b; Leduc et al., 2009c; Leduc et al., 2008; Leduc et al., 2009d; Schmidt et al., 2009a, 2009b) is used to minimize the costs for supplying demand regions (index *k*) with different forms of energy products (index *d*) from either biomass plants or fossil fuels. Biomass is transported from supply regions (index *i*) to possible plant locations (index *j*) where different conversion technologies (index *l*) may be employed to produce different commodities (index *c*). Ethanol, methanol and pellets are transported to the demand regions by truck. Power is directly distributed to the power grid, while heat is delivered to the settlements (index *h*) using pipelines of different sizes (index *ps*). District heating networks of different sizes (index *ns*) have to be built in the settlements to allow heat distribution. Bioenergy competes with fossil fuels (index f). Figure 2 shows the overall scheme of the model. It is static and models one year of operation. All investment costs are annualized assuming an interest rate of 10% and 25 years of economical lifetime. Heating seasons (index t) are used to differentiate between seasonal heating demands.

The total costs in the objective function $f(\mathrm{b},\mathrm{z},\mathrm{q},\mathrm{u})$ are minimized:

$$f(\mathrm{b},\mathrm{z},\mathrm{q},\mathrm{u}) = \sum_{i,o,u} \frac{\varepsilon_o}{1+\varepsilon_o} \hat{q}_{i,o}\, \hat{p}\left(q_u^*\right)^{\frac{1}{\varepsilon_o}} q_u^* b_{i,o,u} + \sum_{i,j,l}\left(c_{i,j,l}^{transb} + c_{j,l}^{prod} + e_l^{ccs} c^{ccs}\right)\mathrm{b}_{i,j,l} + \sum_{j,l} c_{j,l}^{plant}\mathrm{u}_{j,l}^{plant} + \\ + \sum_{j,k,c}\left(c_{j,k,c}^{transc} + c_c^{inv}\right)\mathrm{z}_{j,k,c}^{bio} + \sum_{k,f} c_f^{fossil}\mathrm{z}_{k,f}^{fossil} + \sum_{j,h,ps} c_{j,h,ps}^{pipe}\mathrm{u}_{j,h,ps}^{pipe} + \sum_{h,ns} c_{h,ns}^{dnet}\mathrm{u}_{h,ns}^{dnet} \\ + \sum_{h,t} c_t^{peak}\mathrm{q}_{h,t}^{peak} + \sum_{h,t} c_t^{local}\mathrm{q}_{h,t}^{local} + c^{em}\,\mathrm{totem} \tag{1}$$

where (2)

$$\mathrm{totem} = tx^s\left(\sum_{i,j} e_{i,j}^{trans}\mathrm{b}_{i,j,l} + \sum_{j,k,c} e_{j,k,c}^{trans}\mathrm{z}_{j,k,c} + \sum_{h,t} e_h^{local}\mathrm{q}_{h,t}^{local}\right) + \left(tx_f^f \sum_{k,f} e_f^{fossil}\mathrm{z}_{k,f}^{fossil} + \sum_{h,t} e_{h,t}^{peak}\mathrm{q}_{h,t}^{peak} - \sum_{i,j,l} e_l^{ccs}\mathrm{b}_{i,j,l}\right)$$

The different summands in the objective function represent:

1. Biomass supply costs as described in Appendix A.
2. biomass transportation costs (parameter $c_{i,j,l}^{transb}$), bioenergy production costs (parameter $c_{j,l}^{prod}$) and carbon capture and storage costs (parameter c^{ccs} times the amount of CO_2 emissions captured by unit of biomass e_l^{ccs}) times the amount of biomass (variable $\mathrm{b}_{i,j,l}$).
3. Annualized costs of plant investments (parameter $c_{j,l}^{plant}$) times the binary variable for plant selection ($\mathrm{u}_{j,l}^{plant}$).
4. Costs for transporting energy commodities to demand regions (parameter $c_{j,k,c}^{transc}$) plus investment costs (parameter c_c^{inv}) times the amount of commodities (variable $\mathrm{z}_{j,k,c}^{bio}$). Costs for power transportation and investment are zero as it is assumed that the power can be sold directly to the power grid. For ethanol, methanol and pellets, transportation costs from plants to demand regions by truck are considered. Investment costs c_c^{inv} are zero for biofuels, because no additional investments are necessary to operate cars with ethanol or methanol. For pellets, the investment costs represent the average difference between a pellets boiler and an oil boiler per unit of useful energy produced.
5. Costs for fossil fuels (parameter c_f^{fossil}) times the amount of fossil fuels used in a demand region (variable $\mathrm{z}_{k,f}^{fossil}$).
6. Annualized costs of building a pipeline from the plant to the settlement (parameter $c_{j,h,ps}^{pipe}$) times the binary variable for pipeline selection ($\mathrm{u}_{j,h,ps}^{pipe}$).
7. Annualized costs for installing a district heating network in the settlement (parameter $c_{h,ns}^{dnet}$) times the binary variable for district heating network selection ($\mathrm{u}_{h,ns}^{dnet}$).
8. Costs for producing peak heat (parameter c_t^{peak}) for district heating times the amount of peak heat (variable $\mathrm{q}_{h,t}^{peak}$) produced.
9. Costs for producing local heat including investment and fuel costs (parameter c_t^{local}) times the amount of local heat (variable $q_{h,t}^{local}$) produced.
10. Total CO_2 emissions ($totem$) which consist of: (i) CO_2 emissions of biomass transportation (CO_2 emission factor $e_{i,j}^{trans}$), (ii) CO_2 emissions of commodity transportation (CO_2 emission factor $e_{j,k,c}^{trans}$), (iii) CO_2 emissions of fossil energy production (CO_2 emission factor e_f^{fossil}), (iv) CO_2 emissions of local heating systems (CO_2 emission factor e_h^{local}), (v) CO_2 emissions of peak heat production (CO_2

emission factor $e_{h,t}^{peak}$), and (vi) CO_2 emission savings by BECS in bioenergy production (CO_2 emission factor e_l^{ccs}). Total CO_2 emissions ($totem$) are multiplied by the CO_2 price (parameter c^{em}). Binary parameters tx^s and tx_f^f control if all fossil fuels or only part of the fossil fuels is taxed by a specific policy instrument.

The objective function in equation (1) is minimized subject to the following constraints. Biomass utilization (variable $\mathrm{b}_{i,j,l}$) in the plants is restricted by

$$\sum_{j,l} \mathrm{b}_{i,j,l} \le \sum_{o,u} \hat{q}_{i,o} \left(q_u^*\right)^{\frac{1}{\varepsilon_o}} q_u^* b_{i,o,u}, \tag{3}$$

as described in detail in Appendix A. The convexity condition necessary for the linearization of the supply curve is guaranteed by:

$$0 \le \sum_u b_{i,o,u} \le 1. \tag{4}$$

The plant size constraints production by

$$\sum_i \mathrm{b}_{i,j,l} \le \bar{b}_{j,l}\, \mathrm{u}_{j,l}^{plant}, \tag{5}$$

where parameter $\bar{b}_{j,l}$ is the production capacity of plant j using technology l. The commodity production (variable $\mathrm{z}_{j,c}^{bio}$) is determined by the biomass input and conversion efficiency (parameter $\eta_{j,l,c}^{conv}$) shown in the following equation:

$$\sum_{i,l} \eta_{j,l,c}^{conv} \mathrm{b}_{i,j,l} = \mathrm{z}_{j,c}^{bio}\ . \tag{6}$$

District heat production is modeled with variable q_j^{bio} because it is distributed differently than the other commodities:

$$\sum_{i,l} \eta_{j,l}^{heat} \mathrm{b}_{i,j,l} = \mathrm{q}_j^{bio}, \tag{7}$$

where $\eta_{j,l}^{heat}$ is the conversion efficiency for heat. Distribution of commodities to demand regions *k* is restricted by

$$\sum_k \mathrm{z}_{j,k,c}^{bio} \le \mathrm{z}_{j,c}^{bio}\ , \tag{8}$$

where variable $\mathrm{z}_{j,k,c}^{bio}$ denotes the amount of a commodity c transported from plant location j to demand region k.

Energy demands (parameter $d_{k,d}$) are satisfied by different commodities from bioenergy production (variable $z_{j,k,c}^{bio}$) and by fossil fuels (variable $z_{k,f}^{fossil}$):

$$\sum_{j,c} \eta_{c,d}^{bio} z_{j,k,c}^{bio} + \sum_{f} \eta_{f,d}^{fossil} z_{k,f}^{fossil} = d_{k,d} . \quad \textbf{(9)}$$

In the equation, parameter $\eta_{c,d}^{bio}$ ($\eta_{f,d}^{fossil}$) describes the efficiency of converting bioenergy commodities (a fossil fuel) to forms of useful energy.

The policy instruments are implemented in the following way: the price of carbon emissions is controlled by the value of c^{em} . The binary parameters tx^{s} and tx_{f}^{f} control which CO_2 emissions are taxed by the particular policy instrument. Feed-in tariffs are modeled by setting the fossil power price c_{f}^{fossil} to the level of the tariff. The investment costs for pellet furnaces c_{c}^{inv} are decreased in the pellet subsidy scenario. The compliance with biofuel blending obligations is guaranteed by

$$\sum_{j} z_{j,c}^{bio} \geq f_{c,d}^{blend} \sum_{k} d_{k,d} \quad \textbf{(10)}$$

where $f_{c,d}^{blend}$ is the mandatory share of a bioenergy commodity in total useful energy demand. The part of the model handling the usage of surplus heat for district heating and the district heating infrastructure can be found in Appendix B.

The MIP is finally defined as:

$$\min\left[f\left(\mathrm{b}, z, \mathrm{q}, \mathrm{u}\right)\right] \quad \textbf{(11)}$$

$$s.t.$$

$$\left(3\right) - (10), (B.1) - (B.5)$$

$$0 \leq \mathrm{b}_{i,j,l}, \mathrm{z}_{j,c}^{bio}, \mathrm{z}_{j,k,c}^{bio}, \mathrm{z}_{k,f}^{fossil}, \mathrm{q}_{j}^{bio}, \mathrm{q}_{h,t}^{peak}, \mathrm{q}_{j,h,ps,t}^{dh}, \mathrm{q}_{h,t}^{local}$$

$$\mathrm{u}_{h,ns}^{dnet}, \mathrm{u}_{j,h,ps}^{pipe}, \mathrm{u}_{j,l}^{plant} \in \left\{0,1\right\}.$$

2.6. Policy scenarios

We assess the cost-effectiveness of five energy policy instruments with respect to reducing CO_2 emissions and substituting fossil fuels at least costs. Table 3 reports the levels of the policy instruments considered in the analysis. The baseline scenario (BA) does not contain any policy intervention. The TX policy scenario taxes CO_2 emissions of all fossil fuels, including private heating. With respect to CO_2

emission reduction costs, a carbon tax and a CO_2 emission trading scheme that covers all fossil fuels theoretically produce the same reduction costs if the same price is assigned to CO_2 emissions in the two schemes. The model treats both instruments equally. The results of the TX scenario are therefore also applicable to a CO_2 emission trading scheme for all fossil fuels. A further discussion of carbon tax versus CO_2 emission trading schemes can be found in Pope and Owen (2009). The EU ETS is modeled in the TS scenario where the application of a carbon price is limited to the industrial power and heat production only. Trading of allowances in the EU ETS is not modeled explicitly, instead a constant certificate price is assumed. Investment subsidies are guaranteed to pellet furnaces in the PF scenario. Feed-in tariffs that guarantee fixed levels of power prices are modeled in the FT scenario. In the BF scenario, fixed shares of biofuel in transportation fuel consumption are imposed. The technological development, security, and the ecological effects of carbon storage remain unsecure (Holloway, 1997; Thistle et al., 2006; van der Zwaan and Gerlagh, 2009). Therefore, TX and TS are assessed with and without BECS, the respective scenarios are called TXn and TSn. BECS is not relevant in the assessment of the other policy instruments, because none of them selects BECS as conversion technology. Costs, CO_2 emission reductions, and fossil fuel substitutions in the scenarios are compared to a fossil fuel baseline as outlined in section 2.3.

3. Results

3.1. Costs, emission reductions and fossil fuel substitution

Total CO_2 emission reductions, fossil fuel substitution, and biomass utilization for all policy instrument scenarios are presented in Figure 2 and Figure 3. The figures also show the selected conversion technologies for each policy instrument scenario. Technologies chosen in the baseline scenario (BA),

Table 3: Levels of policy instruments considered in the model.

Policy Instrument	Description	Range	Increment
TX	Tax on CO_2 emissions of all fossil fuels	2 € tCO_2^{-1} to 150 € tCO_2^{-1}	2 € tCO_2^{-1}
TS	CO_2 emission trading scheme in industrial power and heat production	2 € tCO_2^{-1} to 150 € tCO_2^{-1}	2 € tCO_2^{-1}
TXn	Tax on CO_2 emissions of all fossil fuels, BECS is not allowed	2 € tCO_2^{-1} to 150 € tCO_2^{-1}	2 € tCO_2^{-1}
TSn	CO_2 emission trading scheme in industrial power and heat production, BECS is not allowed	2 € tCO_2^{-1} to 150 € tCO_2^{-1}	2 € tCO_2^{-1}
PF	Subsidies to pellet furnaces	23 € KW^{-1} to 968 € KW^{-1}	22.5 € KW^{-1}
FT	Feed-in tariffs for biomass power production	70 € MWh^{-1} to 270 € MWh^{-1}	2 € MWh^{-1}
BF	Biofuel shares imposed	0.20 % to 12.00 %	0.20%

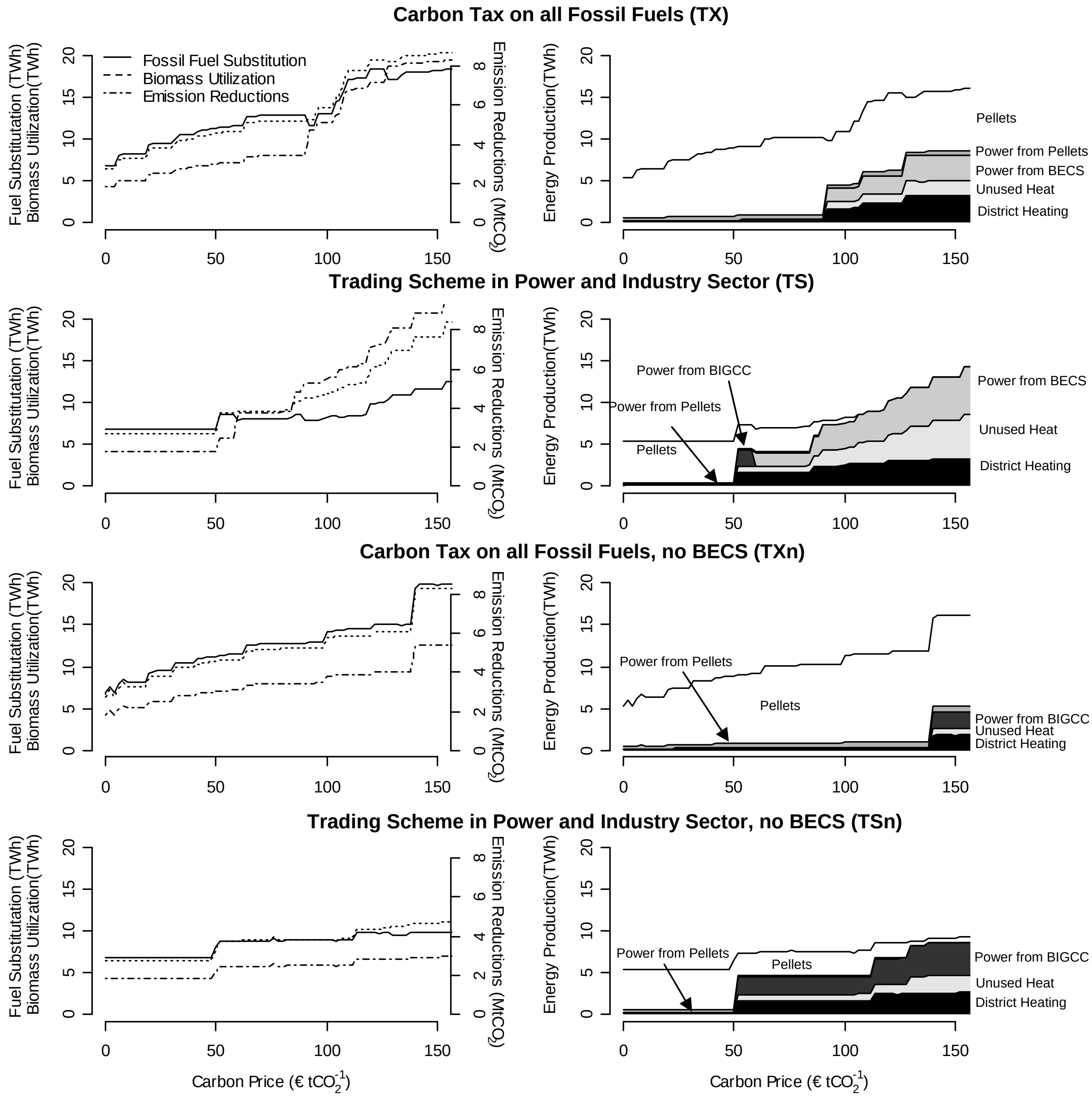

Figure 2: CO_2 emission savings, fossil fuel substitution, biomass usage and technological mix in the CO_2 price scenarios.

which is shown as first point in every figure, are no-regret options, i.e. they are cheaper than the scenario that only applies fossil fuels. In the BA scenario, 1.80 $MtCO_2\ y^{-1}$ are reduced with average costs of -26 € tCO_2^{-1}. Only pellet production is competitive when no energy policy instrument is implemented. In a CO_2 tax system (TX), pellet production is increased at low CO_2 prices and BECS substitutes pellet production if the CO_2 price rises above 92 € tCO_2^{-1}. The additional BECS plants cause an increase in biomass harvests and subsequently an increase in domestic marginal biomass costs. The increased feedstock costs render pellet production unprofitable. The amount of fossil fuels saved per unit of biomass declines when the share of BECS grows in the technological portfolio. The lower conversion

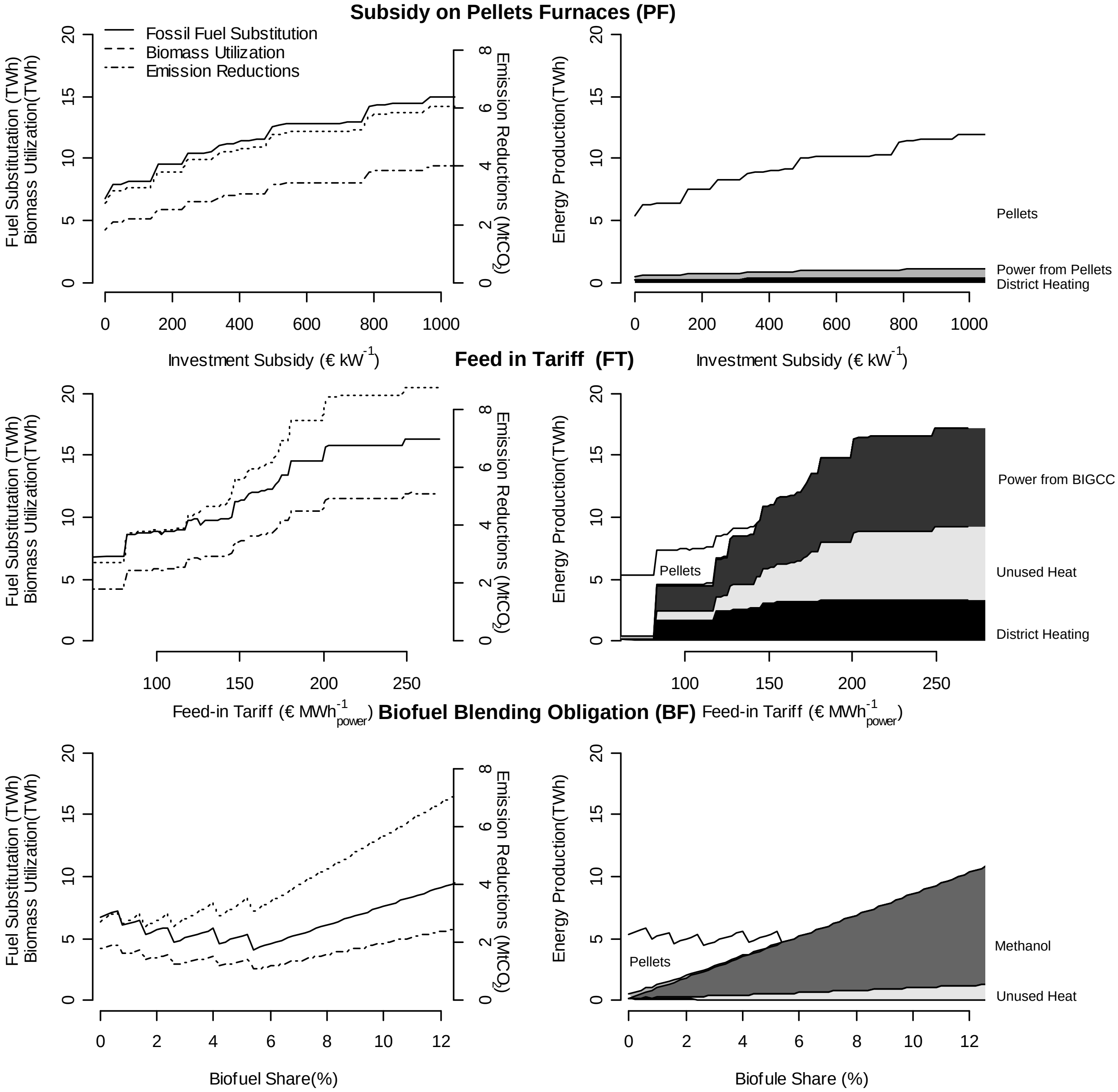

Figure 3: CO_2 emission savings, fossil fuel substitution, biomass usage and technological mix in the additional policy instrument scenarios.

efficiencies of BECS in comparison to pellet production cause the decreasing rate of fossil fuel substitution. In the CO_2 emission trading scheme scenario (TS), CO_2 is only priced in the industrial power and heat production sector. BIGCC replaces pellet production at low CO_2 prices, while BECS replaces BIGCC at CO_2 prices above 60 € tCO_2^{-1}. The rate of fossil fuel substituted per unit of biomass declines. The share of unused surplus heat increases due to restrictions in district heating demand. In the carbon tax scenario that does not allow BECS (TXn), pellet production is the main technological option. However, demand for pellets is constrained by the amount of heating oil that can be replaced by pellets. At a CO_2 price of 140 € tCO_2^{-1} pellet production substitutes the total demand for heating oil and BIGCC is used as additional option to reduce CO_2 emissions. In the CO_2 emission trading scenario without BECS (TSn), pellet production is gradually substituted by BIGCC production. The rate of biomass utilization to fossil fuel substitution declines with increasing shares of BIGCC. In the low cost area, emission reductions and fossil fuel substitutions are cost-effectively achieved in the pellet policy (PF). The pellet policy scenario has, however, an upper limit because of demand limitations. All Austrian single-dwelling heating oil boilers are replaced by pellet boilers at an investment subsidy level of 967.5 € kW^{-1}. BIGCC replaces pellet production in the feed-in tariff scenario (FT) causing a declining rate of fossil fuel substitution per unit of biomass. It can also be observed that the rate of heat used for district heating purposes declines, i.e. heat is wasted because there are not sufficient settlements that can be used as heat sink. Increasing the bioenergy utilization by imposing a mandatory blend of biofuels with fossil gasoline (BF) is an expensive and an ineffective option to mitigating climate change and substituting fossil fuels. Emission reductions and fossil fuel substitution in comparison to the baseline scenario are negative for low biofuel blends and only positive when biofuel legislation imposes blends of gasoline that contain more than 9.2% of biofuel.

3.2. Cost-effective policy instrument comparisons

Cost-effectiveness policy instruments in reducing emissions and substituting fossil fuels are shown in Figure 4. The graph shows that BF causes a decline in CO_2 emission reductions and fossil fuels substituted in comparison to the baseline scenario. The feed-in tariff (FT) rates second worst with regard to emission reductions but is better than the CO_2 emission trading scheme (TS) in substituting fossil fuels. The graph shows similarities between the FT scenario and the TS scenario for low carbon prices. In TS, BIGCC – the exclusive technological option in FT – is chosen as mitigation option at low CO_2 prices. At higher prices, BECS is viable in the TS scenario and therefore the effects of FT and TS start to diverge. It can be observed that the FT scenario and the TSn scenario behave identically because BIGCC is the exclusive technology at all levels for both policy instruments. Scenarios TX, TXn and PF are similar at low CO_2 prices, because pellets are the cheapest option in the three scenarios. Therefore identical technological

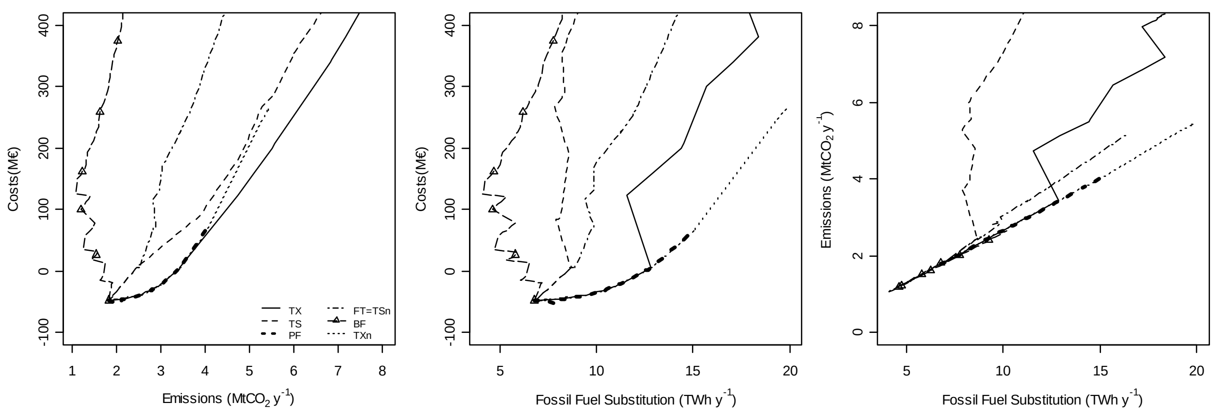

Figure 4: CO_2 emission reductions (left) and fossil fuels substituted (middle) in relation to costs as well as CO_2 emission reductions in relation to fossil fuels substitution (right).

choices are made. However, when BECS is introduced in the TX scenario and BIGCC in the TXn scenario at higher CO_2 prices then the scenario effects diverge. The fossil fuel substitution declines significantly in the TX scenario while increases in fossil fuel substitution remain almost constant in the PF and TXn scenarios. CO_2 emission reductions in the TX scenario are highest of all policy instruments. Considering the policy objectives with respect to cost-effective fossil fuel substitution and CO_2 emission reduction at minimal costs, a comparison of the policy instruments can be achieved by selecting those policy instruments that perform better than any other instrument in one of the three aspects. A sorting algorithm yields that only TX, TXn and PF are effective with this regard.

3.3. Wood supply and utilization

Biomass utilization in the model can go up to 20 TWh y^{-1}. The biomass consumption is additional to the consumption observed currently which reaches 19 TWh (Hagauer et al., 2007; Lebensministerium, 2009). Marginal biomass costs are significantly higher at high utilization levels than currently observed. The model applied in Schmidt et al. (2009b) and results of a study on the potentials of forest wood production (Schadauer, 2004) estimate that the maximum sustainable yield (MSY) of fuel wood from Austrian forests is around 38 TWh y^{-1} assuming that round wood production and forest land cover remain constant at current levels. Therefore, additional supply of around 19 TWh y^{-1} of forest wood is available in a sustainable manner when the current consumption of 19 TWh is taken into account. At the MSY, the marginal costs are at 70 € MWh^{-1}, compared to current levels of 14 € MWh^{-1}. Although marginal costs of domestic forest biomass supply increase significantly, biomass is still utilized at high policy instrument interventions as shown in Figure 2 and Figure 3.

3.4. Sensitivity analysis on fossil fuel prices

Previous sensitivity analysis of the model (Schmidt et al., 2009a, 2009b) have shown that fossil energy prices have the most significant influence on model results. Uncertainties in the development of the costs and efficiencies of the technologies are less important. Instead of conducting a full sensitivity analysis on all model parameters, we only analyze the cost-effectiveness performance of policy instruments at changing price levels of fossil fuels. The main focus of the analysis is to determine if the effectiveness of the instruments with regard to the two policy objectives - CO_2 emission reductions and fossil fuel substitution - when different fossil fuel price levels exist. All policy instrument scenarios have been run with a high and a low fossil fuel price level additionally to the standard price scenario in the previous analysis (see Table 4). Annual energy prices from 2004 to 2008 serve as data source for the high and low price scenarios (Energy Information Administration, 2009; European Energy Exchange, 2009).

Scenario	Power (€ MWh^{-1})	Heating Oil (€ MWh^{-1})	Gasoline (€ MWh^{-1})
Standard	52	44	39
Low	31	28	32
High	66	52	44

Table 4: Energy prices used in the sensitivity analysis.

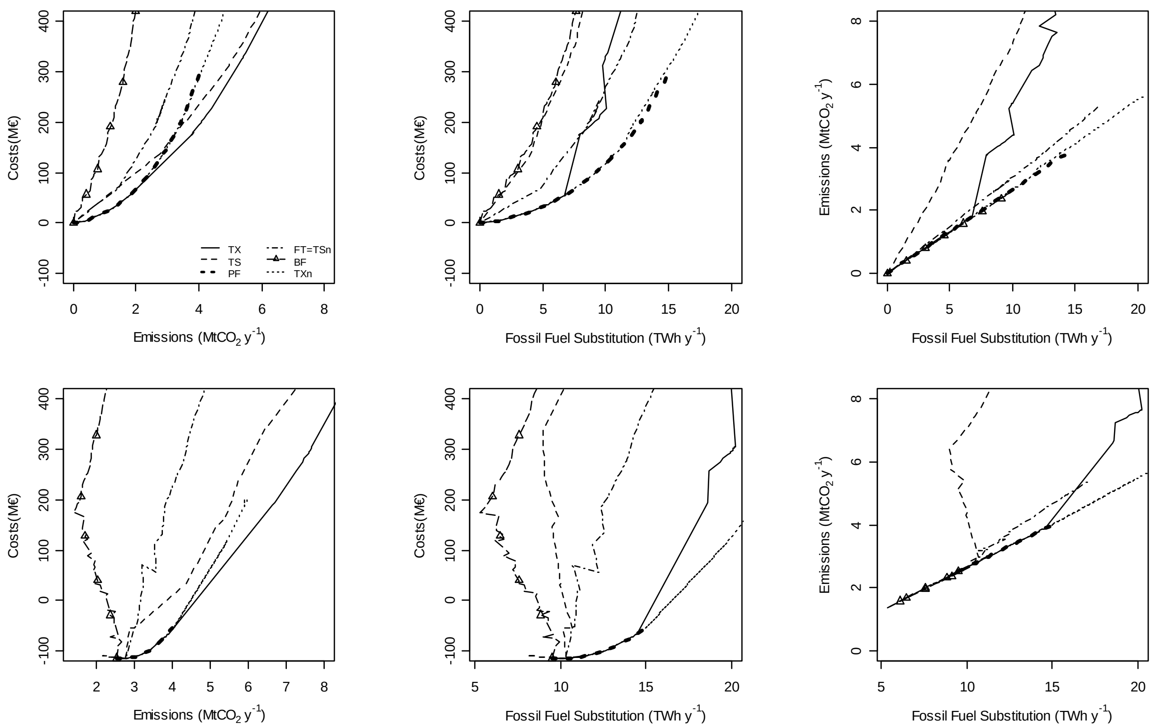

Figure 5: Costs, CO_2 emissions, and fossil fuel substitution in a low (above) and high price scenario (below).

Figure 5 shows the results of the model analysis. At low fossil fuel prices, there are none no-regret options. At high fossil fuel prices, 2.52 $MtCO_2\ y^{-1}$ of CO_2 emissions are reduced without any policy intervention. In the TX scenario, the total costs of CO_2 emission reductions are negative up to a level of 3.87 $MtCO_2\ y^{-1}$. In the average price scenario, this point is reached at 3.08 $MtCO_2\ y^{-1}$. The effectiveness of the policy instruments does not change neither in the low nor in the high scenario, i.e. TX, TXn and PF remain the policy instruments that achieve emission reductions and fossil fuel substitution at least costs. However, absolute system costs differ significantly between the scenarios.

4. Discussion and conclusions

Model results show clearly that the biofuel blending obligation introduced in Austria in 2003 is very expensive and ineffective in achieving the policy objectives considering second generation biofuels, which are considered more energy efficient than first generation fuels from agricultural crops. Fossil fuel substitution and CO_2 emission reductions are both not effectively attained with the current biofuel blending obligation policy instrument. Carbon taxes on all energy sectors are the most cost-effective way of reducing CO_2 emissions. CO_2 emission reductions are much bigger than fossil fuel substitution. However, the trade-off between CO_2 emission reductions and fossil fuel substitution is only relevant for high carbon prices when BECS is introduced. Subsidies for pellet heaters have a comparable performance to a carbon tax. The total performance potentials of this policy instrument are limited due to demand restrictions in the heating sector. A CO_2 trading scheme in the industry sector causes a removal of pellet production from the technological portfolio because the private households have no incentive to switch heating systems in such a scheme. CO_2 emission savings and fossil fuel substitution are therefore smaller than in the tax scenario where all fossil fuels are priced according to their carbon content. If BECS does not become available within the next years, a tax on all fossil fuels is still the most cost-effective way of reducing CO_2 emissions. Total CO_2 emission reduction potentials are significantly lower than with BECS, but fossil fuel substitution is higher. Feed-in tariffs and a CO_2 emission trading scheme show, when BECS is not allowed, same costs and reduction potentials and both are not cost-effective compared to the other policy instruments. All of the modeled policy instruments, besides the carbon tax on all fossil fuels, are currently in place in Austria.

Several reasons may explain why current instruments are implemented although they are not cost-effective in reaching energy policy goals. The most common reason is that other policy objectives shall be attained as well. For instance, technology specific policy instruments like feed-in tariffs perform badly with respect to our policy objectives, but may be necessary to trigger future technological developments (Sandén and Azar, 2005). Biofuel blending obligations are considered measures for rural economic development despite being costly (Berndes and Hansson, 2007; Lehrer). Nevertheless, rural development goals can be more efficiently combined with energy policy goals if biomass resources are directed to other conversion chains than transportation fuel production, i.e. heat or power production. National statistics confirm the recent trend to biomass based heat and power production, resulting from policy interventions in the sector: the number of dwellings heated by biomass increased by 13% from 2003/2004 to 2007/2008, which has resulted in an estimated increase of around 2 $TWh_{biomass}$ (Statistik Austria, 2009). Furthermore, biomass based power production has increased by about 1 TWh in the same period (E-Control, 2009).

Our model results also confirm other research findings. Fuel production is rated worst with respect to cost-effectiveness and CO_2 emission offsets (Grahn et al., 2007; Wahlund et al., 2004). All results depend on our assumed CO_2 emission baseline. Outside of the bioenergy sector, various new CO_2 emission reduction technologies like photovoltaic and wind for the power sector, insulation and solar heating for the heating sector, and electric vehicles in the transportation sector are emerging. Assuming different baseline CO_2 emissions in the bioenergy scenarios – e.g. a power sector with low fossil fuel consumption – changes the relative techno-economic efficiency of bioenergy technologies and therefore also the relative cost-effectiveness of policy instruments. While it does not matter in the assessment of the technology specific instruments – i.e. the biofuel blending obligations, the pellet subsidy and the feed-in tariffs - including additional low carbon technologies in the model have significant influence on model results in the CO_2 price scenarios. The low supply elasticities of forest wood, particularly for small forest owners, indicate that additional supply will be costly to mobilize although maximum sustainable yields are currently not attained. Total bioenergy systems costs mainly depend on costs of additional wood harvests. Incentives to stimulate forest biomass harvests are necessary such as fostering harvesting cooperation and other logistic efforts.

Acknowledgements

The article has been prepared in the framework of the doctoral school Sustainable Development (DOKNE) at BOKU University of Natural Resources and Applied Life Sciences, Vienna, Austria. The doctoral school is funded by the Austrian Research Program on Sustainability “provision” as well as by the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW) and the states Lower Austria, Styria, and Vienna. This article has been also supported by the FP7 project "Climate Change – Terrestrial Adaptation & Mitigation in Europe (ccTAME)" funded by the European Commission and by the Austrian Climate Research Program project "Greenhouse Gas Reduction through Second Generation Biofuels in Austria (GHG-SEBA)".

Appendix

A. Biomass supply

In previous versions of the model (Schmidt et al., 2009a, 2009b) we assumed constant biomass prices and fixed limitations on resource availability which were indicated by the maximum sustainable forest yields (MSY). We extended the model in this article by introducing an inverse biomass supply curve using a constant elasticity function

$$p = Cq^{\frac{1}{\varepsilon}} \tag{A.1}$$

where p is the price, q is the quantity, C is a constant and ε is the supply elasticity. To determine C, a given relation of price and quantity is used, i.e.

$$C = \frac{\hat{p}}{\hat{q}^{\frac{1}{\varepsilon}}} \tag{A.2}$$

where $\hat{p}$ is an observed price and $\hat{q}$ the corresponding quantity in the reference period. Thus, Equation A.2 can be expressed as

$$p = \hat{p}\left(\frac{q}{\hat{q}}\right)^{\frac{1}{\varepsilon}} \tag{A.3}$$

The integral

$$A = \int_0^{q^*} \hat{p}\left(\frac{q^*}{\hat{q}}\right)^{\frac{1}{\varepsilon}} dq = \left(\frac{q^*}{\hat{q}}\right)^{\frac{1}{\varepsilon}} q^* \hat{p} \frac{\varepsilon}{1+\varepsilon} \tag{A.4}$$

yields the area A under the supply curve and thus the biomass supply costs when biomass amount q^* is produced.

Schwarzbauer (1997) estimates different supply elasticities ε_o for different types of forest ownership (index o). Supply elasticities of private owners of small forests are estimated to be lower (around 0.4) than those of private owners of large forests (around 0.5), both are, however, inelastic. The supply elasticities of state managed forests are even higher (around 0.7). Therefore, the model includes three different biomass supply curves with the respective elasticities found in Schwarzbauer (1997). Data on observed quantities $\hat{q}_{s,o}$ by ownership are available on the level of federal states (index s), while price $\hat{p}$ is a single national value because local price variations are not reported (Lebensministerium, 2009). We expect them to be of minor magnitude and account for transportation costs explicitly in the model. To further refine the spatial resolution of the biomass supply, we use spatially explicit estimates on the MSY. Details on the modeling of MSY can be found in Schmidt et al. (2009b). Denoting the MSY of an ownership (index o) in one supply cell (index i) with $\bar{b}_{i,o}$, observed quantity $\hat{q}_{i,o}$ for that cell is determined by

$$\hat{q}_{i,o} = \hat{q}_{s,o} \frac{\bar{b}_{i,o}}{\bar{b}_{s,o}} \tag{A.5}$$

i.e. by simply multiplying the total observed value $\hat{q}_{s,o}$ by the proportion of estimated MSY $\bar{b}_{i,o}$ and total MSY of that state and ownership $\bar{b}_{s,o}$.

Equation A.6 shows a transformation of Equation A.4 where supply by ownership and grid cell are included. The function is convex and can therefore be linearized by separable programming (Jensen and Bard, 2002) which is also shown in the equation:

$$\left(\frac{q^*_{i,o}}{\hat{q}_{i,o}}\right)^{\frac{1}{\varepsilon_o}} q^*_{i,o}\,\hat{p}\,\frac{\varepsilon_o}{1+\varepsilon_o} \approx \frac{\varepsilon_o}{1+\varepsilon_o}\,\hat{q}_{i,o}\,\hat{p}\sum_u \left(q^*_u\right)^{\frac{1}{\varepsilon_o}} q^*_u b_{i,o,u} \quad , \tag{A.6}$$

where parameter q^*_u denotes the share of the observed amount of biomass that is produced, e.g. a value of 0.1 means that 10% of the amount of biomass observed in the reference period is supplied. Variable $b_{i,o,u}$ is a decision variable involved in the separable programming and u is the index of the separable steps. The amount of biomass $b_{i,j,l}$ in a supply cell available for bioenergy production (see model details in section 2.5) is limited by

$$\sum_{j,l} b_{i,j,l} + \hat{q}_{i,o} \le \sum_{o,u} \hat{q}_{i,o} \left(q^*_u\right)^{\frac{1}{\varepsilon_o}} q^*_u b_{i,o,u} \tag{A.7}$$

The observed amount of biomass $\hat{q}_{i,o}$ is added to the left side of equation A.7 because we assume that wood demand of existing consumers remains stable. The following convexity condition is necessary in separable programming:

$$0 \le \sum_u b_{i,o,u} \le 1. \tag{A.8}$$

B. District heating model

Heat production limits the amount of heat available for district heating. The commodity production is modeled on an annual time period. However, variations in heat demand in winter and summer are considered in the model. Seasonal supply of heat in the plant is restricted by

$$\sum_{h,ps} \mathrm{q}_{j,h,ps,t}^{dh} \leq \Delta t_t \mathrm{q}_j^{bio}, \tag{B.1}$$

where parameter Δt_t denotes the relative length of a season.

The production of heat has to meet the demand (parameter $q_{h,t}^{D}$) in each period, which is guaranteed by

$$\eta_{h,t}^{dh}\left(\left(\sum_{j,ps}\eta_{j,h,ps,t}^{trans}\mathrm{q}_{j,h,ps,t}^{dh}\right)+\mathrm{q}_{h,t}^{peak}\right)+\eta_{h,t}^{local}\mathrm{q}_{h,t}^{local}=q_{h,t}^{D}. \tag{B.2}$$

where parameter $\eta_{j,h,ps,t}^{trans}$ denotes the heat losses in the pipe system from the plant to the settlement. Losses in the heat distribution network within the settlement are modeled by parameter $\eta_{h,t}^{dh}$. Parameter $\eta_{h,t}^{local}$ is introduced to describe conversion efficiencies of local heating systems.

The sum of heat produced by the bioenergy plant and by the peak demand boiler has to match the district heating demand (parameter $q_{h,ns,t}^{D}$) in settlement h. This is modeled by

$$\eta_{h,t}^{dh}\left(\left(\sum_{j,ps}\eta_{j,h,ps,t}^{trans}\mathrm{q}_{j,h,ps,t}^{dh}\right)+\mathrm{q}_{h,t}^{peak}\right)=\sum_{ns}q_{h,ns,t}^{D}\mathrm{u}_{h,ns}^{dnet}. \tag{B.3}$$

The existence of a transportation pipeline, in case a settlement is supplied by a bioenergy plant, is ensured by

$$\mathrm{q}_{j,h,ps,t}^{dh} \leq \bar{q}_{ps,t}^{pipe}\,\mathrm{u}_{j,h,ps}^{pipe}, \tag{B.4}$$

where parameter $\bar{q}_{ps,t}^{pipe}$ denotes the capacity of the pipeline.

Only one district heating network can be built in every settlement, which is ensured by

$$\sum_{ns}\mathrm{u}_{h,ns}^{dnet} \leq 1. \tag{B.5}$$

References

Ammann, H., Brecht I., Albisser Vögeli, G., 2009. Comparison of wood-fired heating systems. Agrarforschung 16, 64-69.

Azar, C., Lindgren, K., A., A.B., 2003. Global energy scenarios meeting stringent CO2 constraints - cost-effective fuel choices in the transportation sector. Energy Policy 31, 961-976.

Azar, C., Lindgren, K., Larson, E., Möllersten, K., 2006. Carbon capture and storage from fossil fuels and biomass - costs and potential role in stabilizing the atmosphere. Climate Change 74, 47-79.

Berndes, G., Hansson, J., 2007. Bionergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. Energy Policy 35, 5965-5979.

Bram, S., De Ruyck, J., Lavric, D., 2009. Using biomass: A system perturbation analysis. Appl. Energy 86, 194-201.

Dornburg, V., Faaij, A.P.C., 2001. Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies. Biomass Bioenergy 21, 91-108.

E-Control, 2009. Development of approved green power plants according to decisions of provincial governments (Entwicklung der anerkannten Ökostromanlagen laut Bescheiden der Landesregierungen). E-Control, Vienna.

Energy Information Administration, 2009. Official Energy Statistics from the U.S. Government. Energy Information Administration, Washington.

Eriksson, L.O., Björheden, R.W., 1989. Optimal storing, transport and processing for a forest-fuel supplier. European Journal of Operational Research 43, 26-33.

European Council, 2002. Council Decision of 25 April 2002 concerning the approval, on behalf of the European Community, of the Kyoto Protocol to the United Nations Framework Convention on Climate Change and the joint fulfilment of commitments thereunder Official Journal

European Energy Exchange, 2009. Market Data. European Energy Exchange.

Faaij, A., 2006. Modern Biomass Conversion Technologies. Mitigation and Adaptation Strategies for Global Change 11, 335-367.

Fatih Demirbas, M., 2009. Biorefineries for biofuel upgrading: A critical review. Appl. Energy 86, S151-S161.

Gielen, D.J., Fujino, J., Hasimoto, S., Moriguchi, Y., 2003. Modeling of global biomass policies. Biomass Bioenergy 25, 177-195.

Grahn, M., Azar, C., Lindgren, K., Berndes, G., Gielen, D., 2007. Biomass for heat or as transportation fuel? A comparison between two model-based studies. Biomass Bioenergy 31, 747-758.

Grohnheit, P.E., Mortensen, B.O.G., 2003. Competition in the market for space heating. District heating as the infrastructure for competition among fuels and technologies. Energy Policy 31, 817-826.

Gronalt, M., Rauch, P., 2007. Designing a regional forest fuel supply network. Biomass & Bioenergy 31, 393-402.

Gustavsson, L., Mahapatra, K., Madlener, R., 2005. Energy systems in transition: perspectives for the diffusion of small-scale wood pellet heating technology. Int. J. Technol. Manage. 29, 327-347.

Hagauer, D., Lang, B., Nemestothy, K., 2007. Woodflow Austria 2005. Austrian Energy Agency.

Hamelinck, C.N., Faaij, A.P.C., 2001. Future prospects for production of methanol and hydrogen from biomass. J. Power Sources 111, 1-22.

Holloway, S., 1997. Safety of the Underground Disposal of Carbon dioxide. Energy Convers. Manage. 38, 241-245.

Jensen, P.A., Bard, J.F., 2002. Operations Research Models and Methods. Wiley.

Kraxner, F., Nilsson, S., Obersteiner, M., 2003. Negative emissions from BioEnergy use, carbon capture and sequestration (BECS) - the case of biomass production by sustainable forest management from semi-natural temperate forests. Biomass Bioenergy 24, 285-296.

Lebensministerium, 2007. National Allocation Plan for Austria for the period 2008-2012 (Nationaler Zuteilungsplan für Österreich gemäß § 11 Emissionszertifikategesetz für die Periode 2008-2012). Lebensministerium,, Vienna.

Lebensministerium, 2009. Logging Report 2008 (Holzeinschlagsmeldung 2008). Lebensministerium, Vienna.

Leduc, S., 2009. Development of an Optimization Model for the Location of Biofuel Production Plants, Department of Applied Physics and Mechanical Engineering. Luleå University.
Leduc, S., Lundgren, J., Franklin, O., Schmid, E., Dotzauer, E., 2009a. Location of a biomass based methanol production plant: a dynamic problem in northern sweden. Appl. Energy 87, 68-75.
Leduc, S., Natarajan, K., Dotzauer, E., McCallum, I., Obersteiner, M., 2009b. Optimizing biodiesel production in India. Appl. Energy 86, S125-S131.
Leduc, S., Schmid, E., Obersteiner, M., Riahi, K., 2009c. Methanol production by gasification using a geographically explicit model. Biomass Bioenergy 33, 745-751.
Leduc, S., Schwab, D., Dotzauer, E., Schmid, E., Obersteiner, M., 2008. Optimal location of wood gasification plants for methanol production with heat recovery. Int. J. Energy Res. 32, 1080-1091.
Leduc, S., Starfelt, F., Dotzauer, E., Kindermann, G., McCallum, I., Obersteiner, M., Lundgren, J., 2009d. Optimal location of ethanol ligno-cellulosic biorefineries with polygeneration in Sweden. Energy. doi:10.1016/j.energy.2009.07.018
Lehrer, N., (Bio)fueling farm policy: the biofuels boom and the 2008 farm bill. Agriculture and Human Values. doi: 10.1007/s10460-009-9247-0
Marbe, G., Harvey, S., Berntsson, T., 2004. Biofuel gasification combined heat and power—new implementation opportunities resulting from combined supply of process steam and district heating. Energy 29, 1117-1137.
Nakicenovic, N., Haas, R., Schleicher, S.P., Klettner, C., Kletzan, D., Köppl, A., Türk, A., 2008. Assessment of Austrian contribution toward EU 2020 Target Sharing. Austrian Institute of Economic Research WIFO, Vienna.
Obersteiner, M., Azar, C., Kauppi, P., Möllersten, K., Moreira, J., Nilsson, S., Read, P., Raiahi, K., Schlamadinger, B., Yamagata, Y., 2001. Managing climate risk. Science 294, 786-787.
Paoletta, M.S., Taschini, L., 2006. An Econometric analysis of Emission Trading Allowances, Swiss Finance Institute Research Paper Series. Swiss Finance Institute.
Polagye, B.L., Hodgson, K.T., Malte, P.C., 2007. An economic analysis of bio-energy options using thinnings from overstocked forests. Biomass & Bioenergy 31, 105-125.
Rhodes, J.S., Ketih, D.W., 2005. Engineering economic analysis of biomass IGCC with carbon capture and storage. Biomass & Bioenergy 29, 440-450.
Rolfsman, B., Guastafsson, S.-I., 2002. Energy conservation conflicts in district heating systems. Int. J. Energy Res. 27, 31-43.
Sandén, B.A., Azar, C., 2005. Near-term technology policies for long-term climate targets--economy wide versus technology specific approaches. Energy Policy 33, 1557-1576.
Schadauer, K., 2004. The Austrian forest inventory 2000/02 - Main results (Die Österreichische Waldinventur 2000/02 – Hauptergebnisse). Bundesamt für Wald, Vienna.
Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E., 2009a. Cost-effective CO2 emission reduction through heat, power and biofuel production from woody biomass: a spatial explicit comparison of conversion technologies. Appl. Energy. doi: 10.1016/j.apenergy.2009.11.007
Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E., 2009b. Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. Int. J. Energy Res. doi: 10.1002/er.1623
Schwarzbauer, P., 1997. Austria, in: Solberg, B. (Ed.), Demand and supply analyses of roundwood and forest products markets in Europe Proceedings of the 1st Workshop of the Concerted Action Project AIR3 - CT942288, Helsinki.
Semelsberger, T.A., Borup, R.L., Greene, H.L., 2006. Dimethyl ether (DME) as an alternative fuel. J. Power Sources 156, 497-511.
Sjödin, J., Henning, D., 2004. Calculating the marginal costs of a district-heating utility. Appl. Energy 78, 1-18.
Statistik Austria, 2007. Energy bilances 1970-2006 (Energiebilanzen 1970-2006). Statistik Austria.

Statistik Austria, 2009. Total use of energy sources (Gesamteinsatz aller Energieträger 2003/2004-2007/2008). Statistik Austria.

Styles, D., Jones, M.B., 2007. Current and future financial competitiveness of electricity and heat from energy crops: A case study from Ireland. Energy Policy 35, 4355-4367.

Thek, G., Obernberger, I., 2004. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass & Bioenergy 27, 671-693.

Thistle, D., Sedlacek, L., Carman, K.R., Fleeger, J.W., Bewer, P.G., Barry, J.P., 2006. Simulated sequestration of industrial carbon dioxide at a deep-sea site: Effects on species of harpacticoid copepods J. Exp. Mar. Biol. Ecol. 330.

Uddin, N.S., Barreto, L., 2007. Biomass-fired cogeneration systems with CO2 capture and storage. Biomass & Bioenergy 32, 1006-1019.

Umweltbundesamt, 2008. Austria's National Inventory Report. Umweltbundesamt Österreich.

van der Zwaan, B., Gerlagh, R., 2009. Economics of geological CO2 storage and leakage. Climate Change 93, 285-309.

Wahlund, B., Yan, J., Westermark, M., 2002. A total energy system of fuel upgrading by drying biomass feedstock for cogeneration: a case study of Skelleftea bioenergy combine. Biomass Bioenergy 23, 271-281.

Wahlund, B., Yan, J., Westermark, M., 2004. Increasing biomass utilization in energy systems: A comparative study of CO2 reduction and cost for different bioenergy processing options. Biomass Bioenergy 26, 531-544.

Pope, J., Owen, A.D., 2009. Emission trading schemes: potential revenue effects, compliance costs and overall tax policy issues. Energy Policy 37, 4595-4603.

Additional Article A.1

Regional bioenergy supply and demand and some implications for rural development

Regional bioenergy supply and demand and some implications for rural development

Johannes Schmidt, Sylvain Leduc, Erik Dotzauer and Erwin Schmid[1]

***Abstract* - Pellets for heating, combined heat and power (CHP) and methanol production plants are promising technologies for energy production from forest woods. The spatial distribution of bioenergy demands is one of the factors that determines efficient plant locations. Locating bioenergy plants in rural areas can create employment and income opportunities for local communities. In this study, the determination of optimal plant locations considering three alternative biomass conversion technologies and implications for rural development are analysed with respect to optimal plant locations. A spatially explicit optimization model, integrating a Monte Carlo simulation approach to account for model parameter uncertainty, is used to seek optimal locations of bioenergy plants in Lower Austria. Model results indicate that pellets production is most appropriately located in rural areas, competitive to fossil fuels, and allows substituting the highest amount of fossil fuels when compared to methanol and CHP production.**

INTRODUCTION

Pellets for heating, combined heat and power (CHP) and second generation methanol production plants are promising technologies for energy production from woody feedstock. Besides offsetting greenhouse gas emissions and increasing energy security through substitution of fossil fuels, bioenergy plants are also considered to contribute to rural development (BERNDES und HANSSON, 2007). Different energy commodities can be produced with the plants. The spatial distribution of demands for these commodities is one of the factors that determines efficient plant locations. Employment in the plants as well as in up-stream and down-stream industries can be significant (HILLRING, 2002). Consequently, locating bioenergy plants in biomass rich rural areas could be a measure to foster economic development. In this study, the optimal locations of bioenergy plants considering three biomass conversion technologies i.e. pellets, CHP and methanol production are assessed as well as their implications for rural development. The model is performed for the region Lower Austria including the city of Vienna. A clear characterization of rural and other areas is necessary to assign plant locations. The definition of rural areas according to Palme (1995) is used for this purpose. The distinction of regions is based on the primary economic activity in the district, differentiating between human capital intensive, physical capital intensive and rural regions.

METHODS

A spatially explicit optimization model (LEDUC et al., 2008) is used to seek optimal locations of bioenergy plants in the region of Lower Austria. In the model, bioenergy plants are supplied by domestic forest wood. It is assumed that forests can be harvested up to the maximum sustainable yield. The spatial distribution of biomass supply as well as the spatial distribution of energy demand for transportation fuels and heat is taken into account. Investment costs for district heating networks which are necessary to distribute surplus heat in the bioenergy production and the distribution costs of pellets and methanol are considered as well. The plants compete with fossil fuels. It is assumed that pellets can substitute heating oil in private buildings, district heating can substitute the heating fuels currently in use, power can substitute electricity generated in fossil plants and methanol can substitute fossil gasoline.

Many of the input parameters are uncertain because CHP gasification and methanol plants are currently not available on commercial level and costs are therefore estimates with high uncertainties. Additionally, prices of fossil fuels and CO_2-emissions are highly volatile. Therefore, a Monte Carlo simulation approach is applied to account for uncertainties (SCHMIDT et al., 2009). The optimal location of the plants is derived for each technology separately. Two different sizes (250 MW and 50 MW) are assumed to show the effect of plant size on the optimal locations and on the costs of bioenergy plants.

Table 1. Model results by plant size and technology.

Technology	Parameter	250 MW Plant	50 MW Plant
Methanol	Plants in Rural Areas (%)	0	80
	Costs (% of fossil)	128	150
	Fossil Substitution (TWh)	0.57	0.57
CHP	Plants in Rural Areas (%)	0	9
	Costs (% of fossil)	100	95
	Fossil Substitution (TWh)	1.05	1.05
Pellets	Plants in Rural Areas (%)	33	50
	Costs (% of fossil)	102	97
	Fossil Substitution (TWh)	1.09	1.12

[1] Johannes Schmidt is member of the Doctoral School Sustainable Development at the University of Applied Life Sciences, Peter Jordan Straße 82, 1190 Wien. (Jschmidt@boku.ac.at).
Sylvain Leduc is employed at the International Institute for Applied System Analysis in 2361 Laxenburg, Austria. (leduc@iiasa.ac.at)
Erwin Schmid is Adj. Professor at the Institute of Sustainable Economic Development, University of Applied Life Sciences, Feistmantelstraße 4, 1180 Wien. (eschmid@boku.ac.at).
Erik Dotzauer works at the Mälardalen University, SE-72123 Västerås, Sweden (erik.dotzauer@mdh.se).

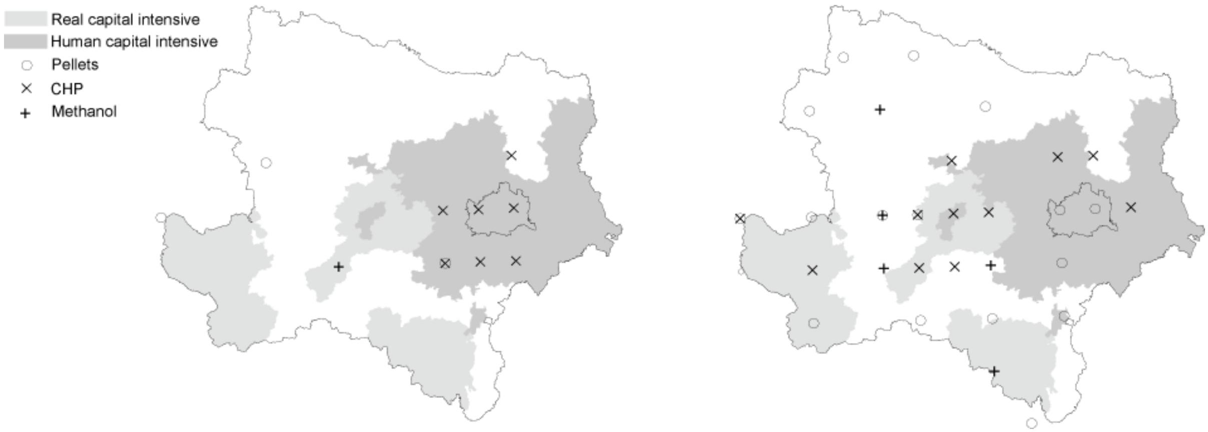

Figure 1. Optimal plant locations for big bioenergy plants (left) and small plants (right) in Lower Austria.

The investment costs per production unit decrease with increasing plant sizes due to economies of scale. The model is setup in a way that at least 50% of the available biomass is used for bioenergy production.

RESULTS & DISCUSSION

Optimal plant locations are reported in Figure 1. Table 1 lists the percentage of plants that are located in rural areas, the production costs in comparison with fossil fuels and the amount of fossil fuels substituted for each technology and plant size. The means of the results of the Monte Carlo Simulation are reported. Small methanol and small pellets plants are more likely to be found in rural areas than bigger plants and CHP plants. Both methanol and pellets plants produce less surplus heat than CHP plants. They therefore do not need to be located close to bigger cities where district heating networks can be built efficiently. The costs for distributing pellets and methanol to end consumers are not as relevant as biomass transportation costs, rural areas are therefore more suitable for these bioenergy systems. Smaller plants produce even less heat and are therefore more likely to be located close to the supply of feedstock than bigger plants. Methanol is not competitive to fossil fuels because investment costs are high for this technology and total conversion efficiencies are low. Pellets plants as well as CHP plants of both sizes are, however, able to produce energy commodities at the costs of fossil fuels. For both technologies smaller plants are slightly cheaper because higher plant investment costs are compensated by lower transportation costs. Regarding the capacity of fossil fuel substitution, CHP and pellets plants are a lot more effective than methanol production because conversion efficiencies are higher. The amount of employment created by bioenergy projects is hard to quantify. It can be, however, assumed that the three technologies have similar demands for working labour and that plants of smaller capacity need relatively more jobs than big plants (BERNDES und HANSSON, 2007).

The results show that locating pellets plants in rural areas is economically viable. Pellets production allows the substitution of more fossil fuels than any of the other technologies. It is also competitive to fossil fuels at current prices. Pellets can be produced in small production units. A wide spread distribution of plants is therefore possible. Especially the North-West of Lower Austria (“Waldviertel”) is well suited for low scale pellets production, which can create employment and income opportunities for the local communities as well as promote competitive local energy systems.

ACKNOWLEDGEMENT

This paper results from a cooperation of the International Institute of Applied System Analysis in Laxenburg, Austria and the Doctoral School Sustainable Development (DOKNE) at the University of Natural Resources and Applied Life Sciences, BOKU, Vienna. The inter- and transdisciplinary school is funded by proVISION, the Federal Ministry of Agriculture, Forestry, Environment and Water Management (BMLFUW), and the provinces Lower Austria, Styria, and Vienna.

REFERENCES

Berndes, G. und Hansson, J. (2007). Bionergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. In: Energy Policy, 35, 5965-5979.

Hillring, B. (2002). Rural development and bioenergy - experiences from 20 years of development in Sweden. In: Biomass and Bioenergy, 23, 9.

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

Palme, G. (1995). Struktur und Entwicklung österreichischer Wirtschaftsregionen. In: Mitteilungen der Österreichischen Geographischen Gesellschaft 137, 393-416.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G. und Schmid, E. (2009). Using Monte Carlo Simulation to Account for Uncertainties in the Spatial Explicit Modeling of Biomass Fired Combined Heat and Power Potentials in Austria. Vienna, Institute for sustainable economic development, University of Natural Ressources and Applied Life Sciences.

Additional Article A.2

Biofuel production in Austria considering the use of waste heat: a study on costs and potentials of greenhouse gas reduction

Biofuel production in Austria considering the use of waste heat: a study on costs and potentials of greenhouse gas reduction

Biogene Treibstoffproduktion in Österreich unter Berücksichtigung der Verwendung von Abwärme: eine Analyse der Kosten und Treibhausgasreduktionspotentiale

Johannes SCHMIDT, Sylvain LEDUC, Erik DOTZAUER, Georg KINDERMANN and Erwin SCHMID

Zusammenfassung

Die Biotreibstoffproduktion mit Technologien der zweiten Generation verspricht geringere Treibhausgasemissionen im Vergleich zu Technologien der ersten Generation. Die Kosten, Emissionen und optimale Standorte von Biomassekraftwerken, die diese neuen Technologien verwenden, werden mit Hilfe eines linearen Integer- Optimierungsmodells für Österreich abgeschätzt. Holz aus der Forstproduktion und von Kurzumtriebsanlagen geht als biogener Rohstoff in das Modell ein. Einnahmen durch den Verkauf der Nebenprodukte Wärme, Strom und Biogas, die in der Treibstoffproduktion entstehen, werden ebenfalls berücksichtigt. Die Modellresultate zeigen, dass der Ausstoß von Treibhausgasemissionen in Österreich durch den Einsatz von Biotreibstoffen um 2%-3,5% verringert werden kann. Allerdings ist nur die Fermentierungstechnologie in der Lage, Treibstoffe zu konkurrenzfähigen Kosten zu produzieren, weil höhere Erlöse durch den Verkauf der Nebenprodukte erzielt werden können.

Schlagworte: Biotreibstoffe, Abwärme, Facility Location Problem, Treibhausgase

---

Erschienen 2009 im *Jahrbuch der Österreichischen Gesellschaft für Agrarökonomie,* Band 18(3): 107-116. On-line verfügbar: http://oega.boku.ac.at

Summary

Biofuel production through second generation technology is expected to lower greenhouse gas (GHG) emissions significantly in comparison to first generation biofuels. A spatially explicit mixed-integer programming model has been built to assess costs, emissions and optimal locations of biofuel production plants in Austria. The model can choose between forest woods and short rotation poplar as possible feedstock as well as between fermentation and gasification technologies. Revenues from selling heat, power and biogas as by-products of biofuel production are considered in this analysis. The results of the model indicate that biofuel production allows a decrease in GHG emissions by 2%-3.5% of total Austrian GHG emissions. They also indicate that only biofuels from the fermentation technology are competitive to fossil fuels due to higher revenues from by-products.
Keywords: biofuels, waste heat, facility location problem, greenhouse gases

1. Introduction

Decreasing dependency on non European oil, climate change mitigation and rural development were until recently the main drivers of biofuel production in Europe (BERNDES and HANSSON, 2007). For these reasons, the European Union set the goal to replace a share of 5.75% of fossil gasoline with biofuels by 2010 and to increase this share to 10% by 2020 (EUROPEAN COMISSION, 2007). In the 2007 edition of the government program, the Austrian government set an even more ambitious goal to reach a 20% share by 2020. However, biofuels are criticized for various reasons. The greenhouse gas (GHG) balance of biofuels is - depending on the kind of feedstock used - at most equivalent or even worse than the one of fossil fuels. The use of fertilizers and land conversions due to feedstock production generates large amounts of GHG emissions (ZAH et al., 2007; SEARCHINGER et al., 2008). Other critics state that producing biofuels from food crops increases food prices which affects mainly the urban poor in developing countries negatively (MÜLLER et al., 2007; GOMEZ et al., 2008). Second generation biofuels produced either through gasification or fermentation are a promising alternative to the problems caused by first generation biofuels which are mainly produced from food crops. Second generation technologies

allow the use of a wide range of different biogenic feedstock and transform the whole crop to fuel instead of converting the grain only (BRIDGWATER, 2006). They therefore perform better in terms of GHG emissions in comparison to first generation plants (ZAH et al., 2007). Furthermore, competition to food production could be minimized if large scale production shifts from food crops to energy crops are avoided (GOMEZ et al., 2008).
This paper assesses the costs of second generation technologies - gasification and fermentation of biomass - using the biofuel model BeWhere developed by LEDUC et al. (2008a). BeWhere analyzes the whole supply chain from biomass production to delivery of the final product and seeks to find optimal locations of biofuel plants. Heat, power and biogas are considered as energy by-products of the biofuel production. Selling them increases the profit of biofuel plants. Also, total GHG emissions can be further decreased by substituting fossil fuels in diverse energy sectors. Using waste heat for district heating purposes is considered in former version of BeWhere. However, it was simply assumed that heat can be sold to the market at a fixed price. This paper introduces an add-on to BeWhere which allows the spatially explicit assessment of waste heat use for district heating. Costs of this application as well as effects on total emissions and on optimal plant locations are analyzed for the case of Austria.

2. Methods and Materials

A spatially explicit mixed-integer programming model has been built to find the optimal location and size of biofuel plants by minimizing the costs of the full supply chain. The supply of biomass is restricted in each supply region. Plants are modeled using energy balance equations, combined with capacity constraints for production. A vehicle fuel demand and a heat demand constraint, which considers competition between bioenergy and fossil fuels, is defined for each demand region. The objective is to minimize the overall costs in order to fulfill the demands for heat and vehicle fuel. The cost function includes costs for the supply of biomass, operation and investment in plants, transportation of biomass and biofuel and investment costs for district heating networks. Evaluating the model by solving the optimization problem generates the optimal locations of production plants and the optimal supply regions. The basic model is presented in detail in LEDUC et al. (2008a), though the version used in this paper contains an add-on which explicitly models the use of the waste heat for district heating purposes. The supply chain consists of biomass production, biomass transport to biofuel plants, production of biofuels and by-products and distribution of biofuels and heat to consumers.

Forest woods and short rotational poplar are considered as feedstocks. Spatial distribution of forestry yields is estimated with increment curves from Assman's yield table (ASSMAN, 1970) and a net primary production map from RUNNING (1994). This is calibrated with the observations from the national forest inventory of Austria (SCHADAUER, 2004). Harvesting costs are a function of tree size (which depends on site quality and rotation time) and the slope. The slope is calculated using a 30x30m digital elevation map from the SRTM (shuttle radar Topography mission) (NASA, 2008). The dimension of the harvested wood used for bioenergy has a diameter below 15 cm. Competition with paper and chipboards is not taken into account in this study. The long rotation periods of around 100 years and the fact that wood residuals from felling remain in the forest support sustainable use of the biomass resources. Short rotational poplar yields are estimated using the biophysical process model EPIC (SCHMID et al., 2006). A share of 10% of arable lands is assumed to be available for poplar plantations. Short rotation poplar management leads to a slightly increase in soil organic carbon stocks compared to crop production on average. The spatial distribution of gasoline consumption is estimated by combining a population map with average consumption values for Austria.

Concerning the biofuel production, two technologies are considered: gasification and fermentation. Table 1 shows the efficiencies of converting biomass to various products for the two technologies. While the delivery of power and biogas is not modeled in detail - it is assumed that they can be sold on the market at a fixed price - the use of waste heat for district heating is handled spatially explicit. Spatial distribution of private and commercial space heating and warm water consumption is estimated. The model combines data on Austrian dwelling areas and on employees based on the census of 2001 with average consumption per square meter of living area and per employee.

Tab. 1: Efficiencies (%) for converting biomass into fuel and by-products

Product	Gasification	Fermentation
Fuel	50.0	29.3
Heat	5.0	23.4
Power	0.0	12.7
Biogas	0.0	18.3

Source: LEDUC et al., 2008a; LEDUC et al., 2008b

The methodology was adapted from DORFINGER (2007). Heat has to be transported to district heating consumers using an extensive pipeline network. The costs of the pipeline network mainly depend on the distance between the plant and the demand, and on the demand density in the settlements. Areas of high heat demand are assumed to be supplied at lower unit costs than low demand areas. Estimations of costs of heat distribution networks based on the heat density or population density give a wide range of costs (SCHIFFER, 1977; KONSTANTIN, 2007). Therefore a sensitivity analysis is used to determine the influence of network infrastructure costs on the costs of the final product.
GHG emissions are compared with those created in a non biofuel scenario. All transport emissions from the biomass production sites to the end consumers are considered. It is assumed that fossil fuelled trucks are used for all transportation means. CO_2 emissions from burning biofuels are assumed to be totally recycled in biomass production. To estimate emission reduction through substitution of fossil transport, power and heating fuels, emission factors which represent the current Austrian fuel mix are taken from the Austrian National Inventory Report.

3. Scenarios and Results

Three different scenarios were used to assess costs, emissions and optimal locations. The base scenario (S1) represents current prices and district heating infrastructure costs taken from SCHIFFER (1977). It is compared to a scenario without heat use (S2) to assess the influence of selling heat on costs, emissions and plant positions. A second district heating scenario (S3) assuming lower infrastructure costs for the pipeline network (KONSTANTIN, 2007) is modeled to test sensitivity of the results to this parameter. In all scenarios 5.75 TWh of biofuels are produced. A total consumption of 100 TWh of fuels is assumed for Austria, a slight increase to the consumption of 96 TWh in 2006 (BITTERMANN, 2007).

Table 2 shows the results of the model for all combinations of technologies, feedstock and scenarios. The cost column gives a comparison of fossil fuel costs with biofuel costs, assuming a cost of 0.6 € per liter for fossil fuels. Emission savings are shown as share of total Austrian emissions in 2006. The last column gives the distance (in millions of km) that a 20 ton truck has to drive to deliver the biomass to the plants and the biofuel to the gas stations. Gasification of poplar (forest wood) needs 22% (46%) of the available biomass. Fermentation uses a higher share of 38% (78%) of biomass due to lower conversion efficiency of biofuel.

3.1 Costs

Producing biofuel from fermentation is in all scenarios cheaper than producing from gasification due to higher revenues from by-products.

Tab. 2: Model results

Technology	**Feedstock**	**Scenario**	**Costs** (% of gasoline costs, 1 liter=0.6 €)	**Emission Savings** (% of total Austrian emissions)	**Distances** (Biomass and biofuel transport in million km)
Gasification	Poplar	S1	118	1.9	11
		S2	124	1.9	10
		S3	116	1.9	11
	Forest Wood	S1	142	1.9	25
		S2	146	1.9	24
		S3	140	1.9	26
Fermentation	Poplar	S1	72	3.2	23
		S2	81	2.8	13
		S3	59	3.3	17
	Forest Wood	S1	112	3.2	49
		S2	129	2.8	43
		S3	100	3.4	48

Source: own calculations

Producing biofuel from poplar is cheaper than producing from forest wood due to lower production costs and due to a decrease of around 50% in transportation distances. A combination of fermentation and poplar is competitive to fossil fuels in all scenarios. Production of biofuel from forest wood by fermentation is competitive in scenario S3, which assumes low district heating infrastructure costs. In all other scenarios, biofuel production is not profitable. Use of waste heat has a significant influence on the costs of biofuel from fermentation. Comparing scenarios S1 and S2, costs go up by 13% (14%) for fermentation of poplar (forest wood). Due to lower heat yields in gasification, the influence of heat on costs is less: costs rise by 4% (3%) in the no heat scenario using poplar (forest wood) as feedstock. In S1 the parameters for the cost function of the district heating infrastructure are estimated from the results in SCHIFFER (1977) while in S3 results from KONSTANTIN (2007) are used. The average heat distribution costs in the model decrease by 40% in S3 due to this parameter change. This decreases the costs of the biofuel from fermentation of poplar (forest wood) by 18% (11%) and makes fermentation of forest wood profitable. Low district heating infrastructure costs are therefore a relevant factor in making biofuel production competitive.

3.2 Emissions

Emission savings from biofuel use are in the range of 1.9% to 3.4% of total annual Austrian emissions in the different scenarios. Biomass and biofuel transportation emissions do not decrease these results significantly. The trucks emit 0.5% to 1.5% of emission savings. Heat use has a significant influence on emission reductions in the fermentation scenarios. Without using waste heat, emission savings are decreased by 13%. However, emission savings per unit biomass are lower for heat than for biomass since the current heating system stock emits generally less GHG per unit of final energy than combustion engines do. The reason is that renewable forms of energy and natural gas are major fuel sources in heating. In case of gasification, emission savings by using waste heat for district heating are negligible.

The model does not account for emissions in the feedstock production. While it can be assumed that forest wood production has insignificant emissions, poplar production may create carbon debts due to fertilizer use and land use conversion (ZAH et al., 2007; SEARCHINGER et al., 2008).

3.3 Locations

Due to different energy yields of fermentation and gasification, more plants are needed when using fermentation (8) than when using gasification (4). Figure 2 shows the optimal locations for plants in scenarios S1 and S2. The plants using poplar as feedstock are located in the east of Austria since poplar production and gasoline demand are concentrated there. Forest wood production is distributed more equally over Austria and therefore plant positions can be also found in the west. Comparing heat and no heat scenarios, a shift of locations in direction of heat demand centers can be observed. These results are backed by the fact that total truck transportation distances are decreased in the no heat scenarios. For gasification of poplar (forest wood), total transportation distances decrease by 7% (6%) if no heat is considered. For fermentation, transportation distances decrease by 40% (12%). These results indicate that longer transportation distances for biomass and biofuel are necessary if plants are placed closer to heat demand centers.

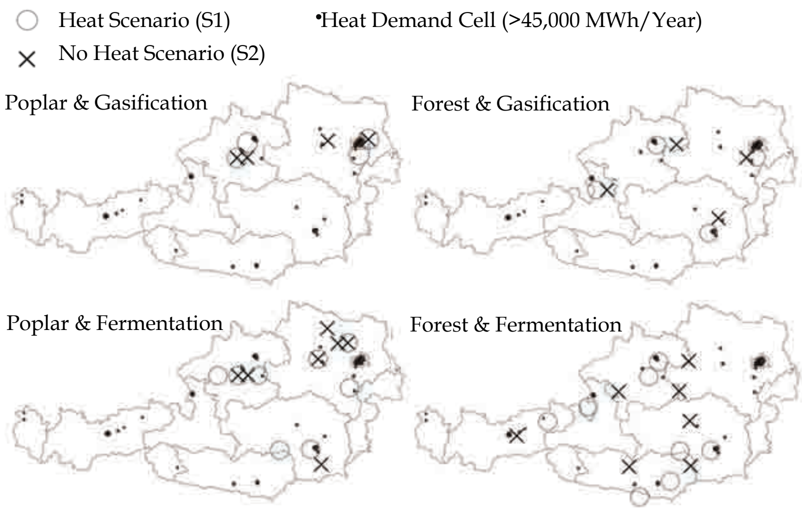

Fig. 2: Plant locations in the heat scenario S1 and the no-heat scenario S2 for all combinations of technology and feedstock. Source: own calculations

4. Conclusions

The analysis shows that the biomass production potential and current biofuel yields allow for attaining the current Austrian biofuel targets using second generation technologies in combination with woody feedstock. Still, only fermentation technology is currently competitive in production costs. The use of by-products of fermentation, especially heat, decreases costs considerably. In Austria, there is a lot of potential to use waste heat from biofuel plants for district heating.

Increasing the biofuel share significantly above 5.75% is only possible through either using expensive gasification technology or introducing poplar as feedstock. Poplar production in large plantations has several drawbacks which are not yet covered by the model. Emissions from land use change as well as fertilizer and pesticide uses in production may offset emission savings. Moreover, competition for the land has to be taken into account in future model versions.

Acknowledgement

This paper is a result of a cooperation of the International Institute of Applied System Analysis in Laxenburg and the Doctoral School Sustainable Development at the Boku in Vienna. The inter- and transdisciplinary school is funded by proVISION, the Federal Ministry of Agriculture, Forestry, Environment and Water Management, and the provinces Lower Austria, Styria, and Vienna. Georg Benke (E7) and the *Fachverband Gas Wärme* provided important data.

References

ASSMANN, E. (1970): The principles of forest yield study. Pergamon.

BERNDES, G. and HANSSON, J. (2007): Bionergy expansion in the EU: Cost-effective climate change mitigation, employment creation and reduced dependency on imported fuels. Energy Policy, 35, S. 5965-5979.

BITTERMANN, W. (2007): Energiebilanzen 1970-2006. Wien: Statistik Austria.

BRIDGWATER, T. (2006): Review Biomass for Energy. Journal of the Science of Food and Agriculture, 86, S. 1755-1768.

DORFINGER, N. (2007): GIS-unterstützte Vergleichsanalyse von Energieholzpotenzialen mit regionalen Wärmeverbrauchswerten. In: Angewandte Geoinformatik. Heidelberg: Wichmann Verlag, S. 153-158.

EUROPEAN COMISSION (2007): Renewable Energy Road Map - Renewable energies in the 21st century: building a more sustainable future. Communication from the Commission to the Council and the European Parliament.

GOMEZ, L. D., STEELE-KING, C. G. and MCQUEEN-MASON, S. J. (2008): Sustainable liquid biofuels from biomass: the writings on the walls. New Phytologist, 178, S.473-485.

KONSTANTIN, P. (2007): Praxisbuch Energiewirtschaft. Heidelberg: Springer Berlin.

LEDUC, S., SCHWAB, D., DOTZAUER, E., SCHMID, E. and OBERSTEINER, M. (2008a): Optimal location of wood gasification plants for methanol production with heat recovery. International Journal of Energy Research, IGEC-III Special Issue.

LEDUC, S., STARFELT, F., DOTZAUER, E., KINDERMANN, G., MCCALLUM, I. and OBERSTEINER, M. (2008b): Optimal location of ethanol ligno-cellulosic biorefineries with polygeneration in Sweden. Submission in progress.

MÜLLER, A., SCHMIDHUBER, J., HOOGEVEEN, J. and STEDUTO, P. (2007): Some insights in the effect of growing bio-energy demand on global food security and natural resources. In Proceedings: Linkages between Energy and Water Management for Agriculture in Developing Countries, Hyderabad India.

NASA – National Aeronautics and Space Administration Agency (2008): Shuttle Radar Topography Mission. http://www2.jpl.nasa.gov/srtm/.

RUNNING, S. W. (1994): Terrestrial remote sensing science and algorithms planned for EOS/MODIS. International Journal of Remote Sensing, 15, S.3587-3620.

SCHADAUER, K. (2004): Die Österreichische Waldinventur 2000/02 – Vielfältige Information aus erster Hand. ÖWI. http://web.bfw.ac.at/i7/oewi.oewi0002

SCHIFFER, H. (1977): Kosten der Energieverteilung bei der Deckung des Raumwärmebedarfs im Haushaltsbereich. München: Oldenbourg.

SCHMID, E., BALKOVIC, J., MOLTCHANOVA, E., SKALSKY, R., POLTARSKA, K., MÜLLER, B. and BUJNOVSKY, R. (2006): Bio-physical Process Modeling for EU25–Concept, Data, Methods and Results. Final Research Report for the EU-FP6 Research Project INSEA. Laxenburg: International Institute of Applied System Analysis.

SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D. and YU, T. (2008): Use of U.S. croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. Science, 319, S.1238-1240.

ZAH, R., BÖNI, H., GAUCH, M., HISCHIER, R., LEHMANN, M. and WÄGER, P. (2007): Ökobilanz von Energieprodukten: Ökologische Bewertung von Biotreibstoffen. Bern: Empa.

Affiliation

Dipl. Ing. Johannes Schmidt
Doctoral School Sustainable Development
Peter Jordan Straße 82, 1190 Wien, Austria
eMail: johannes.schmidt@boku.ac.at

Additional Article A.3

Potentials of bioenergy production within the Austrian forest market

Potentials of bioenergy production in the Austrian forest market

Johannes Schmidt[1], Sylvain Leduc[2,3], Erik Dotzauer[4], Georg Kindermann[2], Thomas Greigeritsch[1], Erwin Schmid[1]

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

Abstract

Forest wood is a substantial and competitive biomass stock for bioenergy production in Austria. Besides increasing forest productivity and harvest efficiencies, waste products from the wood processing industry may be a cost competitive resource for the bioenergy production sector. The aim of this study is to optimize the supply chain of the biofuel industry based on cellulosic biomass by particularly considering the waste products from the wood processing industry. The optimal portfolio of combined heat and power- and second generation ethanol plants is assessed for different CO_2 price scenarios.

The optimal location of plants is evaluated by minimizing the costs of the full supply chain. The model includes biomass harvesting, transport and processing as well as the distribution of the final commodities. Availability of forest wood is geographically explicitly estimated considering future production and demand potentials. Wood imports and sawmill co-products are also included. The model takes into account the wood demands of existing pulp-and-paper industries and bioenergy plants. Two technologies are considered: combined heat and power and second generation ethanol production. The distribution of ethanol and district heat to the consumers is explicitly integrated. Results indicate that an additional 2.9% of Austria's energy consumption may be produced from wood. Rising CO_2-prices increase the share of biofuel production and decrease the share of combined heat and power in the optimal portfolio of technologies.

Keywords: Biofuel, biomass, bioenergy, forest industries, supply chain

1. Introduction

Decreasing dependency on imported fossil oil and climate change mitigation are the main drivers of the European renewable energy policies. The goal of the European Union is to reach 20% of renewable energy consumption by 2020. The commission emphasizes that a significant increase in the use of biomass is necessary to reach these policy targets. Austria has already a high share of renewable energy consumption and committed to increase this share from currently around 23% to 34% by 2020 (COM, 2008). About 43% of the Austrian territory is forest lands and wood is already an important feedstock for biomass based energy generation. In 2004, 37% of the renewable energy was produced from wood (Kopetz and Scheiber, 2006). To meet the 2020 targets, the Austrian biomass action plan estimates that forest harvests have to be increased in a sustainable manner by 10.7 million m^3 of wood until 2020 (BMFLUW, 2006). The efficient use of those additional biomass resources in the different bioenergy industries should be known in designing future energy systems. Optimal portfolios of bioenergy technologies for Austria have previously been assessed (Steininger and Voraberger, 2003) but they did not include the spatial distribution of feedstock potentials and demands. The spatial distribution plays an important role as the transport of biomass is a crucial factor in the total production costs (Eriksson and Björheden, 1989; Bjornstad, 2005). Also, costs of distribution of the final commodities, especially in the case of district heating, depend on the density of the demand in certain areas (Schiller and Siedentop, 2005; Konstantin, 2007). This paper therefore presents an optimization model which minimizes costs of wood based bioenergy industries along the whole supply chain by selecting optimal plant locations, feedstock production sites and demand sites. Combined heat and power (CHP) and second generation ethanol production in multi commodity plants (MCP) are assessed. Different scenarios for biomass price as well as prices of CO_2-emission are assumed.

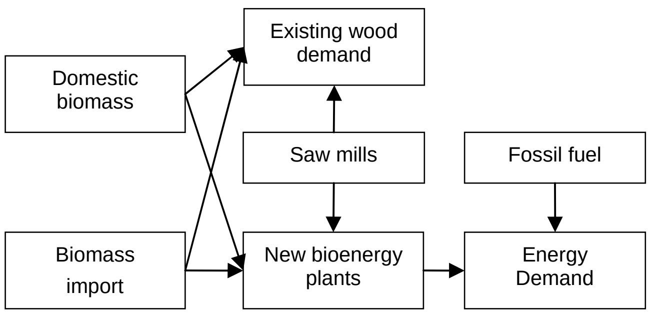

Figure 1: Supply chain of the forestry industry model.

2. Methodology

A spatially explicit optimization model of the supply chain of bioenergy industries is used for the assessment. IT considers industries competing for wood resources. On the supply side, forest wood harvests, sawmill co-products (SCP) and wood imports serve as biomass resources for possible new bioenergy plants. Wood demand of pulp-and-paper mills, of existing bioenergy plants and of private households is considered on the demand side (Figure 1). The structure and the quantities of the wood flow are based on the Austrian Wood Flow Accounts 2005 (Hagauer et al., 2007). The model assumes that the existing wood demand has to be fulfilled, allowing new plants to be built only if there is enough surplus of wood available. The model is spatially explicit and the transportation of wood from biomass supply to demand spots is considered. Also, the distribution of ethanol and heat to the consumers is included in the model. The model selects optimal locations of bioenergy plants by minimizing the costs of biomass supply, biomass transport and energy distribution. Full costs and emissions at the optimal locations are calculated. Spatial distribution of forestry yields is estimated with increment curves from Assman's yield table (Assman, 1970) and a net primary production map from Running (1994). This is calibrated with the observations from the national forest inventory of Austria (Schadauer, 2004). Harvesting costs are a function of tree size (which depends on site quality and rotation time) and the slope steepness. The slope steepness is calculated using a 30x30m digital elevation map from the shuttle radar topography mission (NASA, 2008). The dimension of the harvested wood used for bioenergy has a diameter below 15 cm, wood of bigger diameters is left for sawmills. Furthermore, the production of SCP by sawmills is also considered in the model. Import locations and import quantities are taken from market statistics. Imports are assumed to be transported by trucks.

Domestic wood demands of pulp-and-paper mills, biomass fired CHP and district heating (DH) plants and private households are included. The fuel wood consumption of private households was modeled by the heat demand model presented by Schmidt (2008). It estimates the spatial distribution of fuel consumption for heating purposes in Austria, differentiated by the heating fuels currently in use.

CHP and MCP are modelled as energy production technologies. Table 1 shows the efficiencies of converting biomass to various products for the two technologies. While the delivery of power and biogas is not modelled in detail – it is assumed that they can be sold on the market at a fixed price – the use of heat for district heating is handled spatially explicit as described in Schmidt (2008). The costs for delivering the transportation fuels to the final consumers are also part of the model.

he model calculates the amount of green house gas (GHG) emissions offset by bioenergy use. The commodities produced in the plants substitute fossil fuels in transportation, power generation of gas fired power plants and in heat generation. The emission factors are taken from Umweltbundesamt (2007). A mixed integer linear programming model is used to optimize the supply, processing and delivery of biomass and bioenergy. A detailed description of the model is given in Leduc et al. (2008), which is here extended by considering biomass based CHP production and existing biomass demands in pulp-and-paper industries, sawmills and energy installations.

3. Scenario and Sensitivity Analysis

This study assesses how changes in the prices of biomass supply, in the demand of competing industries, and in CO_2-prices affect the total production potentials of bioenergy and the optimal mix of technologies through several scenarios and sensitivity analysis. The baseline scenario (S1) assumes an increase in total wood harvesting, while demand and prices reflect the current wood market in Austria. Generally, an increase in the use of forest products is expected by 2020 (Schwarzbauer, 2005; Teräs, 2006). In scenarios S2 to S4 prices of imports, SCP and of forest wood are increased by 20%, respectively. The wood demand from the pulp-and-paper industry is increased by 25% in S5 and the supply of SCP is increased by 10% in S6. A high competitive scenario (S7) combines scenarios S2-S6.

Table 1: Conversion efficiencies of bioenergy technologies in %.

Technology	Ethanol	Heat	Power	Biogas
MCP (Leduc, 2008)	29.2	23.4	12.7	18.3
CHP (Dornburg and Faaij, 2001)	0	55	35	0

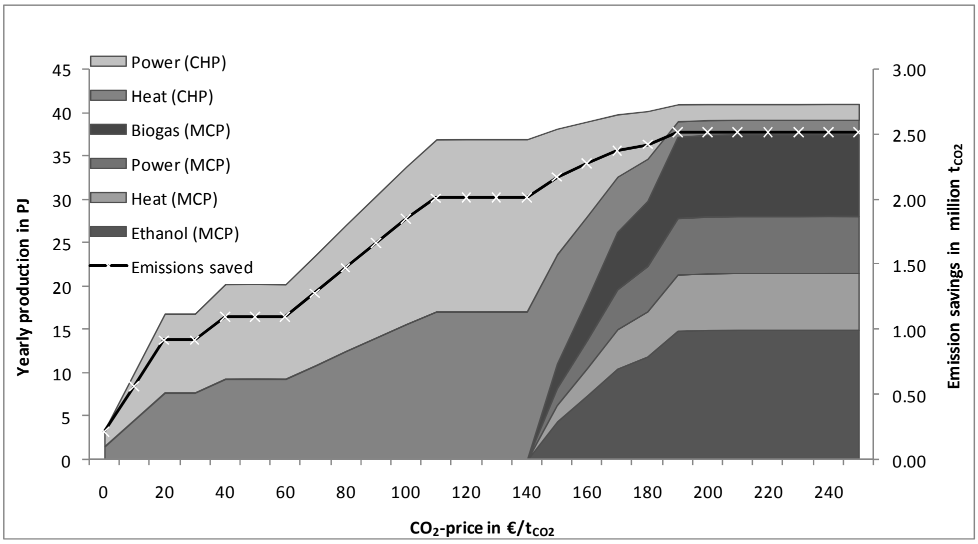

Figure 2: Diffusion of technologies and emission savings depending on CO_2 price.

In the sensitivity analysis of S8 to S32 the effect of increasing emission allowance prices on the optimal technological mix is assessed. Prices are increased from 0 to 250 €/t_{CO2}. Assumptions for prices of fossil power generation, of fossil transportation fuels and of natural gas are taken from the high price scenario developed by the EIA for 2020 (EIA, 2008). The reference costs for heating systems are taken from the high-price scenario in Kranzl and Haas (2008). Prices of emission allowances are assumed to be 20 € / t_{CO2} in S1-S7, which represents the mean price at the European Energy Exchange spot market in 2005. In the baseline scenario, the demand for wood as well as the supply of wood imports and of SCP is calibrated to the Austrian Wood Flow Accounts. An increase in domestic wood harvests of seven million cubic meters is assumed, according to the forest model described above. Prices of forest wood harvesting, of SCP and of wood imports are set to average prices of official market statistics. The capacity of both CHP plants and MCP is set to 200 MW. At this capacity and at 7,200 full load hours, one plant needs 576,000 m^3 of wood per year to be operated.

4. Model Results

The effect of changes in the forest market are analyzed at a low carbon price scenario (20 € / t_{CO2}). A summary of the results – the amount of energy produced, the number of plants built and the proportion of SCP to total biomass use – can be found in Table 2. Only CHP plants are built and imports are never used as feedstock for plants in the seven scenarios. In S2, no effects on the total output are estimated as imports are not used at all in the baseline scenario. Prices of SCP have a significant impact on the total energy production as shown in S3. The increase in the price of domestic wood production in S4 yields an increase in the competition for SCP. A decline in bioenergy production is therefore observed. Increasing the demand of the pulp-and-paper industry also has significant effects (S5). Due to the additional demand the feedstock prices increase as cheap sources of wood are getting scarce and less plants are consequently built. S6 assumes that the production of sawmills increases. The additional supply allows that another plant is built. In S7, scenarios assumptions of S2-S6 are combined. In that case, there is not much potential for bioenergy production left, as only one plant can be built. Increases of biomass supply prices and of concurring wood demand is not offset by the additional supply of SCP. Generally the competition for SCP is most intensive. Increasing SCP use by concurring industries has a major effect on the total bioenergy production potentials in Austria. This is mainly due to the fact that small wood users like small district heating plants and single stove heating rely on the wood supply out of local forests in the model results. Still, for large bioenergy plants like the ones discussed in this paper, logistic is a major cost factor. Decentralized production of the feedstock implies high transportation costs making plant projects unprofitable.

Figure 2 depicts the diffussion of the technologies depending on the price of CO_2. At low CO_2-prices there is very little potential for additional bioenergy plants. Only one CHP-plant is built assuming that CO_2 emissions are cost-free. Increasing CO_2 prices proivde incentives for more plants to be built. At a price level of 110 € / t_{CO2} the whole available biomass supply is used. Still, at this price level, only CHP plants are built. Increasing prices further allow MCP to go into model solution. CHP plants are substitued by MCP with raising price levels because MCP save more emissions per unit of generated energy. Reference technologies for heat and power, i.e. the fuels currently consumed

Table 2: Results of scenarios S1-S7.

	Scenario description	Energy production (% of production in S1)	Number of plants built	Proportion SCP (% of total biomass use)
S1	Baseline	100	5	64
S2	Imports prices plus 20%	100	5	64
S3	SCP prices plus 20%	40	2	24
S4	Forest wood prices plus 20%	80	4	68
S5	Pulp-and-paper industry demand plus by 25%	80	4	61
S6	Sawmills production plus 25%	120	6	60
S7	S2-S6 combined	20	1	53

in heat and gas fired power generation emit less GHG than the reference technology in transportation, i.e. fossil transportation fuels. Additionally the energy production per unit of biomass is higher for MCP than for CHP although the total theoretical efficiency is better for CHP (0.9 for CHP, 0.84 for MCP). This is due to the fact that CHP has a high proportion of heat production. Heating demand for district heating is subject to significant demand variations. It is not possible to use the co-produced heat for other useful purposes during periods of low heat demand. MCP produces less heat per unit of biomass which reduces losses of heat due to demand constraints. The total emissions saved ranges from 200,000 t_{CO2} for the zero emission price scenario up to 2.5 million t_{CO2} for the high emission price scenario as shown in Figure 2. The model results show that an additional 2.9% of the Austrian energy demand at 2004 consumption levels can be supplied by bioenergy at prices of 250 € / t_{CO2}.

5. Conclusion

The biomass action plan assumes that an additional amount of 10 million m^3 of wood is necessary to meet the renewable energy targets. This cannot be achieved by increasing the Austrian production only. The sustainably available, additional domestic wood harvests from forests sum up to 73% of that amount. At a price of emission allowances of 110 € / t_{CO2}, this potential can be mobilized. However, lower prices have a significant impact on the amount of wood that is harvested. Also, bioenergy production is sensitive to prices of biomass and to wood demand of concurring industries, as feedstock prices constitute a significant part of total production costs. Production of second generation biofuels, heat, power and biogas in MCP saves more emissions than power and heat generation in CHP. However, CHP is much cheaper and consequently MCP is only a profitable option at emission allowance prices of 150 € / t_{CO2}.

6. References

Assmann, E. (1970), *The principles of forest yield study. Pergamon*.

Bjornstad, E. (2005), 'An engineering economics approach to the estimation of forest fuel supply in North-Trondelag country, Norway', *Journal of Forest Economics* **10**, 161-188.

BMLFUW (2006), 'Nationaler Biomasseaktionsplan für Österreich', Lebensministerium BMLFUW.

BMLFUW (2007), 'Holzbedarf für energetische Verwertung', Lebensministerium BMFLUW.

COM (2008), *Directive of the European Parliament and of the council on the promotion of the use of energy from renewable sources*, Commission of the European Union.

Dornburg, V. & Faaij, A. P. (2001), 'Efficiency and economy of wood-fired biomass energy systems in relation to scale regarding heat and power generation using combustion and gasification technologies', *Biomass and Bioenergy* **21**, 91-108.

EIA (2008), 'International Energy Outlook 2008', Technical report, Energy Information Administration.

Eriksson, L. O. Björheden, & Rolf, W. (1989), 'Optimal storing, transport and processing for a forest-fuel supplier', *European Journal of Operational Research* **43**, 26-33.

Hagauer, D.; Lang, B. & Nemestothy, K. (2007), 'Wood Flow Austria 2005', Austrian Energy Agency.

Konstantin, P. (2007), *Praxisbuch Energiewirtschaft*, Springer Berlin Heidelberg.

Kopetz, H. & Scheiber, E. (2006), 'Basisdaten Bioenergie Österreich 2006', Österreichischer Biomasse-Verband.

Kranzl, L. & Haas, R. (2008), 'Strategien zur optimalen Erschließung der Biomassepotenziale in Österreich bis zum Jahr 2050 mit dem Ziel einer maximalen Reduktion an Treibhausgasemissionen', Energy Economics Group, TU Vienna.

Leduc, S.; Starfelt, F.; Dotzauer, E.; Kindermann, G.; McCallum, I.; Obersteiner, M. & Lundgren, J. (2008), 'Optimal location of ethanol ligno-cellulosic biorefineries with polygeneration in Sweden', Submitted to Renewable Energy.

Running, S. W. (1994), 'Terrestrial remote sensing science and algorithms planned for EOS/MODIS', International Journal of Remote Sensing **15**, 3587-3620.

Schadauer, K. (2004), 'Die österreichische Waldinventur 2000 / 02 - Vielfältige Information aus erster Hand', ÖWI.

Schiller, G. & Siedentop, S. (2005), 'Infrastrukturfolgekosten der Siedlungsentwicklung unter Schrumpfungsbedingungen', *DISP* **160**, 83-93.

Schmidt, J. (2008), 'Surplus Heat from Bioenergy Production for District Heating: an Austrian Case Study', Interim Report, Institute for Applied Systems Analysis.

Schwarzbauer, P. (2005), *Lignovisionen*, Wien, chapter Long-Term Supply and Demand Projections for Wood Products in Austria until 2020. A contribution to the UN-ECE/FAO 'European Forest Sector Outlook Study'.

Steininger, K. W. & Voraberger, H. (2003), 'Exploiting the Medium Term biomass Energy Potentials in Austria', *Environmental and Resource Economics* **24**, 359-377.

Teräs, T. J. (2006), 'Future Fibre Demand and Fibre Production in Central Europe', *International Paper World* **11**, 64-67.

Umweltbundesamt (2007), Austria's National Inventory Report, Umweltbundesamt.