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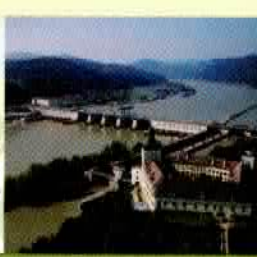

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Modeling of the Bioenergy Sector with the Simulation Tool SimBioSys

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Abstract: Due to the high importance of bioenergy in today's energy system and the vast potentials of biomass, scenarios for the future development of the bioenergy sector are of major interest. There are numerous factors which influence the medium to long-term prospects of bioenergy, including fossil fuel price developments, technological progress, energy demand trends and many more. Simulation tools are a means for handling the complexity of and interactions between these influencing factors and deriving well-founded scenarios.

This work provides insight into the modelling approach of the simulation tool *SimBioSys* and presents exemplary simulation results for the development of the Austrian bioenergy sector up to 2030 in an ambitious support scenario. The simulation results include the share of biomass in the total energy consumption, the energy output broken down by technology groups, the achieved annual greenhouse gas mitigation and fossil fuel saving as well as cost analyses.

Keywords: Bioenergy, Biomass, Scenarios, Simulation tool, Energy modelling

1 Introduction

The enhanced use of bioenergy is of major strategic importance for the future energy supply and the establishment of a sustainable energy system. Considering the political effort in Europe (and other parts of the world) to increase the utilization of bioenergy (e.g. biomass action plan [1], RES-E directive [2], directive on the promotion of the use of biofuels [3] and the proposal for a RES-directive [4]), it is essential to carry out profound systematic and strategic investigations about possible medium- and long-term developments in the bioenergy sector.

There is a big variety of options to utilize biomass for energy, both concerning the primary energy resources (e.g. forest wood, industrial wood residues, different energy crops, agricultural wastes, biogenous municipal solid wastes) and the technologies applied. Energy services that can be provided with biomass include electrical applications, space and water heating as well as large-scale heat generation and mobility. However, biomass resources are limited and the way these limited resources are utilized determines the ecological and economic efficiency of the bioenergy sector.

The paper is organized as follows:

- In section 2 the objective of this work is described.
- Section 3 deals with the methodological approach, the data structures and the main simulation algorithms of the model.
- In section 4 exemplary simulation results are presented.
- In section 5 conclusions are derived.

2 Objective

The core objective of this work is to provide insight into the modelling approach which is applied in the simulation tool *SimBioSys* (*Sim*ulation model for the *bio*-energy *sys*tem). The model description comprises a specification of the basic modelling approach, the input data and influencing factors as well as the core algorithms used to simulate future investments in bioenergy plants.

Furthermore, exemplary simulation results for the Austrian bioenergy sector up to 2030 are presented. The simulation results of the simulation model provide insight into numerous aspects, including the following:

- What is the achievable contribution of bioenergy to the energy supply under certain framework conditions?
- To what extent can bioenergy contribute to reducing greenhouse gas (GHG) emissions and fossil fuel consumption?
- What are the prospects for different bioenergy technologies?
- What are the costs and benefits of an enhanced bioenergy use?
- How can the available biomass resources in a certain region/country be utilized in a most efficient way?

3 Methodology

3.1 Basic approach

The following figure illustrates the basic idea behind the modelling approach. There are numerous factors which have a major influence on future investments in bioenergy plants and, in effect, on the future development and structure of the bioenergy sector. These factors include domestic resource potentials and their supply costs, economics of bioenergy technologies which can be influenced significantly by technological progress, fossil fuel price developments and energy policy framework conditions, energy demand trends / energy efficiency as well as the current bioenergy use (i.e. the deployment of bioenergy plants in

preceding years)[1]. Within the scenario simulation, the future deployment of bioenergy plants is determined on a yearly basis, based on these influencing factors and a deployment algorithm which was developed specifically for this model (section 3.3).

Subsequently, the resulting scenario is evaluated with regard to several aspects, including the contribution of bioenergy to the energy supply, costs and benefits of the energetic use of biomass and price developments of biomass resources. Apart from these systemic interpretations, technology-specific conclusions can be derived, for example with regard to the foreseeable importance or the market potential of a certain bioenergy technology.

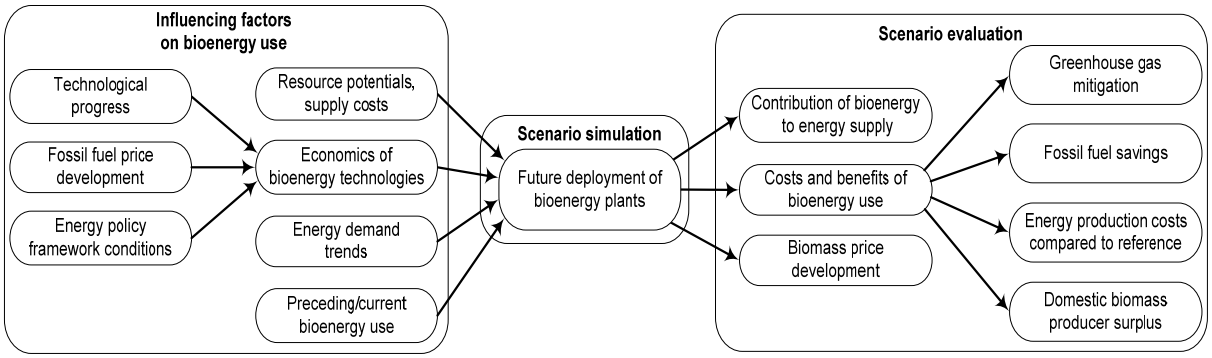

Figure 1. Illustration of the basic idea behind the modelling approach.

3.2 Model input data – data structures

The main data structures of the model are shown in Figure 2. There are three technology categories: heat generation plants, electricity / combined heat and power (CHP) plants and conversion technologies (including primarily biofuel production plants). Each output of bioenergy technologies is assigned to a certain output cluster, which is characterized by specific demand-side potentials and reference systems (reference costs / prices, GHG emissions and fossil fuels consumptions). Demand-side potentials are the upper limits of energy required of a certain type, for example heat from small-scale boilers with less than 15 kW rated power. Energy demand trends, increasing energy efficiency and projected market diffusion of other renewable energy technologies (like solar thermal collectors) are the main influencing factors on the demand-side potentials of bioenergy technologies.

The data structure “technology type” contains technology-specific data such as efficiencies, power range, investment, operation and maintenance costs, technology-specific GHG emissions (e.g. for auxiliary energy) etc.

[1] Needless to say, there are various other influencing factors (such as the deployment of other renewable energy technologies) and interconnections between influencing factors (e.g. impacts of technological progress on biomass supply costs) which are not explicitly shown in this illustrative figure.

Biomass potentials are structured into “fuel types”. The input data for each fuel type include potentials and costs in the form of a dynamic supply curves (see section 3.2.3), import prices and embedded use of fossil fuels as well as embedded GHG emissions.

Each technology type is associated with one or more fuel types. The combination of a technology type with a fuel type is referred to as “utilization path” or “technology path”. Energy production costs, depending on the fuel price, technology-specific costs and technology data are calculated for technology paths. The specific GHG emissions per energy output (based on the embedded emissions of the fuel and the technology-specific emissions) as well as the specific fossil fuel consumption are also path-specific properties.

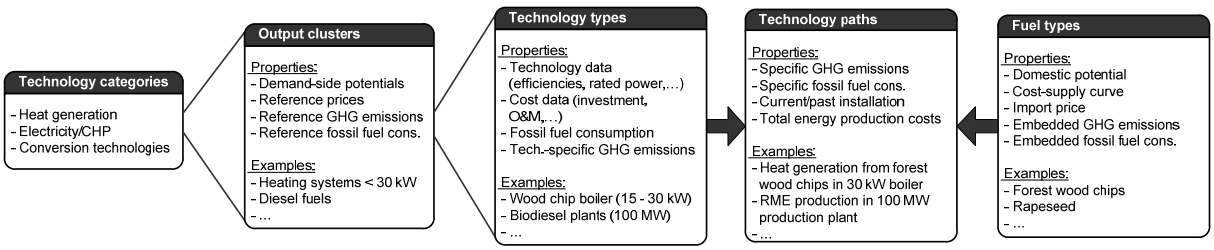

Figure 2. Main data structures of the model SimBioSys.

3.2.1 Technologies

Table 1 shows the list and classification of bioenergy technologies considered in the current data set of the model. For each technology category the main output and optional secondary outputs are specified and each output is assigned to a certain output cluster, depending on the plant size and/or type. For heating systems / heat plants, the heat output is considered as the main output, for electricity and CHP plants electricity and for conversion technologies the calorific value of the produced fuel. Technology data like rated power [MW] or investment costs [€ MW^{-1}] or main efficiencies [1] refer to the main output. Optional secondary outputs include heat from CHP generation, electricity from polygeneration plants or non-energetic outputs like DDGS (animal fodder) from ethanol plants. Generation costs, specific GHG mitigation etc. always refer to the main output and secondary outputs are considered via credits (see section 6).

Due to significant *economies of scale*–effects in heat generation costs and the fact that demand-side potentials are a considerable restriction for heat generation from biomass, heat is subdivided into several clusters. Since all power generation technologies are assumed to be grid-connected and therefore have the same reference system, there is only one general electricity cluster. Fuels produced by biomass conversion technologies are subdivided into gaseous, 1st and 2nd generation fuels to account for their different blending properties and to some extent different reference prices.

Table 1: Structuring of bioenergy technologies and output clusters

Category	Output clusters	Technology types
Heat generation (main output: heat)	**Heat:** (wood log/general)[2] < 15 kW therm. 15 to 30 kW therm. 30 to 100 kW therm.	Wood log boilers Wood chip boilers Pellet boilers Cereal boilers Plant oil boilers
	Heat: 100 kW to 1 MW therm. 1 to 5 MW therm. > 5 MW therm.	Straw heat plants Wood chip heat plants Pellet heat plants
Electricity / CHP generation (main output: electricity, secondary output: heat)	**Electricity:** General electricity cluster **Heat:** < 100 kW therm. 100 kW to 1 MW therm. 1 to 5 MW therm. > 5 MW therm.	Boilers with Stirling engine Biogas plants ORC plants Steam turbine plants Fuel cells (MCFC) Integrated gasification combined cycle plants
Conversion technologies (main output: refined fuels, secondary outputs: heat, electricity, non-energy products)	**Fuels:** 1st generation liquid biofuels 2nd generation liquid biofuels Gaseous biofuels Other fuels **Electricity:** General electricity cluster **Heat:** < 100 kW therm 100 kW to 1 MW therm. 1 to 5 MW therm. > 5 MW therm.	Oil press Biodiesel plant Bioethanol plant – DDGS Bioethanol plant – biogas
		Fischer-Tropsch plants Lignocellulosic ethanol plants
		Anaerobic digestion–conditioning–feed-in plants Gasification plants
		Biorefineries Polygeneration plants

3.2.2 Reference systems

In order to compare energy production from biomass with conventional technologies, suitable reference systems have to be defined for all technology clusters. Since practically all simulation results (including the simulated deployment and economic performance of bioenergy plants, the achieved GHG mitigation and fossil fuel savings etc.) depend on the reference systems assumed, the choice of appropriate reference systems is of major importance. Also, it is crucial that future developments (especially fuel price developments) assumed for the different fossil fuels / reference systems are consistent.

Figure 3 illustrates the default methodology which is applied for deriving consistent reference prices for all technology clusters. Based on a general trend in fossil fuel price development, consistent price scenarios for crude oil and natural gas and in further consequence prices for

[2] For small-scale heating systems the heat clusters are not only subdivided according to their power ranges but also into „general“ and „wood log-derived heat”. This allows for the implementation of an exogenous decline in the use of wood log which is due to a shift to higher automated heating systems. This shift has been observed in the last decade and is expected to continue.

oil products (heating oil, diesel and gasoline) and natural gas prices for small-scale and large-scale consumers are derived. As a reference prices for liquid transport fuels diesel and gasoline wholesale prices and for biomass-derived substitute/synthetic natural gas (SNG) natural gas wholesale prices are used.

The economics of heat, electricity and combined heat and power (CHP) technologies are assessed on the basis of the heat and electricity generation costs, respectively. Therefore, technological and cost data of representative fossil fuelled technologies also have an impact on the reference prices / costs which are used for bioenergy technologies of these categories. For small-scale heating systems a mix of oil and gas boilers with the same power range is considered as the reference system and for large-scale heat generation according natural gas heating plants. The default reference system for electricity is a modern combined cycle gas turbine (CCGT).

However, due to the major impact of the choice of reference systems on the simulation results, sensitivity analyses with other reference systems (e.g. coal power plants for electricity) are considered to be essential.

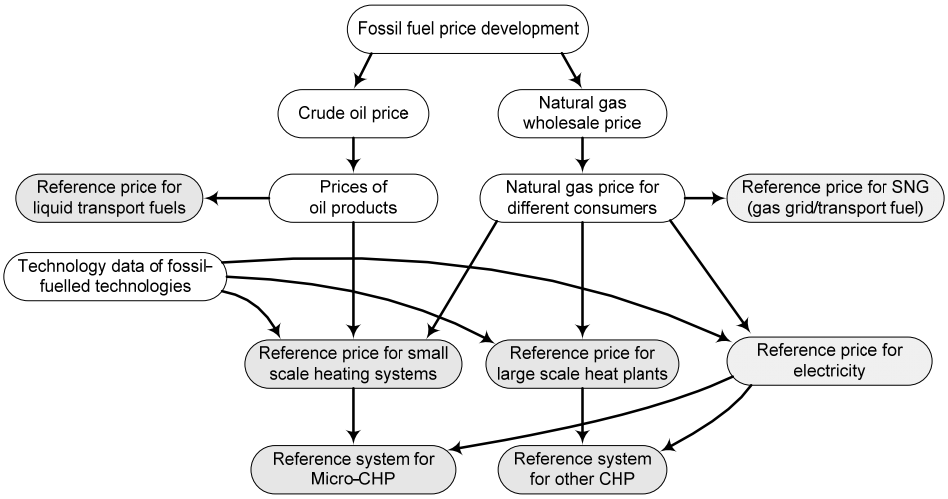

Figure 3. Default reference prices: influencing parameters and interconnections.

3.2.3 Biomass resources and supply curves

The domestic potentials of biomass resources are represented by dynamic continuous supply curves within the model. Supply curves represent the amount of a fuel which can – ceteris paribus – be mobilized at various prices. The attribute “dynamic” indicates that in general, supply curves change over time. Figure 4 shows an exemplary supply curve for energy wood from Austrian forests.

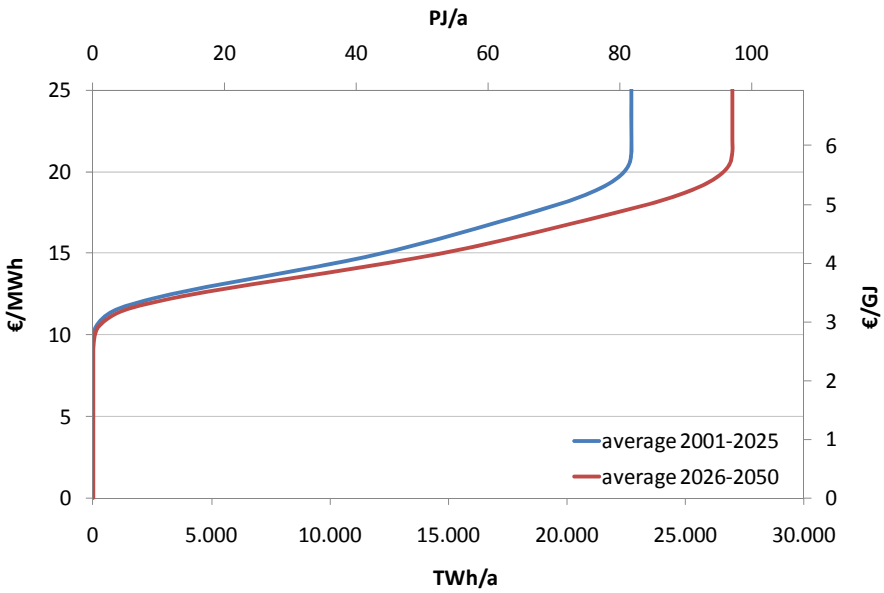

Figure 4: Example for a dynamic supply curve for energy wood from Austrian forests (preliminary result of the project "KlimAdapt", baseline scenario) [5].

Imports of biomass resources from outside the region/country under consideration are taken into account in the following way:

- If there are not sufficient domestic biomass resources available to supply the demand of existing bioenergy plants, the shortage is met with imports.
- The prices of imports are defined exogenously and are – contrary to domestic resources – not influenced by the demand.
- For the fulfilment of quotas, the use of domestic resources can either be prioritized or not. In the first case, imports are only used if there are no enough domestic resources available to fulfil the quota and in the second imports are used as soon as they allow for the quota to be fulfilled in a more cost-effective way.

3.2.4 Subsidies for bioenergy

The model allows for the simulation of different support schemes for bioenergy. These support schemes include investment subsidies, premiums for energy from biomass plants, feed-in tariffs for electricity from bioenergy plants and obligatory quotas. All subsidies are defined on a yearly basis. Table 2 gives an overview of the support schemes and their properties.

Table 2. Support schemes and their properties

Type of subsidy	Description
Investment subsidy	Defined as share of total investment costs [€/kW], values are defined for technology types, support costs incur in the year of installation
Premium	Subsidy on energy production in [€/MWh], values are defined for technology types, support costs incur during operation (i.e. each year) and are independent from reference price and fuel price developments
Quota	Obligatory generation in [TWh/a], quotas are usually defined for one technology cluster (e.g. electricity) but can also comprise several clusters (e.g. liquid and gaseous transport fuels), certificate price is equal to LRMC of most expensive plant which contributes to fulfilment of quota, support costs incur annually and are influenced by reference and biomass price developments
Feed-in tariffs (FITs)	Guaranteed price for electricity from bioenergy plants [€/MWh], values are defined on technology type-level and can vary depending on fuel type used, FITs remain constant for the whole lifetime of plant (usually 15 years) regardless of reference price, support costs incur annually and are influenced by reference and fuel prices developments

3.3 Simulation algorithms

3.3.1 Deployment of competitive plants

Within the deployment algorithm of the model *SimBioSys*, investments in bioenergy plants are simulated based on a myopic least-cost approach. It is assumed that in each simulation period (each year) the decision-making structure of potential investors in bioenergy is based on a comparison of the total energy production costs (i.e. the long-run marginal costs – LRMC) of bioenergy technologies with those of the according conventional reference system. Energy policy instruments like investment subsidies and tax incentives are taken into account in the calculation of the energy generation costs.

Simply put, bioenergy plants are deployed if they are competitive under the framework conditions of the current simulation period and if there are free demand-side and resource potentials. Apart from these restrictions, diffusion barriers which are modelled with an S-shaped diffusion curve limit the annual deployment of bioenergy plants on a per-cluster-basis. The parameters of the cluster-specific diffusion curves are derived from developments observed in the past (e.g. small-scale heating systems) and exogenous scenarios (e.g. gaseous transport fuels based on projected stock of gas-fuelled vehicles), respectively.

In Figure 5a the algorithm which is applied for determining the “additional competitive power capacity” (ACPC) of a bioenergy technology. This figure is to illustrate the basic approach for one simulation period and one fuel, on the assumption that this fuel is utilized by only one technology type:

Based on the already installed capacities, the “initial“ demand q^* for *fuel a* and, based on the supply curve in the current period $q_{BM}(p)$, the according market price p^* are determined. In the situation shown in Fig. 5a, the potential of fuel *a* is not used exhaustively and the LRMC of technology 1 at the price p^* are lower than the according reference price/costs $c_{ref,1}$, additional capacities are competitive and can be installed. The ACPC ($P_{econ,1}$) is calculated from the potential ($q_0 - q^*$) which can be utilized in a competitive way, the annual full load

hours $T_{FL,1}$ and the main efficiency η_1 of the technology, according to Eq. (3.1). (Variable declarations are summarized in section 6.)

$$P_{econ,1} = \frac{(q_0 - q^*)}{T_{FL,1}} \cdot \eta_1 \qquad (3.1)$$

In general, a certain biomass resource can be utilized by a number of different technologies. Hence, several utilization paths compete for limited resources. In reality not only the "most competitive" plants are installed and market players are not able to anticipate the effect of an increasing demand on the market price of a commodity. The deployment algorithm of the model *SimBioSys* was designed in order to reflect these observations.

Figure 5b illustrates the deployment algorithm for the case of one fuel which is utilized by two technologies. In this example both technologies are competitive in the range q^* to q'. In the simulation algorithm the potential $(q' - q^*)$ which is competed for by the two technologies is distributed proportionally to their "indicators of competitiveness" a_k. The ACPCs for the range q^* to q' are calculated according to Eq. (3.2) to (3.4). In the range $(q_0 - q')$ only technology 1 is competitive and therefore is assigned the whole resource potential.

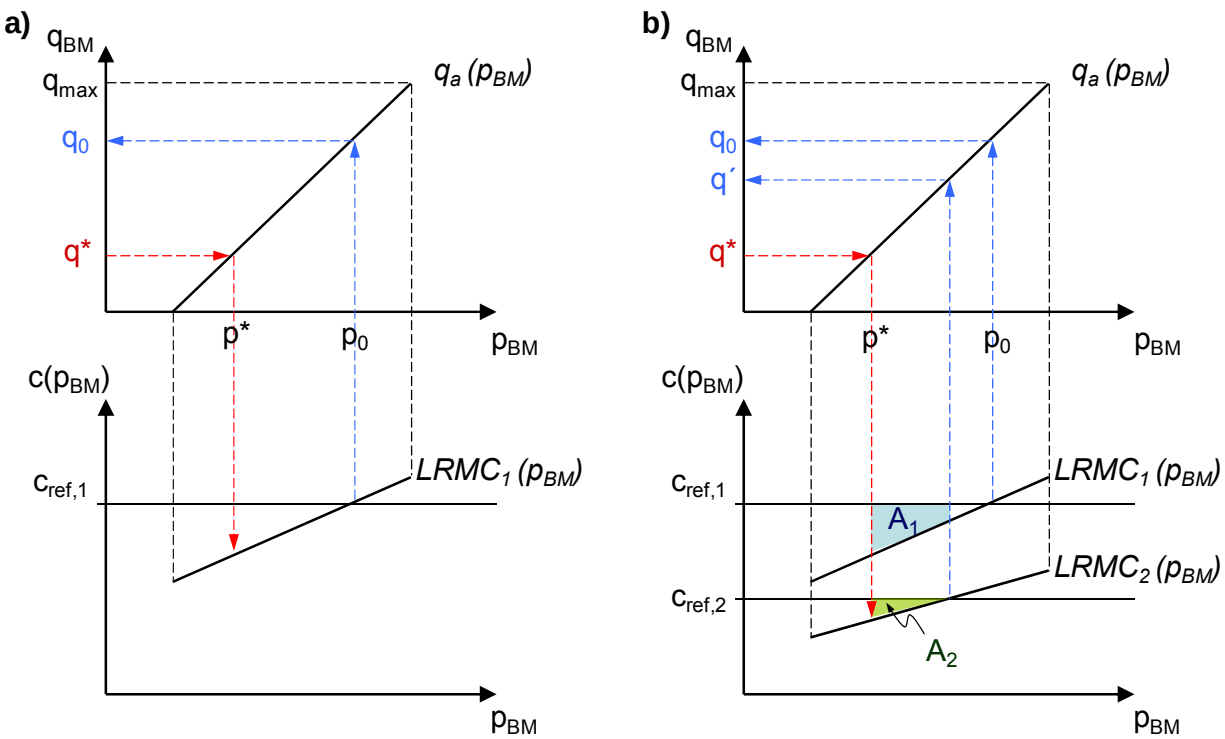

Figure 5. Illustration of the deployment algorithm for one fuel and one (a) and two technologies (b)

$$a_k = \frac{A_k}{c_{ref,k}} \qquad (3.2)$$

$$Q_{econ,k} = \frac{(q' - q^*) \cdot a_k}{\sum_{i=1}^{n} a_i} \qquad (3.3)$$

$$P_{econ,k} = \frac{Q_{econ,k}}{T_{FL,k}} \cdot \eta_k \qquad (3.4)$$

In the most general case, the deployment of a multitude of technologies, based on numerous biomass resources is simulated in the way described above. For each resource the fuel potential which can be utilized in a competitive way is subdivided into a sufficient number of fractions. For each of these fractions, the indicators of competitiveness are determined for each technologies and the potential distributed according to Eq. (3.3).

In the explanations above, the impact of minimum plant capacities and demand-side potentials as well as diffusion barriers have been neglected. These aspects are considered as follows:

- If the ACPC determined within the deployment algorithm is less than the minimum capacity of the according technology, the deployment is set to zero.
- The total generation of each cluster-specific output (both of the main and of secondary outputs) may not exceed the demand-side potential and the maximum increase according to the diffusion curve. The additional installation of each technology is limited accordingly.

The cluster-specific diffusion curves are specified by the parameters α_j and $\Delta y_{max,j}$. The maximum additional generation $y_{add,j}$ is calculated on the basis of these parameters, the current generation y_j and the demand-side potential $y_{max,j}$ according to Eq. (3.5). Fig. 6a shows the maximum additional generation as a function of the achieved demand-side potential for different parameter settings. Fig. 6b shows the according diffusion curves.

$$y_{add,j} = \alpha_j \cdot y_j \left(1 - \frac{y_j}{y_{\max,j}}\right) \cdot \Delta y_{\max,j} \qquad (3.5)$$

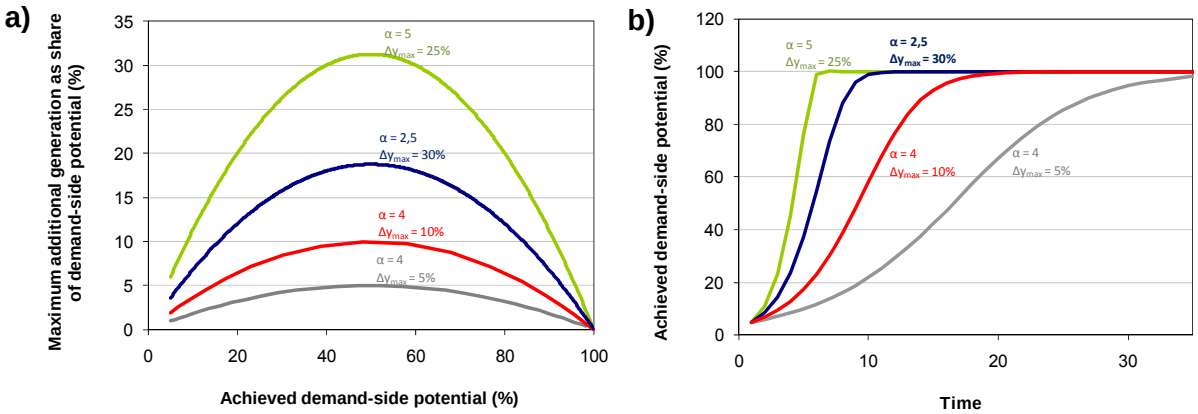

Figure 6. Maximum additional generation as a function of the achieved demand-side potential for different parameter settings (a) and the according diffusion curves (b).

3.3.2 Simulation of quotas

Obligatory quotas can be specified for output clusters or groups of output clusters, for example for liquid transport fuels or separately for 1st and 2nd generation biofuels. Sub-quotas

are also possible. The fulfilment of quotas has priority against the deployment of competitive plants. If more than one quota is specified, quota priorities can be assigned.

Quotas are assumed to be fulfilled in the most cost-effective way. Hence, the modelling approach is to derive a “least-cost supply curve” (LCSC) for the energy output in demand, and determine the plant capacities required to reach the quota. The following figures illustrate the approach of the “quota algorithm”.

In this example it is assumed that there are three technologies which can contribute to the fulfilment of the quota. Technology 1 and 2 utilize biomass resource “a” and technology 3 biomass resource “b”. Fig. 7a shows the supply curves of the biomass resources $p_{BM,a}(q_{BM,b})$ and Fig. 7b the energy / fuel production costs of the three technologies (*LRMC*$_1$ to *LRMC*$_3$) as functions of the amount of biomass used.

From the cost functions of the technologies the LCSC (which shows the energy/fuel production costs as a function of the fuel/energy supply) is derived. Starting at c_0, technology 1 is the cheapest option for producing the energy output $(q_{a,1} \cdot \eta_1)$. The next segment of the LCSC is made up by technology 2 due to a higher efficiency than technology 1, resulting in a lower slope of the LRMC-curve. From c_2 to c_3 both technology 2 and technology 3 contribute to the LCSC since they do not compete for the same fuel (as it is the case for technology 1 and 2). At c_3 the maximum supply of fuel a is reached. The last segment of the LCSC is therefore made up by technology 3 alone.

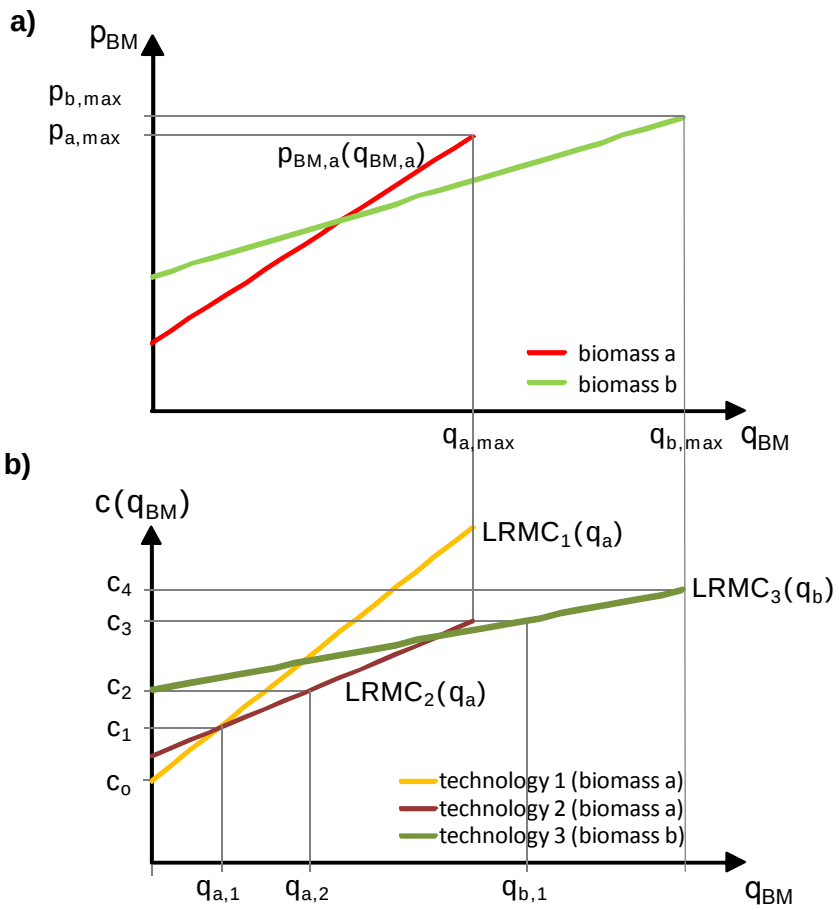

Figure 7. Illustration of the quota algorithm (part 1): supply curves of two fuels (a) and according energy / fuel generation costs of three technologies.

The demand which results from a given quota is represented by the vertical red line in Fig. 8. The intersection point determines the "certificate price" p_C which results from the quota. At $q_{a,pc}$ and $q_{b,pc}$ (on the biomass supply curves), the LRMC of technology 2 and technology 3 are equal to p_c (Eq. (3.6)). The production capacities required to reach the quota in a most cost-effective way are determined according to Eq. (3.7).

Minimum capacities of bioenergy plants are also considered within the actual quota algorithm. Diffusion barriers are not taken into account.

$$LRMC_2(q_{a,pc}) = LRMC_3(q_{b,pc}) = p_c \tag{3.6}$$

$$P_{quota,1} = \frac{q_{a,1}}{T_{FL,1}} \cdot \eta_1 , \qquad P_{quota,2} = \frac{(q_{a,pc} - q_{a,1})}{T_{FL,2}} \cdot \eta_2 , \qquad P_{quota,3} = \frac{q_{b,pc}}{T_{FL,3}} \cdot \eta_3 \tag{3.7}$$

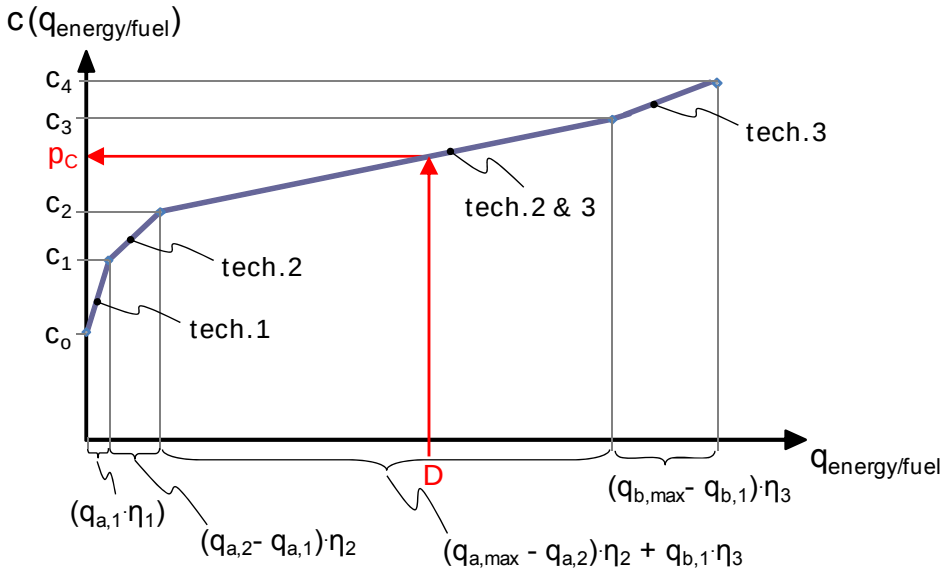

Figure 8. Illustration of the quota algorithm (part 2): resulting "least-costs supply curve" for the energy / fuel output in demand.

4 Results

The following figures show exemplary simulation results of the model *SimBioSys*. The simulation is **based on preliminary input data** derived from the project "Bioenergy-Strategy 2050" [6] as well as preliminary results from the project KlimAdapt [5] and ALPot [7]. The purpose of this section is to give an impression of the output data of the model, not to analyze this exemplary scenario.

The main scenario settings for the simulation run are summarized in Table 3 and Fig. 9 to Fig. 14 show some main results: Fig. 9 shows the share of bioenergy in the total primary energy consumption and in the sectors heat, electricity and transport fuels. Due to the given support schemes a significant increase is achieved. The share of biofuels in the transport sector is determined by the biofuel quota. The steps in the biofuel share are a consequence

of the minimum plant sizes assumed. In this scenario the biofuel quota is reached with biodiesel produced from (primarily imported) rapeseed.

Fig. 10 shows the primary energy consumption of biomass broken down by biomass type and Fig. 11 the output of bioenergy plants broken down by output clusters. In Fig. 12 the achieved GHG mitigation broken down by output clusters and the total fossil fuel saving are shown. Fig. 13 shows the average GHG mitigation costs on a per-cluster-basis and Fig. 14 the total producer surplus of domestic biomass fuel producers (defined as the difference of provision costs and market price). Due to increasing fossil fuel prices, advancing exploitation of biomass potentials and respective biomass price increases from 2010 to 2020, the total biomass producer surplus shows a significant increase.

Table 3: Main scenario settings for the exemplary simulation run

Characterization	Ambitious support scenario without significant improvements in energy efficiency
Price scenario	Crude oil price rising from about 60 $\$_{2007}$/bbl (average 2009) to 113 $\$_{2007}$/bbl in 2030, electricity wholesale price rising from about 66 $€_{2007}$/MWh in 2008 to 85.7 $€_{2007}$/MWh in 2030
Energy demand scenario	Based on baseline scenario according to [8]: Increase in gross inland consumption from 397 TWh/a in 2008 to 450 TWh/a in 2030
Support schemes	Small-scale heating systems: investment subsidies (20%)
	Liquid biofuels: Obligatory quota (10 % from 2020 to 2030)
	CHP plants: Fuel- and technology-specific feed-in tariffs (ranging from 66 €/MWh for steam turbine plants > 5 MW to 170 €/MWh for Biogas plants < 100 kW)
Simulation period	2011 to 2030 (data from 2001 to 2010 based on historic deployment / forecast)

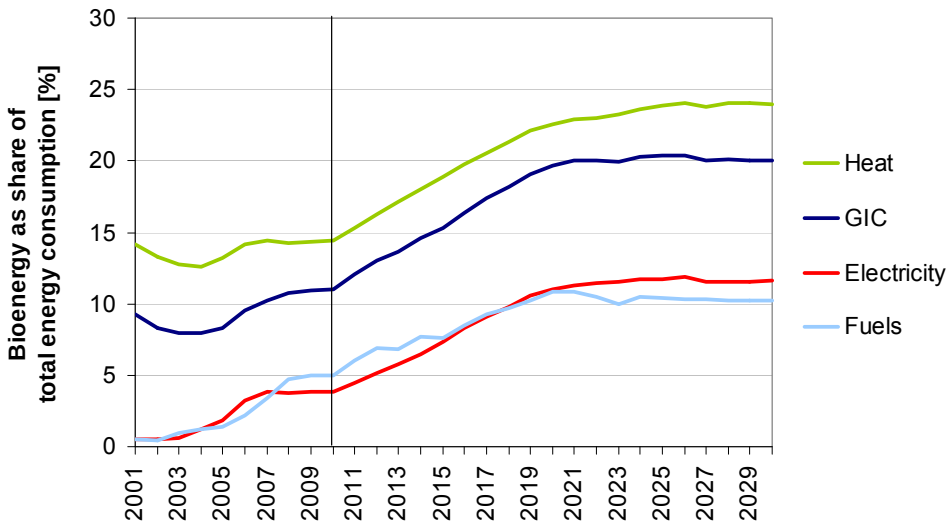

Figure 9: Results of the exemplary simulation run: Share of bioenergy in the gross inland consumption (GIC) and in the sectors heat, electricity and transport fuels.

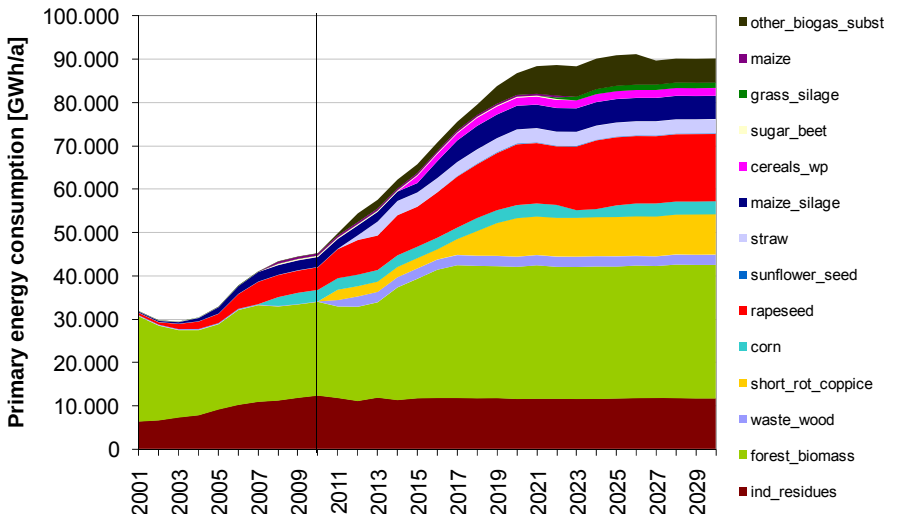

Figure 10: Results of the exemplary simulation run: biomass primary energy consumption

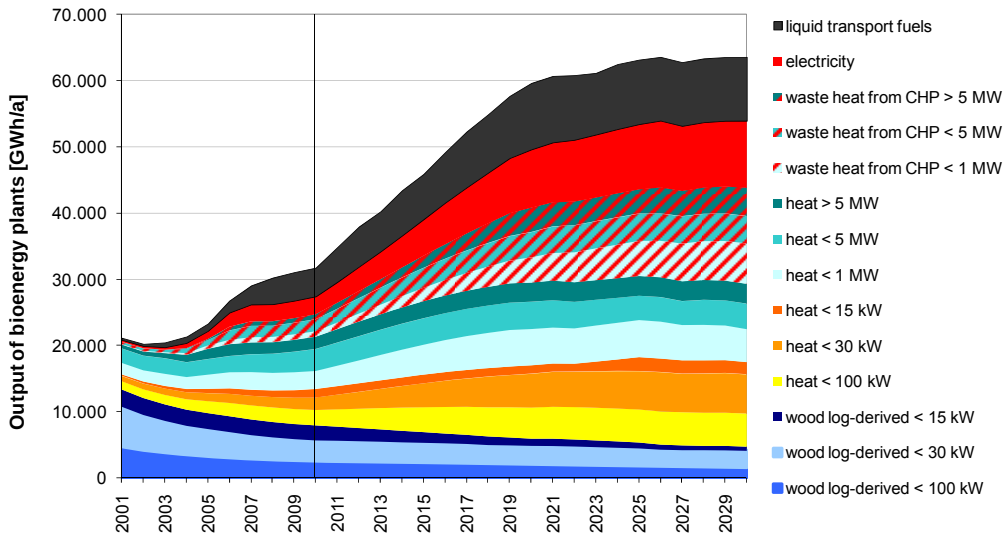

Figure 11: Results of the exemplary simulation run: output of bioenergy plants

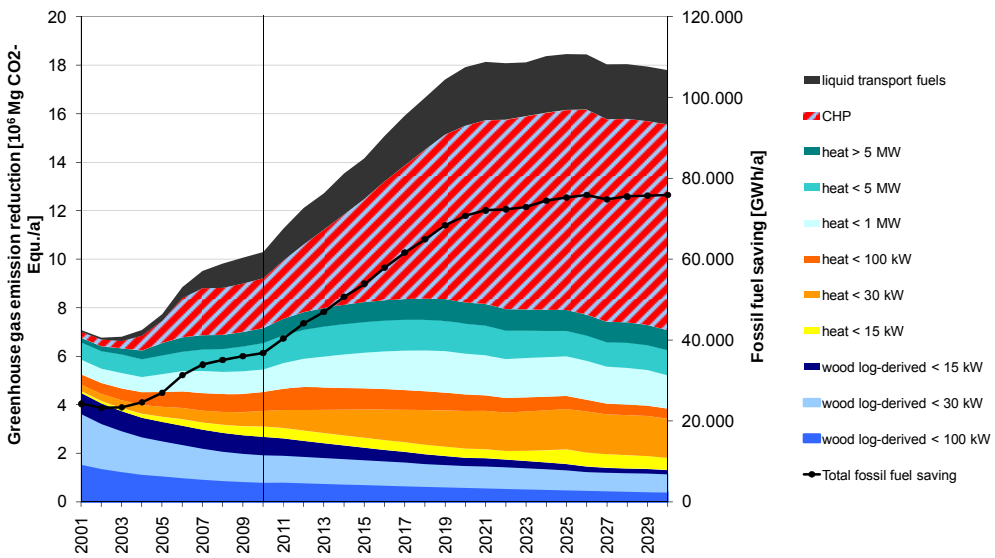

Figure 12: Results of the exemplary simulation run: GHG mitigation and fossil fuel saving

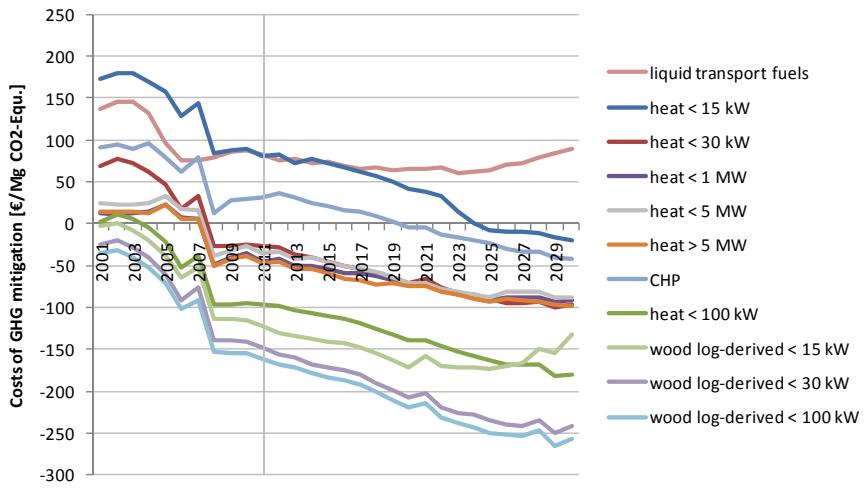

Figure 13: Results of the exemplary simulation run: Cluster-specific average GHG mitigation costs

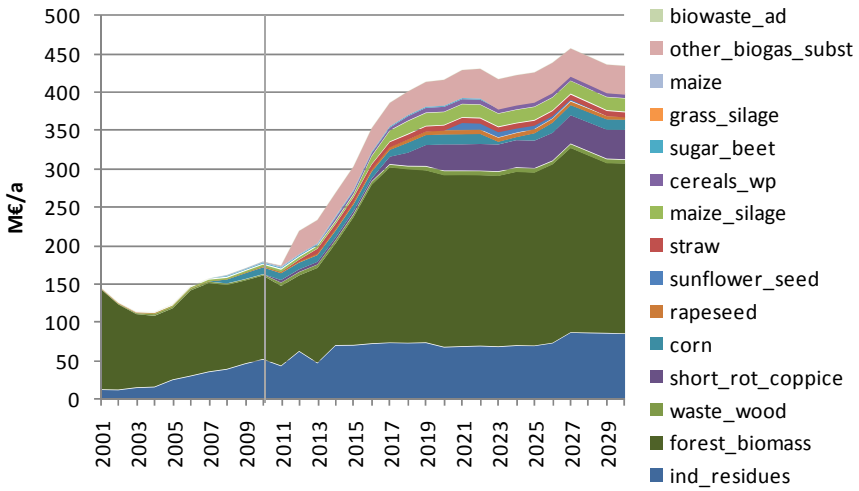

Figure 14: Results of the exemplary simulation run: total producer surplus of domestic biomass fuel producers

5 Conclusions

The model *SimBioSys* is a suitable tool for deriving medium to long-term scenarios for the bioenergy sector. The following aspects are considered crucial for deriving well-founded scenarios:

- Taking into account the big variety of bioenergy options: It is necessary to consider a considerable number of technologies (ranging from small-scale heating systems to large-scale biofuel production plants), biomass resources and energy services that can be provided with bioenergy.
- Defining appropriate reference systems and deriving consistent scenarios for fossil fuel price developments. Especially for biomass heating systems it is crucial to account for *economies-of-scale* effects and comparing bioenergy systems with conventional systems of the same rated power.

- Taking into account numerous influencing parameters including different support schemes, technological progress, energy demand trends as well as the growing importance of other renewable energies and their impacts on the demand-side potentials of bioenergy technologies.
- Deriving appropriate algorithms for simulating investment decisions. A special focus should be put on avoiding *penny-switching* effects and modelling resource competition among bioenergy technologies. Within the modelling approach of the model *SimBioSys*, the available resource potential which can be utilized economically, is distributed among the competitive bioenergy technology based on an "indicator of competitiveness".
- Biomass resource potentials and their costs of provision need to be modelled in an appropriate way. By using continuous supply curves it is possible to avoid *penny-switching* effects, to model biomass fuel price developments endogenously and to take into account that provision costs often vary over a wide range.
- Evaluating the simulation results with regard to costs and benefits. The focus of the scenario evaluation of the model *SimBioSys* is on additional costs compared to conventional technologies and costs of support schemes on the one hand and GHG mitigation effects, fossil fuel savings and domestic biomass producer surplus on the other.

6 Nomenclature and further equations

η_i	Main efficiency of technology "i" [1]
$\eta_{therm,i}$	thermal efficiency of CHP/conversion technology "i"
$\eta_{ele,i}$	electrical efficiency of conversion technology "i" [1]
$\eta_{byprod,i,b}$	byproduct "b" output of conversion technology "i" [t MWh_{input}^{-1}]
$c_{I,i}$	Investment costs per MW (main output) [€ MW^{-1}]
$c_{O\&M,i}$	Operation and maintenance costs [€ MW^{-1} a^{-1}]
$T_{FL,i}$	Annual full load hours of technology "i" [h a^{-1}]
$p_{BM,a}$	Price of biomass resource "a" [€ MWh^{-1}]
$p_{ref,y}$	Reference price of output cluster "y" [€ MWh^{-1}] ([€ Mg^{-1}] for byproducts)
$LRMC_i$	Long run marginal costs (total energy generation costs of main output) of technology "i" [€ MWh^{-1}]
α_i	Capital recovery factor

$$\alpha_i = \frac{(1+i_i)^{n_i} \cdot i_i}{(1+i_i)^{n_i} - 1} \qquad (6.1)$$

i_i Interest rate assumed for technology "i" [1]

n_i Depreciation period assumed for technology "i" [a^{-1}]

Short run marginal costs of heat generation plants:

$$SRMC_i = \frac{p_{BM,a}}{\eta_i} + \frac{c_{O\&M,i}}{T_{FL,i}} \tag{6.2}$$

Short run marginal costs of electricity/CHP plants (y stands for the according heat cluster):

$$SRMC_i = \frac{p_{BM,a}}{\eta_i} + \frac{c_{O\&M,i}}{T_{FL,i}} - p_{ref,y} \cdot \frac{\eta_{therm,i}}{\eta_i} \tag{6.3}$$

Short run marginal costs of conversion technologies, including biofuel production, polygeneration and biorefineries ("y1", "y2" and "b" stand for the according heat, electricity and by-product cluster):

$$SRMC_i = \frac{p_{BM,a}}{\eta_i} + \frac{c_{O\&M,i}}{T_{FL,i}} - p_{ref,y1} \cdot \frac{\eta_{therm,i}}{\eta_i} - p_{ref,y2} \cdot \frac{\eta_{ele,i}}{\eta_i} - p_{ref,b} \cdot \frac{\eta_{byprod,i,b}}{\eta_i} \tag{6.4}$$

Long run marginal costs:

$$LRMC_i = SRMC_i + \frac{c_{I,i} \cdot \alpha_i}{T_{FL,i}} \tag{6.5}$$

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