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Abstract

Austria aims at increasing its share of renewable energy production by 11% until 2020. Combined Heat and Power (CHP) plants fired by forest wood can significantly contribute to attaining this target. However, the spatial distribution of biomass supply and of heat demand limits the potentials of CHP production. This paper 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. Optimal locations of plants are clustered around big cities in the East of Austria. At current power prices, biomass based CHP production allows producing around 3% of Austria's total current energy demand. Yet, the heat utilization decreases when CHP production increases due to limited heat demand that is suitable for district heating.

Keywords

Combined Heat and Power, District Heating, Bioenergy, Biomass, Mixed Integer Programming, Monte-Carlo Simulation

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Nomenclature

Variables	
$\mathrm{b}_{i,j}$	Biomass transportation
u_j^{plant}	Binary variable for plant investment
$\mathrm{u}_{j,h,ps}^{pipe}$	Binary variable for investment in district heating network
$\mathrm{u}_{h,ns}^{dnet}$	Binary variable for investment in transportation pipeline
p_j^{chp}	Power production in the CHP plant
p^{fp}	Power production with fossil fuels
q_j^{chp}	Heat production in the CHP plant
$\mathrm{q}_{h,t}^{peak}$	Peak heat production
$\mathrm{q}_{h,t}^{local}$	Local heat production
$\mathrm{q}_{j,h,ps,t}^{dh}$	Heat transportation from plant to district heating network
p^{tot}	Total CHP power production
q^{tot}	Total fossil heat generation substituted by district heating from biomass CHP
$\mathrm{p}_{par_l}^{tot}$	Elasticity of power production
$\mathrm{q}_{par_l}^{tot}$	Elasticity of heat substitution
Parameters	
p^D	Power demand
$q_{h,t}^D$	Heat demand
$q_{h,ns,t}^D$	Heat demand in district heating networks of different size
$\bar{b}_i$	Biomass supply
$\bar{q}_j$	CHP production capacity
$\bar{q}_{ps,t}^{pipe}$	Capacity of heat transportation pipeline
η_j^{chp}	Conversion efficiency in CHP plant
α_j	Alpha value of CHP plant
$\eta_{j,h,ps,t}^{trans}$	Transportation efficiency of heat pipeline
$\eta_{h,ps,t}^{dh}$	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
c_i^{sup}	Costs of biomass supply
$c_{i,j}^{trans}$	Costs of biomass transportation
c_j^{prod}	Costs of CHP production
c_j^{plant}	Costs of plant investment
$c_{j,h,ps}^{pipe}$	Costs of transportation pipeline investment
$c_{h,ns}^{dnet}$	Costs of district heating network investment
c_t^{peak}	Costs of peak heat production
c_t^{local}	Costs of local heat production
c^{fp}	Costs of power generation with fossil fuels
c^{em}	CO_2-price

$e_{i,j}^{t}$	CO_2-emission factor of biomass transportation
e^{fp}	CO_2-emission factor of power generation with fossil fuels
e_{h}^{local}	CO_2-emission factor of local heat production
e^{peak}	CO_2-emission factor of peak heat production
q_{h}^{Dd}	Private heating demand
q_{h}^{Dc}	Commercial heating demand
$A_{h,bt,ba}$	Dwelling area
$EC_{bt,ba}$	Heat consumption coefficient
$EM_{h,es}$	Number of employees
ECE_{es}	Heat consumption per employee
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
χ_{bt}^{dh}	Heating system usage factor
$\Delta s_{h,t}$	Proportional heat consumption in season
con	District heating connection rate
lo_{l}	Lower bound of plausible range of parameters
up_{l}	Upper bound of plausible range of parameters
par_{l}	Input parameter vector
n	Number of runs in Monte-Carlo Simulation
β_0, β_l	Regression coefficients
e	Error term
Subscripts	
j	Plant locations
i	Biomass supply sites
h	Settlements
ns	District heating network size
ps	Pipeline size
t	Season
bt	Building type
ba	Building age
es	Economic sector
l	Model input parameter

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 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% to 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 matters too [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 [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 which have the strongest influence on the total potentials. Parameter influence on model output is expressed by elasticity estimations. The Median Absolute Percentage Error 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 are discussed in sections 2.2-2.5. The handling of parameter uncertainty is described in section 2.6. Following the results in section 0, the sensitivity analysis is presented in section 3. The discussion and conclusions close the paper in section 4.

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

2.1 The model

Austria is divided into 150 biomass supply regions ( ). Possible plant locations ( ) are deterministically spread at a vertical and horizontal distance of 0.41 degrees over Austria. Biomass is harvested and transported (variable) from the supply regions to the plants. Investments into plants are modeled by the binary variable The plants produce power (variable and heat (variable). Powerdemand (parameter) is satisfied by and power production with fossil fuels (variable).

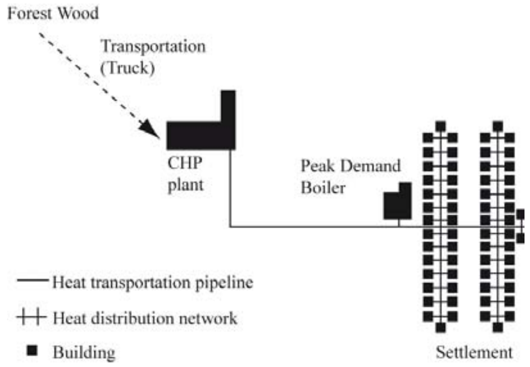

Figure 1: Model of biomass fired CHP-plants

Heat consumption is modeled by seasons ( ). Heat is transported to the boundaries of the settlements ( ) with transportation pipelines (binary variable) of varying sizes ( ). District heating distribution networks (binary variable) of different extensions ( ) distribute the heat within the settlements. Heat transported from CHP plants to the settlements (variable) and heat from peak boilers (variable) 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 by small boilers inside of the buildings.

Biomass utilization in the plants is restricted by

(1)

where parameter denotes the total amount of biomass available in supply region . The capacity of a CHP plant constraints the production by

(2)

where parameter is the total annual heat production capacity of plant . Heat and power production is determined by the biomass input and conversion efficiency (parameter in

(3)

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

. (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}:

$$\sum_j \mathrm{p}_j^{chp} + \mathrm{p}^{fp} = p^D. \tag{5}$$

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

$$\sum_{h,ps} \mathrm{q}_{j,h,ps,t}^{dh} \le \Delta t_t \mathrm{q}_j^{chp}, \tag{6}$$

where parameter Δt_t denotes the relative length of a season.

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

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

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 $\eta_{h,ps,t}^{dh}$. Parameter $\eta_{h,t}^{local}$ 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 $q_{h,ns,t}^D$) in settlement h. This is modeled by

$$\eta_{h,t}^{dh}\left(\left(\sum_{j,ps} \eta_{j,h,ps,t}^{trans}\, \mathrm{q}_{j,h,ps,t}^{dh}\right) + \mathrm{q}_{h,t}^{peak}\right) = \sum_{ns} q_{h,ns,t}^D \mathrm{u}_{h,ns}^{dnet}. \tag{8}$$

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

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

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

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

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

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

$$\begin{aligned} f(\mathrm{b},\mathrm{p},\mathrm{q},\mathrm{u}) &= \sum_{i,j} \left(c_i^{sup} + c_{i,j}^{trans} + c_j^{prod}\right)\mathrm{b}_{i,j} \\ &+ \sum_j c_j^{plant} \mathrm{u}_j^{plant} + \sum_{j,h,ps} c_{j,h,ps}^{pipe} \mathrm{u}_{j,h,ps}^{pipe} \\ &+ \sum_{h,ns} c_{h,ns}^{dnet} \mathrm{u}_{h,ns}^{dnet} + \sum_{h,t} c_t^{peak} \mathrm{q}_{h,t}^{peak} \\ &+ \sum_{h,t} c_t^{local} \mathrm{q}_{h,t}^{local} + c^{fp} \mathrm{p}^{fp} \\ &+ \begin{pmatrix} \sum_{i,j} e_{i,j}^{\ t} \mathrm{b}_{\mathrm{i,j}} + e^{fp}\, \mathrm{p}^{fp} \\ + \sum_{h,t} e_h^{local} \mathrm{q}_{h,t}^{local} \\ + \sum_{h,t} e^{peak} \mathrm{q}_{h,t}^{peak} \end{pmatrix} c^{em}. \end{aligned} \tag{11}$$

The different summands in the objective function are:

1. Biomass supply costs (parameter c_i^{sup}), transportation costs (parameter $c_{i,j}^{trans}$) and bioenergy production costs (parameter c_j^{prod}) times the amount of biomass used.
2. Annualized costs of investing in a plant (parameter c_j^{plant}) times the binary variable for the plant selection.
3. Annualized costs of building a pipeline from the plant to the settlement (parameter $c_{j,h,ps}^{pipe}$) times the binary variable for the pipeline selection.
4. 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.
5. Costs for producing peak heat (parameter c_t^{peak}) times the amount of peak heat produced.
6. Costs for producing local heat including investment and fuel costs (parameter c_t^{local}) 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. CO2-emissions of biomass transportation (emission factor $e_{i,j}^{t}$), emissions of fossil power production (emission factor e^{fp}), emissions of local heating systems (emission factor e_h^{local}) and emissions of peak heat production (emission factor e^{peak}) are multiplied by the CO2-price (parameter c^{em}).

The MIP is finally defined as:

$$\min[f(\mathrm{b},\mathrm{p},\mathrm{q},\mathrm{u})] \tag{12}$$

$$s.t.$$

$$(1)-(10)$$

$$0 \leq \mathrm{b}_{i,j}, \mathrm{p}_j^{chp}, \mathrm{p}^{fp}, \mathrm{q}_j^{chp}, \mathrm{q}_{h,t}^{peak}, \mathrm{q}_{j,h,ps,t}^{dh}, \mathrm{q}_{h,t}^{local}$$

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

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 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 dataset [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. The biomass is gasified with pressurized air. The resulting gas is burnt in a gas turbine, using combined cycle CHP technique [20]. Table 1 lists economical and technical plant parameter values for the model.

Investment Costs	78 M€
Fixed O&M Costs	2.50% of investment
Variable O&M Costs	3.276 € / $MWh_{biomass}$
Plant Size	130 $MW_{biomass}$
Minimum Load	30.00%
CHP conversion efficiency	90.00%
Alpha factor	91.50%
Full Load Hours	7200 hours/year
Lifetime	25 years

Table 1: Technical and economical parameters of gasification plant [20]

2.4 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 buildings are computed for all Austrian settlements. The geographical position and size of each settlement is known with a spatial resolution of 1 km^2. The methodology was used before on an aggregated national and regional scale [22, 23] as well as on spatially explicit scales [11, 24].

Private Dwellings Heating Demand Model

A bottom up approach is applied to estimate the heat demand of private dwellings. The age and type of dwelling areas and the spatial distribution of the areas is known. This data is combined with typical energy coefficients for those buildings. The dwellings data is based on the Austrian Buildings- and Dwellings Census [25]. The final energy demand denoted by q_h^{Dd} is estimated for each settlement h. It describes the amount of energy necessary to heat the dwelling stock. The calculation is given in Eq. (13). Buildings already connected to a district heating network are not included in the calculation:

(13)

The dwelling areas (parameter) differentiated by building type ( ) and building age ( ) are combined with energy coefficients (parameter). 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) and a constant indoor temperature of 20° Celsius, 24 hours a day [24]. Behavior of consumers who generally decrease the temperature throughout the night or when nobody is in the dwelling is considered by introducing an usage factor (parameter) into Eq. (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 [26]. Climatic influences are regarded by correcting the heat demand using parameter that denotes local heating degree days.

Commercial Heat Demand Model

A different calculation procedure is used for commercial buildings. No data on the type of commercial activity is available in conjunction with commercial building areas. However, the number of employees (parameter) per economic sector is known in all settlements. Primary energy consumption for space heating and warm water (parameter per employee and per economic sector can be calculated from the Austrian analysis of useful energy [27]. Equation (14) shows the calculations of the final energy demand, denoted by :

(14)

Local heating degree days (parameter) are used to correct for spatial climatic variations. Parameter 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 denotes the average efficiency of heating systems used in commercial buildings.

Total Heat Demand Model

The combination of private and commercial heating demand and the determination of seasonal heating demand is shown in Eq. (15). Parameter denotes the proportion of the heat demand that is consumed in season in settlement and is calculated as the proportion of heating degree days in the season and of total heating degree days per year. Parameter denotes the connection rate, i.e. the proportion of district heating consumption to total heat consumption.

(15)

2.5 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 of different sizes are calculated as average costs from typical cost structures in the industry [28]. 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 are the most expensive part of the district heating system due to the large extension of such networks [29, 30]. 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 [31]. When information on the structure of settlements is available, a classification of settlements could be used to estimate district heating distribution costs [32]. However, such data is 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 [29]. It is used in this study. Figure 2 compares this estimation to a cost calculation in a real world project [30]. 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.

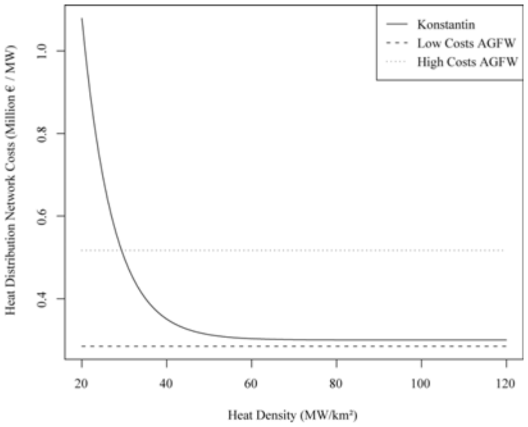

Figure 3: Comparison of district heating network costs in Konstantin [29] and AGFW [30]

Local heating systems, whose costs are denoted by parameter , concurr with district heating. The costs of such systems are determined from literature [33]. 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 [34].

2.6 Model parameter uncertainty

The values of some model parameters are highly uncertain. 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) (see Table 2). The remaining parameters are not stochastically modeled because they are either determined by results of pre-analysis (optimal plant capacity), they are known with high accuracy (, emission factors), they are non restricting constraints ( ), they are determined by another stochastically modeled parameter (the value of determines and) or they are known to have little influence on model output from previous sensitivity analysis ($\eta^{dh}_{h,ps,t}$ $\eta^{local}_{h,t}$, c^{prod}_{j}, $c^{pipe}_{j,h,ps}$). 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, i.e. $\mu = (up_l + lo_l)/2$ and $\sigma = (\mu - lo_l)/1.96$ as proposed in [35]. It is assumed that there is no covariance between the parameters. 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 which are used for further analysis.

Parameter	**Lower bound** lo_l	**Upper bound** up_l	**References**
Annualized District Heating Costs c^{dist}_{h} *(% of standard calculation)*	50	150	[29, 30]
Biomass Supply $\bar{b}_i$ *(% of standard calculation)*	95	105	Expert opinion
Biomass Costs c^{sup}_{i} *(€/GJ)*	4.34	5.83	[41]
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)*	62	80	[33], district heating prices
CarbonPrice c^{em} *(€/t_{CO2})*	6	30	Prices at European Energy Exchange 2005-2008, [42]
Connection Rate con *(%)*	61	74	Expert opinion
Power Price c^{fp} *(€/MWh)*	30	79	[43] and Prices at European Energy Exchange 2006-2008, [42]

Table 2: Ranges of model input parameters

Results

2.7 Optimal Locations

Possible plant locations are deterministically spread at a vertical and horizontal distance of 0.41 degrees 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 to 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 to 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.

2.8 Power and Heat Production Potentials

Potentials of CHP production are measured with variable – representing the total power production in CHP plants – and variable – representing the total local heat production substituted by district heating. The model

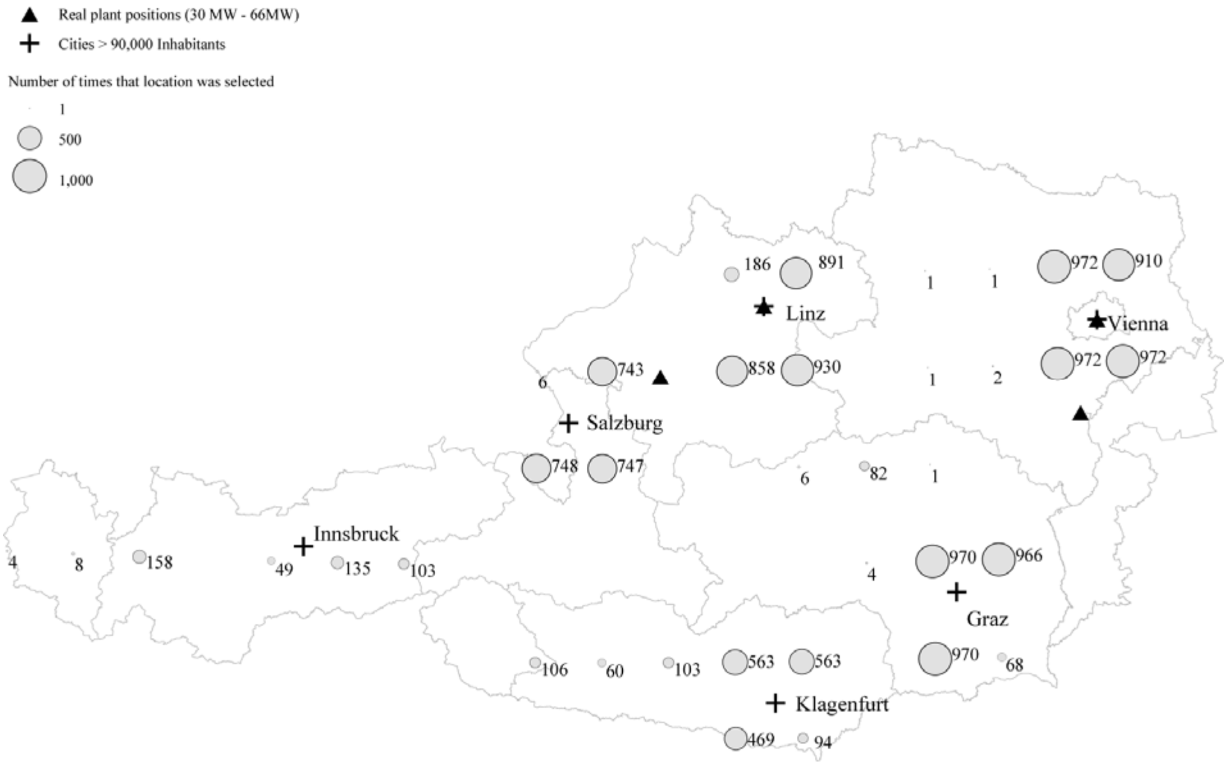

Figure 4: Number of times plant locations were selected in 1000 model runs

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	-

Table 3: Power price intervals for analysis of production potentials (€/MWh)

results are presented as probability distributions due to Monte Carlo simulations. The distributions of and 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 (see section 3). 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 (see Table 3 and Figure 4). Consequently, the variance of model results is reduced within each interval which provides a better picture of bioenergy production potentials. The power production and heat utilization potentials in 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 (6.24 - 4.91 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

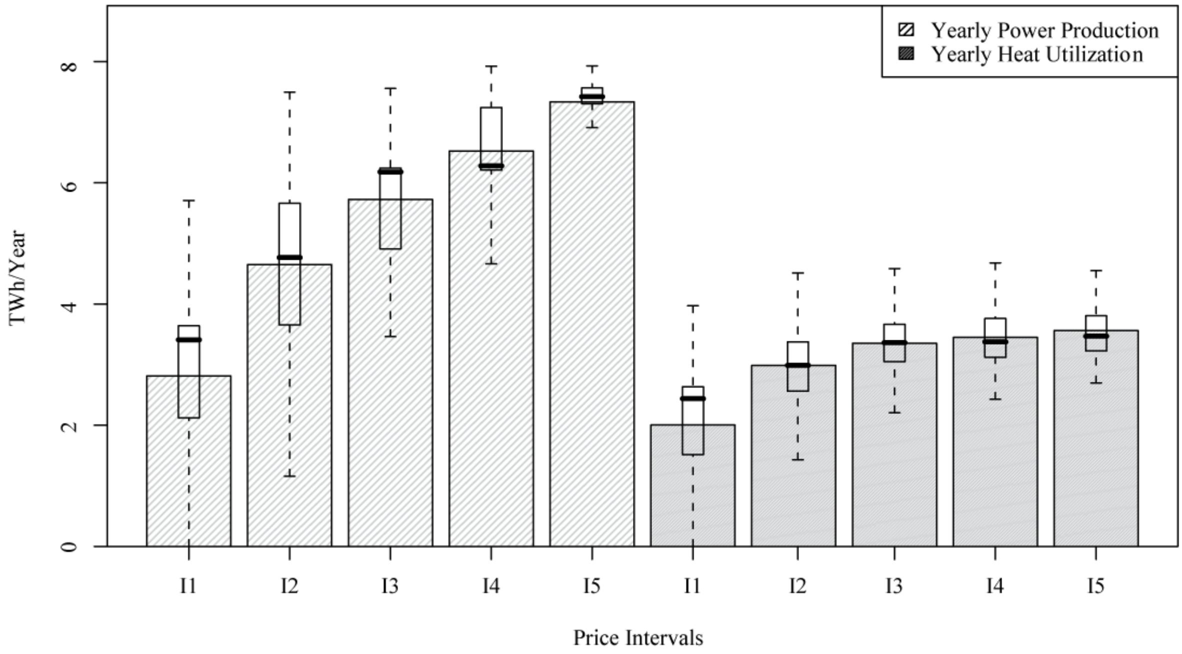

Figure 5: Power production and heat utilization at different price intervals I1-I5 (for intervals see Table 3). The bars represent the mean of the distribution of the results.

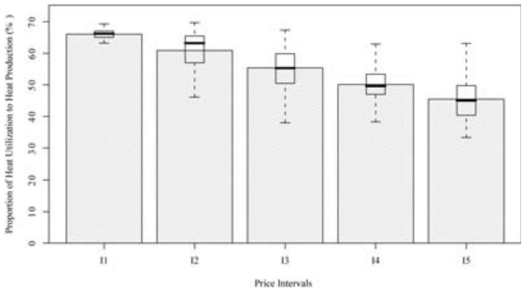

Figure 6: Proportion of heat utilization to heat production.

lowest price interval I1 corresponds to 4.62% (3.55 - 6.08%) of Austrian power consumption. At prices of above 65 € / MWh$_{\text{power}}$ (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 range of model results declines as power prices get higher because cost variations become less influential.

In CHP plants, the production of heat is higher than of power 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 is declining 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. Secondly, the total heat demand in some settlements is low. Big plants like the ones assessed in the model produce excess heat in areas with low population densities.

3. 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 chance of the output to relative changes in the input [36]. Elasticities can be defined for all possible combinations of input parameters and output variables. Variable is used for further descriptions. The elasticities of variable are calculated likewise. The elasticity is defined as

$$\text{—— ——,} \tag{16}$$

where is the elasticity of to parameter .

The derivative —— 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 [37]

$$+,. \tag{17}$$

where coefficient is the intercept, coefficients are the regression coefficients and is an error term. The parameter vectors which represents the input to the Monte Carlo simulation and the corresponding result vectors , both consisting of elements, 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 estimator exhibits a fit of . The signs of the coefficients have the expected direction for all parameters. The response surface is used to numerically compute the elasticities:

$$\text{—— —— ——} \tag{18}$$

When no power is produced at all, the elasticity is not defined as the denominator of the fraction in Eq. (18) is 0 in such a case. Undefined elasticities are excluded from further calculations. The means of each elasticity distribution and for all observed parameter/output combinations are reported in Table 4. 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 tothe power output, i.e. the absolute value of the parameters is greater than 1. 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, i.e. the heating demand is a function of the connection rate. Increasing the heating demand allows the supplying of more heat to the settlements by decreasing infrastructure costs. Transportation costsshow 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

Parameter	**Mean of Elasticity**		**MdAPE**	
	$p_{par_l}^{tot}$	$q_{par_l}^{tot}$	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_h^{dist}	-0.23	-0.52	4.87	11.48
Transportation costs $c_{i,j}^{trans}$	-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 $\bar{b}_i$	0.82	0.23	1.66	0.49
Costs of fossil power production c^{fp}	1.34	0.76	24.12	15.10

Table 4: Results of sensitivity analysis: mean of elasticities and MdAPE.

the parameter contributes a lot to the uncertainty of the model. To estimate the contribution of a parameter to model uncertainty, the Median Absolute Percentage Error (MdAPE) [38] is calculated as error measure from the response surface following [35]. The results are reported in Table 4. 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 has a low elasticity, it contributes a lot to the uncertainty of the model. The same is the case

for district heating infrastructure costs . They show a high contribution to uncertainty with regard to the heat output. Both parameters and show a wide plausible range of values which explains the high contribution to model uncertainty.

4. Discussion and Conclusions

There is a considerable potential for CHP production at price levels between 52 and 57 € / MWh_{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. Others [39] estimate costs of biomass based CHP production to be around 54 € /MWh_{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_{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 paper 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, i.e. the plants

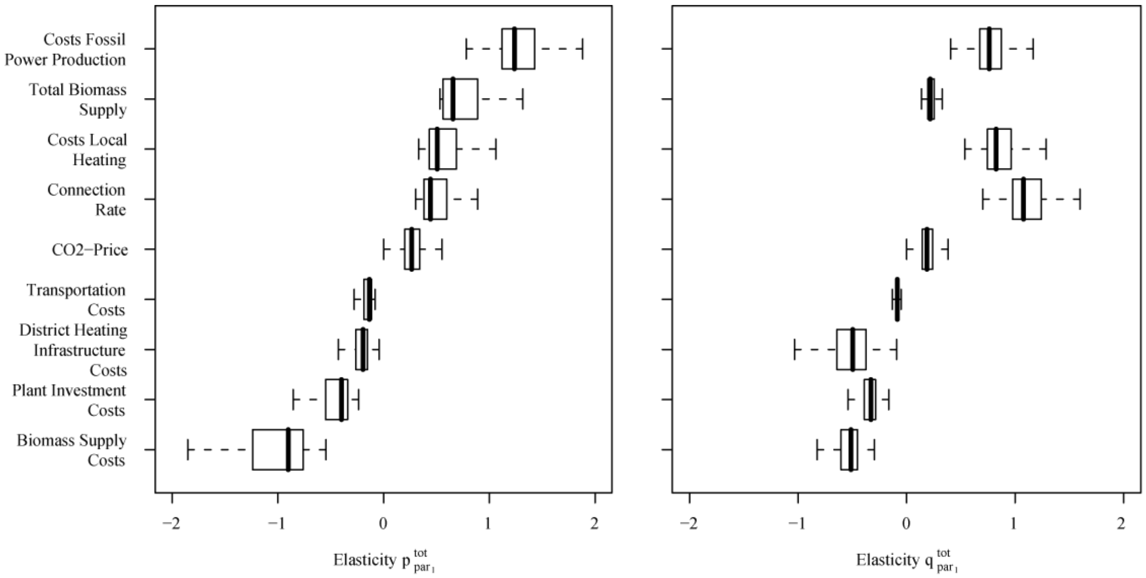

Figure 7: Results of sensitivity analysis: boxplots of distribution of elasticities.

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 is only a limited number of settlements where heat demand densities are high enough to allow building district heating networks. Lower heat demand densities due to better insulation of buildings [23] and warmer winter temperatures due to climate change [24] may further 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, e.g. 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 while other technologies like second generation biofuel production may become sound alternatives of wood use in the future [40]. Future application of the model to assess the competition of different technologies should therefore be an important research opportunity.

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