DISSERTATION

An assessment of the implications, costs and benefits of bioenergy use based on techno-economic approaches

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Abstract

Efforts to reduce greenhouse gas emissions and increase the share of renewable energy have led to notable progress in bioenergy use in Austria and other Central European countries in recent years. Within this thesis, crucial aspects regarding the implications and prospects of bioenergy use are assessed based on techno-economic approaches.

In the first part of this work, the costs of greenhouse gas mitigation and fossil fuel replacement of bioenergy technologies are assessed for the specific situation in Austria. The results indicate that biomass heating systems and heating plants are often the most cost-efficient option. Under favourable conditions, the use of combined heat and power plants allows for higher quantities of greenhouse gas mitigation and fossil fuel replacement per unit of biomass consumed. A relatively poor performance with regard to this criterion is the main drawback of advanced biofuels, albeit that technological progress may result in substantial reductions in production costs.

In the second part, statistical data on the current biomass use and international biomass trade, as well as literature data on biomass potentials in Central Europe are reviewed critically. With regard to the structure of bioenergy use and unused biomass potentials, the situations in the considered countries prove to be very inhomogeneous. Different methodologies applied for assessing cross-border trade related to bioenergy indicate that the most significant streams in the Central European region are imports of wood fuels to Italy, Denmark and Austria. The recent growth in the consumption of biofuels for transport is resulting in rapidly increasing trade volumes and a growing dependence on biofuel imports. For the case of Austria it is shown that with feedstock for biofuel production and indirect trade streams taken into account, cross-border trade of biomass is more than twice as high as energy statistics suggest.

Part III is dedicated to the question of how future developments of the bioenergy sector can be modelled based on techno-economic approaches, in order to derive well-founded medium to long-term scenarios. The modelling approach applied in the simulation tool *SimBioSys,* its fundamental principles and exemplary simulation results for the Austrian bioenergy sector are presented. The simulation results emphasize that bioenergy has a crucial role to play in enhancing energy security, reducing GHG emission and substituting fossil fuels in Austria. Furthermore, they indicate that due to the numerous options of bioenergy use, a strategic and targeted promotion of the most efficient applications is of crucial importance for the economic and environmental efficiency of the bioenergy sector.

Keywords: bioenergy technologies, climate mitigation, fossil fuel replacement, economic efficiency, techno-economic assessment, biomass potentials, biomass trade, scenarios, energy modelling, bioenergy sector, Austria, Central Europe

Kurzfassung

In Österreich und anderen mitteleuropäischen Ländern ist es in den letzten Jahren zu einer starken Ausweitung der energetischen Biomassenutzung gekommen. In der vorliegenden Arbeit werden die Kosten und Nutzen, sowie die Perspektiven und Implikationen der Energieerzeugung aus Biomasse mithilfe techno-ökonomischer Ansätze analysiert.

Im ersten Teil der Arbeit werden die Kosten der Treibhausgaseinsparung und Substitution fossiler Energieträger ermittelt, die mit dem Einsatz verschiedener Bioenergie-Technologien verbunden sind. Die Ergebnisse zeigen, dass Biomasse-Heizsysteme und -Heizwerke häufig die kosteneffizienteste Option darstellen, unter günstigen Rahmenbedingungen jedoch mit Biomasse-Kraft-Wärme-Kopplung höhere spezifische Einsparungen (bezogen auf den Primärenergieeinsatz) erzielbar sind. Im Gegensatz dazu ist die Nutzung synthetischer biogener Kraftstoffe mit verhältnismäßig geringen Einsparungen verbunden; dies stellt einen wesentlichen Nachteil dieser Nutzungspfade dar, selbst wenn die Produktionskosten durch technologischen Fortschritt längerfristig erheblich sinken sollten.

Im zweiten Teil werden statistische Daten zur derzeitigen Biomassenutzung, internationalem Biomassehandel und Abschätzungen von primärenergetischen Potenzialen in Mitteleuropa einer kritischen Prüfung unterzogen. Die Ergebnisse zeigen sowohl hinsichtlich der Struktur der Biomassenutzung, als auch hinsichtlich der ungenutzten Potenziale in den einzelnen Ländern ein sehr heterogenes Bild. Verschiedene methodische Ansätze zur Analyse von Handelsströmen ergeben, dass internationaler Biomassehandel sukzessive an Bedeutung gewinnt; insbesondere im Bereich der biogenen Kraftstoffe, wo Österreich und Mitteleuropa zunehmend auf Importe angewiesen sind. Neben den in Energiestatistiken erfassten direkten Handelsströmen spielen indirekter Biomassehandel und Importe von Rohstoffen zur Erzeugung biogener Kraftstoffe eine wesentliche Rolle. Im Fall von Österreich liegen diese in Summe in der gleichen Größenordnung wie direkte Handelsströme.

Teil 3 befasst sich mit der Modellierung des Bioenergie-Sektors auf Basis eines techno-ökonomischen Ansatzes, der im Simulationsmodell *SimBioSys* implementiert wurde. Mit dem Modell erstellte längerfristige Szenarien des österreichischen Bioenergie-Sektors zeigen, welche Rolle Biomasse in einem zukünftigen Energiesystem zukommen kann, und unterstreichen die Bedeutung zielorientierter, auf die effizientesten Nutzungspfade fokussierter Förderstrategien.

Schlagwörter: Bioenergie-Technologien, Klimaschutz, Substitution fossiler Energieträger, techno-ökonomische Analyse, Biomassepotenziale, Biomassehandel, Energiemodellierungen, Bioenergie-Sektor, Österreich, Mitteleuropa

Executive summary

The thesis is structured into three parts: The focus of Part I is on bioenergy technologies. The costs of greenhouse gas (GHG) mitigation and fossil fuel replacement (abatement costs) of bioenergy technologies for heat, electricity and transport fuel production are assessed for the specific situation in Austria. Part II is primarily based on statistical data on bioenergy use in Austria and other Central European countries as well as results of studies assessing the biomass potentials in the Central European region. Based on a critical review of these data, conclusions about the implications of recent developments in bioenergy use with a special focus on international biomass trade are assessed and conclusions about future prospects derived. In Part III the modelling approach of the simulation model *SimBioSys* and exemplary simulation results for the development of the Austrian bioenergy sector during the next decades are presented. The simulation results provide insight into possible development paths, major influencing factors as well as costs and benefits of bioenergy use.

Part I: Techno-economic assessment of bioenergy technologies

The core issues of the European and Austrian energy policy agendas include reducing GHG emissions and dependence on fossil fuels in a cost-efficient way. Within Part I of this study, the abatement costs of currently established and upcoming bioenergy technologies of different capacities for heat, electricity and transport fuel production are assessed. With regard to costs, fuel prices and other parameters representative values for the situation in Austria are assumed. The abatement costs are defined as the incremental costs compared to reference systems based on fossil fuels per unit decrease in GHG emissions or fossil fuel demand, respectively.

The results show that the abatement costs of wood-based heat generation technologies substituting oil-fired boilers and gas-fired heating plants, respectively, are in the range of -45 € per ton CO_2-equivalent (€/t CO_2-eq.) and -11 € per MWh higher heating value (€/MWh_{HHV}) to 93 €/t CO_2-eq. and 24 €/MWh_{HHV}. Heating systems around 50 kW show the lowest abatement costs. For combined heat and power (CHP) plants, two different cases with regard to heat utilization are assumed. Under optimal conditions (100% of generated heat displaces fossil fuel-based heat production), abatement costs of wood-based technologies, substituting electricity from modern combined cycle gas turbines, range from 5 €/t CO_2-eq. and 1 €/MWh_{HHV} to 201 €/t CO_2-eq. and 38 €/MWh_{HHV}. Representative values of typical CHP plants with a capacity of 1 MW_{el} and more are in the magnitude of 50 €/t CO_2-eq. and 10 €/MWh_{HHV}. Under less favourable conditions (assuming 3000 heat full load hours per year), abatement costs of typical CHP plants are around 100 €/t CO_2-eq. and 17 €/MWh_{HHV} higher. The costs of GHG mitigation and fossil fuel saving with established transport fuels (biodiesel and ethanol from starch or sugar) range from 71 €/t CO_2-eq. and

8 €/MWh$_{HHV}$ to 200 €/t CO_2-eq. and 82 €/MWh$_{HHV}$ For liquid fuels from lignocellulosis, abatement costs are estimated 147 €/t CO_2-eq. and 38 €/MWh$_{HHV}$ to 240 €/t CO_2-eq. and 59 €/MWh$_{HHV}$. The abatement costs of with synthetic natural gas are found to be significantly lower: 75 €/t CO_2-eq. and 14 €/MWh$_{HHV}$ to 128 €/t CO_2-eq. and 23 €/MWh$_{HHV}$.

The results suggest that the substitution of fossil fuel-based heat generation is often the most cost-efficient way of reducing GHG emissions and fossil fuel demand with biomass. Typical abatement costs of biomass CHP technologies are in a similar range as those of heat generation under favourable conditions only. However, a core advantage of CHP are higher achievable values of fossil fuel saving and GHG mitigation per unit of biomass used. In contrast, this is found to be the main drawback of synthetic transport fuels from wood. Sensitivity analyses and projections up to 2030 illustrate the effect of commodity price increases, technological development and other parameters on specific abatement costs.

Part II: Bioenergy in Central Europe with a particular focus on the situation in Austria – Recent developments, international biomass trade and future prospects

In order to assess future prospects of bioenergy use, it is essential to have thorough knowledge of the status quo, recent developments and unused primary energy potentials. To this end, statistical data on the current biomass use and international biomass trade streams as well as data on biomass potentials in literature need to be reviewed and discussed. In Part II of this work this is done for the Central European (CE) region, with a special focus on international biomass trade and the situation in Austria.

The contribution of biomass and wastes to the energy supply in CE countries ranges from 2.8% in Italy to 14.9% in Denmark (2008). Due to European directives and according national support schemes, the share of biomass in the total energy consumption has been increasing significantly in recent years, especially in Denmark (+6% from 2000 to 2008), Germany (+4.8%), Austria (+4.5%) and Hungary (+3.9%). The main progress was achieved in the field of electricity and CHP generation as well as the production and use of biogenic transport fuels.

With regard to the compilation and interpretation of statistics on international biomass trade, various challenges need to be addressed. Data on biomass cross-border trade in energy statistics do not cover the whole range of biomass used for energy recovery, such as energy crops for biofuel production or biomass which is originally intended for material uses but ultimately ends up in energy production (indirect trade). Therefore, methodological approaches to gain insight into recent developments and the status quo of biomass trade are proposed and discussed. Subsequently, it is analysed which Central European countries act as importers and exporters of biomass, and trade streams are mapped.

The main importers of wood fuels in CE are Italy, Denmark and Austria. Cross-border trade of wood pellets and other wood fuels has increased significantly in recent years. For Denmark pellets are the most important biomass import stream. Austria, being a net exporter of wood pellets, is importing considerable amounts of wood residues; directly as well as indirectly in the form of industrial roundwood.

With regard to direct trade of biogenic transport fuels, Austria, Italy and Poland are the main importers (primarily biodiesel). Although growing rapidly, cross-border trade related to biofuels is still rather moderate compared to (indirect and direct) trade of wood fuels in CE. However, there is strong evidence that the CE region is currently becoming increasingly dependent on imports of biofuels as well as feedstock for biofuel production.

For the case of Austria, a detailed assessment of trade streams, including trade streams which are not considered in energy statistics, namely indirect trade of wood-based fuels and energy crops intended for biofuel production is carried out. The results indicate that recently, the net imports of biomass accounted for up to 20% of the total bioenergy use in Austria. This is about twice as high as data in energy statistics suggest.

The results and methodological approaches of studies assessing biomass potentials indicate that there are considerable unused biomass resources available in Austria and other CE countries. Part II of this thesis also provides insight into the – among the considered countries highly inhomogeneous – structures of biomass potentials, their current exploitation and the achievable contribution to the energy supply. With regard to the EU's 2020-targets, it is undisputed that bioenergy has a crucial role to play, and therefore deserves special attention in the design of policies promoting renewable energy.

Part III: Modelling the Bioenergy System – Scenarios of the Austrian Bioenergy Sector

This part is dedicated to the question of how future developments of the bioenergy sector can be modelled based on techno-economic approaches, in order to derive dynamic medium to long-term scenarios of bioenergy use. There are numerous factors which influence the prospects of bioenergy, including fossil fuel price developments, technological progress, energy demand trends and many more. The simulation model *SimBioSys*, which was developed in the course of this thesis, is a suitable tool for handling the complexity of and interactions between these influencing factors and deriving well-founded scenarios of the bioenergy sector. Part III provides insight into the fundamental principles and the core algorithms of the modelling approach, which are based on profitability analyses of the different biomass utilization paths. Economic framework conditions like subsidies or prices for fossil fuels as well as supply curves for biomass are the main influencing parameters.

Exemplary simulation results provide insight into the prospects of bioenergy use in Austria under different framework conditions. With the first group of simulations, the prospects of the **Austrian bioenergy sector up to 2030 with a special focus on agricultural biomass** are assessed. The following scenarios are analysed: *No Policy Scenarios* (no subsidies or tax incentives for bioenergy), *Current Policy Scenarios* (current subsidies and tax incentives) und *Specific Support Scenarios* (increasing levels of financial incentives for certain utilization paths). The results of the *No Policy* and *Current Policy Scenarios* are evaluated primarily with regard to the importance of agricultural biomass to the energy supply. The main purpose of the *Specific Support Scenarios* is to illustrate the cost-benefit ratios (greenhouse gas mitigation and substitution of fossil fuels vs. costs) of different utilization paths and to derive conclusions regarding favourable focal points for funding. With regard to the fossil fuel price developments, two scenarios are distinguished: *Level 2006* (real prices remain constant at the level of the year 2006) and *FAO/Primes* (increasing real prices for fossil fuels with a crude oil price exceeding 100 $\$_{2007}$/bbl in 2020).

Under the support scenario *No Policy* and the price scenario *Level 2006* practically no utilization paths of energy crops are competitive. Until 2030, the only notable contribution of agricultural biomass to the energy supply originates from the use of straw and (to a very moderate extent) plant oil in CHP plants. However, in this scenario the bioenergy sector is dominated by the use of forest biomass and wood processing residues for residential and district heating as well as steam generation. The main difference in the price scenario *FAO/Primes* is the clearly higher exploitation of forest biomass potentials for heat generation. Apart from that, electricity generation in large biogas plants (with an electrical power of 500 kW and more) using maize silage is to some extent competitive. Still, agricultural biomass plays a rather insignificant role.

The *Current Policy Scenarios* illustrate to what extent agricultural biomass could be utilized in a profitable way up to 2030 if the current support schemes and tax incentives are maintained. In contrast to the *No Policy Scenarios*, these scenarios show a substantial increase in the demand for energy crops, and the question of what type of energy crops are preferred, gains in importance. Therefore, three scenarios with different focuses of energy crop production are assessed: *Conventional crops*, *biogas plants* and *lignocellulosic feedstock*. The best cost-benefit ratio as well as the highest expansion of agricultural bioenergy is achieved with a focus on lignocellulosic biomass (short rotation coppice). The greenhouse gas reduction from agricultural bioenergy in this scenario accounts for 3 Mt CO_2-Equ. in the year 2020 und 5.7 Mt in 2030. The savings of fossil fuel consumptions amount to 15 TWh in 2020 and 27 TWh in 2030. However, the arable land used for energy crop production accounts for about 300,000 ha in 2020 and 600,000 ha in 2030 (close to one fourth/half of the total arable land in Austria). The savings achievable with a focus on *conventional crops* and *biogas plants* are clearly lower.

It is concluded that in the case of a continuing increase in fossil fuels prices, agricultural biomass of domestic origin could be of some significance for the Austrian bioenergy sector.

However, the production of large quantities of energy crops entails a reduction of the self-sufficiency in food and feed crops, unless increases in crop yields are achieved or the demand for food and feed crops declines (e.g. through changes in nutritional behaviour). Intercropping may be an option for producing biogas feedstock without interfering with food and feed production, but under the current framework conditions the potentials are found to be rather moderate. However, the longer-term potentials might prove to be clearly higher, as research in this field may lead to optimized crop rotations and cultivation methods. Apart from energy crops, straw, other plant residues and manure represent a limited but (with regard to ecological issues) favourable and yet hardly used potential for agricultural energy generation.

The second group of simulations are **climate-sensitive scenarios of the Austrian bioenergy sector up to 2050**, based on the climate scenarios A2, A1B and B1 according to IPCC (2000). The climate-sensitive (scenario-specific) influencing parameters which are taken into account include: the development of energy demand (residential heat and electricity for cooling), supply potentials of forest biomass and prices of fossil fuels (based on scenarios in literature). The simulation results illustrate that the impact of these climate-sensitive influencing parameters are very moderate, compared to the influence of different support policies for bioenergy. Therefore it is concluded that a strategic and targeted promotion of bioenergy use has priority over measures in the bioenergy sector to adapt to climate change.

1 Preface

1.1 Motivation

Among the different renewable energy sources, bioenergy is of crucial importance for the future energy supply in Central Europe.[1] Not only because it already has the highest share of all RES, but also due to the vast potentials of biomass, and the fact that it can be used in all energy sectors: for sole heat and electricity or combined heat and power generation as well as for the production of transport fuels.

There is a wide variety of technological options for generating energy from biomass. Numerous further technologies are currently being developed and made ready for the market. Moreover, the wide range of biomass resources, including woody biomass, different energy crops as well as wastes and residues of various origins is increasingly being tapped, further contributing to the diversity of utilization paths. Figure 1-1 shows a systematic illustration of bioenergy utilization paths, ranging from the provision of biogenic energy carriers over various conversion technologies to different end uses. The economic and ecological efficiencies of the variety of biomass utilization paths depend on numerous factors; they are highly diverse and therefore require close investigation.

In order to assess future prospects of bioenergy use, it is essential to have thorough knowledge of the status quo, recent developments and unused primary energy potentials in the region under consideration. To this end, statistical data on the current biomass use as well as data on biomass potentials in literature need to be reviewed and discussed critically. A special focus is given to methodologies for assessing international biomass trade streams, as they are only partly covered in energy statistics.

In order to gain insight into the prospects of bioenergy use, well-founded scenarios are of great value. In the context of medium to long-term scenarios, it is necessary to consider both techno-economic properties of bioenergy technologies and systemic characteristics. The latter include a variety of factors which influence the market potential of bioenergy, such as demand-side potentials of bioenergy technologies, supply potentials and costs of biomass resources, market diffusion patterns, energy demand trends, competition with other renewable energy technologies and many more. Simulation tools are a means for handling the complexity of and interactions between these influencing factors and deriving well-founded scenarios.

[1] Within this work, the term “bioenergy” is used for all kinds of biomass use for energy production. “Biofuels” is used for liquid and gaseous fuels produced from biomass and usually used for mobility, such as biodiesel, ethanol, Fischer-Tropsch-Diesel or biomethane (cleaned and conditioned biogas from anaerobic digestion).

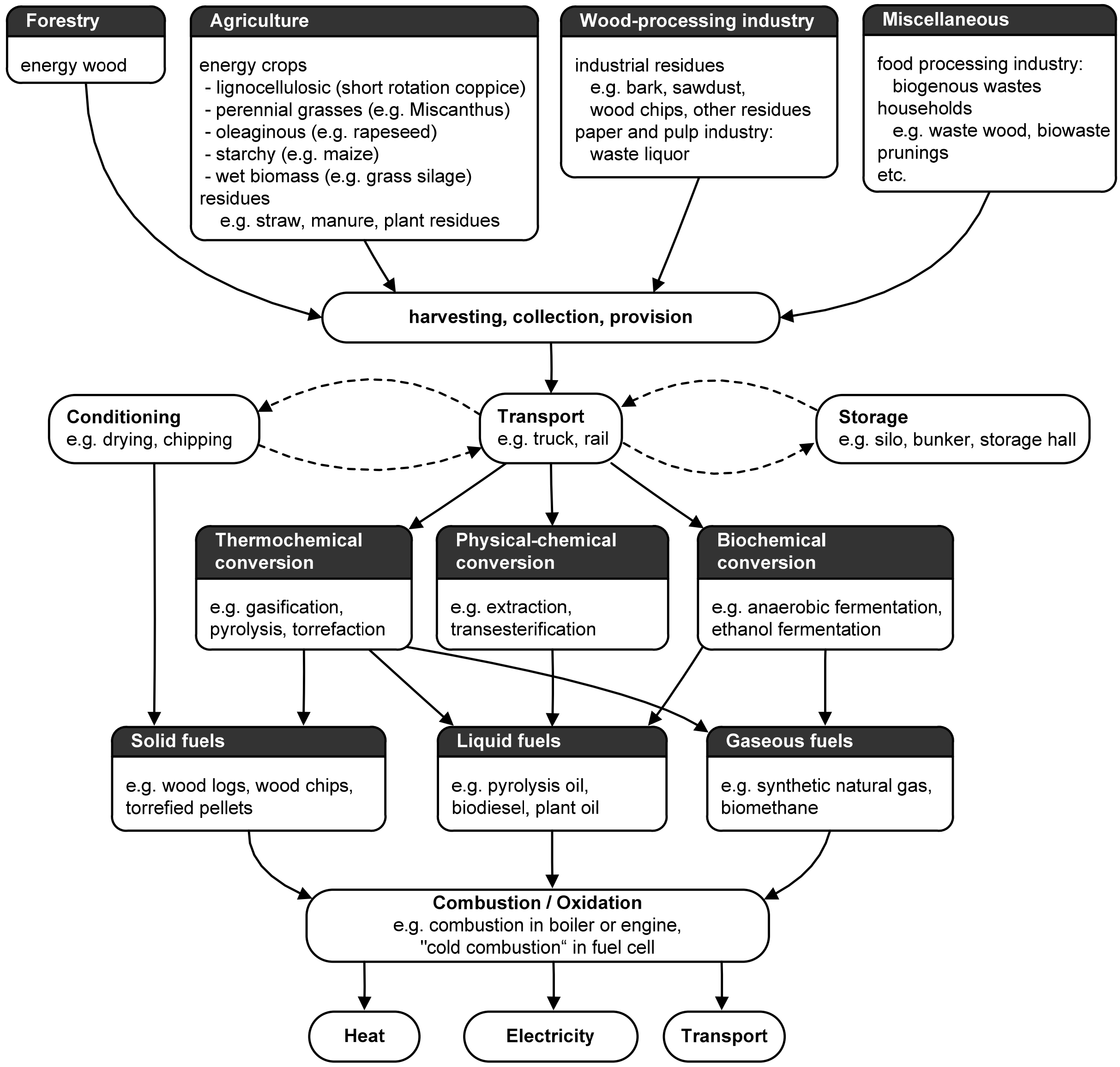

Figure 1-1. Systematic illustration of the variety of bioenergy utilization paths
Source: own illustration based on Kaltschmitt et al. (2009)

1.2 Objective and methodological approaches

The core questions of this thesis are:

- What are the costs and benefits of bioenergy use with regard to costs, greenhouse gas (GHG) mitigation and fossil fuel replacement?
- What is the current importance of bioenergy for the energy supply in Austria and other Central European (CE) countries, and to what extent does the increasing use of bioenergy effect international biomass trade?

- To what extent can bioenergy contribute to a sustainable energy system in the next two to four decades?
- What are the key factors for the establishment of an efficient bioenergy system and what are the core issues and challenges which need to be addressed in energy policies?

In order to explore these questions, the following approaches are applied:

- Techno-economic assessments are carried out for bioenergy technologies relevant for Central Europe, as well as according reference technologies.
    - o The economics of these technologies are investigated for the specific situation in Austria. In a second step future prospects are assessed, based on literature data on technological progress, projected cost reductions and fuel price scenarios up to 2030.
    - o With the life-cycle software GEMIS (Global Emission Model of Integrated Systems; Oeko-Institut, 2010) the cumulated fossil fuel demand and GHG emissions of the considered technologies are determined.
    - o Finally, the specific costs of GHG mitigation and fossil fuel replacement of the different technologies, as well as the reductions per quantity of biomass used, are compared.
    - o Sensitivity analyses are carried out for the most significant influencing parameters, and the impact of alternative reference systems is investigated.
- The evolution of bioenergy use in Central European countries in recent years is explored with regard to the following aspects:
    - o The development and structure of the current bioenergy use, with a special focus on country-specific characteristics and the impact of EU Directives
    - o The importance and development of international biomass trade related to bioenergy; different methodological approaches are applied, in order to tackle the difficulties related to inadequate data in statistics
    - o The current exploitation of biomass supply potentials, as well as the prospects for an enhanced bioenergy use, and issues to be addressed in future bioenergy policies
- In an attempt of creating a simulation tool which is suited for deriving dynamic medium to long-term scenarios for bioenergy use, the model *SimBioSys* was implemented. The main characteristics and features of the model are:
    - o It is a myopic bottom-up simulation model for the bioenergy sector.
    - o Based on continuous supply curves for biomass resources, the deployment of bioenergy plants is simulated by determining the biomass demand where the

energy production costs of bioenergy technologies and the respective reference technologies are in equilibrium.
  - The model allows for the simulation of four different support schemes for bioenergy: investment subsidies, quotas, premia and feed-in tariffs.
  - The simulation results are evaluated by numerous criteria, providing insight into the costs and benefits of bioenergy in the resulting scenario.
  - The model is implemented in the numerical computing environment *MATLAB*.
- With the model *SimBioSys*, the prospects of bioenergy use in Austria are explored:
  - In the first group of scenarios, a special focus is given to agricultural bioenergy. It is investigated, how the use of bioenergy evolves under different framework conditions, und which utilization paths of agricultural biomass show the best cost-benefit ratio.
  - With the second group of scenarios the impact of climate change on the development of the Austrian bioenergy sector is analysed by comparing "climate-sensitive" with "baseline" scenarios.

1.3 Outline

After this preface (section 1), the work is structured in three parts:

The topic of **Part I** is a techno-economic assessment of currently established and advanced bioenergy technologies. After an introduction (section 2), the methodology and data are described (section 3). The results are presented in section 4, and section 5 provides a summary and discussion.

Part II gives an overview of recent developments, the current state and future prospects of biomass use in CE. The different situations in CE countries with regard to the amount and structure of bioenergy use are discussed in section 6. The topic of section 7 is international biomass trade and of section 8 potentials and prospects for an enhanced use of bioenergy. Section 9 finishes Part II with conclusions and a discussion of policy implications.

In **Part III** the software tool *SimBioSys* and simulation results of this tool are presented. Section 10 includes an introduction as well as a brief overview of energy models used for simulating the bioenergy sector in literature. The basic approach, algorithms, data structures and exogenous scenario parameters of the model are described in section 11. Exemplary simulation results for the Austrian bioenergy sector are illustrated and discussed in section 12.

Section 13 concludes with a synthesis and outlook. The annex (section 14) contains a list of abbreviations, technology data and nomenclature and formulae used in Part I and III, references and the lists of figures and tables.

Part I:

Techno-economic assessment of bioenergy technologies

2 Introduction

Two of the major challenges of the European Union's and Austria's energy policy are to reduce greenhouse gas (GHG) emissions and dependence on fossil fuels (EC, 2009a). Bioenergy is generally expected to make a significant contribution to these energy policy targets (see BMLFUW et BMWFJ, 2010 or Resch et al., 2008a), as biomass currently has the highest share of all renewable energy sources in Austria (and the EU), its primary energy potentials are still far from exploited and bioenergy can be used in all energy sectors: for sole heat production or combined heat and power (CHP) generation as well as for the production of biofuels. Furthermore, there is a wide variety of technologies and biomass types, and plant sizes range from small single stoves to large-scale plants. Hence, there are numerous pathways for energy conversion from biogenic energy carriers, each of which has specific properties with regard to GHG mitigation, fossil fuel replacement and economics.[2]

2.1 Biomass and fossil fuel consumption in Austria

Biomass currently accounts for about 15% of the total primary energy consumption in Austria (all data about the current energy use stated here are based on Statistik Austria, 2010a and Statistik Austria, 2010b and refer to 2008). Until the end of the 20th century, the energetic use of biomass was virtually limited to heat generation (residential heating as well as process heat generation in the industry). Today biomass accounts for about 30% of the total energy demand for space and water heating. Despite the growing importance of renewable energy sources, fossil fuels account for more than 50% (heating oil currently accounts for 74 PJ and natural gas for 76 PJ). Therefore, the use of biomass in the heat sector still holds the opportunity for substituting significant amounts of fossil fuels.

Due to the implementation of support schemes, biomass has also become increasingly important for district heating, power generation and in the transport sector in recent years and decades. About 38% of the district heat supply is currently based on biomass (25.5 PJ), with 17% coming from heating plants and 21% from CHP plants (biogenic fraction of waste not included). The non-renewable production of district heat is dominated by natural gas: 32% of the total supply originate from natural gas CHP and 10% from heating plants.

In the electricity sector, the implementation of feed-in tariffs resulted in an increase of the biomass share from around 3% in the late 1990s to 6.5% in 2008. Fossil fuel-based electricity

[2] A concise version of Part I has been published in "Applied Energy", a journal of Elsevier, under the title "Assessing the economic efficiency of bioenergy technologies in climate mitigation and fossil fuel replacement in Austria using a techno-economic approach" (Kalt et Kranzl, 2011a).

generation accounts for about 30% (with more than half of this coming from natural gas-fired power plants), the rest is primarily hydropower.
As a consequence of obligatory quotas and tax incentives, the share of biofuels in road transport fuel consumption increased from less than 1% in 2005 to approximately 7% in 2009 (Winter, 2010). The fossil fuel consumption in the transport sector accounts for about 300 PJ/a (about 75% diesel and 25% gasoline).[3]

2.2 Objective and outline

Comparing GHG mitigation costs of different technologies is a commonly used approach for identifying efficient strategies for achieving climate policy targets (e.g. IEA, 2009a and Bloomberg New Energy Finance, 2010). However, there is scarce literature comparing GHG mitigation costs of different bioenergy technologies, taking into account the wide range of plant sizes and variable operational characteristics, such as annual full load hours or heat utilization rates of CHP plants.
The objective of this work is to assess GHG mitigation costs as well as costs arising from replacing fossil fuels with bioenergy technologies for the situation in Austria. Biomass and fossil fuel prices are based on specific data for Austria. Plant costs (investment, operation and maintenance costs) were also preferably taken from studies referring to the situation in Austria. The selection of bioenergy and reference technologies is based on which plant types and sizes are common in Austria. In addition, upcoming technologies which are likely to become important in the future are taken into account, such as small-scale CHP with Stirling engines and Organic Rankine Cycle (ORC) or advanced bioenergy technologies like FT- (Fischer Tropsch-), SNG- (synthetic natural gas) or BIGCC-plants (biomass integrated gasification combined cycle).
The results of this study are to provide insight into the question of how limited biomass resources can be utilized in a most efficient way, and how bioenergy can contribute to the achievement of energy policy targets in a cost-efficient way. In contrast to other publications on this topic, a core objective of this study is to highlight the influence of plant sizes and other parameters on the efficiency of bioenergy technologies for GHG mitigation and fossil fuel replacement.
Despite high volatility of fuel prices and big uncertainties related to future technology costs, it is deemed essential to consider possible future developments, in order to derive recommendations for energy policy strategies. Therefore, projections for technological developments, plant costs and fuel prices are used to assess trends up to 2030.

[3] A more detailed description of the Austrian bioenergy sector is provided in section 6.4.

The paper is organized as follows: In section 3 the methodological approach is described and data used in this work are summarized. Section 4 provides the results for the default case (sections 4.1 to 4.3), a summary (4.4) and outlook to 2030 (4.5) as well as sensitivity analyses (4.6). In section 5 the results are discussed conclusions are derived.

3 Methodology and data

3.1 Methodological approach

The methodological approach consists of the following steps:

First, default reference systems are defined for each cluster of bioenergy technologies. The selection of reference technologies is based on the current supply structure in the according energy sector (see section 1.1); those fossil-based energy systems which are most likely to be replaced with bioenergy technologies are defined as default reference system. Table 3-1 gives an overview of the technology clusters and their fossil fuel-based reference systems in the default case and sensitivity analyses (alternative cases). GHG mitigation costs of heating systems and heat plants are calculated on the basis of the heat generation costs. Since oil-fired boilers are still very common in Austria (especially in non-urban regions, where modern biomass systems are more likely to be installed than in urban areas), oil-fired boilers are considered as reference technologies for biomass systems. Oil fired stoves are the reference system for biomass stoves. CHP plants are compared with the reference power generation technology on the basis of the electricity generation costs. Due to the increasing electricity demand in Austria and the fact that natural gas-fired combined cycle gas turbines (CCGT) are assumed to constitute the price setting technology, modern CCGT are considered as reference technology in the default case. The production costs of liquid and gaseous biofuels are directly compared with wholesale prices of the fuel they displace (i.e. fossil diesel, gasoline or natural gas). The alternative reference systems are discussed in section 4.6.3.

Next, a default set of technology data, representative fuel prices etc. is compiled. These data are summarized in section 2.2 and the Appendix, respectively. Third, the costs of bioenergy and reference technologies are compared on the basis of the energy generation costs (long run marginal costs, LRMC). The production of waste heat in CHP plants as well as by-products of biofuel production plants are taken into account in the form of revenues (see section 14.3.1 in the Annex for the formulas). Following Gustavsson et Madlener (2003) and IEA (2009b), the GHG mitigation costs of a bioenergy technology x are defined as the incremental generation costs ΔC_x per unit decrease in GHG emissions ΔE_x:

$$C_{mit} = \frac{\Delta C_x}{\Delta E_x} = \frac{C_x - C_r}{E_r - E_x} \qquad (3\text{-}1)$$

where C_x (C_r) denote the energy generation costs and E_x (E_r) the specific GHG emissions resulting from energy generation with the bioenergy technology (the reference system). Only systems with $(E_r - E_x) > 0$ are assessed, i.e. technologies which have lower specific GHG emissions than the reference system. In the case of transport fuels, wholesale prices of the displaced fuels represent the reference cost. Engine modifications and additional costs which might arise from the displacement of fossil fuels with biofuels are not taken into account.

The mitigation cost can be interpreted as the minimum incentive in the form of a carbon tax which is required to equal the additional cost of a bioenergy system with the cost of the reference system. Taxes, tax incentives and other subsidies which are currently in place are not considered in this calculation.

When E_x and E_r in Eq. (3-1) are replaced by the specific cumulated fossil fuel demand of the bioenergy technology D_x and of the reference technology D_r, Eq. (3-1) defines the cost of fossil fuel replacement. Auxiliary energy consumption, (fossil fuel-based) peak load coverage in biomass heating and CHP plants, energy consumed in the fuel supply chain and the related GHG emissions are taken into account for bioenergy and reference technologies.

Table 3-1. Bioenergy technology clusters and reference technologies.

Bioenergy technology cluster	Default reference system	Alternative reference systems (sensitivity analysis)	Value of comparison (C_x and C_{ref})
Wood log/ Pellet stove (8 kW)	Oil-fired stoves (8 kW)	–	Heat generation cost
Small scale heating systems (12/25/50 kW)	Oil-fired boilers (12/25/50 kW)	Oil-fired boilers with solar thermal system	Heat generation cost
Heating / process heat plants (0.5/2/5 MW)	Natural gas-fired heating /process heat plants (0.5/2/5 MW)	–	Heat generation cost
CHP plants (15 kW_{el} to 50 MW_{el})	Natural gas-fired CCGT	CCGT with CHP/CCS, Hard coal-fired CPP with or without CCS	Electricity generation cost (with heat credits)
Liquid transport fuels	Diesel / petrol	–	Production cost (C_x) / wholesale price (C_{ref})
Gaseous transport fuels	Natural gas	–	Production cost (C_x) / wholesale price (C_{ref})

3.2 Data

The default technology data, including capacities, efficiencies, default full load hours per year, specific GHG emissions and cost of bioenergy and reference technologies are stated in Table 14-1 to Table 14-3 in the Annex. The specific GHG emissions used in this work are based on datasets of the GEMIS model (Oeko-Institut, 2010) which have been adopted according to the assumed technology data (e.g. efficiencies). The specific GHG emissions related to the production of biofuels are partly based on the “typical greenhouse gas emission saving” stated in Annex V of EU Directive 2009/28/EC (EC, 2009a) (see Table 14-3). The default fuel prices and by-product credits are given in Table 3-2. Calculations based on these data are referred to as “default case” for the base year 2010. All monetary data are real prices/costs with the base 2008. The calculatory life-time of heat generation plants (bioenergy and reference technologies) is generally assumed to be 20 years, those of CHP and biofuel production plants 15 years.

Table 3-2. Default fuel price assumptions for the reference year 2010 (all prices without taxes)

Small consumers	€/MWh_{HHV}	€/MWh_{LHV}	References and comments
Wood log	–	28.00	based on Austrian Chamber of Labour (2010) and Austrian Chamber of Agriculture (2010)
Wood pellets (in bags)	–	43.92	ProPellets (2010), average price 2005 to 2008
Wood pellets (bulk)	–	35.45	ProPellets (2010), average price 2005 to 2008
Plant oil	–	61.31	production costs in decentralized oil press (see section 3.3.1)
Wood chips	–	22.00	based on Austrian Chamber of Agriculture (2010)
Natural gas	41.53	45.95	Statistik Austria (2010c), average price 2005 to 2008
Domestic fuel oil	46.67	49.64	Statistik Austria (2010c), average price 2005 to 2008
Diesel (private)	–	54.88	Statistik Austria (2010c), average price at station 2005-2008
Diesel (commercial)	–	36.91	Statistik Austria (2010c), average price 2005-2009
Petrol (private)	–	54.48	Statistik Austria (2010c), average price at station 2005-2008 (ROZ 95)
Large consumers / buyers	**€/MWh_{HHV}**	**€/MWh_{LHV}**	**References and comments**
Wood chips	–	20.00	based on Austrian Chamber of Agriculture (2010)
Straw	–	16.36	assumed provision costs of 65 €/t (Kalt et al., 2010a)
Natural gas	28.37	31.38	Statistik Austria (2010c), average price 2005 to 2007 (no data for 2008 available)
Heavy fuel oil	25.14	27.05	Statistik Austria (2010c), average price 2005 to 2008
Hard coal	–	9.28	Statistik Austria (2010c), average price 2005 to 2008
Diesel (spot price)	40.06	42.61	Statistik Austria (2010c), average spot price 2005 to 2008 ARA
Petrol (spot price)	38.74	42.12	Statistik Austria (2010c), average spot price 2005 to 2008 ARA
Rapeseed	–	40.88	Statistik Austria (2010d), average producer price 2005 to 2008
Plant oil	–	43.47	production costs in centralized oil press (see section 3.3.1)
Wheat grain	–	24.34	Statistik Austria (2010d), average producer price 2005 to 2010
Sugar beet	–	34.18	Statistik Austria (2010d), average producer price 2005 to 2011
Biogas feedstock	–	18.00	typical provision cost, based on Kalt et al. (2010a)
Credits for byproducts	**€/t**	**€/MWh**	**References and comments**
Rapeseed press cake	120.00	–	UFOP (2010), representative value for 2005 to 2008
Rapeseed meal	110.00	–	UFOP (2010), representative value for 2005 to 2009
Crude glycerol	80.00	–	based on Toro et al. (2009)
DDGS	115.00	–	based on credit for rapeseed meal (according to Urdl et al. (2010) 5 €/t above price for rapeseed meal)
Electricity	–	63.90	generation cost of reference technology (natural gas IGCC plant)
Heat (credit for feed-in)	–	20.00	based on Hagauer et al. (2007a)
Heat (credit for direct utilization)	–	20.94 - 66.21	heat generation cost of reference technologies (see section 4.1.1)

Based on Obernberger et Thek (2008), a real discount rate of 7% is assumed for bioenergy plants assumedly purchased and operated by companies (CHP, heating plants and biofuel production plants). For small-scale heating systems (assumedly purchased by private persons) a discount rate of 4% is assumed, reflecting the lower opportunity costs for private investments. The default values of annual full load hours of heat production plants are based on educated guesses (see Haas et al., 2010 and RES-H-Policy, 2011).

4 Results

4.1 Heat generation technologies

The heat generation technologies considered here include stoves and small-scale heating systems for residential heating, heating plants and process heat plants. The capital costs of small-scale heating systems include the boiler, peripheral equipment as well as fuel storage and buffer heat storage tanks. Fuel storage tanks are required for pellet and oil-fired systems. For wood log and wood chip heating systems, costs for fuel storage space are neglected as it is assumed that these systems are only installed if sufficient storage space is available. Based on Hartmann et al. (2007) buffer storage tanks are taken into account for wood log (100 litre per kW), wood chip and pellet boilers (20 l/kW). Warm water storage tanks which are required for all technologies are not considered in the calculations. The capital costs for large-scale biomass heating plants comprise the whole plant, including a gas-fired peak load boiler and building construction.

4.1.1 Heat generation cost

The heat generation costs of small-scale heating systems in the default case are shown in Figure 4-1. For illustrative purposes, taxes are also shown here, even though they are not considered in the calculation of abatement costs. Gas-fired heating systems are also included for illustration purposes. It is evident that biomass heating systems are most economic in the 50 kW-category, whereas the heat generation costs of all biomass-fired 12 kW-systems (excluding taxes) are higher than those of oil and gas-fired systems. This is due to different cost structures and significant economies of scale effects in capital costs of biomass systems; higher capital costs are less relevant for larger heating systems and are partly compensated by lower fuel prices (with the exception of plant oil-fired boilers). The different cost structures of biomass systems also results in a lower sensitivity to volatility of fuel prices and implicate that biomass heating systems are more competitive at higher annual full load hours (see section 4.6.1).

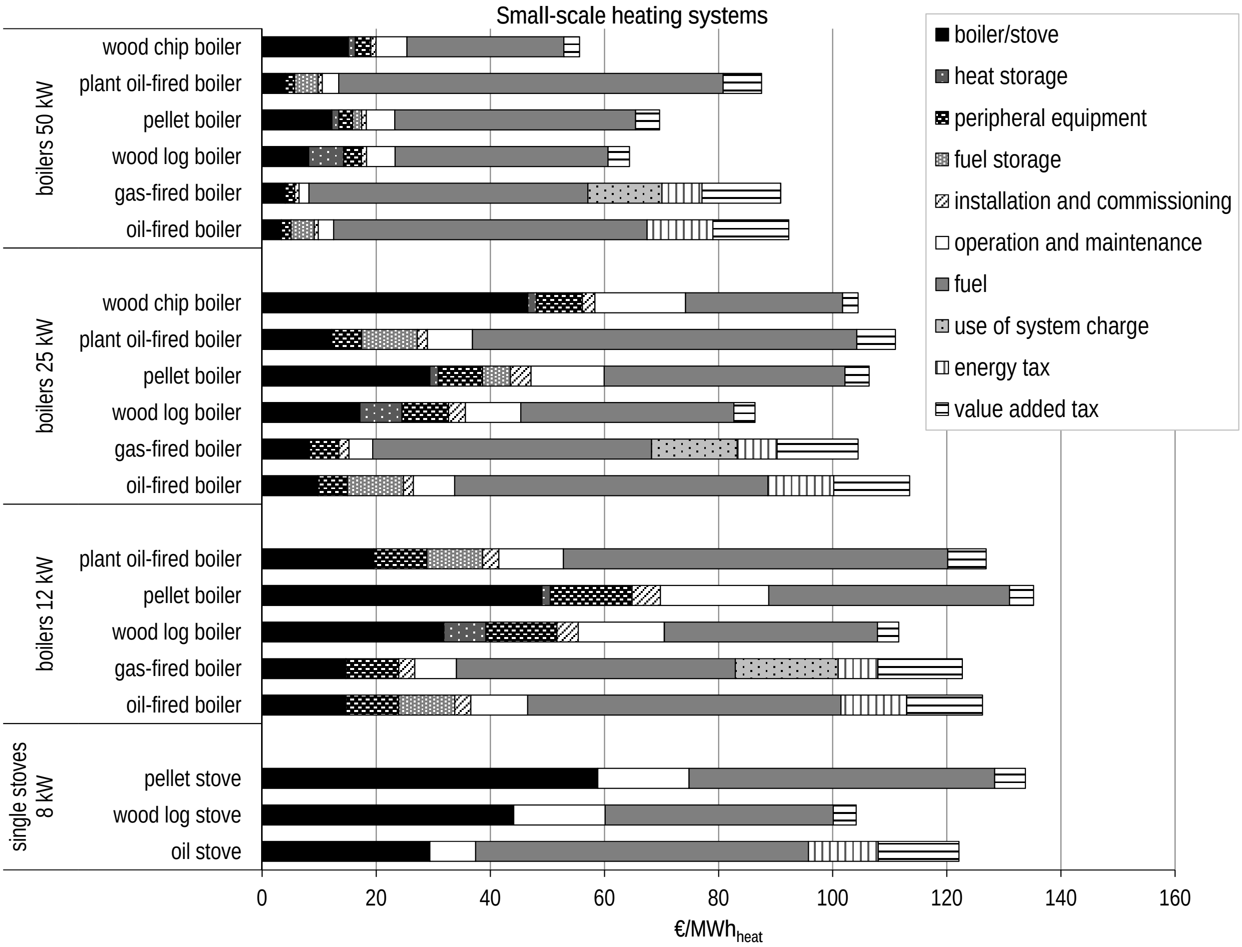

Figure 4-1. Specific heat generation costs of small-scale biomass (wood log, pellet, wood chip and plant oil boilers and stoves) and reference plants (oil- and natural gas-fired boilers and stoves)

Energy taxes: natural gas 0.066 €/m^3, domestic fuel oil 0.098 €/l, heavy fuel oil 67.70 €/t (Statistik Austria, 2010c). VAT is 20% for fossil fuels and 10% for wood fuels and agricultural products.

Use of system charges for gas are different for each province and depend on the annual consumption; based on E-Control (2010) the following representative charges are assumed: 18/15/13 €/MWh for 12/25/50 kW boilers.

Wood log systems are basically the cheapest biomass boiler systems in the categories 12 and 25 kW, despite the additional costs for buffer heat storage tanks which are required to compensate the low flexibility of wood log boilers. However, operating wood log systems is less convenient than other heating systems; this loss of comfort is not considered in monetary terms here. Furthermore, a benefits of pellet and plant oil boilers, which is high energy density of the fuel, resulting in less storage space, is not taken into account. In the 50 kW-category wood chip boilers are the cheapest option.

To sum up, small-scale biomass heating systems are basically competitive with the reference systems. In some cases the heat generation costs in the default case are actually lower than those of oil and gas-fired systems, even if currently valid tax benefits are not taken into account.

Figure 4-2 shows a comparison of energy generation costs of heating plants and process heat plants. The annual full load hours are assumed 3000 h/a for heating plants and 6000 h/a for industrial process heat plants. For biomass heat plants it is assumed that 10% of the annual heat demand is covered with natural gas-fired peak load boilers. (The capital cost of the peak load boiler is included in the total capital investment of the plants.)

Again, larger bioenergy plants are more competitive due to the structure of the energy generation cost and the higher capital costs of bioenergy systems. In the case of biomass heat plants, it is distinguished between wood chip-fired and straw-fired plants. Under the default price assumptions, the lower fuel price of straw does not compensate the additional capital cost compared to wood chip-fired plants[4]. Due to the high utilization throughout the year, industrial biomass plants are the most competitive.

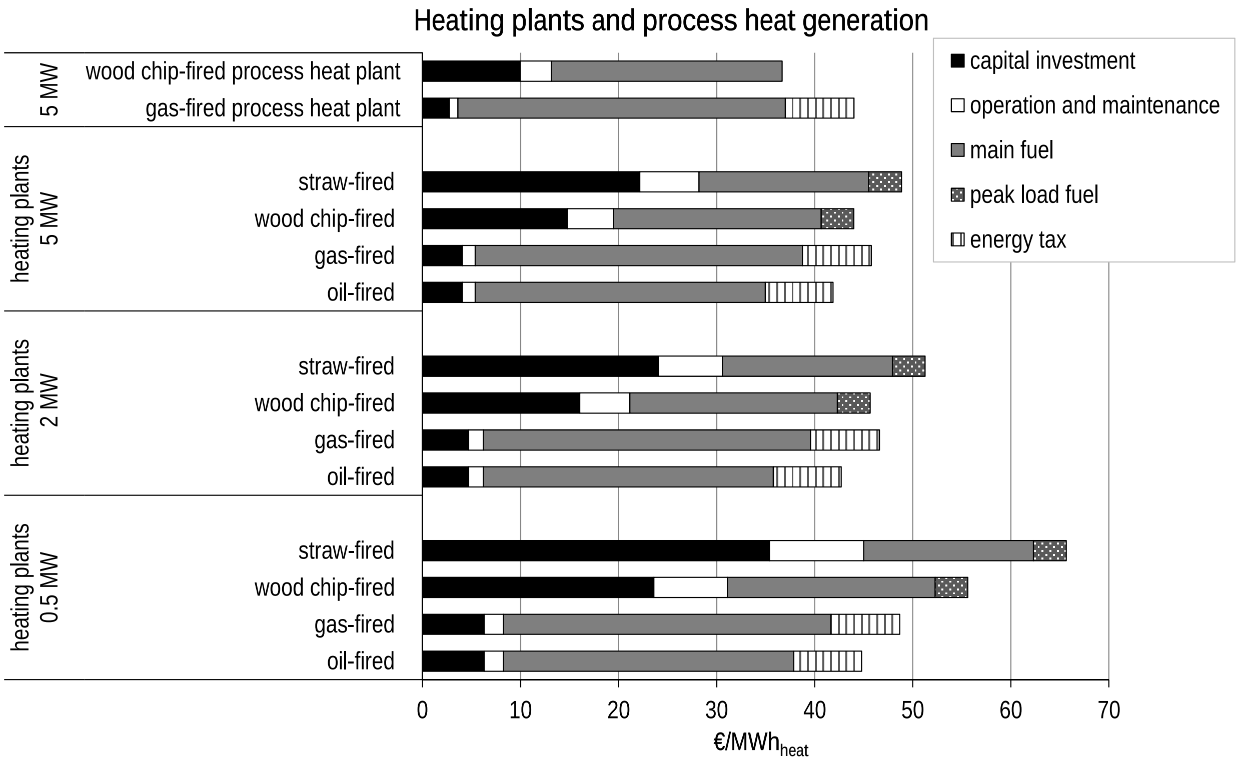

Figure 4-2. Specific heat generation cost of biomass heating plants and process heat plants (wood chip and straw plants) and reference plants (oil- and natural gas-fired plants)

[4] There are hardly any straw-fired boilers installed in Austria and data on investment cost are scarce. Based on Leuchtweis (2008), they are assumed to be 50% higher than those of wood chip-fired plants.

4.1.2 GHG emissions and cumulated fossil fuel demand

Figure 4-3 shows the specific GHG emissions and fossil fuel demand of the considered heat generation technologies. The data are cumulated values over the entire utilization path. They include greenhouse gases emitted and fossil fuels consumed during the production or extraction, processing and transport of the fuel (the transport distance from the production site is generally assumed 100 km), as well as those related to the utilization, including the construction of the utilization plant, auxiliary energy and combustion of the fuel. For heating plants, GHG emissions and fossil fuel consumption resulting from fossil fuel-based peak load coverage is also taken into account (error bars in Figure 4-3). Possible carbon stock changes related to biomass use are not taken into account, as it is assumed that the considered utilization paths do not result in land use change. Hence, the combustion of biomass fuels is considered carbon neutral.

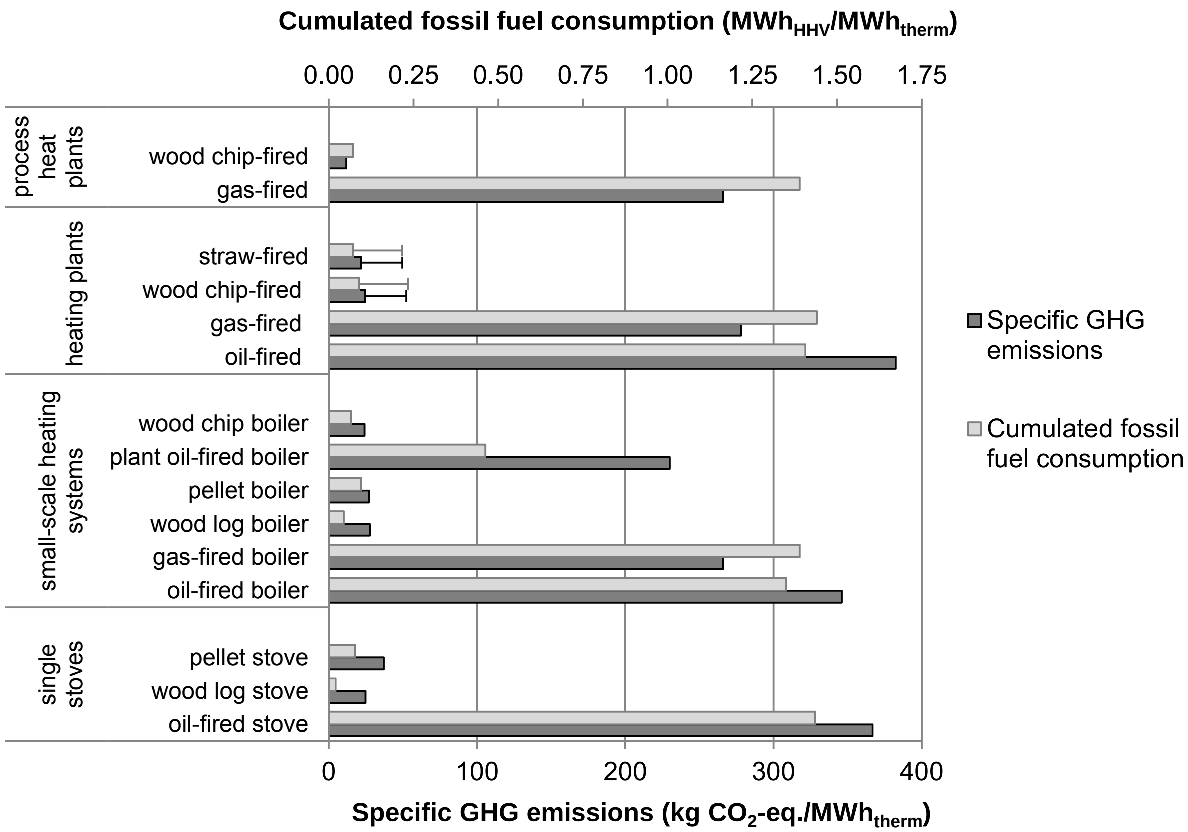

Figure 4-3. Specific GHG emissions and cumulated fossil fuel consumption of heat generation technologies

(Error bars represent additional GHG emissions / fossil fuel consumption for peak load coverage.)

Source: own calculations based on Oeko-Institut (2010)

Figure 4-3 shows that typical specific GHG emissions of heat generation technologies based on fossil fuels are about 250 to 300 kg CO_2-eq./$MWh_{therm.}$ higher than those of wood- and straw-based technologies. With regard to the cumulated fossil fuel consumption, the differences range from about 1.15 to 1.4 MWh_{HHV}/$MWh_{therm.}$. Due to a relatively high demand of energy and fertilizers in the agricultural production of oilseeds, and despite the fact that revenues for the substitution of soya meal imports are considered in the assessment, plant oil-fired boilers show clearly higher values than the other bioenergy technologies.

4.1.3 Cost of GHG mitigation and fossil fuel replacement

The cost of GHG mitigation (fossil fuel replacement) depend on the specific GHG emissions (specific fossil fuel demand) per unit of energy produced, as well as the energy generation cost of the technology compared to the reference technology (Eq. 3-1). Figure 4-4 illustrates the costs of GHG mitigation and fossil fuel replacement of biomass heat generation systems in the default case. For illustrating the influence of volatile fuel prices, error bars representing a +/-10% spread from the default biomass price are also plotted (fossil fuel prices are kept constant). The magnitude of the error bars provides insight into the sensitivity of the abatement cost of each technology to fuel price fluctuations. Plant oil boilers show a very high sensitivity, whereas straw heating plants are very insensitive to fuel price fluctuations.

The costs of GHG mitigation of wood-based heating systems (boilers and stoves) in the default case range from -45.3 €/t CO_2-eq. (50 kW wood chip boiler) to 92.6 €/t CO_2-eq. (15 kW pellet stove). The corresponding cost of fossil fuel saving range from -11.4 €/MW_{HHV} to 23.5 €/MWh_{HHV}. For wood-based heating systems, a fuel price variation of +/-10% results in a deviation of about +/-12 €/t CO_2-eq and +/-3 €/MWh_{HHV}.

The GHG mitigation costs of plant oil boilers are significantly higher than those of wood-based boilers. This is primarily due to the higher GHG emissions related to the production of plant oil, which result in clearly lower GHG mitigation per unit of heat produced (116 kg CO_2-eq./MWh_{heat} compared to about 320 kg CO_2-eq./MWh_{heat} achieved with wood-fired boilers).

4.2 Combined heat and power generation

The biomass CHP technologies considered here include biogas and plant oil CHP plants, wood chip- and straw-fired ORC (organic rankine cycle) and steam turbine plants, wood chip-fired boilers with Stirling engines and CHP technologies based on biomass gasification (downdraft gasifier with gas engine, fluidized bed gasifier with gas engine and ORC process, biomass integrated gasification combined cycle; BIGCC). The plant sizes range from 35 kW_{el} (Stirling engine) to 50 MW_{el} (BIGCC). In consideration of the biomass CHP plant types and sizes currently installed in Austria, the focus is on plants with a rated power of less than 10 MW_{el}.

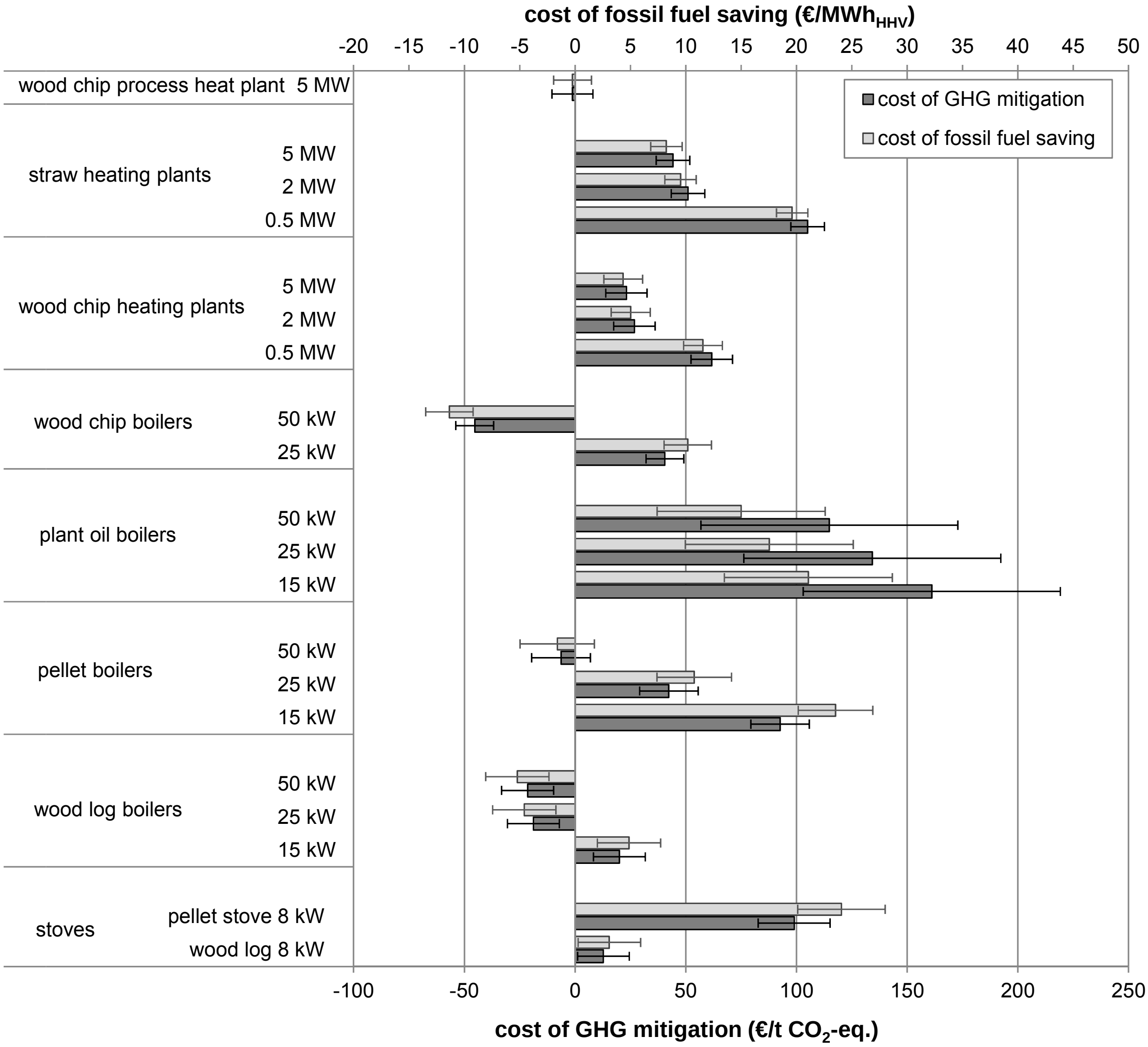

Figure 4-4. Cost of GHG mitigation and fossil fuel saving with biomass heating systems, heating plants and process heat plants. Error bars represent a +/-10%-spread of biomass fuel prices from default data.

In order to achieve a maximum economic and ecologic efficiency, biomass CHP plants need to be designed with consideration of the annual heat load duration curve at the site (Obernberger et Thek, 2008). The objective is to achieve high capacity utilization throughout the year (large number of thermal full load operating hours). However, it needs to be assumed that biomass CHP plants are often located at less-than-ideal sites and operated in suboptimal ways.

Therefore, two exemplary cases which are to illustrate the bandwidth of possible operating modes of CHP plants are assumed. In mode 1 (“heat grid feed-in”) it is assumed that all generated heat is fed into a large heat grid throughout the whole year. This represents an optimal case in terms of fuel utilization. Based on Hagauer et al. (2007a), a uniform heat revenue of 20 €/MWh_{heat} is assumed for all technologies in mode 1.

Mode 2 (“direct heat use”) represents a situation where heat from the CHP plant is actually utilized only 3000 hours per year. The rest of the year, the heat output is assumed to remain unused, or be used for purposes which neither produce a profit, nor result in the substitution fossil fuels. Hence, the annual average of “useful heat capacity” in mode 2 $P_{heat,2}$ amounts to

$$P_{heat,2} = P_{el} \cdot \frac{\eta_{heat}}{\eta_{el}} \cdot \frac{3000}{T_{FL}} \qquad (4\text{-}1)$$

where P_{el} denotes the electrical power, η_{heat} and η_{el} the thermal and electrical efficiencies and T_{FL} the annual full load operating hours of the CHP plant. In this mode it is assumed that heat from the CHP plant directly substitutes heat from dedicated reference heating plants. Therefore, the heat credit corresponds to the specific generation cost of a gas-fired heating plant with the same thermal power as the CHP plant and ranges from about 20 (50 MW_{el}-BIGCC) to 66 €/MWh_{heat} (15 kW_{el}-plant oil CHP plant). It is further assumed that an additional gas-fired boiler is required to cover the heat demand at times of peak load in this mode, causing additional investment and fuel costs as well as additional GHG emissions (see Table 14-2 in the Annex). As for biomass heating plants, it is assumed that 10% of the annual heat demand is covered with the peak load boiler.

4.2.1 Electricity generation cost

Figure 4-5 shows the results of the economic assessment of biomass CHP plants and the reference technologies in the two modes of operation for the default case. The power generation cost of biomass CHP plants range from 68.94 €/$MWh_{el.}$(50 MW_{el}-BIGCC) to 311.14 €/MWh_{el} (wood chip boiler with 35 kW_{el}-Stirling engine) in mode 1 and 84.14 to 320.67 €/MWh_{el} (same technologies) in mode 2. The cost of the reference system CCGT (natural gas) account for 65.30 €/MWh_{el}, those of the alternative reference systems range from 41.41 (hard coal-fired condensing power plant) to 78.18 €/MWh_{el} (natural gas CCGT with CHP in mode 2).

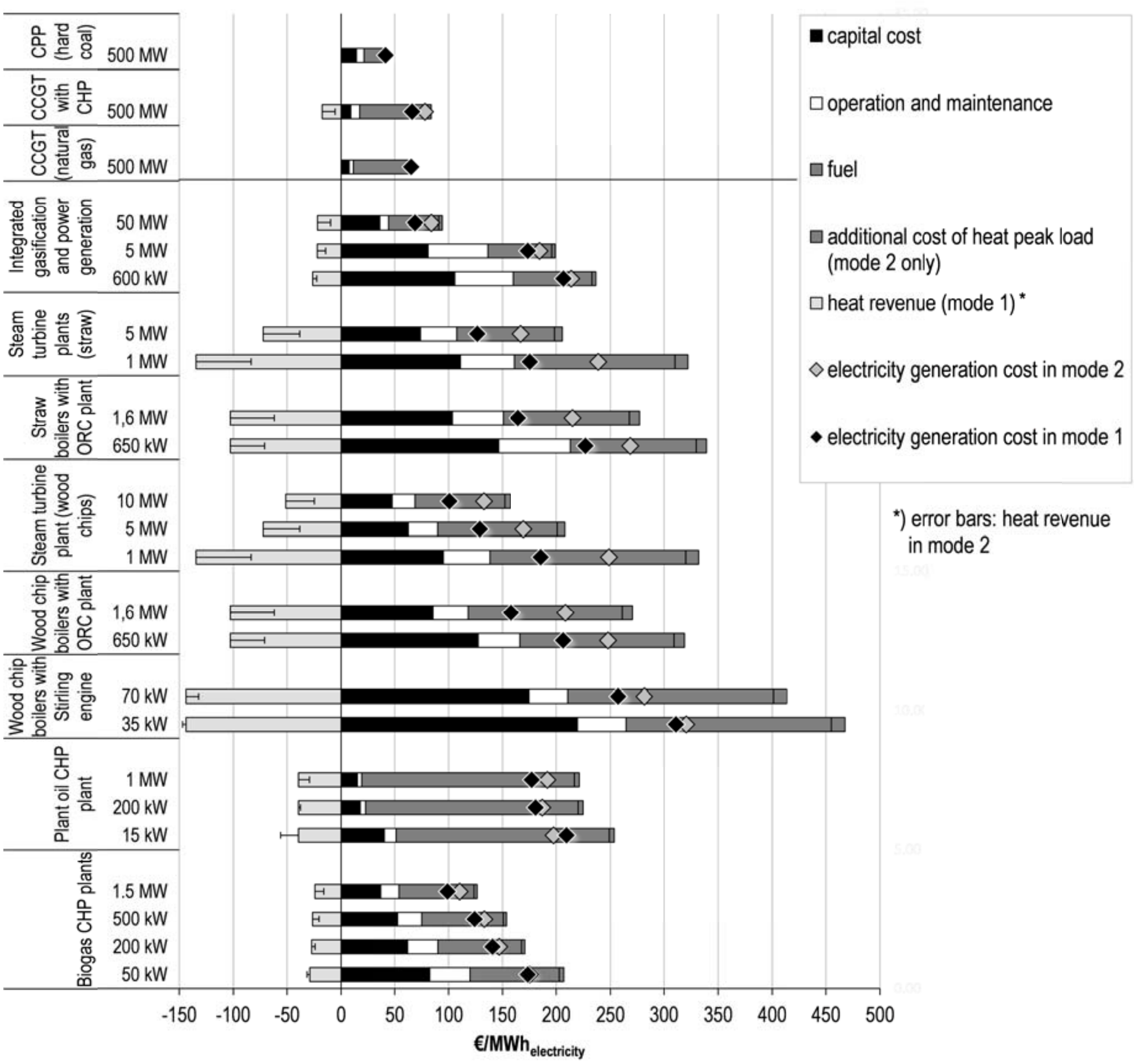

Figure 4-5. Specific power generation cost of biomass CHP plants and the reference technologies combined cycle gas turbine (CCGT) and hard coal-fired condensing power plant (CPP)

(modes 1 and 2 are described in the text; plant specifications refer to electrical power)

4.2.2 GHG emissions and cumulated fossil fuel demand

Figure 4-6 illustrates the specific GHG emissions and cumulated fossil fuel demand of the considered electricity generation technologies. The total amount of GHG emissions and fossil fuel consumption is attributed to electricity generation here, regardless of the quantity of heat produced. For this reason and the fact that a CCGT generating both electricity and heat has a lower electrical efficiency than a CCGT without CHP (see Table 14-2 in the Annex), the specific GHG emissions and fossil fuel consumption of the former are slightly higher than those of the latter, as Figure 4-6 shows. However, if heat credits are taken into account, the opposite is true (see section 4.6.3 and Table 4-2, respectively).

As already mentioned in the context of heat generation technologies, it is obvious that wood- and straw-based bioenergy technologies show clearly lower values than plant oil-based CHP plants. Apart from that, the figure illustrates that the cumulated fossil fuel consumption of biogas CHP plants with the assumed substrate mix (90% maize silage and 10% manure by energy input) is in a similar range as the one of plant oil CHP plants, whereas the specific GHG emissions are significantly lower. Another interesting result is that the specific GHG emissions of modern coal-fired power plants are about twice as high as those of CCGT.

A direct comparison with the values for heat generation technologies in Figure 4-3 is not possible due to the different reference units ($MWh_{el.}$ and $MWh_{therm.}$, respecitively). In section 4.4 a direct comparison based on the primary energy consumption is presented.

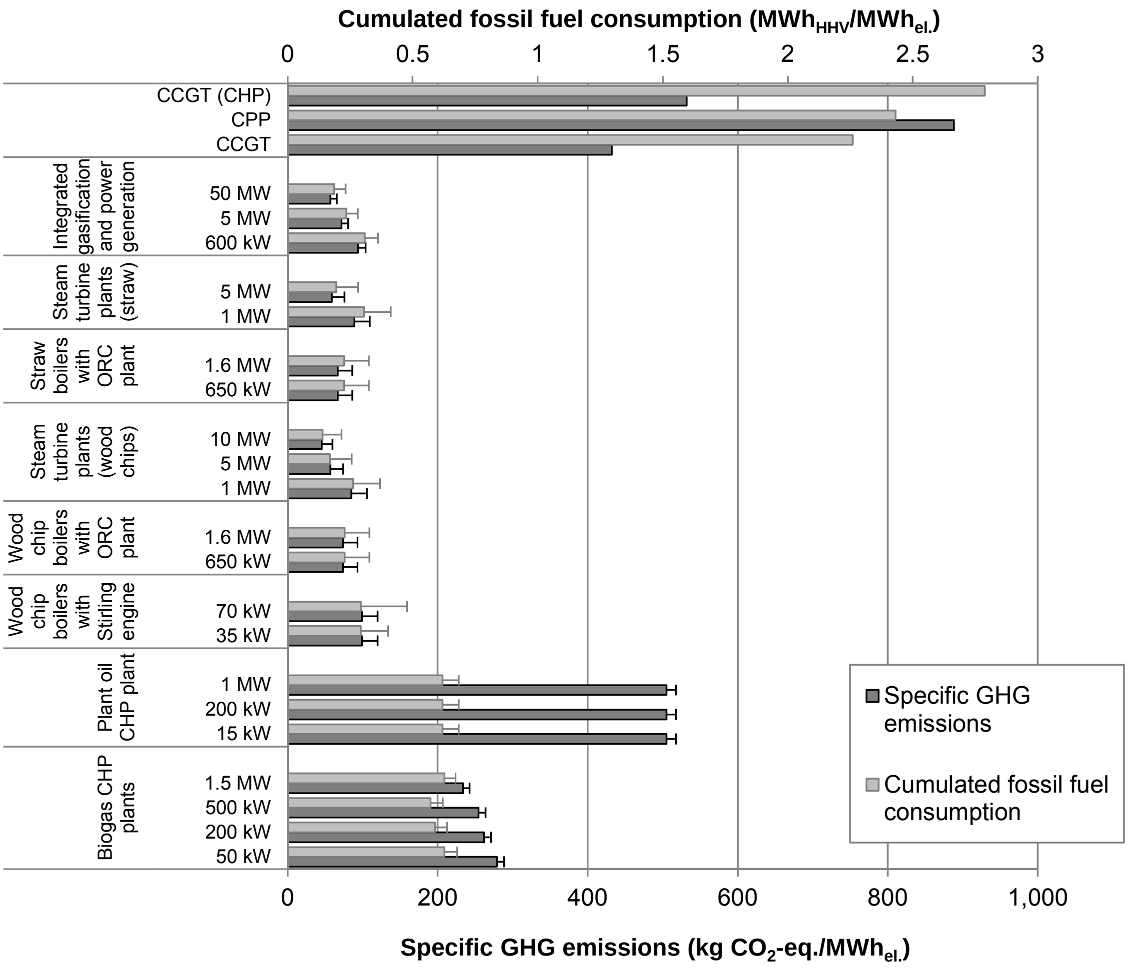

Figure 4-6. Specific GHG emissions and cumulated fossil fuel consumption of electricity generation technologies

(error bars represent additional GHG emissions / fossil fuel consumption for peak load coverage in mode 2)

Source: own calculations based on Oeko-Institut (2010)

4.2.3 Cost of GHG mitigation and fossil fuel replacement

Figure 4-7 shows the abatement costs of biomass CHP plants in the default case with a natural gas CCGT as reference system for mode 1 (main bars) and 2 (error bars). The costs of GHG mitigation and fossil fuel replacement range from 5.36 €/t CO_2-eq. and 1 €/MWh_{HHV} (50 MW_{el}-BIGCC) to 304.54 €/t CO_2-eq. and 32.26 €/MWh_{HHV} (15 kW_{el}-plant oil CHP plant) in mode 1 and 37.95 €/t CO_2-eq. and 6.97 €/MWh_{HHV} to 890.21 €/t CO_2-eq. and 47.47 €/MWh_{HHV} (same technologies) in mode 2.

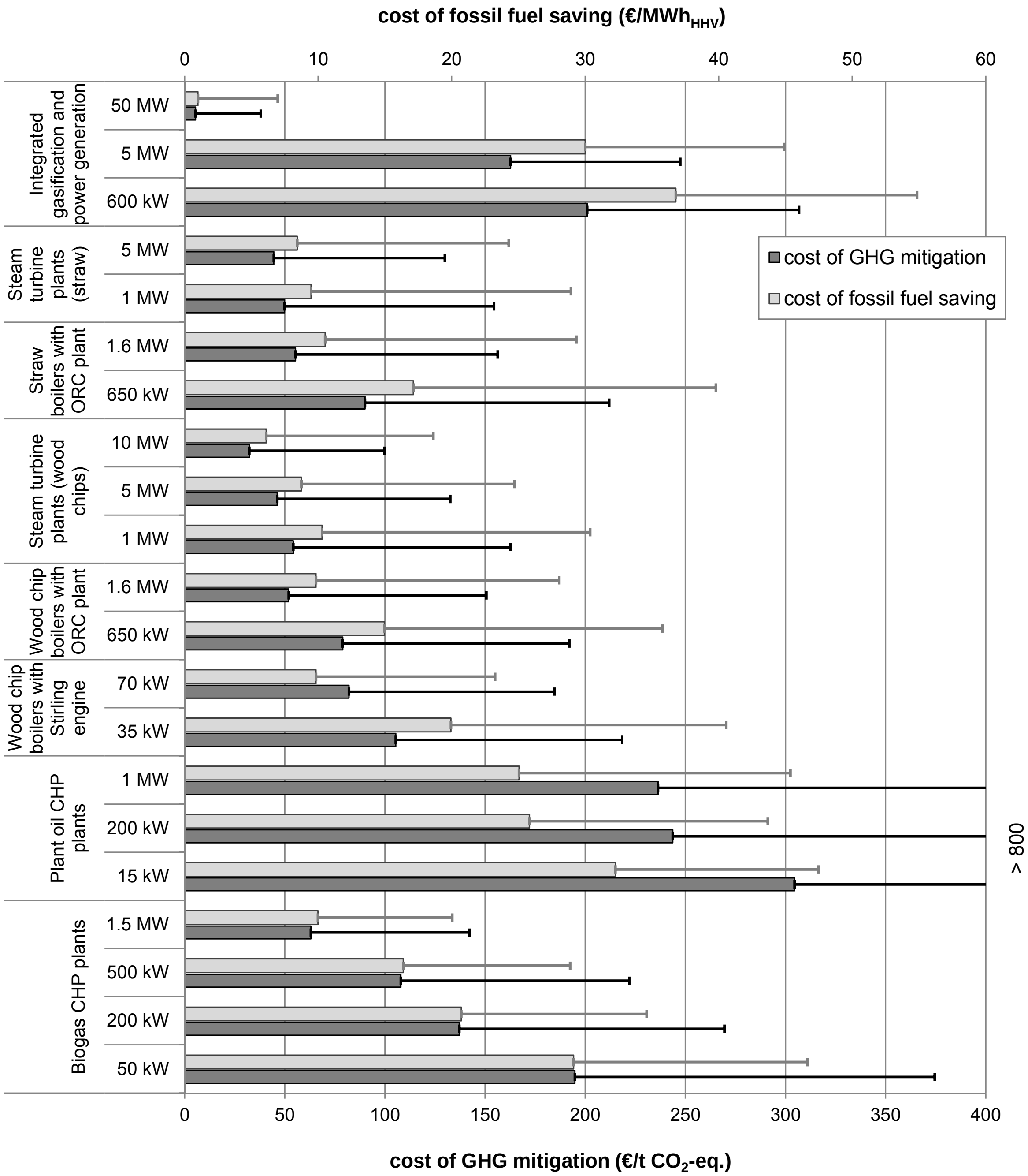

Figure 4-7. Cost of GHG mitigation and fossil fuel saving with biomass CHP plants in mode 1 "heat grid feed-in" (main bars) and mode 2 "direct heat use" (error bars).

In mode 1 (i.e. under the assumption of a maximum heat utilization), typical abatement costs of representative plants with a capacity from about 1 to several MW_{el}, which includes the majority of CHP plants currently in operation in Austria, are in the magnitude of 50 €/t CO_2-eq. and 10 €/MWh_{HHV}. “Small-scale” gasification plants and plant oil-fuelled engines in this power range display clearly higher abatement costs of up to 200 and 300 €/t CO_2-eq., respectively, and more than 30 €/MWh_{HHV}.

4.3 Biofuels

The substitution of fossil fuels with biofuels in the transport sector is possible by the use of blends with a low (e.g. B5, i.e. 5% biodiesel in fossil diesel fuel) or a high share of biofuel (e.g. E85, i.e. 85% ethanol with 15% gasoline) or pure biofuels. Depending on fuel type (and biofuel blend, respectively), a direct substitution of fossil fuels might or might not be possible without engine modifications or additional costs, depending on vehicle and engine specifications. For the benefit of simplicity, this aspect is neglected and transport fuels are compared directly on the basis of energy content (LHV) here. Specific advantages and disadvantages of biofuels that arise from fuel properties or framework conditions are not discussed in detail (e.g. high quality of FT fuels, or the small number of vehicles running on gaseous fuels in Austria).

4.3.1 Biofuel production cost

Figure 4-8 shows a comparison of biofuel production costs with wholesale prices of fossil fuels in the default case. The type of biofuel with the cheapest production cost is plant oil produced in a centralized press (43.47 €/MWh_{LHV}). Since pure plant oil is a niche product with limited fields of application and largely regional distribution patterns in Austria (Winter, 2010), a direct substitution of fossil fuels with plant oil from centralized production is considered inapplicable and only plant oil from decentralized oil presses is considered as diesel substitute. Among the other biofuels, production costs range from 44.80 €/MWh_{LHV} (SNG from 110 MW-plant) to 116.33 €/MWh_{LHV} (biomethane from 300 kW-plant). The production costs of biodiesel and ethanol (which are the predominant biofuels today) produced in large-scale production plants are in the magnitude of 50 to 80 €/MWh_{LHV} in the default case, whereas wholesale prices of fossil fuels amount to approximately 42 €/MWh_{LHV}.

A comparison of the cost structures reveals the clearly higher share of feedstock cost for biodiesel and ethanol compared to second generation biofuels from lignocellulosic biomass (2^{nd} generation biofuels) and biomethane. Therefore, the production costs of the latter are less sensitive to feedstock price variations and investment cost reductions through technological learning have a higher impact on total production costs. Apart from that, a higher flexibility with regard to feedstock and an overall wider feedstock basis are considered key advantages of

2nd generation biofuels and biomethane. However, the investment costs of second generation biofuel production plants are only estimates (based on Hamelinck et Faaij, 2006, and Gassner et Maréchal, 2009), as these technologies are still in the development and demonstration phase.

Possible benefits of small-scale production plants, such as lower transport costs and regional supply and marketing are not explicitly taken into account here, since they depend on numerous factors and generalizations are hardly possible. Assuming that small consumer prices of liquid and gaseous fossil fuels (about 55 and 46 €/MWh$_{LHV}$, respectively) instead of wholesale prices are to be considered as the reference would bring production costs of decentralized plants significantly closer to the reference prices. This assumption would, however, correspond to neglect of costs for distribution and marketing, and is therefore not applied.

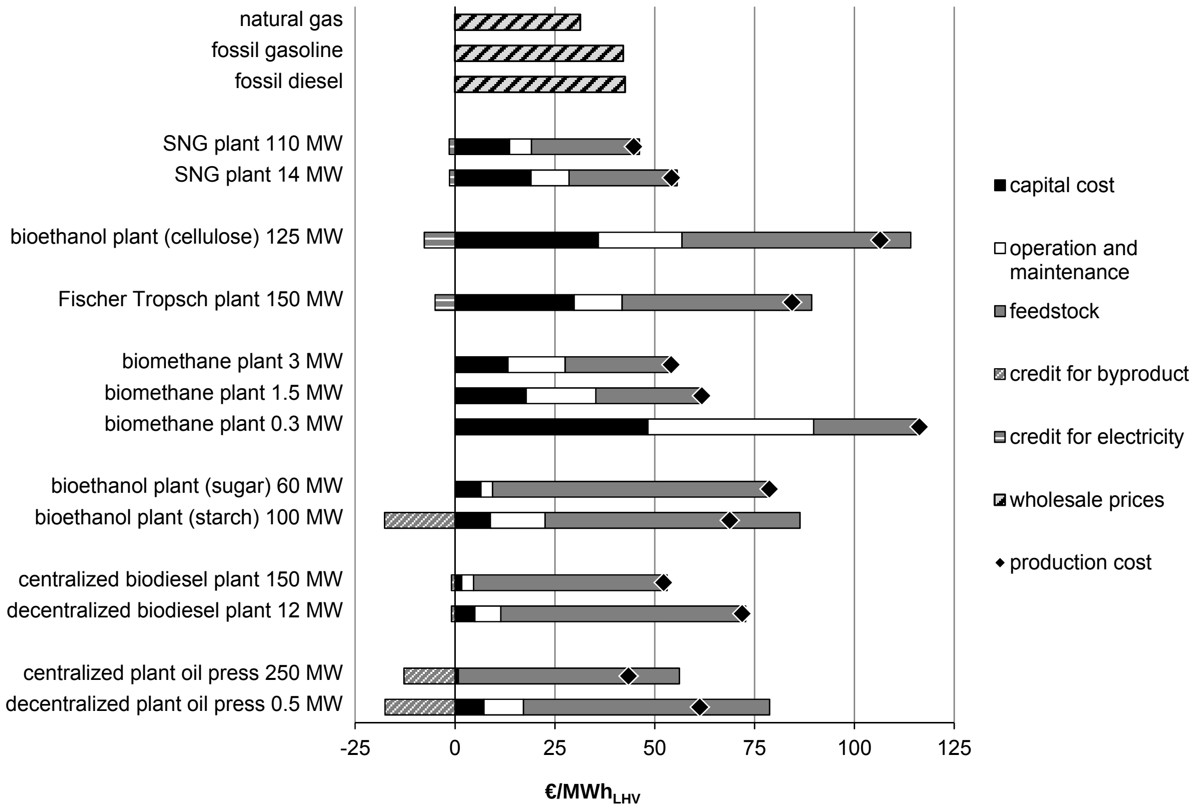

Figure 4-8. Specific production costs of biofuels in the default case.

4.3.2 GHG emissions and cumulated fossil fuel demand

Figure 4-9 shows the specific GHG emissions and cumulated fossil fuel demand related to the use of biofuels and fossil fuels. The GHG emissions resulting from use of rape seed biodiesel are typically 45% of the GHG emissions from the use of fossil diesel (EC, 2009a). The GHG emissions from plant oil used as transport fuel are slightly lower than those of biodiesel. For ethanol from sugar and starch the relative GHG saving amounts to approximately 60%, if the process energy is assumed to be generated in a natural gas CHP plant. Biomethane from anaerobic digestion (90% maize and 10% manure by energy input) shows relatively low GHG emissions of about 85 kg CO_2-eq./MWh. However, as the reference fuel for gaseous fuels is natural gas, the GHG saving of biomethane also amounts to around 60%.[5]

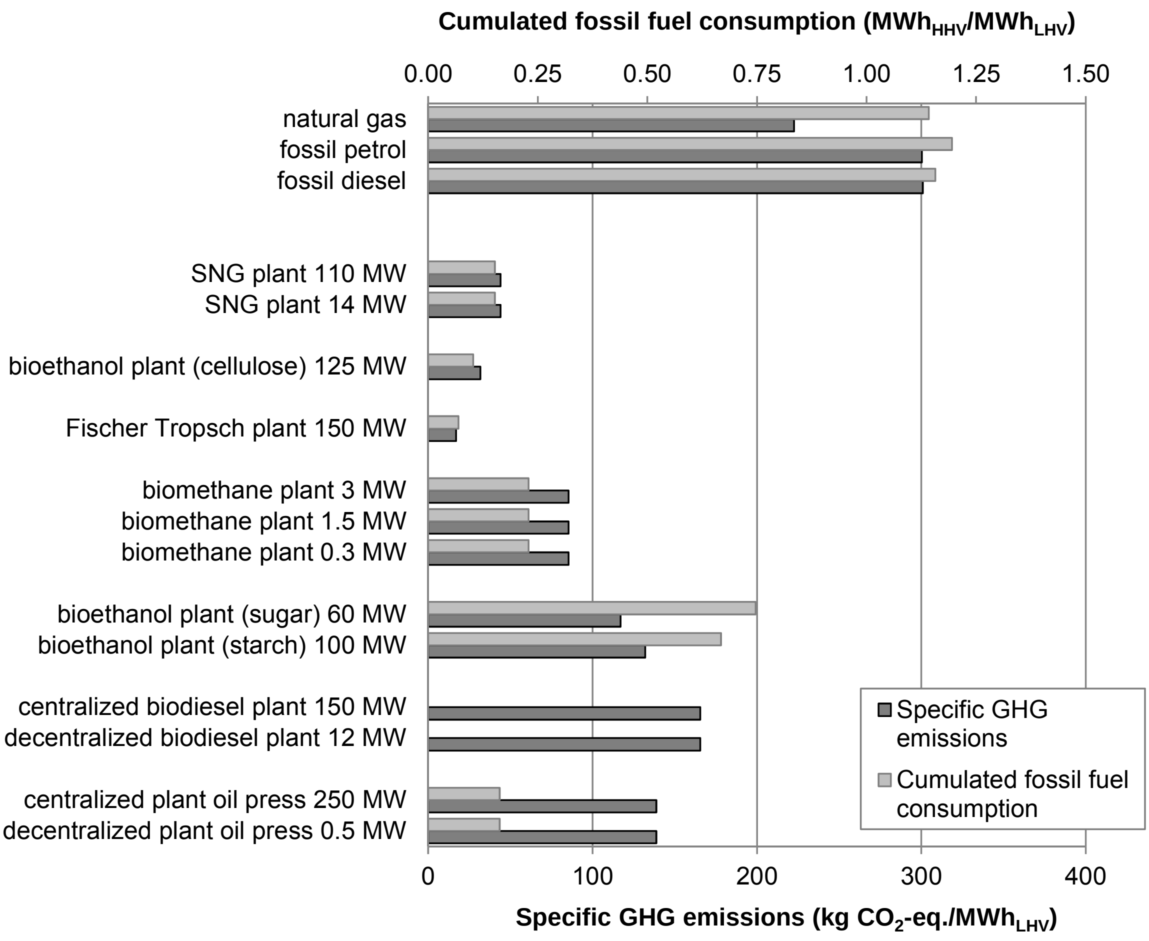

Figure 4-9. Specific GHG emissions and cumulated fossil fuel consumption of biofuel production technologies
(The values for fossil fuels include emissions / fossil fuel demand resulting from the supply chain as well as from combustion. The slightly negative values for fossil fuel consumption of biodiesel plants, resulting from credits for the by-products press meal and glycerol are not shown; see Table 14-3 in the Annex)
Source: own calculations based on Oeko-Institut (2010), EC (2009a) (data on biodiesel, ethanol, FT-diesel)

The feedstock assumed for 2nd generation biofuel production is forest wood chips. The production and use of 2nd generation biofuels, including Fischer Tropsch-diesel, ethanol from

[5] There are of course several other options for "1st generation" biofuel production, especially with regard to the feedstock used. However, the options described here are representative technologies for the case of Austria.

lignocellulosic feedstock and SNG is generally related to clearly lower GHG emissions than "1st generation biofuels". With regard to the cumulated fossil fuel demand, plant oil and biodiesel show a very good performance due to credits for the by-products press meal and glycerol. The fossil fuel demand of bioethanol production is relatively high because of a high process energy demand.[6] The fossil fuel demand of second generation biofuel production is comparatively low, as the biomass feedstock is partly used for process energy generation in the assumed plant concepts.

4.3.3 Cost of GHG mitigation and fossil fuel replacement

The abatement costs resulting from the production and use of biofuels are shown in Figure 4-10. Biodiesel from centralized production displays the lowest costs (71.24 €/t CO_2-eq. and 8.21 €/MWh_{HHV}), followed by SNG from centralized production (77.29 €/t CO_2-eq. and 13.55 €/MWh_{HHV}) and plant oil produced in decentralized presses (115.26 €/t CO_2-eq. and 18.81 €/MWh_{HHV}).

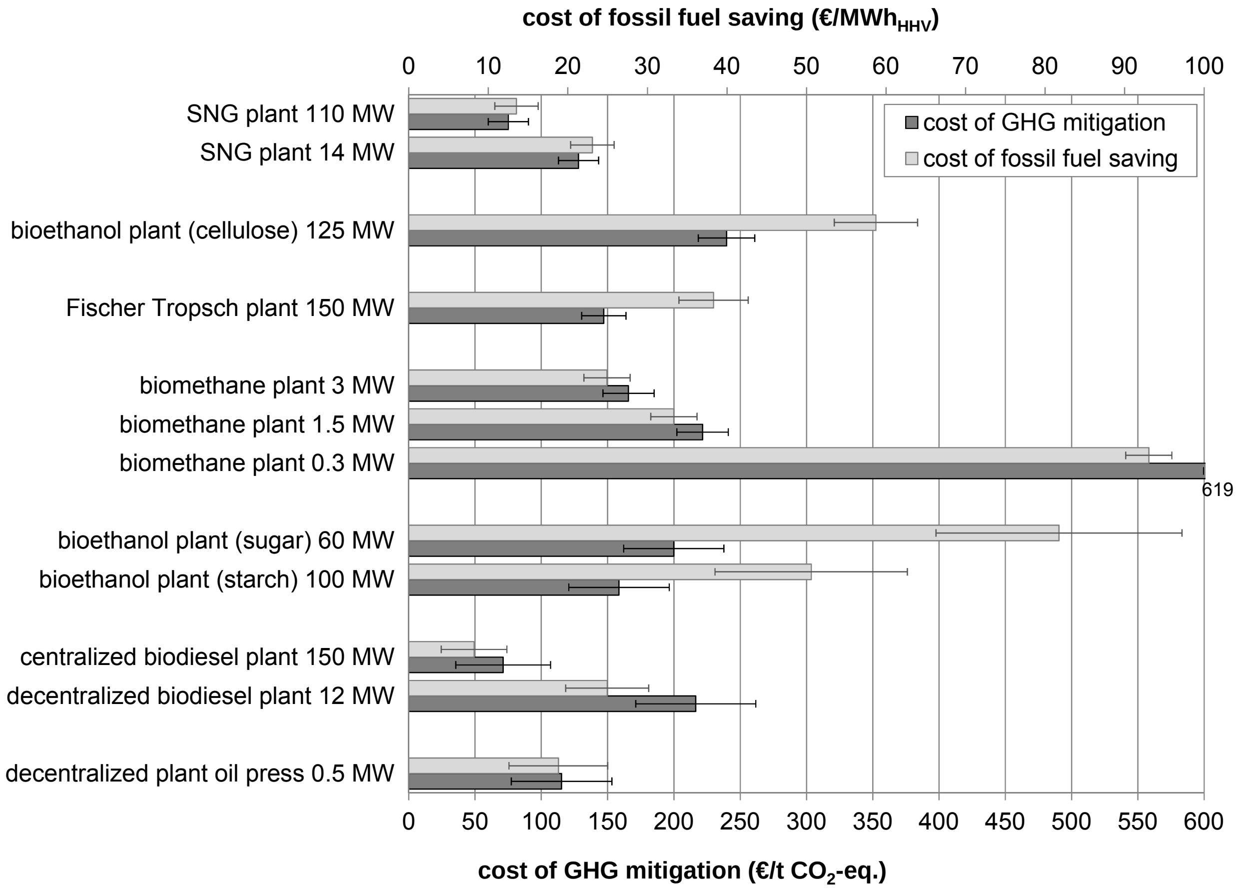

Figure 4-10. Cost of GHG mitigation and fossil fuel saving with biofuels. Error bars represent a +/-10%-spread of biomass fuel prices from default data.

[6] This is of course only true if fossil fuels are used for the generation of process energy, as it is assumed here. Alternatively, straw or other types of biomass can be used, resulting in a clearly better GHG and fossil fuel balance.

Due to a high specific energy demand of bioethanol plants, the costs of fossil fuel saving with ethanol are very high (about 50 to 80 €/ MWh_{HHV}, depending on the biomass feedstock used). The costs of GHG mitigation with ethanol range from 158.58 (starch crops as feedstock) to 245.34 €/t CO_2-eq. (lignocellulosic crops as feedstock). The only plant type with higher costs of GHG mitigation and fossil fuel saving is the 300 kW-biomethane plant (619 €/t CO_2-eq. and 93 €/MWh_{HHV}).

4.4 Summary

The abatement costs of the considered bioenergy technologies range from about -45 to 619 €/t CO_2-eq. and -11.4 to 93 €/MWh_{HHV}, respectively. Apart from differences between technologies, feedstock types and applications, plant sizes often have a significant impact. This is especially true for small-scale heating systems, CHP plants and small-scale biofuel production plants with very pronounced economies of scale-effects. Also, site-specific conditions and according operating modes of CHP plants need to be distinguished.

Figure 4-11 shows a comparison of the costs and quantities of GHG mitigation of all wood-based bioenergy technologies in the default case. In order to allow for a direct comparison of the quantity of GHG mitigation achieved with heat, CHP and biofuel production plants, the GHG mitigation (plotted on the abscissa) is related to the biomass primary energy input. Hence, the quantity of GHG emissions saved by utilizing 1 MWh_{LHV} of biomass is plotted. Since a direct comparison between different feedstock types is not reasonable (e.g. between wood and biogas feedstock), technologies based on feedstock other than wood are not included.

Figure 4-11 provides insight into how wood biomass can be utilized in a most cost-efficient (regarding costs of GHG mitigation) and most effective way (regarding the quantity of GHG mitigation) in the default case and under the assumption of the default reference systems: Judging by the rough location of the technology groups in this graph, heat generation is superior to 2^{nd} generation biofuels and CHP plants in mode 2 with regard to both criteria. Comparing CHP plants in mode 1 and heat generation plants is only possible on a per plant basis, since there is a large intersection of the groups. Several CHP plants show higher specific GHG mitigation than heating plants and wood log boilers, but small scale pellet and wood chip boilers are among the technologies with the highest values. The best performance is, however, achieved with a 50 MW-BIGCC plant, which also has abatement costs close to zero in the default case.

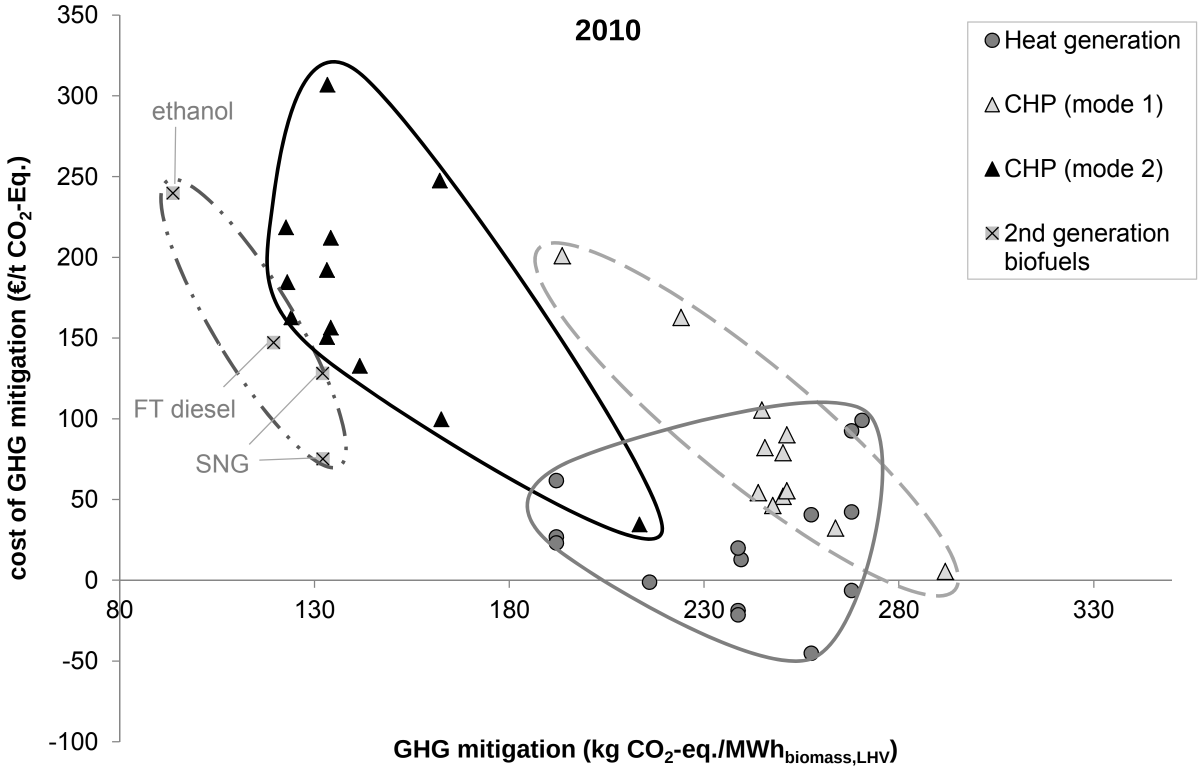

Figure 4-11. Comparison of wood-based bioenergy utilization paths with regard to GHG mitigation in the default case (2010)

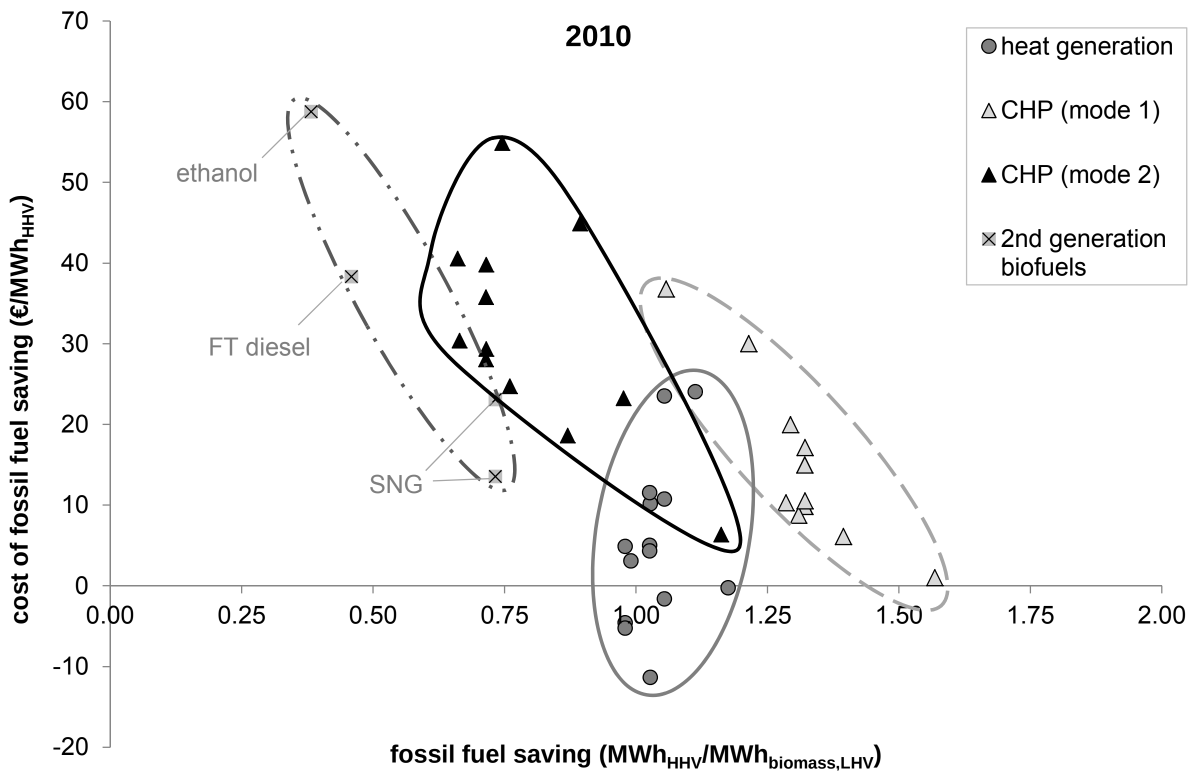

Figure 4-12. Comparison of wood-based bioenergy utilization paths with regard to fossil fuel replacement in the default case (2010)

Figure 4-12 shows the comparison of wood-based technologies with regard to costs and quantity of fossil fuel replacement. The relative location of technology groups is similar to Figure 4-11, but CHP technologies generally show a better performance with regard to the quantity of fossil fuel saved per unit of biomass consumed. The majority of CHP plants in mode 1 allow for higher fossil fuel savings than heat generation technologies, albeit partly at higher costs. Therefore, the question of whether and to what extent biomass CHP should be favoured to heat-only generation amounts to a trade-off between economic and resource efficiency.

4.5 Outlook to 2030

Despite substantial uncertainties related to estimates of future fuel prices and technological developments, this section is dedicated to analysing possible impacts of future developments up to 2030. The core assumptions for this assessment include a fossil fuel price increase of 45% compared to the default case (cp. Capros et al., 2008 or IEA, 2009a), increased efficiencies of both bioenergy and reference technologies and cost reductions due to technological learning. As modelling technological learning in bioenergy systems is not straightforward (see Junginger et al., 2006, for example), the assumed cost reductions up to 2030 are based on estimates in literature. The assumed improvements in efficiencies and costs of heating systems and CHP plants are primarily based on the GEMIS database (Oeko-Institut, 2010) and those of second generation biofuel production technologies on Hamelinck et Faaij (2006)[7]. In a first step, the default reference technologies are assumed. In section 4.6.3.2, alternative reference systems are discussed.

Biomass price estimates up to 2030 are considered highly speculative, and therefore the results are shown for a broad range of price developments, ranging from constant real prices to an increase of 145% (i.e. a 100% coupling of biomass to fossil fuel price developments).[8]

[7] Assumed reductions of investment and O&M costs due to technological learning up to 2030: 6% for biogas, plant oil CHP and steam turbine plants, 7% for ORC plants, 10% for small-scale heating systems, 19% for FT-plants, 20% for gasification CHP plants, 21% for SNG plants, 23% for biomethane plants, 25% for Stirling engine systems, 31% for biodiesel and ethanol plants (starch and sugar) and 53% for lignocellulosic ethanol plants. The efficiencies of most technologies are assumed to increase; the following relative increases refer to the efficiency of main output, i.e. thermal efficiency for heat generation systems, electrical efficiency for CHP plants and conversion efficiency for biofuel production plants: 5% for ethanol plants (sugar and starch), 6% for small-scale heating systems, 8% for SNG plants, 10% for biomethane plants, 12% for steam turbine plants, 15% for biogas and plant oil CHP plants, 20% for gasification plants, 27% for ORC plants, 33% for Stirling engine systems and 36% for lignocellulosic ethanol plants. Parameters of technologies not mentioned here are assumed to remain constant. Data for reference power plants in 2030 are stated in Table 14-2 in the Annex.

[8] Biomass feedstock prices are sometimes assumed to decline due to improvements in production and supply logistics and technological learning (see Hamelinck et Faaij, 2006, for example). However, as

Figure 4-13 and Figure 4-14 show the results for 2030. Compared to the results for the default year, the following differences are apparent: Although heating systems still show a good performance with regard to costs, their superiority is not as pronounced as in the default case. Even under the assumption that biomass prices show the same relative increase up to 2030 (upper error bars), the costs of fossil fuel reduction and GHG mitigation decrease. This is partly due to the assumed learning effects (cost reduction of 10% and efficiency increased by 6%), but also due to the structure of the heat generation costs, compared to the reference systems (see sensitivity analysis in section 4.6.2).

As a result of increased electrical efficiencies, higher savings per fuel input are achieved with biomass CHP plants. In operation mode 2, most CHP plants are less efficient with regard to costs than 2nd generation biofuels. For the production of 2nd generation biofuels, technological learning is assumed to result in significant cost reductions. The costs of GHG mitigation with liquid fuels range from about 46 to 121 €/t CO_2-eq., depending on the biomass price, those of SNG (centralized production) from -28 to 34 €/t CO_2-eq. This is roughly in the range of CHP in mode 1. However, the substitution of fossil transport fuels with 2nd generation biofuels (especially FT diesel and ethanol) still results in very low GHG mitigation and fossil fuel replacement per unit of biomass used, due to moderate conversion efficiencies. For SNG, the relatively low GHG emissions of the reference system (natural gas as transport fuel) are the main reason for the moderate GHG mitigation. The best performance with regard to GHG mitigation as well as fossil fuel saving in this projection is achieved with the 50 MW-BIGCC plant in mode 1. There are of course big uncertainties with regard to future plant costs, as large scale BIGCC plants are not yet commercially available. However, it is worth mentioning that the power generation costs of this technology are lower than those of a CCGT plant under the given assumptions, resulting in negative abatement costs, even in mode 2.

bioenergy is gaining in importance, domestic biomass potentials are getting increasingly exploited and prices are determined primarily by market mechanisms, it is assumed that biomass price developments will show some correlation to fossil fuel price trends, at least as long as fossil fuels are the predominant source of energy.

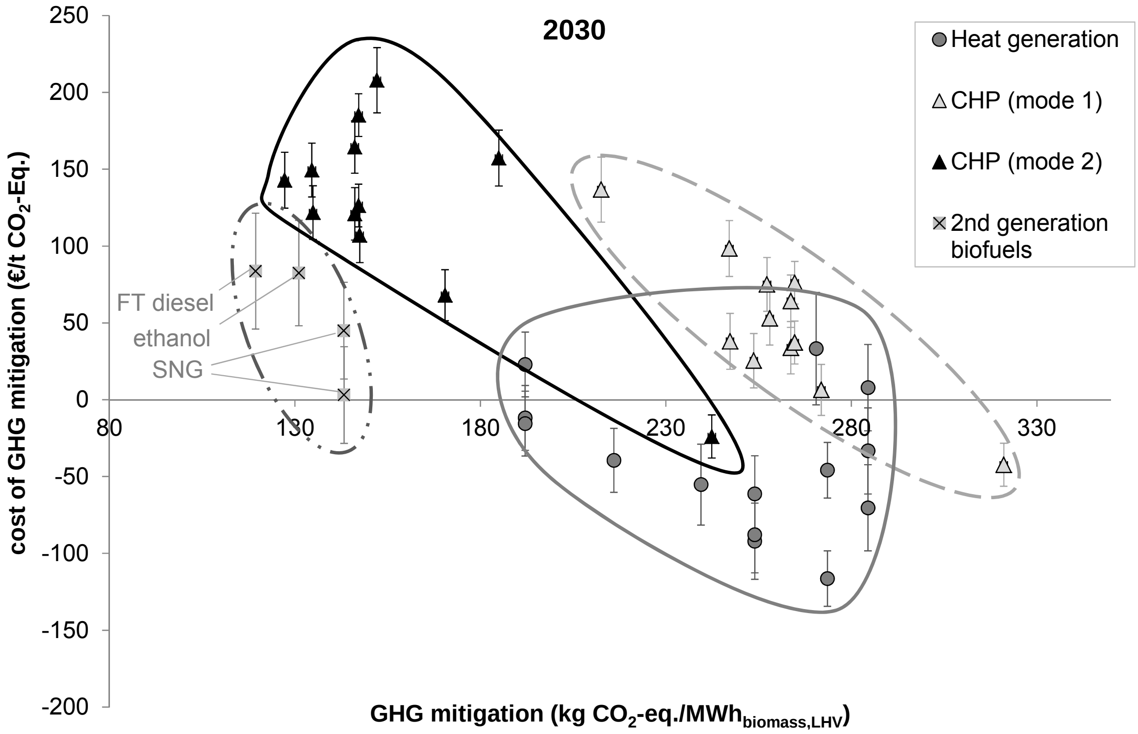

Figure 4-13. Comparison of wood-based bioenergy utilization paths with regard to GHG mitigation in 2030

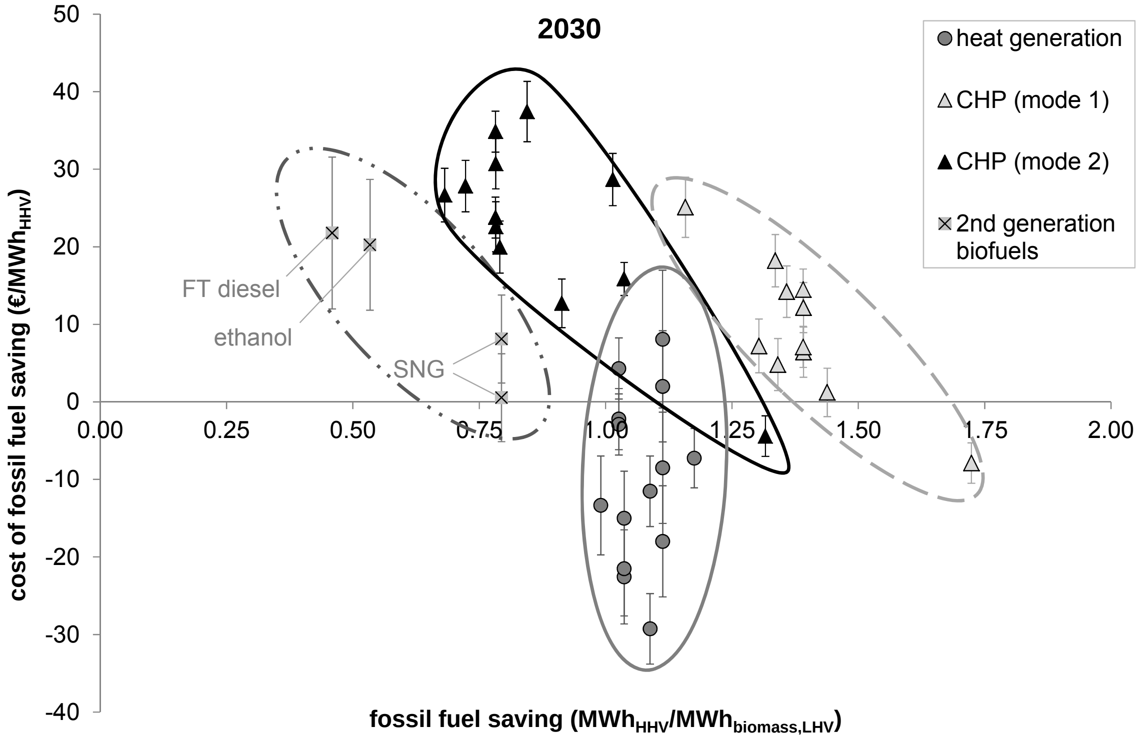

Figure 4-14. Comparison of wood-based bioenergy utilization paths with regard to fossil fuel saving in 2030

4.6 Sensitivity

The following sections include sensitivity analyses concerning annual full load operating hours (4.6.1), fuel prices (4.6.2) and alternative reference systems (4.6.3). The analyses are based on the default cases for 2010, or 2030 if stated explicitly. To keep this section compact, only GHG mitigation costs are analysed.

4.6.1 Full load hours

4.6.1.1 Small-scale heating systems

As mentioned before, wood-fired heating systems are more economic at higher annual full load hours, due to lower fuel and higher capital costs compared to the fossil fuel-based reference systems. Figure 4-15 shows the cost of GHG mitigation of small-scale biomass heating systems in the default case as a function of annual full load hours. In the range of 1000 to 2000 h/a, which can be considered a realistic spread for residential heating, the GHG mitigation costs of 12 and 25 kW pellet boilers, for example, range from 59.5 to 159 €/t CO_2-eq. and 22 to 83.5 €/t CO_2-eq., respectively. Therefore, under unfavourable conditions GHG mitigation with small-scale biomass heating systems (and also heating plants) can be much more expensive than in the default case. On the other hand, biomass heating systems are highly beneficial for buildings and applications with a relatively constant base heat load throughout the year and annual operating hours amounting to 3000 and more (such as hospitals, public indoor swimming pools, retirement homes or industrial enterprises). In contrast to wood-fired boilers, plant oil boilers show a very moderate sensitivity, as the capital costs are only slightly higher than those of conventional oil-fired boilers.

4.6.1.2 CHP

By assuming two different modes for CHP with regard to heat utilization, the fact that the performance of biomass CHP highly depends on the heat utilization and the specific framework conditions, respectively, was already considered in the default case. However, as the assumption of 3000 full load hours in mode 2 is somewhat arbitrary, Figure 4-16 shows the sensitivity of CHP plants to varying heat full load hours. (For better readability, not all plant sizes are plotted.) In contrast to mode 1, the heat credit in mode 2 depends on the plant size, as it is assumed that it directly substitutes heat that would otherwise be generated with reference boilers (see section 4.2). The figure illustrates that especially for small-scale CHP plants with high thermal efficiencies, such as Stirling engine or ORC systems, higher heat full load hours (5 000 instead of 3 000, for example) result in a significant reduction of the GHG mitigation costs (90.5 instead of 218.5 €/t CO_2-eq. for the case of a 35 kW-Stirling engine or 75 instead of 151.5 €/t CO_2-eq. for a 1.6 MW-wood-chip-ORC plant).

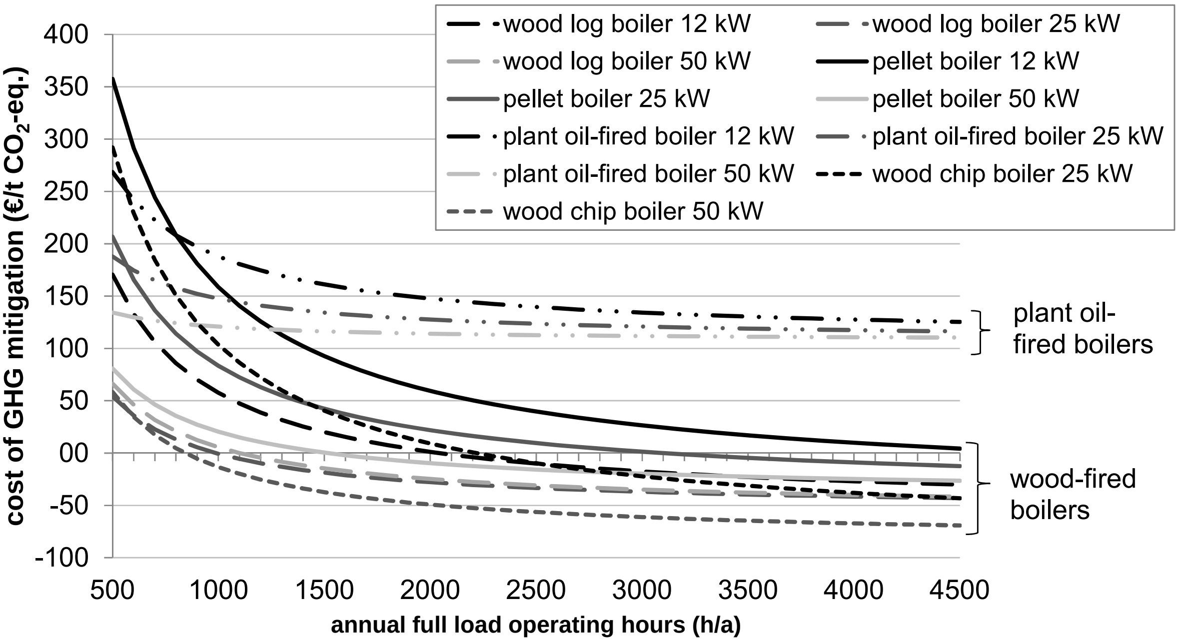

Figure 4-15. Sensitivity of GHG mitigation cost of small-scale biomass heating systems to variation of annual full load hours
(Both full load hours of the reference and the biomass systems are varied.)

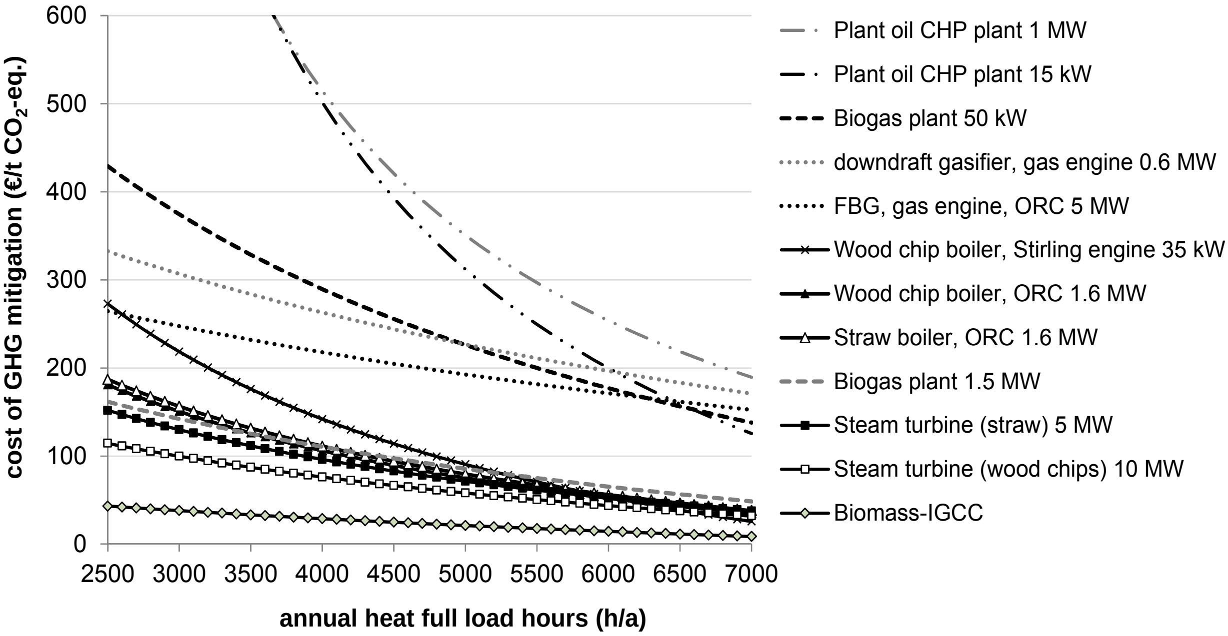

Figure 4-16. Sensitivity of GHG mitigation cost of CHP plants (mode 2) to heat full load hours

4.6.2 Fuel prices

Needless to say, fuel prices have a high impact on the economics and GHG mitigation costs of bioenergy systems. Diverging fossil fuel and biomass price developments are basically considered less likely than correlated price trends. For the following sensitivity analyses, identical relative price increases for all fuels are assumed. In other words, it is assumed that the overall price level (for biogenic and fossil fuels) is shifting relative to the default case. This assumption is to illustrate fundamental aspects arising from the structure of energy generation costs.

4.6.2.1 Small-scale heating systems

Figure 4-17 shows the results for small-scale heating systems. The price level is varied by -50% to +100% from the default case. Due to the lower sensitivity of heat generation costs of wood-fired boilers to fuel price variations, the costs of GHG mitigation decrease at higher price levels. For the case of 25 kW-wood chip boilers, for example, the costs vary from 43 to -84 €/t CO_2-eq. Hence, as fuel price levels are assumed to increase in future years and decades, the economics of wood-fired heating systems can be expected to improve (and GHG mitigation costs to decrease), even if biomass prices show the same relative price increase as fossil fuels. In contrast, plant oil-fired boilers show increasing GHG mitigation costs at higher price levels, as they are even more sensitive to fuel price variations than the reference systems.

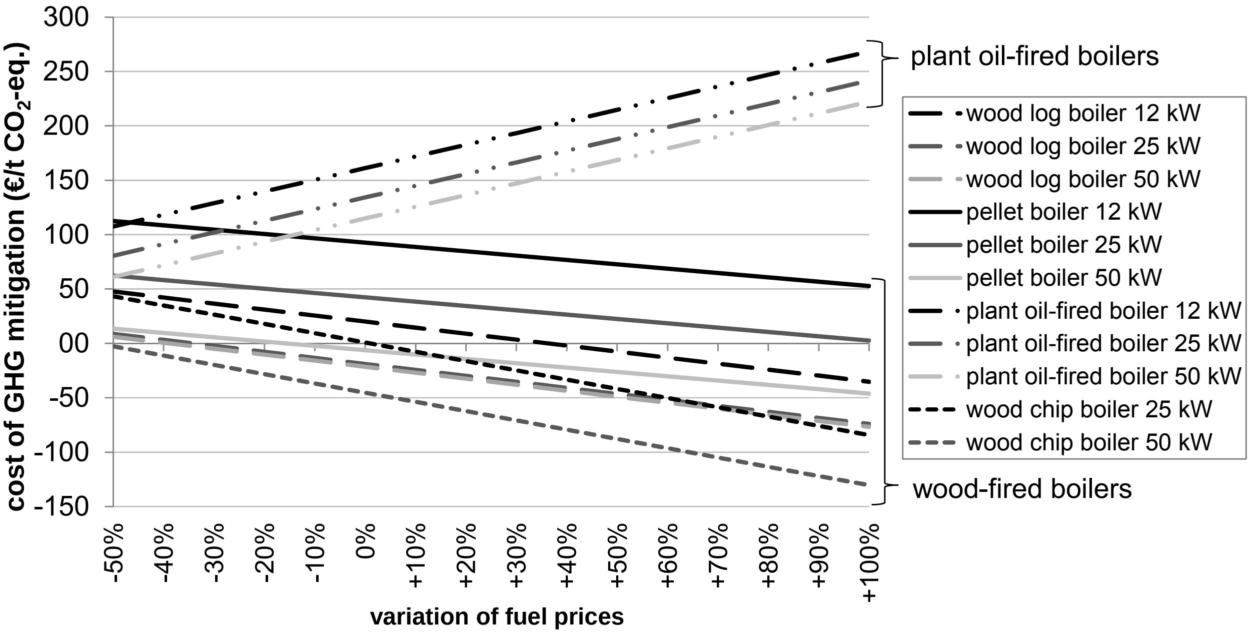

Figure 4-17. Sensitivity of GHG mitigation cost of small-scale biomass heating systems to variation of fuel prices
(Fuel prices of both the reference and the biomass systems are varied.)

4.6.2.2 Biofuels

Figure 4-18 shows the GHG mitigation costs of biofuels as a function of fuel/feedstock price variations. The assumption of equal relative price variations is extended to credits for by-products here. The figure shows that there are only two technologies which (in terms of GHG mitigation costs) benefit from increasing price levels: SNG production and biomethane plants. The mitigation costs of FT-plants and pant oil presses are almost constant for all price levels and those of the other technologies increase with higher price levels. The decisive factor is the contribution of feedstock costs (minus by-product revenues) to the production costs (see Figure 4-8). Only if it amounts to less than the total reference price, increasing price levels result in lower mitigation costs. As this is only the case for SNG and biomethane plants, these are the only biofuel production technologies which do not depend on technological improvements or diverging biomass and fossil fuel price developments to become more economic.

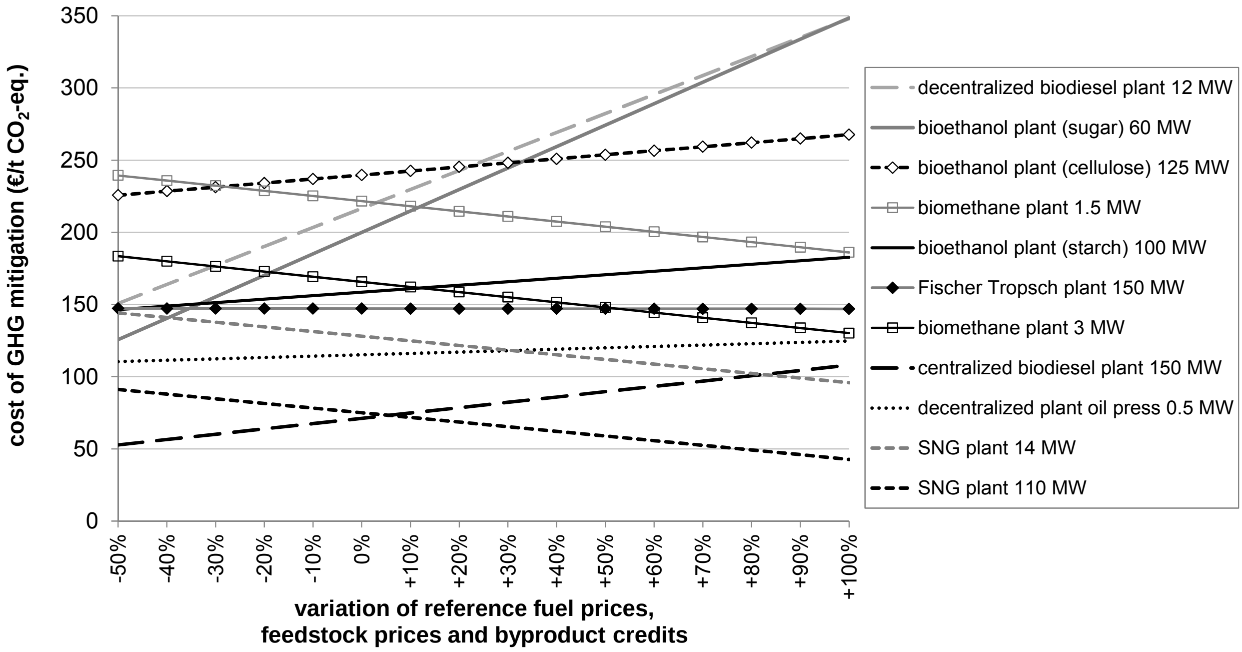

Figure 4-18. Sensitivity of GHG mitigation cost of biofuel production technologies to variation of commodity prices
(Reference fossil fuel prices, biomass feedstock prices and credits for by-products are varied. 0.3 MW-biomethane plant is not shown.)

4.6.3 Alternative reference systems

The choice of reference systems is of major importance for techno-economic assessments of bioenergy systems and other technologies. As described above, the default reference systems have been thoroughly selected based on the structure of the current energy supply in Austria.

However, as it is impossible to determine definite and universally valid reference systems, the sensitivity of the results to alternative reference systems (stated in Table 3-1) is analysed here.

4.6.3.1 Small-scale heating systems

Oil-fired boilers with solar thermal support systems for space and water heating are assumed as alternative reference systems for small-scale biomass heating systems. The cost data and other parameters of the assumed solar thermal systems are stated in Table 4-1. Given the assumed heat yields from the solar systems, the specific GHG emissions and fossil fuel consumption values of the reference systems are reduced by 16 to 22%[9]. The heat generation costs of 12, 25 and 50 kW-systems amount to 83, 113 and 128 €/MWh_{heat} (without taxes), respectively, and are 23 to 28% higher than those of the default reference systems. The 12 kW-pellet boiler is the only biomass heating system that has higher specific costs than the alternative reference systems. Consequently, if oil-fired boilers with solar thermal systems are assumed as reference, the abatement costs are negative for all but one biomass heating system, ranging from -125 to 14 €/t CO_2-eq. and -30 to 3.6 €/MWh_{HHV}.

Table 4-1. Parameters of the solar thermal systems for assumed for different boiler capacities Source: based on Haas et al. (2010)

boiler capacity	solar collector area	annual useful heat production 2010	annual useful heat production 2030	investment cost of solar thermal system 2010	investment cost of solar thermal system 2030	operation and maintenance cost
kW	m^2	$kWh_{heat}(m^2 \cdot a)^{-1}$	$kWh_{heat}(m^2 \cdot a)^{-1}$	€	€	$€a^{-1}$
12	15	320	380	9,788	8,075	130
25	25	320	380	15,539	12,820	216
50	40	320	380	23,679	19,535	346

In the projection to 2030, the economics of the alternative reference system improve due to the assumed fossil fuel price increase and a cost reduction of the solar thermal system (-17.5%, based on Haas et al., 2010). However, the specific costs are still 7 to 10% higher than those of the default reference system. To sum up, under the assumed conditions biomass heating systems are cost-effective technologies for reducing GHG emissions and fossil fuel consumption, even in comparison to boilers with solar thermal systems.

[9] The calculations presented here are not applicable to low-energy buildings, as they have a more balanced heat demand profile throughout the year due to a higher share of water heating in the total heat demand. This results in a higher efficiency of the solar thermal systems, and lower specific costs. However, this aspect amounts to the questions of energy demand trends and energy efficiency, which are discussed in section 4.

4.6.3.2 Electricity generation

In the default case, modern natural gas IGCC plants are assumed as reference system. For the base year 2010, the following alternative reference systems come into consideration: coal-fired condensing power plants (CPP) or gas-fired IGCC plants with CHP generation. For 2030, power plants with carbon capture and storage (CCS) are taken into account. The electricity generation costs, specific GHG emissions and fossil fuel consumption are summarized in Table 4-2.

Table 4-2. Parameters of the alternative reference systems for CHP generation

	Now (default)			2030			
	Natural gas CCGT	Coal CPP	Natural gas CCGT with CHP[b]	Natural gas CCGT	Coal CPP	Natural gas IGCC with CCS[c,e]	Coal IGCC with CCS[d,e]
Electricity generation cost[a] (€/MWh_{el})	65.30	41.41	66.27 (78.18)	83.67	48.59	105.27	64.32
Specific GHG emissions (g CO_2-eq·kWh_{el}^{-1})	432.0	888.1	337.2 (454.1)	417.0	786.1	46.5	112.8
Specific fossil fuel consumption (MWh_{HHV}·MWh_{el}^{-1})	2.26	2.43	1.66 (2.34)	2.19	2.15	2.34	2.22
Cost of GHG mitigation compared to reference system without CHP / CCS (€·(t CO_2-eq.)$^{-1}$)	-	-	10.2 (-)	-	-	64.44	29.47

a) electricity generation costs do not include costs for CO2 transport and storage

b) CHP mode 1 (values in parenthesis: CHP mode 2), reference system: natural gas CCGT without CHP (no value for mode 2, as (Er - Ex) < 0)

c) reference system: natural gas CCGT without CCS

d) reference system: coal CPP without CCS

e) based on Metz et al. (2005), additional cost for CO2 transport and storage are assumed 6.12 €/t CO2-eq.

If coal-fired power plants are assumed as reference system (as is usually done for the case of Germany; see WBGU, 2009 or König, 2009, for example), the reference electricity price in 2010 is 41.41 €/MWh_{el} and the reference GHG emissions related to electricity generation 888.1 kg CO_2-eq./MWh_{el}. Assuming this reference system, typical abatement costs of biomass CHP plants with 1 MW_{el} and more are in the magnitude of 50 €/t CO_2-eq. and 12 €/MWh_{HHV} in mode 1 and 120 €/t CO_2-eq. and 36 €/MWh_{HHV} in mode 2. The quantity of GHG emissions and fossil fuel savings per unit of biomass used amount to more than 300 kg CO_2-eq./MWh_{LHV} and 1.3 MWh_{HHV}/MWh_{LHV}, respectively. A comparison with the values in Figure 4-11 indicates that if coal-fired power plants are assumed as reference system, biomass CHP stands out as a favourable way of reducing GHG emissions, explaining the recommendation for using biomass for CHP in WBGU (2009). (With regard to fossil fuel replacement, the differences to the default case are negligible.) However, for the case of Austria, coal-fired power plants are not considered an appropriate reference system, as the current contribution of coal to Austria's electricity supply is less than 10%, and the commissioning of further coal power plants is highly unlikely.

Table 4-2 shows the electricity generation costs and GHG emissions of the alternative reference system "natural gas-fired CCGT with CHP".[10] In mode 1, the costs are 1 €/MWh_{el} higher and the GHG emissions (due to the heat credit) 22% lower than those of the default reference system. Therefore, if this alternative reference system is assumed for biomass CHP plants in mode 1, the GHG savings are somewhat lower (-10 to -41 t CO_2-eq./$MWh_{biomass,LHV}$ or, in relative numbers -4 to -20%) and the mitigation costs up to 24% higher than in the default case. Contrary to this, if the alternative reference system in mode 2 is assumed for biomass CHP plants in mode 2, the performance of bioenergy systems improves in a similar magnitude. Hence, the effect of assuming CCGT with CHP as reference system results depends on the operation mode. If a CCGT plant without CHP is considered as reference technology and the one with CHP as the technology under consideration, the costs of GHG mitigation in mode 1 account for 10.2 €/t CO_2-eq. If mode 2 is assumed, the CHP plant has higher specific GHG emissions.

The projected costs of GHG mitigation of coal and natural gas IGCC power plants with CCS in the year 2030 amount to 29.5 and 64.44 €/t CO_2-eq., respectively (cp. Metz et al., 2005). Especially coal power plants with CCS are therefore sometimes considered a cost-effective way of reducing GHG emission in the electricity sector. However, power plants equipped with CCS have lower net electrical efficiencies, resulting in an increased primary energy consumption and higher dependence on fossil fuel imports. Therefore, if reducing this dependence is seen as a core energy policy target, fossil fuel-based electricity generation with CCS is not a reasonable option.

[10] In contrast to the data shown in Figure 4-6, heat credits are taken into account here.

5 Discussion, interpretation and conclusions

5.1 Country-specific aspects

The results for the default case represent what is assumed typical situations and framework conditions in Austria with regard to system costs, fuel prices, operating hours etc. Differing fuel prices, reference systems and typical full load of heating systems are considered the most likely reasons for significantly different outcomes. For example, the prices of pellets in some European countries (e.g. Germany and Sweden) have been clearly higher than in Austria in recent years (Pellet@las, 2010), and also end-consumer prices of fossil fuels (excl. taxes) vary from country to country (EC, 2011). In Gustavsson et al. (2007), typical full load hours of heating systems in Sweden are stated to be 2500. Compared to the default case in Austria (1 500 h/a), this makes a big difference as Figure 4-15 illustrates. Hence, country-specific assessments of abatement costs are considered necessary, as regional differences can have a significant impact on the results.

Taking this into account, the results of this work are largely in line with data in literature: According to JRC et al. (2007) and De Santi et al. (2008), the costs of GHG mitigation of the conventional biofuel production technologies considered here range from approximately 100 to 240 €/t CO_2-eq. at a crude oil price of 50 €/bbl under European framework conditions. Those of liquid 2nd generation biofuels from wood are estimated around 200 €/t CO_2-eq. The results of several studies referring to the situation in Germany are compared in SRU (2007). Typical mitigation costs of conventional biofuels are found to be 100 €/t CO_2-eq. and above (those of plant oil are estimated 63 €/t CO_2-eq.). Considering the highly volatile crude oil and agricultural prices in recent years, the results of these studies are surprisingly agreeing. For electricity generation in Germany coal power plants are often defined as reference system, resulting in GHG mitigation costs around 30 to 60 €/t CO_2-eq (SRU, 2007). Therefore, biomass CHP is usually considered the most efficient way of reducing GHG emissions in Germany (see also WBGU, 2009 and König, 2011). Based on our results, it is concluded that these results and recommendations are plausible, but not applicable to Austria, where coal is of minor importance. For biomass heat generation, typical mitigation costs in Germany are estimated 40 €/t CO_2-eq. in SRU (2007), which is also in line with the results of this work. The wide rage of mitigation costs, depending on plant sizes and full load hours are, however, not mentioned.

In Wahlund et al. (2004) the costs of different options for substituting fossil fuels with wood biomass are compared for the specific situation in Sweden. The authors conclude that the substitution of coal with pellets gives the highest potential and lowest costs for reducing GHG emissions. Due to the rather moderate importance of coal in the Austrian energy supply (less than 10% of the total electricity supply in 2008), this result is not applicable to the situation in

Austria. In Schmidt et al. (2010b) a spatially explicit modelling approach is applied to assess the efficiency of upcoming bioenergy technologies for reducing GHG emissions and fossil fuel replacement compared to the use of wood pellets for heating. The results indicate that biofuel production is inefficient whereas BIGCC and bioenergy systems with carbon capture and storage might be viable options at high CO_2 prices.

To sum up, the results of this study are basically valid for the case of Austria and the validity for other countries and regions needs to be examined in detail. Apart from the default fuel prices and technology data assumed, especially the reference systems need to be considered, as current energy supply structures vary widely from region to region, and technologies or fuels which are most likely being replaced by bioenergy technologies are to be assumed as reference systems.

5.2 Interpretation and conclusions

Bioenergy is the most important renewable energy source used for GHG mitigation and fossil fuel replacement in Austria. With the increasing exploitation of sustainable biomass potentials, the question of how limited biomass resources can be utilized in a most efficient way is gaining in importance. The economic efficiency of bioenergy for GHG mitigation and fossil fuel replacement vary widely for different plant types and energy services (heat and/or electricity or mobility), plant sizes and other parameters like annual full load hours. The results for technologies which are not yet deployed (like 2nd generation biofuel or BIGCC plants) as well as such with rather insecure cost data (like straw heating plants or Stirling engines) are to be seen as best possible estimates.

In the default case, the lowest costs of GHG mitigation and fossil fuel saving among the technologies considered in this study are achieved with 50 kW-small-scale heating systems. Heating systems and heat plants generally show a good performance, with GHG mitigation costs of typically 0 to 50 €/t CO_2-eq. and less than 10 €/MWh_{HHV} when substituting oil-fired boilers and gas-fired heating plants, respectively. However, modern biomass heating systems around 15 kW show clearly higher abatement costs of up to 100 €/t CO_2-eq. and 25 €/MWh_{HHV}. In order to achieve high values of GHG mitigation and fossil fuel saving with biomass CHP generation, it is essential that the heat output is utilized to a high degree. In practice, this can be achieved by choosing suitable locations for CHP plants and appropriate dimensioning, based on measured or well-estimated heat load duration curves, so that CHP plants are used for base heat load coverage and thermal full load hours above 6000 h/a or so are achieved (cp. Obernberger et Thek, 2008). If this is the case, the costs of GHG mitigation and fossil fuel saving of most technologies account for less than 100 €/t CO_2-eq. and 20 €/MWh_{HHV}. (exceptions being plant oil CHP plants, small-scale biogas plants and small-scale gasification technologies which are not yet fully established). Significantly lower abatement costs of less than 50 €/t CO_2-eq. and 10 €/MWh_{HHV} are possible with large-scale CHP plants; especially BIGCC is found to be a promising technology.

Technological progress is assumed to lead to improved efficiencies of biomass CHP plants, resulting in enhanced competitiveness and reduced abatement costs. This is also true for 2nd generation biofuel production technologies. However, the results show that even if abatement costs with these technologies might decrease to about or less than 50 €/t CO_2-eq. and 10 €/MWh_{HHV}, one major drawback remains: the quantity of GHG mitigation and fossil fuel saving per unit of biomass consumed is clearly lower than what is achieved with heat and CHP technologies. The abatement costs of currently established biofuel technologies are found to range from about 70 to 220 €/t CO_2-eq. and 8 to 80 €/MWh_{HHV}. Compared to 2nd generation biofuels, CHP and heat production technologies, the production costs of biodiesel and ethanol are highly sensitive to feedstock price variations, and abatement costs increase at higher commodity price levels.

In connection with projections to 2030, two crucial questions arise: (1) How are energy demand structures and demand-side potentials of bioenergy technologies going to develop and (2) what other renewable energy technologies are expected to be available and compete with bioenergy? Residential heating is very likely the sector where the most significant reductions in fuel consumption will be achieved through energy efficiency measures and the deployment of solar thermal systems and heat pumps. Decreasing heat loads have a significant impact on the economic efficiency of biomass heating systems and plants, as those market segments where bioenergy systems are most economic shrink. Speaking in terms of the illustrations in Figure 4-11 to Figure 4-14, this trend can be interpreted as a shift of the imaginary center of the category “heat generation” towards the more expensive systems. A trend towards less annual full load hours (which is sometimes expected due to enhanced building quality and global warming) also results in higher abatement costs. Still, as significantly reducing the residential heat demand by refurbishing the existing building stock will probably take several decades (cp. Haas et al., 2010), and currently more than 50% of the residential heat demand in Austria is covered with fossil fuels, the use of biomass in the heat sector is considered a cost-efficient way of reducing GHG emissions and fossil fuel demand in the future energy system (cp. Kalt et al., 2010b). Future demand-side potentials for heat from biomass CHP are primarily located in the industry, as declining residential heat loads and densities are adverse framework conditions for district heating, and residential heat demand is subject to high seasonal fluctuations, whereas process heat for industrial applications is usually required throughout the whole year.

Liquid biofuels are sometimes seen as the only short-term alternative to fossil fuels in the transport sector. Still, as long as fossil fuels can be substituted cost-efficiently in the heat sector, it is questionable why efforts to reduce fossil fuel consumption should focus on the transport sector. In the medium to long term, significant reductions in fuel demand might be achievable with more efficient vehicles as well as by electrification. However, as liquid (or gaseous) transport fuels are indispensable for certain applications (especially ship and air traffic), the (partial) substitution of fossil fuels with biofuels is unavoidable, albeit on the long term.

One aspect which is not taken into account in detail in this work is the impact of different fuel or feedstock types and supply chains. The results of this work are based on the most common fuels and supply chains, and it is generally assumed that biomass is produced without causing land use change. Utilization of waste streams usually shows clearly better values with regard to GHG emissions and cumulated fossil fuel demand than intentionally planted energy crops (see Zah et al., 2007). This is especially relevant for biogas technologies (biogas CHP plants and biomethane production), which show clearly better performances if biogenic wastes are used, rather than energy crops. On the other hand, if biomass fuels are produced or harvested in an unsustainable way, resulting in land use change and changes in soil carbon stocks, GHG balances of bioenergy deteriorate significantly.

To conclude, bioenergy is capable of contributing to two major energy policy targets: reducing GHG emission and dependence on fossil fuels. The latter is seen as a main advantage compared to CCS, which results in additional primary energy demand. However, the economic efficiency of bioenergy technologies and applications differ significantly and therefore, energy policy measures should focus on promoting the most efficient utilization paths identified in this work.

Part II:

Bioenergy in Central Europe with particular focus on the situation in Austria – Recent developments, international biomass trade and future prospects

6 The contribution of biomass to the energy supply

Among the different renewable energy sources (RES) bioenergy is of crucial importance for the current and future energy supply in Central Europe (CE). With regard to the "2020-RES-targets" (as defined in the 2009-EU Directive on the promotion of the use of energy from renewable sources; EC, 2009a) the current structure of bioenergy use, recent developments and the availability of environmentally compatible resource potentials are of high interest.

Within Part II of this thesis, statistical data on the current biomass use and international biomass trade in Central Europe, as well as data on biomass potentials in literature are reviewed critically. Different methodologies for assessing cross-border trade related to bioenergy use are discussed and the impact of the increasing utilization of biomass for energy on trade streams is assessed. The considered countries include Austria, Czech Republic, Germany, Hungary, Poland, Slovenia and Slovakia as well as Italy and Denmark[11].

6.1 Outline

The sections of this part are organized as follows: After this introduction, section 6 provides insight into the structure of energy consumption and bioenergy use in CE (sections 6.2. to 6.3.3). A special focus is given to the situation in Austria (section 6.4). The topic of section 7 is international trade of biomass. After discussing methodological issues of assessing cross-border trade related to bioenergy (7.1), net imports and exports of wood and biofuels are analysed (7.2). In section 7.3 trade streams of wood in CE are mapped. For the case of Austria a comprehensive assessment of cross-border trade related to bioenergy use is carried out (7.4).

Section 8 deals with prospects for a further increase of bioenergy use, EU energy policy framework conditions and biomass resource potentials in the considered countries. Section 9 includes a discussion, conclusions and policy implications.[12]

6.2 The structure of energy consumption in Central Europe

Despite the geographical vicinity of the considered countries, the structures of their primary energy consumption (gross inland consumption; GIC) are quite inhomogeneous (Figure 6-1;

[11] These countries are referred to as "CE countries", even though Italy and Denmark are usually not considered to be part of Central Europe. They have been included primarily because of their significant cross-border trade streams as well as their characteristic biomass consumption profiles.

[12] Excerpts from Part II have been published in "Energy Resources: Development, Distribution, and Exploitation", published by Nova Science Publishers Inc. (Kalt et al., 2011b)

all data stated here refer to 2008). On an average the share of fossil fuels (petroleum, natural gas, lignite and hard coal) accounts for 80% of the total energy sources used, with Slovenia and Slovakia being least dependent on fossil fuels (both about 70%). The share of hard coal and lignite ranges from less than 10% (Italy) to more than 50% (Poland) and the contribution of petroleum from 21% (Slovakia) to 43% (Italy). The share of natural gas is especially high in Hungary's and Italy's GIC (both close to 40%) and relatively low in Poland and Slovenia (both slightly more than 10%). In the Slovak Republic nuclear energy accounts for as much as 23% of the GIC, whereas in Austria, Denmark, Italy and Poland there are no nuclear power plants in operation.

There are also significant differences with regard to energy consumption per capita. In Hungary and Poland it accounts for 108 GJ/a, whereas in the Czech Republic it is 182 GJ/a and in Germany 175 GJ/a. In the other countries it ranges from about 125 to 170 GJ/a.

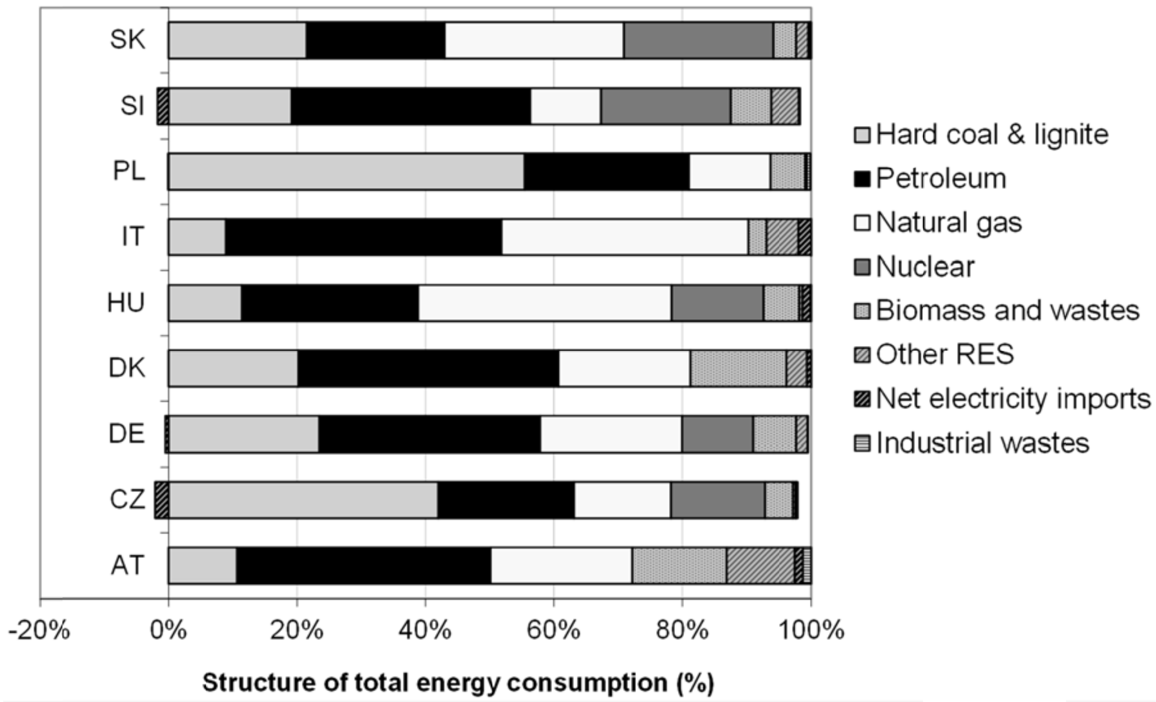

Figure 6-1. Structure of the GIC in CE countries in 2008.
Sources: Eurostat (2010a), own calculations

6.3 The contribution of bioenergy in Central Europe

The shares of renewable energies in the GIC of the considered countries range from 5% in the Czech Republic to 25.3% in Austria (2008), with biomass and wastes accounting for an average of more than 70% of all renewables.[13] In the Czech Republic, Poland and Hungary biomass and wastes account for more than 90% of all RES.

[13] The fact that non-renewable wastes are also included in "biomass and wastes" is neglected here.

The share of biomass and wastes in the GIC is illustrated in the map in Figure 6-2. It is highest in Denmark (14.9%) and Austria (14.7%). The high contribution in Denmark is a result of ambitious energy policy measures which led to a significant increase of biomass use in combined heat and power (CHP) and district heating plants (largely based on imported biomass, as will be shown in section 7), especially since the early nineties.

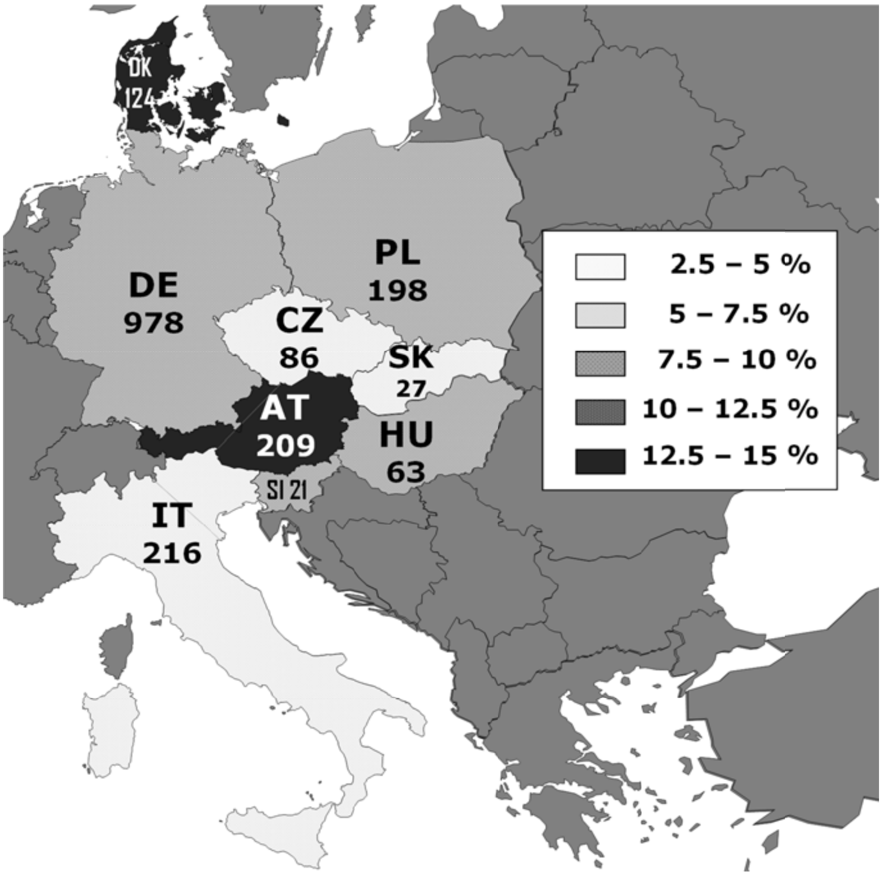

Figure 6-2. Bioenergy as share of gross inland energy consumption in 2008 (values in PJ/a). Source: Eurostat (2010a)

For the case of Austria the following reasons for the high importance of biomass have been identified: (i) Austria is a heavily wooded country. Almost 50% of the total Austrian area is forests, which is clearly more than in most other CE countries[14]. (ii) The use of biomass for residential heating is traditionally high in Austria. Especially in the eighties log wood boilers gained in importance due to the oil price shock and in recent years pellet boilers and other modern biomass heating systems have become increasingly popular (partly due to attractive investment subsidies). Today about 30% of the total residential heat demand is met with biomass (Statistik Austria, 2010e). (iii) The prominent role of the wood processing industries in Austria was crucial for the development of the bioenergy sector. First, they provide substantial

[14] Only Slovenia has an even higher share of approximately 60%.

amounts of wood residues for energy use and second, a high proportion of their energy demand is covered with biomass. Therefore, the bioenergy share in the energy supply of the industrial sector is also exceptionally high.

6.3.1 The structure of biomass use and recent developments

In Figure 6-3 the historic development of the share of biomass and wastes in the total GIC is illustrated for each CE country. The figure shows that in most countries the contribution of biomass has been increasing significantly in recent years. The most notable developments were achieved in Germany and Denmark, but also in Austria, Czech Republic, Hungary and Slovakia the importance of biomass for energy production has been increasing steadily; especially since the year 2000 or so. In Austria the biomass consumption has more than doubled from 1990 to 2008, but due to the rising total energy consumption (about 34% increase from 1990 to 2008), the biomass share only showed an increase of about 60%.[15]

In absolute numbers the biomass consumption in CE increased from about 450 PJ in 1990 to 1,950 PJ in 2008. Remarkably, the progress in Germany accounted for more than 50% of this increase. In 2008 about 50% of the total amount of biomass used for energy recovery in CE was consumed in Germany. The biomass consumption per capita is highest in Austria (25 GJ in 2008), followed by Denmark (22.7 GJ), Germany (12 GJ) Slovenia (10.5 GJ).

Figure 6-4 shows that the main increase in bioenergy use was achieved in the field of electricity and CHP generation. The share of biomass for heat-only production, accounting for about 80% in the nineties has recently gone down to less than 50%. The main reason for the increase in electricity and CHP generation was the implementation of the “EC Directive on electricity production from renewable energy sources” (EC, 2001) and the introduction of according support schemes (e.g. the German Renewable Energy Sources Act).

Among the considered countries the share of electricity generation from biomass and wastes to the total electricity consumption ranges from less than 1% in Slovenia to more than 10% in Denmark. In Austria (6.4%), Germany (5.3%) and Hungary (4.7%) the ratio is also relatively high, whereas in Czech Republic, Italy, Poland and Slovakia it is about 2%. In the early nineties only the biomass share in Austria’s electricity consumption accounted for more than 2%.

[15] In most CE countries the energy consumption declined during this period.

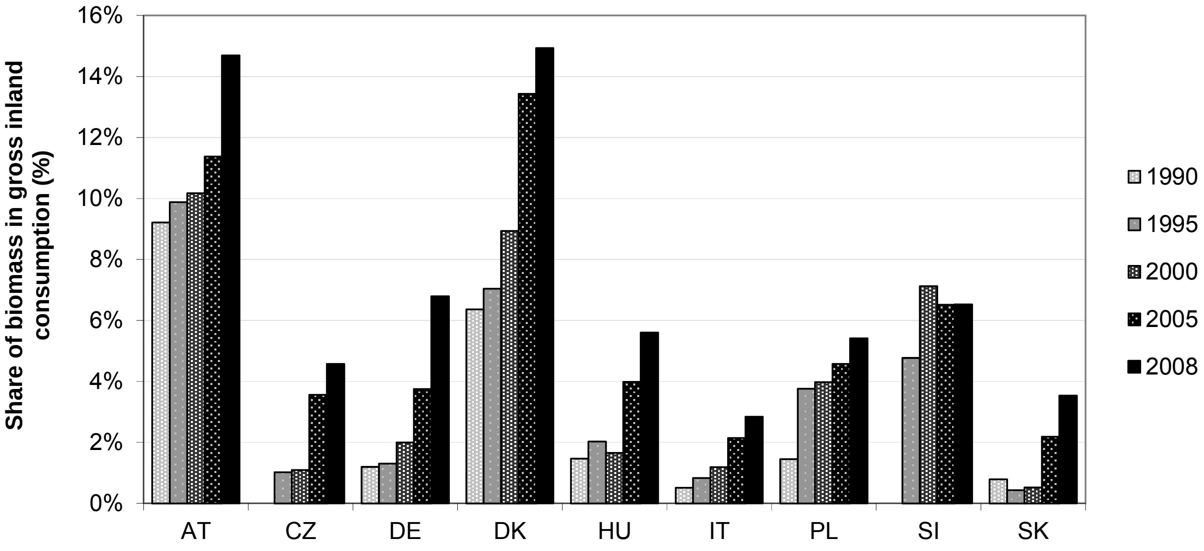

Figure 6-3. Development of bioenergy as share of GIC from 1990 to 2008.
Source: Eurostat (2010a), own calculations

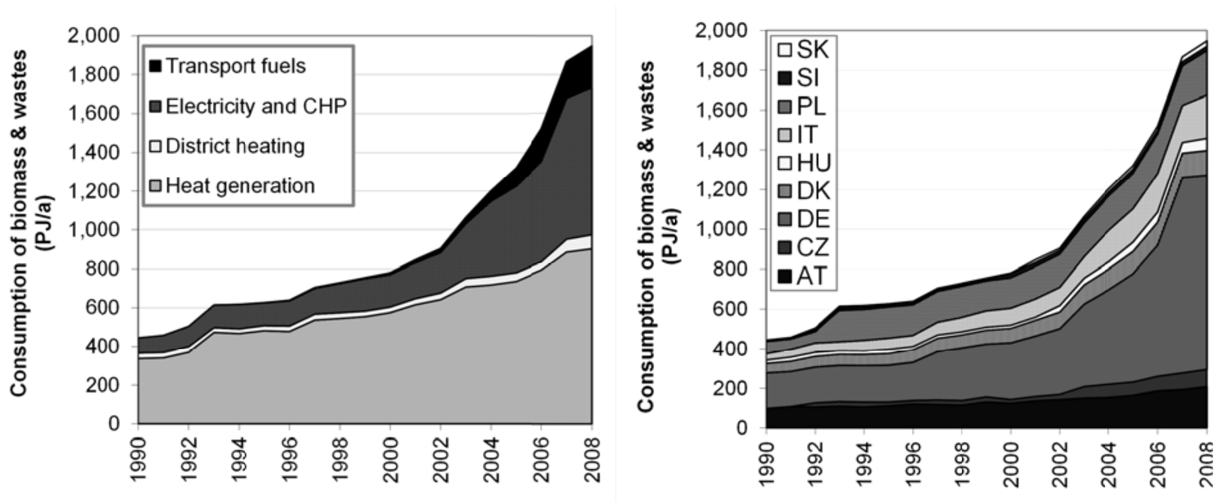

Figure 6-4. Biomass consumption in CE countries from 1990 to 2007 broken down by application (left) and country (right)
Source: Eurostat (2010a), own calculations

6.3.2 Biofuels for transport

The main progress in the use of biofuels started in 2003, as a consequence of Directive COM 2003/30/EC on the promotion of the use of biofuels for transport ("Biofuel Directive"; EC, 2003). According to the directive, EU Member States are required to establish national targets on the proportion of biofuels in the transport sector. The following reference values for national targets are stated in this directive: 2% by the end of 2005 and 5.75% by the end of 2010, calculated on the basis of energy values.

The progress in the considered countries according to the national progress reports in the context of the Biofuel Directive (EC, 2009b and EC, 2010a) as well as the national target values are shown in Figure 6-5. The figure illustrates that there are sometimes big differences between the data according to Eurostat (2010a), represented by error bars, and the data stated in the biofuel reports, indicating that the consumption of biofuels is partly not captured appropriately in energy statistics. This is particularly true for Slovakia as well as for the 2008-data for Italy and Poland.

However, progress was very uneven among CE countries. Based on the national progress reports, Austria had the highest share of biofuels in 2009 (7%), followed by Germany (5.5%), Poland (4.63%), Hungary (3.75%) and Italy (3.47%). Up to 2007, Germany was the European leader in the field of biofuels. It had already surpassed its 2010-target of 6.25% in 2006, but in 2009 the share of biofuels had dropped to 5.5%, due to an abolishment of the tax exemption for biofuels (see section 6.3.3). In most other CE countries no appreciable progress was reported until 2008 or 2009. Denmark’s latest report (for the year 2008) indicates a biofuel share of only 0.12%. According to DEA (2009), Denmark aims at achieving the indicative 5.75%-target in 2012, after a gradual phase-in starting in 2010.

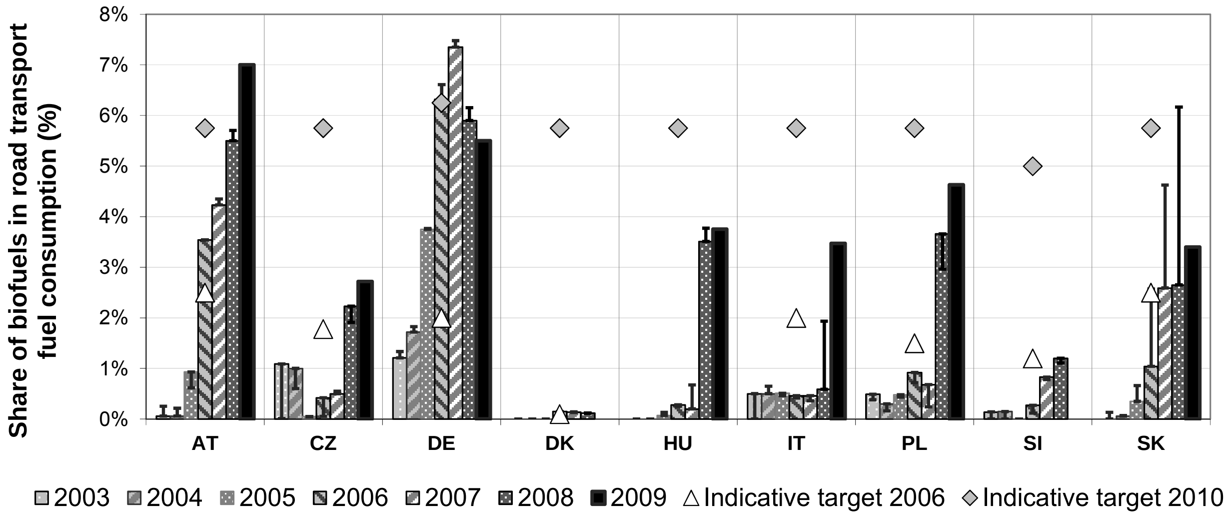

Figure 6-5. Share of biofuels for transport and national indicative target values in the context of Directive COM 2003/30/EC.
Sources: EC (2009b), EC (2010a) (no data for 2009 available for Denmark and Slovenia); error bars: data according to Eurostat (2010a), own calculations

Figure 6-6 shows the historic development of biodiesel and bioethanol production in CE countries. Germany is the major producer of both biofuels. The German biodiesel production accounted for about 50% of the total production in the EU in the years 2002 to 2007. Thereafter the production in Germany declined and its share in the total production in the EU decreased to about 28% (2009).[16]

The capacity of biodiesel and bioethanol production plants being built recently in CE is considerable: From 2007 to mid-2010, the installed biodiesel production capacities increased from 3.8 Million tons per year (Mt/a) to 9.7 Mt/a (EBB, 2011). The bioethanol production capacities installed in CE increased from 1.94 Mt/a in mid-2008 to 3.1 Mt/a in mid-2010 (ePURE, 2011). About 50% of these capacities are located in Poland (0.56 Mt/a).

At full capacity, biodiesel and bioethanol plants installed in mid-2010 could produce as much as 7.8% of the total fuel consumption in road transport in CE (2008). Hence, with regard to the available production capacities, the 5.75%-target for 2010 could theoretically be easily achieved. However, actual production figures have been clearly below the capacities and the question of whether or not the target will be (has been) achieved remains questionable; especially with regard to the recent developments in Germany. Throughout the EU-27, the indicative target is considered very unlikely to be reached according to Resch et al. (2008a).

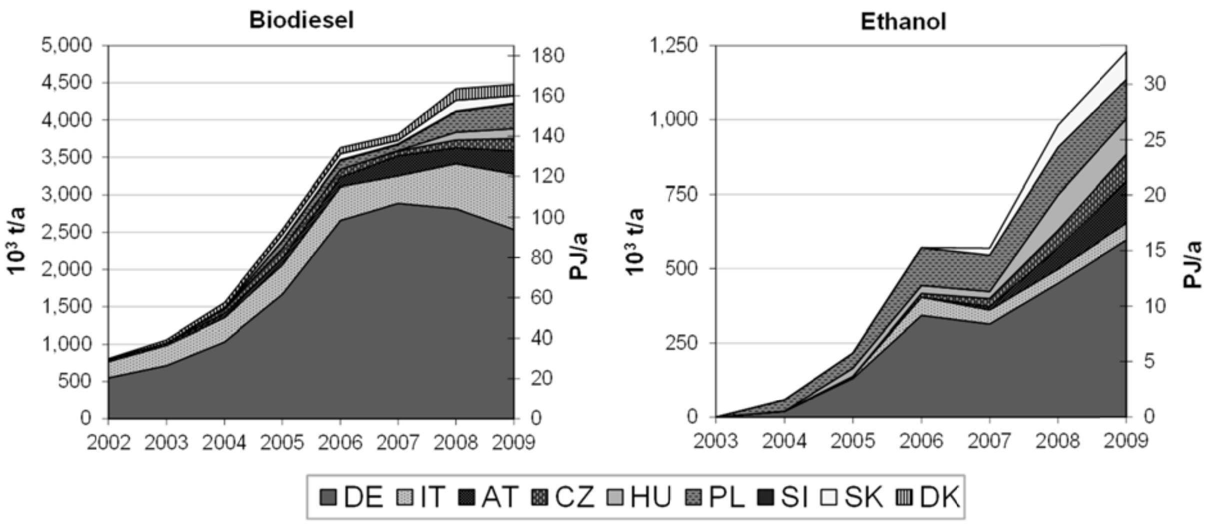

Figure 6-6. Production of biodiesel and bioethanol in CE countries (quantity in tons and net calorific value of the fuels produced).
Sources: EBB (2011), ePURE (2011), own calculations[17]

According to EC (2009b) the self-sufficiency of biofuels for transport of the EU-27 (defined as the ratio of production to consumption) decreased from 109% in 2005 to 73% in 2007. Throughout CE countries, the self-sufficiency of biodiesel was 83% and the one of bioethanol 76% in 2009 (calculation based on EBB, 2011, ePURE, 2011 and preliminary data according to EurObserv'ER, 2010). However, as biofuels are partly produced with imported feedstock,

[16] An increase in tax levels for pure biodiesel in Germany in 2007 has severely affected the competitiveness of biodiesel, and numerous production plants have gone out of operation.

[17] For biodiesel production only aggregated data for Denmark and Sweden are available. The data for Denmark shown in the figure are therefore based on the installed production capacities.

these calculations actually do not bear any information as to what extent the biofuel supply is based on imports. This aspect will be discussed in more detail for Austria and Germany in section 7.

6.3.3 Support schemes for bioenergy

In the field of transport and electricity generation from RES, EU directives issued after 2000 resulted in a notable growth in bioenergy use in most CE countries. For heat generation no such directive was issued before Directive 2009/28/EC ("2009-RES-Directive"; EC, 2009a) and policy support was limited to diverse national or regional support schemes. These include investment subsidies (e.g. Austria, Germany, Slovenia), tax incentives (e.g. Austria, Germany), bonuses to electricity feed-in tariffs for the utilization of waste heat from combined heat and power plants (e.g. Czech Republic, Germany), certificate systems (e.g. Italy) and soft loans (e.g. Poland, Slovenia) (Resch et al., 2008b).

The most common instruments to promote biofuels in the transport sector are tax relieves and obligations to blend. According to EC (2009b) all CE countries used tax exemptions as the main support measure in 2005 and 2006. In Austria and Slovakia there were also obligations to blend. Since 2007 this policy instrument has also been adopted in Germany, Czech Republic, Italy and Slovenia, mostly in combination with increasing levels of taxation. For example in Germany the law on biofuel quotas ("Biokraftstoffquotengesetz") which came into force in January 2007 put an end to total tax exemption and established an obligation to blend (4.4% for biodiesel in diesel fuel and 1.2% for bioethanol in petrol). As it was shown above, this resulted in a trend reversal in the biofuel consumption in Germany.

A major indirect support scheme for bioenergy and other low-carbon RES is the EU Emission Trading Scheme for greenhouse gases (EU ETS), which operates in the EU-27 plus Iceland, Liechtenstein and Norway. It was launched in 2005 and covers CO_2 emissions from power stations, combustion plants and other industrial plants with a net heat excess of more than 20 MW (EC, 2010b).

6.4 The development of bioenergy use in Austria

This section provides a closer insight into the historic development of biomass use in Austria, based on national statistics (Statistik Austria, 2010a) which are more detailed than the ones available on Eurostat (2010a). Figure 6-7 shows the development of biomass primary energy consumption broken down by biomass types. For the years 1970 to 2004, the biomass consumption is broken down by the categories "wood log" and "other biomass and biofuels". The data for the biogenic fraction of municipal solid wastes are estimates based on the total energy use of wastes and an assumed biogenic share of 20%. More detailed data are available for the years 2005 to 2009, as shown in the figure. The biogenic share of wastes was in the range of 17 to 24% during this period.

Figure 6-7 also shows the share of biomass in the total gross inland consumption, which increased from less than 6% (less than 50 PJ/a) during the mid-1970 to 15% (210 PJ) in 2009. The main increase in biomass use took place during the periods 1980 to 1985 and 2005 to 2009. Until the year 1999 the use of wood log for domestic heating accounted for more than 50% of the total biomass use for energy. The rest was primarily wood wastes and residues of the wood processing industries as well as waste liquor of the paper and pulp industry. Especially during the last five years, the different types of wood biomass, including forest wood chips, industrial residues and other wood wastes as well as liquid and gaseous biomass have become increasingly important, whereas wood log remained relatively constant at about 60 PJ/a. Hence, wood log accounted for only 30% of the total biomass use in 2009.

Figure 6-8 shows the development of biomass final energy consumption from 1970 to 2009. The data are broken down by fuels used for residential heating or industrial heat production (further broken down by wood log and other biomass), district heat, electricity and transport fuels from biomass.[18] In 2009, wood log and other biogenic fuels used for heat generation accounted for 65.6% of the biomass final energy consumption, district heat generated with biomass for 13.5%, electrical energy from biomass power plants for 8.5%, and transport fuels for 12.4%.

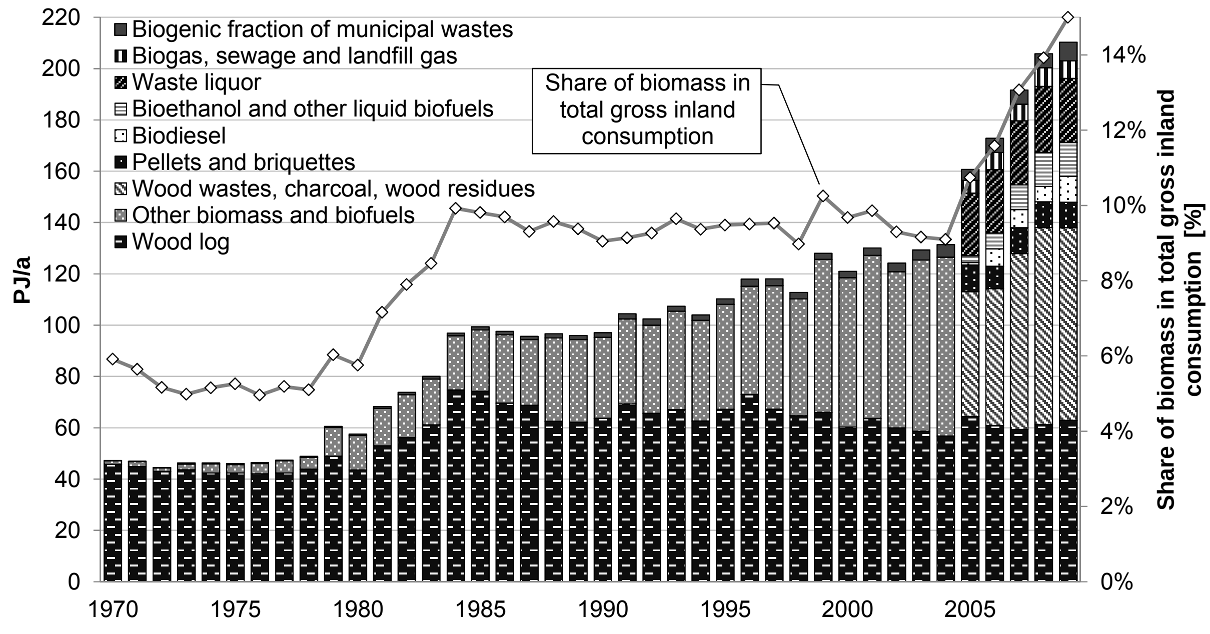

Figure 6-7. Biomass gross inland consumption in Austria from 1970 to 2009 and biomass share in total primary energy consumption
Source: Statistik Austria (2010a)

[18] “Final energy consumption” covers energy supplied to the final consumer for all energy uses.

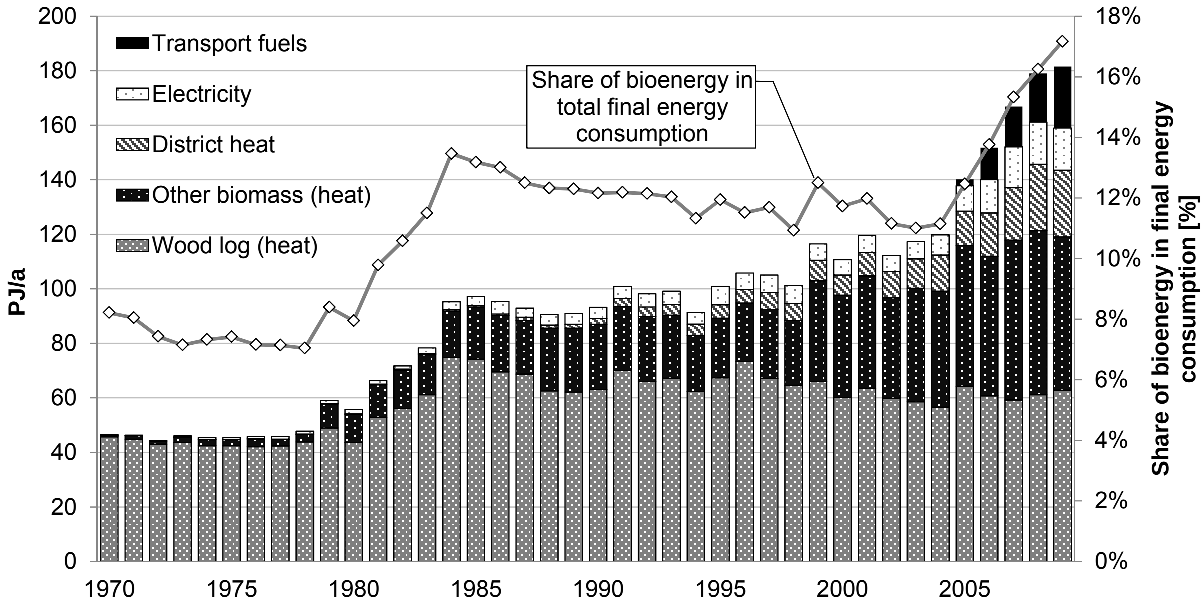

Figure 6-8. Biomass final energy consumption in Austria from 1970 to 2009 and biomass share in total final energy consumption
Source: Statistik Austria (2010a)

7 Cross-border trade of biomass for energy

Well-functioning international biomass markets are considered one of the key factors for mobilizing the global biomass production potential and serving the growing demand for biomass for energy (Heinimö et al., 2007). Heinimö et Junginger (2009) argue that international biomass trade for energy is still in its initial phase and global trade volumes of certain biomass types (e.g. wood pellets, ethanol or plant oil) have already increased significantly in recent years. Projects studying international bioenergy markets and trade have been launched, such as the international collaboration project entitled “Task 40: Sustainable International Bioenergy Trade: Securing Supply and Demand”, which is carried out within the framework of the IEA Bioenergy agreement (see IEA, 2010a and IEA, 2010b). The objective of Task 40 is to “support the development of a sustainable, international, bioenergy market, recognising the diversity in resources [and] biomass applications […] by providing high quality information and analyses for market players, policy makers, international bodies as well as NGOs”. More specifically, one of the core objectives is to “map and provide an integral overview of biomass markets and trade on global level”.

The analyses presented in this section are intended to contribute to this objective by providing insight in current state of cross-border trade in CE, the impact of increasing bioenergy use on biomass streams as well as by carrying out a critical review of data in statistics and discussing methodological aspects.

7.1 Methodological aspects

As Heinimö et Junginger (2009) emphasize, no comprehensive statistics and summaries aggregating separate biomass trade flows for energy generation are available and there are several challenges related to measurement of internationally traded volumes of biomass for energy generation. Many biomass streams are traded for several applications, including material or foodstuff, as well as energy purposes (e.g. wood chips or vegetable oil), or they are traded for material uses and ultimately end up in energy production (indirect trade). Feedstock used for biofuel production and indirectly traded biomass are generally not accounted for as internationally traded biomass in energy statistics.

Table 7-1 gives an overview of the methodological approaches applied in this section, their advantages and drawbacks as well as the biomass types considered, references and databases used. For data from trade statistics the CN codes of the respective commodities are provided (see EC, 2007).

The following methodological approaches are applied: First, the net imports (or net exports) of the following biomass types are analysed on the basis of energy statistics and other statistical data[19] (section 7.2): wood and wood waste, wood pellets, biodiesel and bioethanol (direct trade) and wood residues (indirect trade in the form of roundwood in the rough). These data provide a rough overview about which countries act as net importers and exporters, and on the importance of direct cross-border trade of biomass for energy. Next, direct trade streams of wood log (fuelwood) and other wood fractions in the CE region are mapped, in order to identify the main trade streams (section 7.3).

However, since the statistical data used for these approaches are fragmentary and do not cover the whole range of biomass trade relevant for bioenergy use, a complete assessment is carried out for the exemplary case of Austria (section 7.4). This includes an assessment of indirect trade of wood-based fuels and of feedstock used for biofuel production. The assessment of indirect trade is based on a comprehensive analysis of international and domestic wood trade flows (i.e. imports and exports of the wood-processing industries as well as trade streams between the industries), in order to capture the total quantity of biomass used for energy generation and originating from non-domestic production.

Finally, the impact of increasing resource demand for biodiesel production on trade statistics of oilseeds and plant oil is exemplarily analysed for the cases of Germany and Austria (section 7.5).[20]

[19] Apart from energy statistics (Eurostat, 2010a), data have been obtained from FAO (2010a) and Pellet@las (2010).

[20] For the conversion of trade data given in mass units to energy units, the following LHV are assumed (cp. Statistik Austria, 2010a): wood log and wood residues: 14.4 MJ/kg, wood pellets: 18 MJ/kg, biodiesel: 37 MJ/kg, bioethanol: 26.7 MJ/kg.

Table 7-1. Data used and methodologies applied for assessing international biomass trade.

Short description	**Types of biomass, databases/references used, CN codes (if applicable)**	**Characteristics and features (favourable: +, adverse: –)**
Assessment of net imports / net exports based on energy and other statistics (Section 7.2)	• Wood and wood wastes used for energy (Eurostat, 2010a) • Wood pellets (Pellet@las, 2010) • Indirect trade of wood residues (based on roundwood statistics according to FAO, 2010a) • Biodiesel and bioethanol (Eurostat, 2010a)	+ Avoidance of error sources related to trade statistics + Trade streams of products with no separate CN codes can be assessed + Volumes which are not covered in trade statistics can be assessed (e.g. blends of biofuels with fossil fuels) – Neglect of the lag between production and consumption as well as stockkeeping results in errors – No information about trade partners – Trade of upstream products (e.g. energy crops for transport fuel production) is not taken into account
Investigation and mapping of trade statistics (Sections 7.3 and 7.4.2)	• Wood residues and pellets (UN Comtrade, 2009 and Eurostat, 2011; CN codes 4401 2100, 4401 2200, 4401 3010, 4401 3040 and 4401 3020) • Wood log (UN Comtrade, 2009 and Eurostat, 2011; CN code 4401 1000) • Waste wood (Eurostat, 2011; CN code 4401 3080 and 4401 3090)	+ Use of official data on international trade volumes + Information about trade partners available – Several error sources related to trade statistics, e.g. shipments below declaration limit not included, commodities may be recorded under wrong CN Codes, country of origin or ultimate destination may be unknown in case of transit – No differentiation between energy and non-energy use (no separate CN Codes) – Different biomass types sometimes aggregated under one code (e.g. pellets included in 4401 3010 until 2008) – Only quantities of specific products included; trade of upstream products not considered (e.g. trade of oilseeds or plant oil intended for biodiesel production)
Assessment of total cross-border trade related to bioenergy use (exemplary assessment for the case of Austria) (Section 7.4)	• Direct trade: energy statistics (Statistik Austria, 2010a) • Indirect trade with wood-based fuels: statistics of wood processing industries and supply statistics (BMLFUW, 2010; FAO, 2010a etc.) • Feedstock for biofuel production: biofuel statistics (Winter, 2010), supply balances for agricultural commodities (Statistik Austria, 2010f)	+ Provides comprehensive insight into biomass trade relevant for bioenergy use + Indirect trade streams and trade with upstream products (feedstock for biofuel production) can be assessed – High data requirements, data need to be collected from different databases and statistics of industries – Complete assessment of indirect trade streams not possible due to insufficient data availability – Preselection of commodities is necessary; selection is not straightforward and background knowledge of trade streams is required
Assessment of direct and indirect effects of biomass use on trade flows of related products (Section 7.5)	• Biodiesel (impact of biodiesel production on oilseed and plant oil trade streams); biodiesel production: EBB (2011); rapeseed production: Eurostat (2010a); oilseed, plant oil and palm oil trade statistics: UN Comtrade (2009); CN codes 1205, 1514, 1511	+ Suitable for fuels with several upstream products which can be used for energy and other purposes + Indirect and spillover effects can be assessed – Selection of commodities which are taken into account is not straightforward; background knowledge/presumptions on indirect effects required – Only rough conclusions are possible due to uncertainties related to other influencing factors – Information on conversion processes and efficiencies required

7.2 Net imports and exports of wood and biofuels

Under disregard of the time lag between biomass production and consumption, the difference can be considered as net imports (or net exports, respectively). The main advantages of this approach are its simplicity, and the fact that numerous error sources related to trade statistics are avoided. On the other hand, due to the neglect of intentional stockkeeping and the above-mentioned time lag (which can be especially relevant during dynamic market developments), the results of this approach can only be seen as rough estimates. With regard to net exports, it may result in an overestimation of trade streams. Another drawback is that no information about trade partners can be obtained.

7.2.1 Wood and wood waste

Figure 7-1 shows the net imports of "wood and wood wastes", based on energy statistics (Eurostat, 2010a).[21] The data indicate that especially the net imports of Italy and Denmark have increased significantly in recent years. More than 30% of the wood biomass consumption in Italy and about 25% of the consumption in Denmark is based on imports. According to ENS (2009), the net imports of wood chips, wood pellets and wood log accounted for 19.5 PJ in 2008 (1.8, 15.5 and 2.2 PJ, respectively).

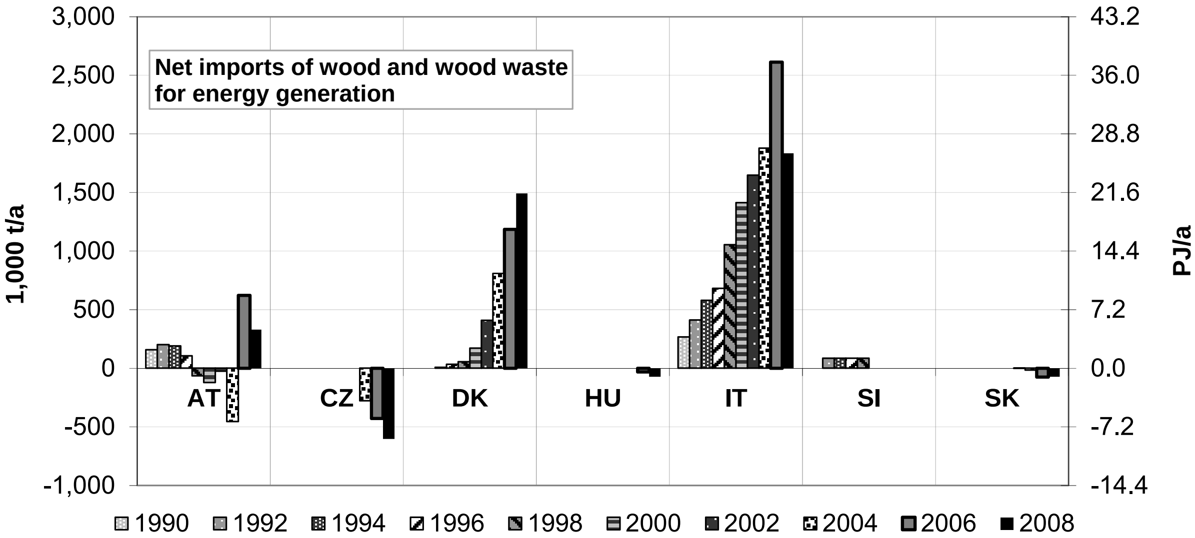

Figure 7-1. Net imports of wood biomass for energy generation based on energy statistics. (no data for Germany and Poland available)
Source: Eurostat (2010a); own calculations

[21] According to the definition by Eurostat, the category "wood and wood wastes" covers "a multitude of woody materials generated by industrial processes or provided directly by forestry and agriculture (firewood, wood chips, bark, sawdust, shavings, chips, black liquor, etc.) as well as wastes such as straw, rice husks, […] and purpose-grown energy crops (poplar, willow, etc.)".

Austria has turned from net exporter to net importer in recent years, reflecting the increasing demand for wood fuels during this period (see section 7.4). Czech Republic on the other hand has been exporting increasing amounts of wood biomass.

7.2.2 Wood pellets

Wood pellets are well suited for transportation due to their high density and energy content. Recent policy and market changes have stimulated an increasing demand for wood pellets (Peksa-Blanchard et al., 2007) and given an impetus to international trade with wood pellets. Figure 7-2 illustrates the net imports of wood pellets from 2001 to 2008. The increase in international trade is especially apparent in the data for Austria, Germany, Denmark and Poland. Denmark and Italy have been importing significant amounts of wood pellets in recent years, whereas the other CE countries are net exporters. It is remarkable that pellets account for the largest single fraction of biomass for energy imports to Denmark.

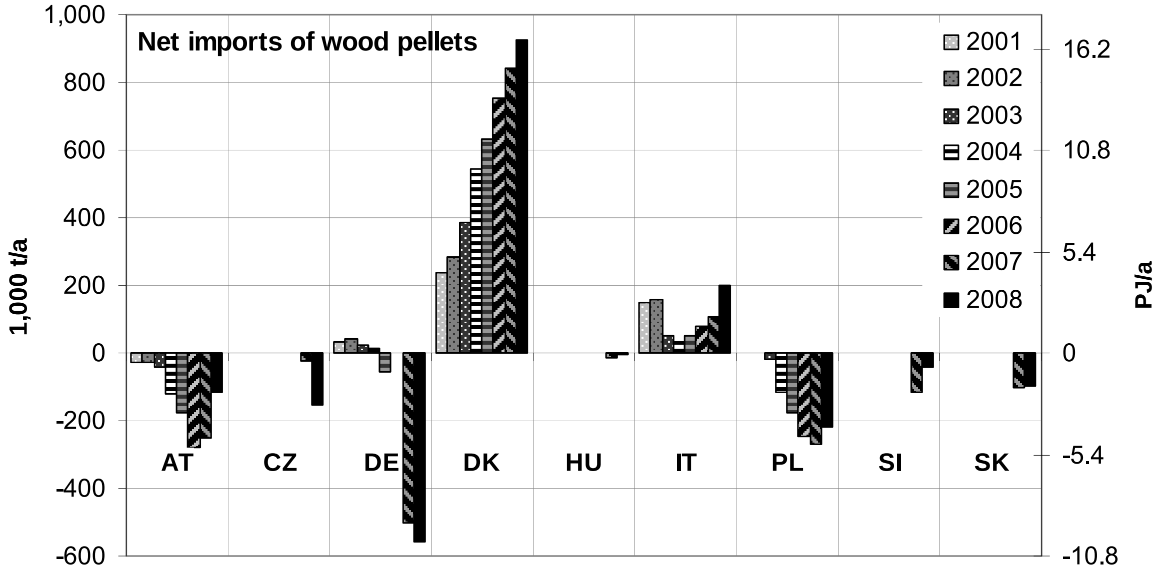

Figure 7-2. Net imports of wood pellets based on production and consumption statistics. Source: Pellet@las (2010), own calculations

7.2.3 Indirect imports of wood residues

A large percentage of raw wood being shipped for the production of sawnwood or other wood products actually ends up as by-products (bark, sawdust, wood chips etc.). Due to the vast amounts of roundwood being traded globally, these indirect imports of wood residues are of some significance. Heinimö et Junginger (2009) argue that indirect trade of biomass through trading of raw wood and material by-products composes the largest share of global biomass trade.

Figure 7-3 shows the net imports of raw wood and the estimated indirect net imports of wood residues from 1991 to 2007.[22] Austria and Italy are the main importers of raw wood in CE. While Italy shows a declining trend, Austria's net imports have almost doubled since the mid-1990s. The main exporters of industrial raw wood are Germany and the Czech Republic.

Figure 7-3 provides a rough overview into the quantities of indirectly traded wood residues, and into which countries are net importers and which are net exporters of roundwood. However, it needs to be considered that wood residues are not only used for energy recovery but also for material uses, primarily the production of paper, pulp and wood boards. Therefore it is necessary to analyse the trade flows within the countries, in order to gain insight into the quantities relevant for bioenergy use. In section 7.4.4 this is done for the case of Austria.

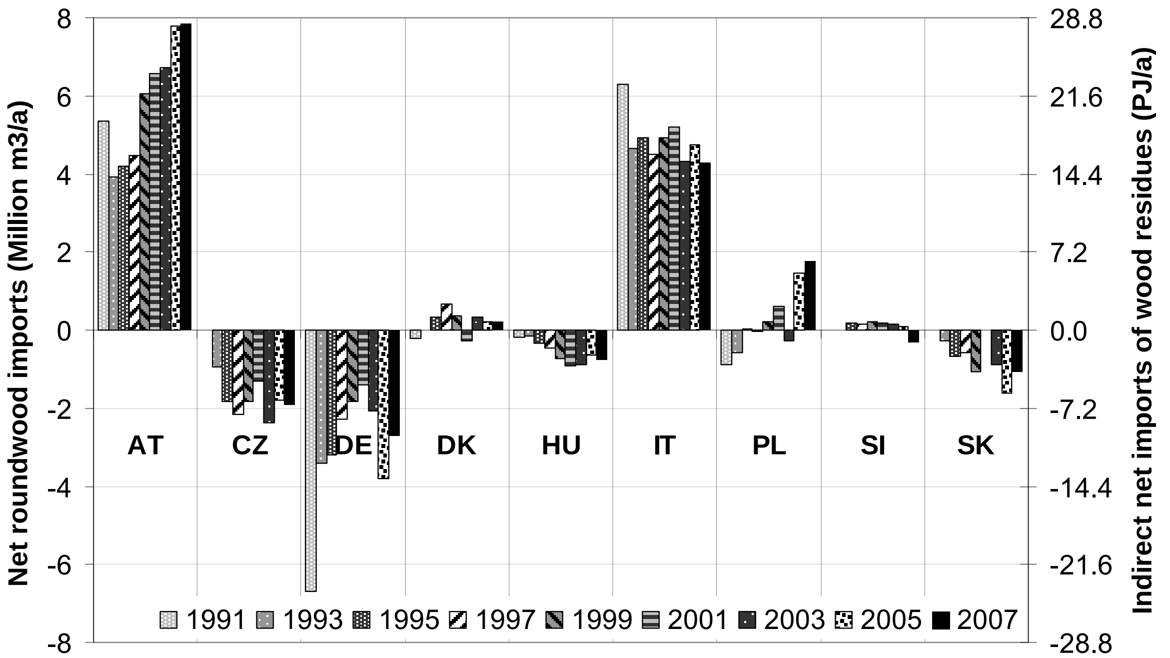

Figure 7-3. Net imports of raw wood (in million m^3; left axis) and the according indirect net imports of wood residues (in PJ; right axis).[23]

Source: FAO (2010a); own calculations

7.2.4 Liquid biofuels for transport

With the growing demand for biofuels for transport[24], the volumes of internationally traded biofuels have been increasing strongly in recent years. The total biodiesel imports of CE

[22] There are several other streams of indirect biomass imports, including for example waste wood in the form of wood products or residues from sawnwood processing. However, cross-border trade of industrial roundwood is considered to be by far the most significant indirect biomass stream (see section 7.4).

[23] Based on Heinimö et Junginger (2009) who estimate that 40–60% of roundwood can be converted into forest products, it is assumed that 50% of the industrial roundwood end up as residues.

countries (with trade between CE countries included) increased from 70,000 t in 2005 to about 800,000 t in 2008 and the total exports from 210,000 t to 480,000 t. The total bioethanol imports increased from zero to 420,000 t and the exports from 30,000 t to 190,000 t during the period 2005 to 2008 (Eurostat, 2010a).

The following figures show the development of net imports of biodiesel and ethanol for the CE countries as well as the aggregated data for the CE region. Apparently, Austria was the main importer of biodiesel during this period, whereas Czech Republic, Germany and Denmark stand out as net exporters. The net trade flows of bioethanol are much lower, except for the case of Poland. With regard to the development during the period 2005 to 2008, which was characterized by substantial increase in biofuel use in CE (see section 6.3.2), it is evident that production could not keep pace with the growing demand. The aggregated data for all considered countries illustrate that despite the rapidly increasing production (see Figure 6-6) the CE region turned from a net exporter into a net importer of both biodiesel and ethanol.

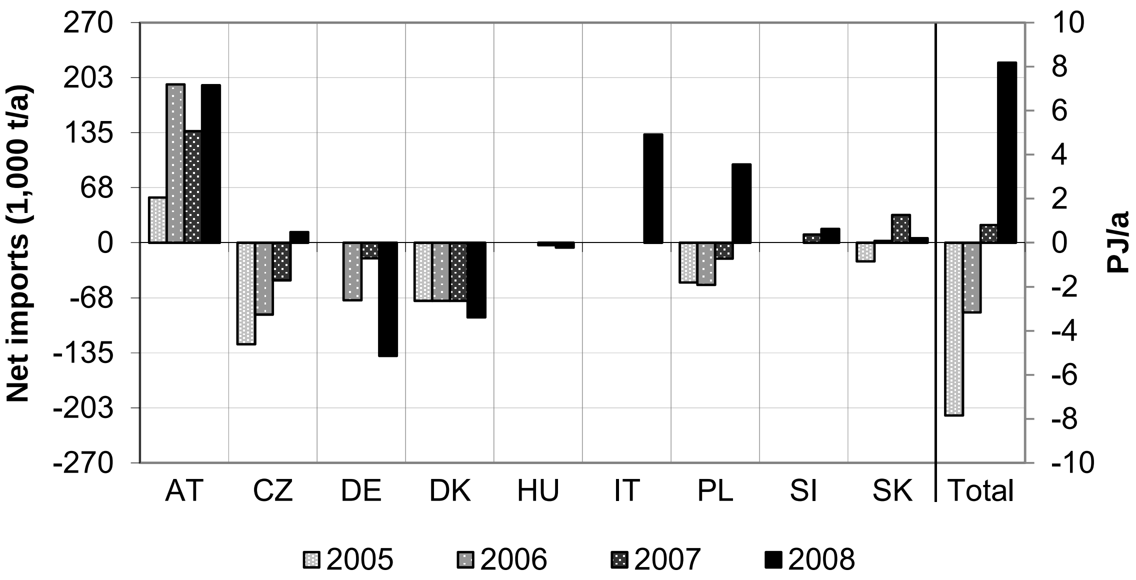

Figure 7-4. Net imports of biodiesel based on energy statistics.
Source: Eurostat (2010a), own calculations

Analyses of biofuel trade streams based on trade statistics (UN Comtrade, 2009 or Eurostat, 2011) prove to be problematic, as statistical compilation of these data is still in the early stages. Only since 2008, there is a separate CN Code for biodiesel (3824 9091). Before that date, biodiesel had to be classified under a general CN subheading together with other chemical products[25] (Freshfields Bruckhaus Deringer, 2008). Furthermore, the quantities

[24] Only biodiesel and bioethanol are considered here. Apart from these biofuels, vegetable oil is of some significance in Germany and Austria (EurObserv'ER, 2010).

[25] CN Code 3824 9098 "chemical products and preparations of the chemical or allied industries, including those consisting of mixtures of natural products".

reported under the newly established CN Code are highly incomplete, as only biodiesel shipped in its pure form is included.[26]

Bioethanol is classified under CN code 2207 0000, together with any other sort of "denatured ethyl alcohol and other spirits of any strength", making it impossible to map trade streams of bioethanol used as transport fuel. Apart from that, like biodiesel ethanol is also shipped in blends of different proportions, further complicating analyses of trade streams.

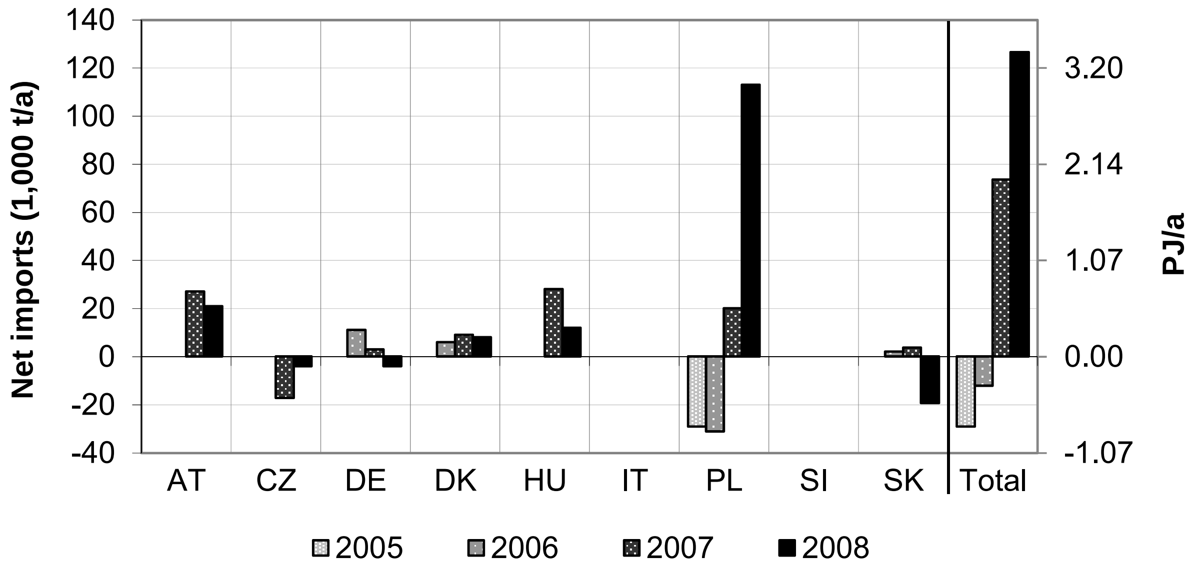

Figure 7-5. Net imports of bioethanol based on energy statistics.
Source: Eurostat (2010a), own calculations

7.3 Streams of wood biomass in Central Europe

Based on trade statistics (UN Comtrade, 2009), the following figures show wood biomass streams in the CE region. Figure 7-6 shows the trade streams of wood log (fuelwood; CN code 4401 1000 "wood in logs, in billets, in twigs, in faggots or in similar forms") in the year 2007.

With total net imports amounting to 7.4 PJ in 2007, Italy is the main importer of wood log. However, Italy's wood log imports in 2007 accounted for only slightly more than 20% of its total imports of wood biomass (cp. Figure 7-1). More than 50% of Italy's wood log imports come from CE countries. The rest is imported primarily from Croatia and Bosnia-Herzegovina. Further major wood log streams are from the Netherlands (i.e. from overseas) to Germany and from Ukraine to Hungary. Austria is also importing noteworthy amounts of wood log from Czech Republic, Slovakia and Hungary. However, in total the net imports to Austria accounted for less than 5% of its total wood log consumption in 2007.

[26] For example, the biodiesel imports reported by Austria in 2008 account for only 20% of the import quantities according the biofuel reports persuant Directive 2003/30/EC (Winter, 2010). However, these incomplete data suggest that Austria importing biodiesel primarily from Germany.

It has to be noted that the data reported in trade statistics are connected with high uncertainties. This becomes obvious when data reported by the importing country are compared with the respective data reported by the exporting country, as these data are often highly inconsistent. It is assumed that these discrepancies are primarily due to different regulations concerning the notification of imports and exports, as well as methodologies of data collection.

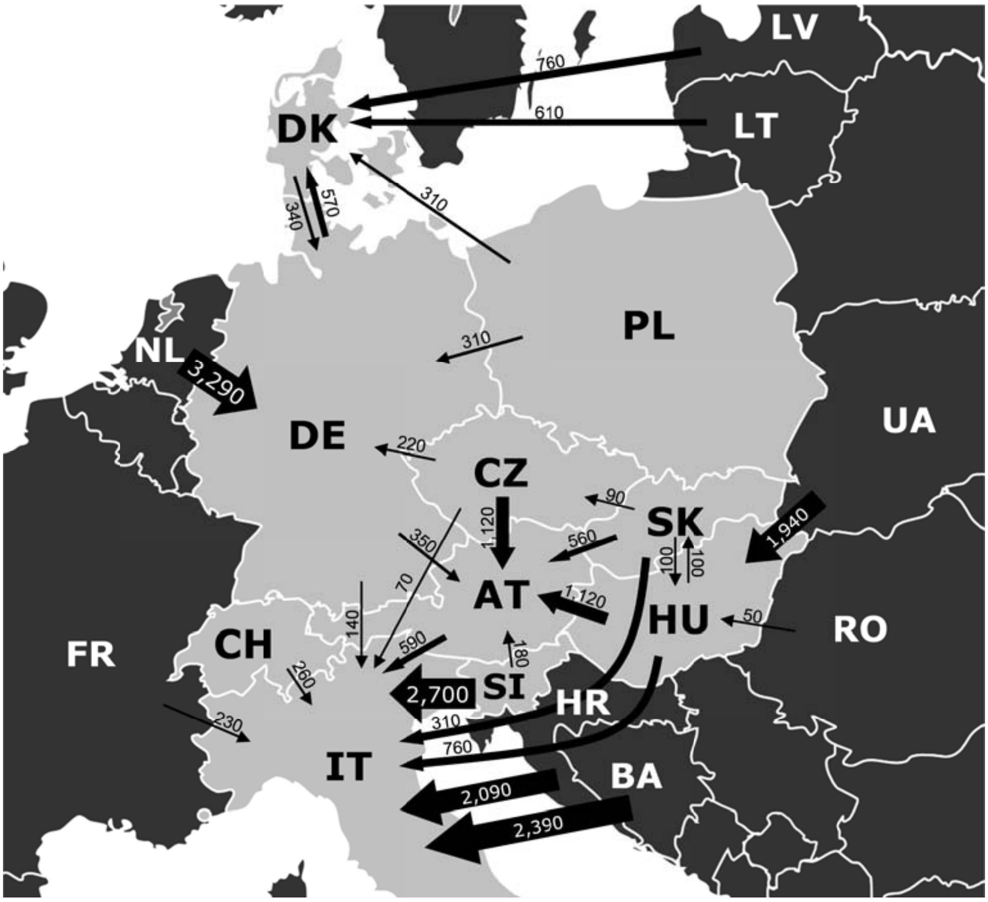

Figure 7-6. Cross-border trade of wood log in Central Europe in 2007
(in TJ/a; flows smaller than 50 TJ/a are not depicted; unlabelled neighbouring countries do not have any relevant trade flows.)[27]*.*
Source: Data obtained from UN Comtrade (2009), own calculations and illustration

Even though wood log trade among some CE countries has been developing strongly in recent years (especially imports to Italy, increasing by close to 400% in the last ten years or so according to UN Comtrade, 2009), it is concluded that the trade volumes of wood log are rather insignificant in relation to its utilization in CE.

[27] Data reported by the importing and the exporting country often show significant discrepancies; in Figure 7-6 and Figure 7-7 always the higher value is shown.

Figure 7-7 illustrates the cross-border trade of wood chips, sawdust, pellets etc. (in the following the term "wood residues" is used for these fractions)[28]. The quantities are clearly higher than those of wood log shown above. However, this category also includes wood which is used for material purposes.

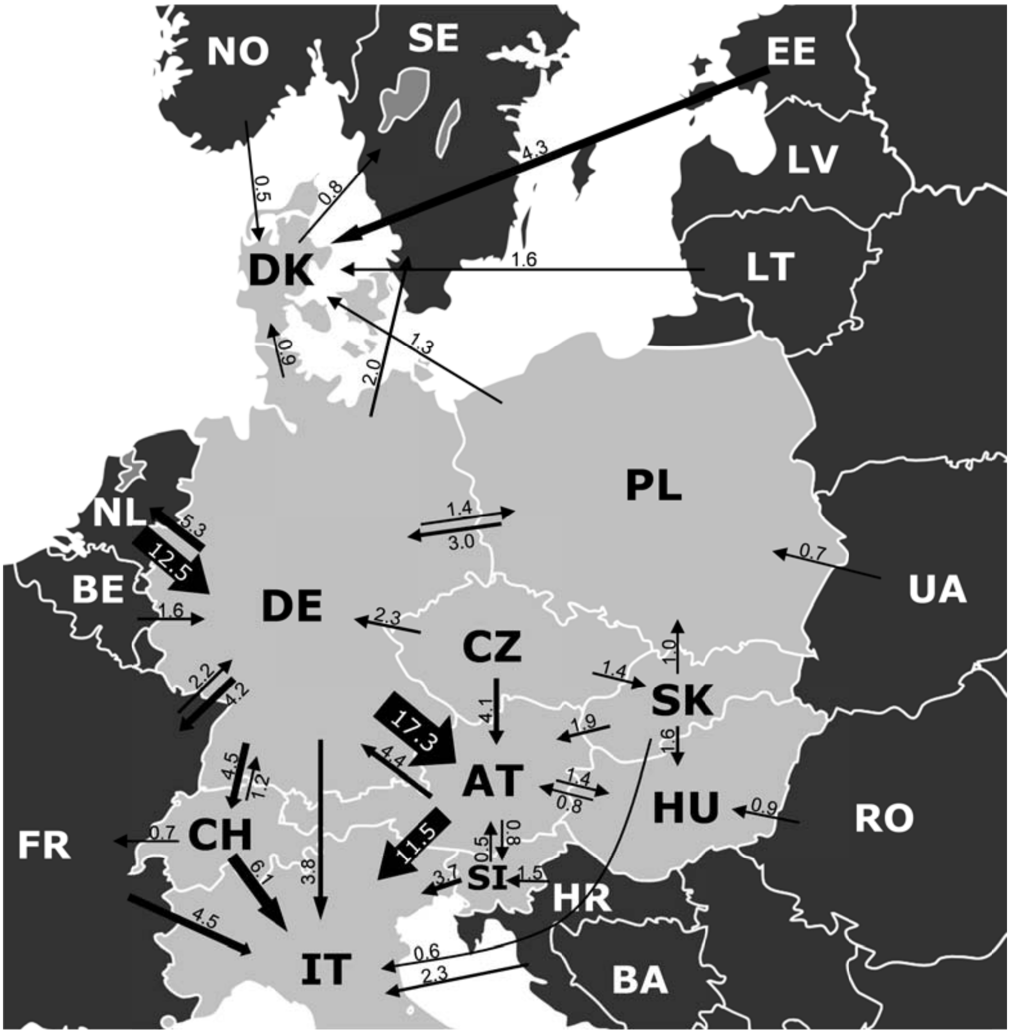

Figure 7-7. Cross-border trade of wood residues (including wood chips, sawdust, briquettes, pellets etc. for energy and material purposes) in Central Europe in 2007
(in PJ/a; flows smaller than 0.5 PJ/a are not depicted).
Source: Data obtained from UN Comtrade (2009), own calculations and illustration

It is clear to see that apart from German overseas imports via the Netherlands, and Denmark's imports from the Baltic States, the main streams are Austria's imports from Germany and Austria's exports to Italy. The figures confirm that Austria and Italy are the main net importers of wood residues in CE. For the case of Austria, this is partly due to the high demand of the

[28] "Wood in chips or particles": sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms (CN Codes 4401 2100, 4401 2200 and 4401 3010).

paper and pulp industry and the board industry, but wood residues (and pellets, which are included here) have been increasing used for energy production in recent years (see section 7.4.4). From 1996 to 2007 Austria's total import quantity of wood residues increased from 0.85 Mt to 1.9 Mt. However, clearly larger quantities are traded indirectly in the form of raw wood, as it was shown in section 7.2.3.

7.4 Cross-border trade related to bioenergy use in Austria

This section provides a more detailed insight into the relevance of biomass cross-border trade for bioenergy use in Austria. First, imports and exports according to energy statistics (covering only directly traded biomass intended for energy production) are analysed (section 7.4.1). Next, trade streams of wood fuels from and to Austria are mapped based on trade statistics (section 7.4.2). Section 7.4.3 deals with international trade related to biogenic transport fuels, as these streams are not adequately captured in energy and trade statistics. Based on the Austrian biofuel reports persuant Directive 2003/30/EC (Winter, 2010) and supply balances of agricultural commodities (Statistik Austria, 2010f), it is assessed to what extent the biofuel supply in Austrian originates from imported fuels and feedstock. Finally, an analysis of indirect trade with wood-based fuels, based on a comprehensive analysis of wood flows which includes imports and exports as well as domestic trade streams of the wood-processing industries, is presented in section 7.4.4. A summary of the findings is provided in section 7.4.5.

7.4.1 Biomass trade according to energy statistics

Figure 7-8 shows the imports and exports of biomass used for energy production in Austria according to energy statistics (Statistik Austria, 2010a), broken down by the different types of liquid biofuels, pellets and briquettes, wood log and charcoal.[29] Primarily due to increasing imports of biodiesel and wood log, the net imports covered in energy statistics were clearly positive since 2006. In the years 2006 and 2009, they accounted for close to 10% of the GIC of biomass in Austria.

[29] Disaggregated data for these fractions are only available for the period 2005 to 2009 in Statistik Austria (2010a); in statistics for the preceding years biomass is only broken down by wood log and "biogenic fuels", including all types of biomass apart from wood log (cp. Figure 6-7).

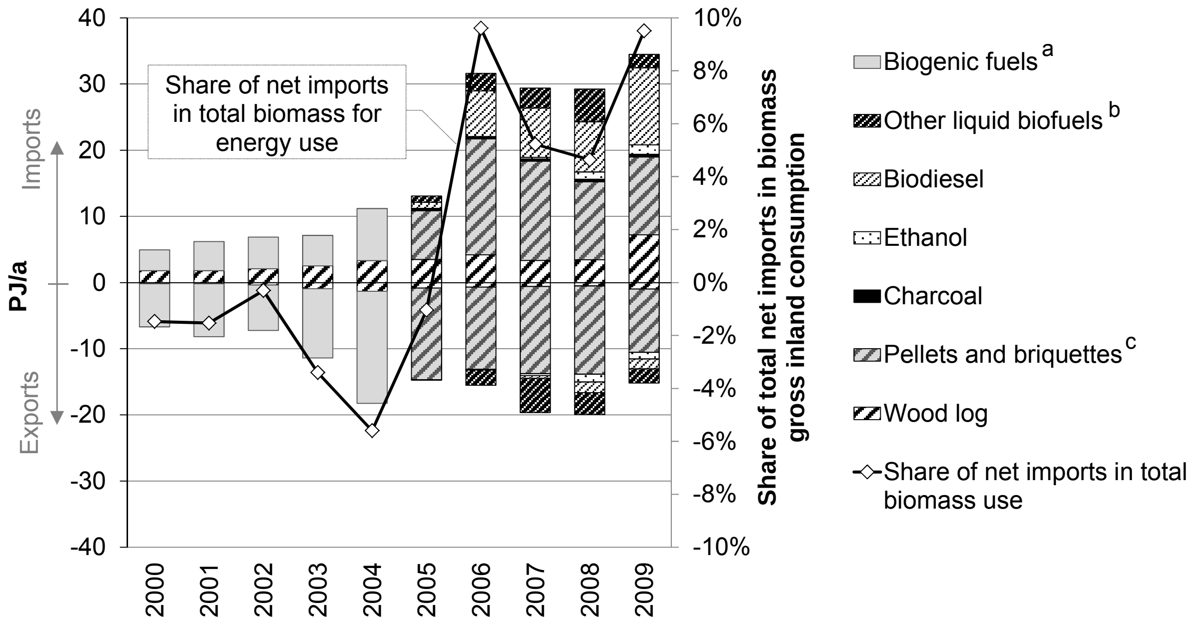

Figure 7-8. Imports and exports of biogenic energy carriers according to energy statistics
Source: Statistik Austria (2010a), own calculations

a) Up to 2004, all types of biomass apart from wood log were aggregated under this category.
b) "Other liquid biofuels" comprise all types of pure biofuels, i.e. pure vegetable oil as well as pure biodiesel and ethanol, whereas the categories "Biodiesel" and "Ethanol" contain only biofuels in blends.
c) A comparison with trade statistics suggests that the category "Pellets and briquettes" also comprises unrefined wood chips, sawdust and wood residues (see section 7.4.2).

7.4.2 Wood fuel trade streams according to trade statistics

In the previous sections it was already mentioned that Austria's net imports of wood fuels have increased strongly in recent years, and that wood fuels are primarily traded with neighbouring countries (cp. Figure 7-6 and Figure 7-7). Figure 7-9 provides insight into the dynamics of trade streams; it shows a comparison of the net trade streams with wood log, wood residues and wastes as well as pellets during 2000 to 2005 (annual average) with the streams in 2009. For the year 2009, separate data on wood pellet trade are available under the CN Code 4401 3020. In the preceding years pellets have been recorded together with sawdust, briquettes and other agglomerated forms of sawdust under CN Code 4401 3010.

Figure 7-9 illustrates that especially the wood imports from the northern and eastern neighbouring countries have risen sharply in recent years. The total net imports from Czech Republic, Slovakia and Hungary accounted for approximately 2 PJ per year during the period 2000 to 2005. In 2009 the net imports from these countries amounted to more than 10 PJ, and an additional 1.3 PJ were imported from Romania. Together, this is equivalent to 5% of the total biomass GIC in Austria in 2009. However, Germany and Italy are still Austria's main trade partners. The net imports from Germany amounted to 7.7 PJ in 2009, compared to an average of 5.1 PJ during 2000 to 2005, and the net exports to Italy have increased from 6.1 to 7.7 PJ. With more than 5 PJ in 2009, pellet exports to Italy are by far the most important pellet trade stream.

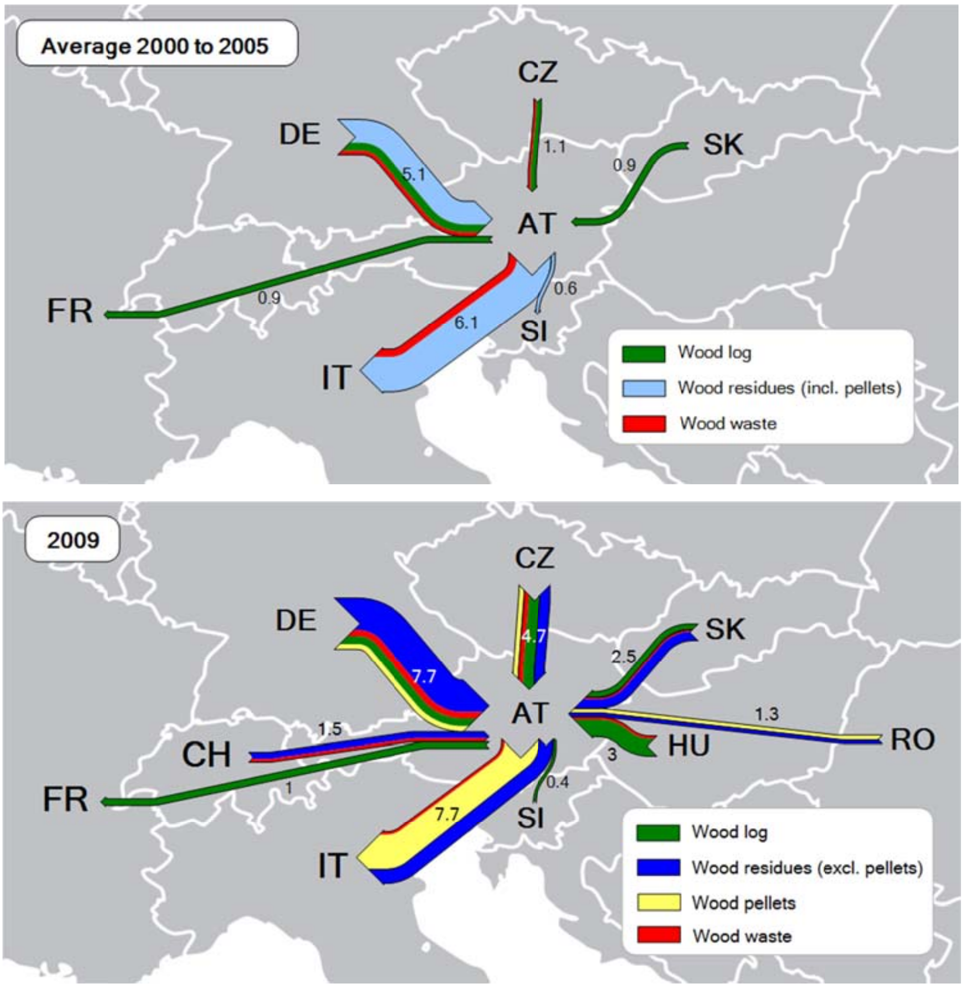

Figure 7-9. Comparison of the net trade streams with wood log, wood residues, pellets and wood waste in 2009 (bottom) with the annual average during 2000 to 2005 (top)
(values in PJ, only streams above 0.3 PJ are not shown)
Source: Eurostat (2011), own calculations and illustrations

7.4.3 Cross-border trade related to biofuels

The increasing use of biogenic transport fuels (biodiesel, vegetable oil and ethanol) in recent years resulted in a significant increase of cross-border trade. Apart from direct trade with biofuels cross-border trade of feedstock used for biofuel production need to be taken into account.

7.4.3.1 Biodiesel

Figure 7-10 shows the development of biodiesel production and direct imports and exports according to the official biofuel reports pursuant to Directive 2003/30/EC (Winter, 2010). The figure shows that imports accounted for approximately 50% of the inland consumption in the period 2005 to 2009. Close to one fourth of the domestic production of biodiesel, which increased from 70,000 t (2005) to more than 320,000 t (2009) during this period was exported. With regard to vegetable oil used for transportation, there are hardly any reliable data, as production volumes in statistics are not differentiated by intended uses and due to largely regional distribution channels. According to Winter (2010), approximately 17,000 to 18,000 t (0.6 to 0.67 PJ) of vegetable oil were used for transportation annually during 2007 to 2009. It is assumed that at least the quantities which are used in agriculture (approximately 2,700 t or 0.1 PJ in the year 2009) originate from domestic production.

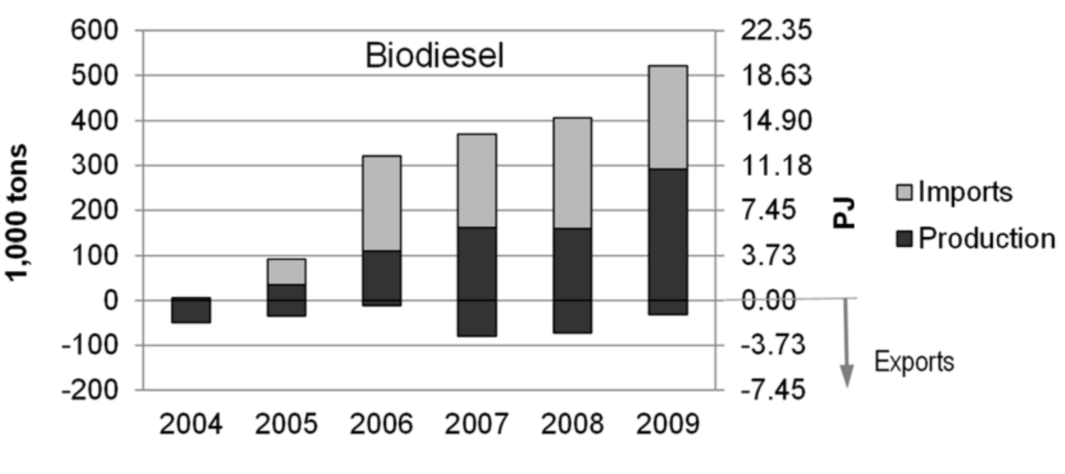

Figure 7-10. Austrian biodiesel supply from 2004 to 2009 according to the official biofuel report persuant Directive 2003/30/EC
(Stockkeeping is neglected.)
Source: Winter (2010), own calculations

In order to provide insight into the impact of biodiesel and vegetable oil for energy use on Austria's trade streams, the supply balance for vegetable fats and oils is shown in Figure 7-11. The supply balance shows “sources” (imports and domestic production) as well as “sinks” (processing and human consumption, exports and industrial uses). It is clear to see that the rapidly increasing industrial use of vegetable oils and fats (i.e. primarily biodiesel production) was facilitated by a significant increase in imports, whereas domestic production remained almost constant. The self-sufficiency (calculated on the basis of the oil yield from domestic oilseed production) decreased from about 60% (marketing years 1998/99 to 2000/01) to less than 30% (2007/08: 23%, 2008/09: 27%). Today, industrial uses exceed the quantity used for processing and human consumption in Austria.

Figure 7-12 shows the supply balance for biodiesel, based on the data shown in Figure 7-10 and Figure 7-11. The separation of inland production into production based on domestic and imported feedstock is based on the rate of self-sufficiency for vegetable fats and oils in the according marketing year.

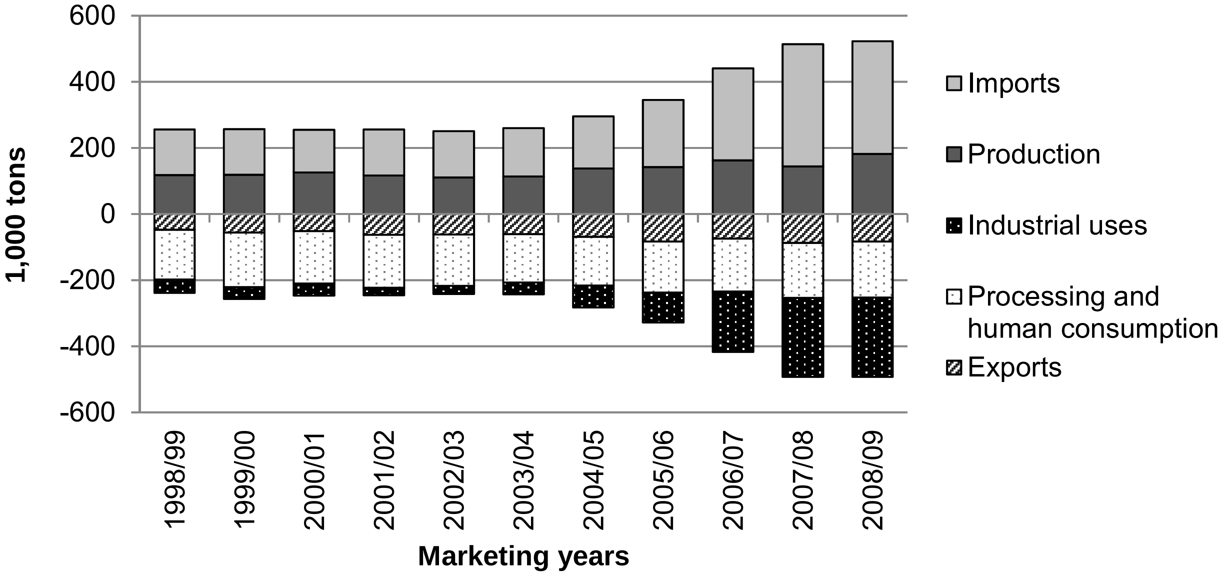

Figure 7-11. Supply balance for vegetable fats and oils

(Losses, stockkeeping and animal feed are not shown due to negligible quantities.)

Source: Statistik Austria (2010f)

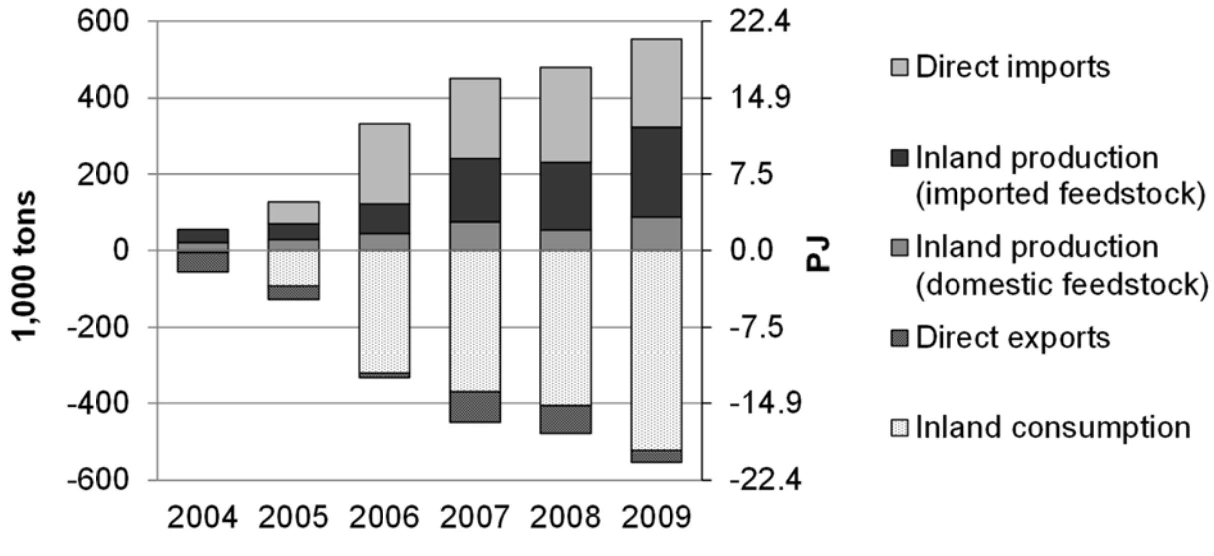

Figure 7-12. Supply balance for biodiesel in Austria

Sources: Winter (2010), Statistik Austria (2010a), Statistik Austria (2010f), own calculations

To conclude, the additional demand for energetic uses of vegetable fats and oils was almost exclusively covered with imports. The most important trade streams are imports of rapeseed oil from the eastern neighbouring countries and Eastern Europe, but Austria is also importing increasing amounts of palm oil: From 2000 to 2008 the net imports increased from about 13,000 t to 47,000 t (UN Comtrade, 2009).

7.4.3.2 Bioethanol

The Austrian production of bioethanol used for transportation is limited to one large-scale plant, located in Pischelsdorf in Lower Austria and operated by the AGRANA holding company. The plant became fully operational in mid-2008[30] and has a capacity of approximately 190,000 t/a (5.1 PJ/a). Figure 7-13 shows the bioethanol production, imports and exports in Austria from 2007 to 2009. Whereas in 2007 and 2008, Austria was a net importer of bioethanol, the net exports in 2009 amounted to about 28% of the production.

The annual feedstock demand at full capacity is reported to account for 620,000 t (75% wheat and triticale, 15% maize and 10% sugar juice). According to Kopetz et al. (2010), the agricultural land used for the production of “ethanol feedstock” in 2007 was 6.749 ha. There are no profound data available on the feedstock supply in 2008 and 2009, but according to the operator’s financial report for the business year 2009/10 (AGRANA, 2010), most originated from domestic production.

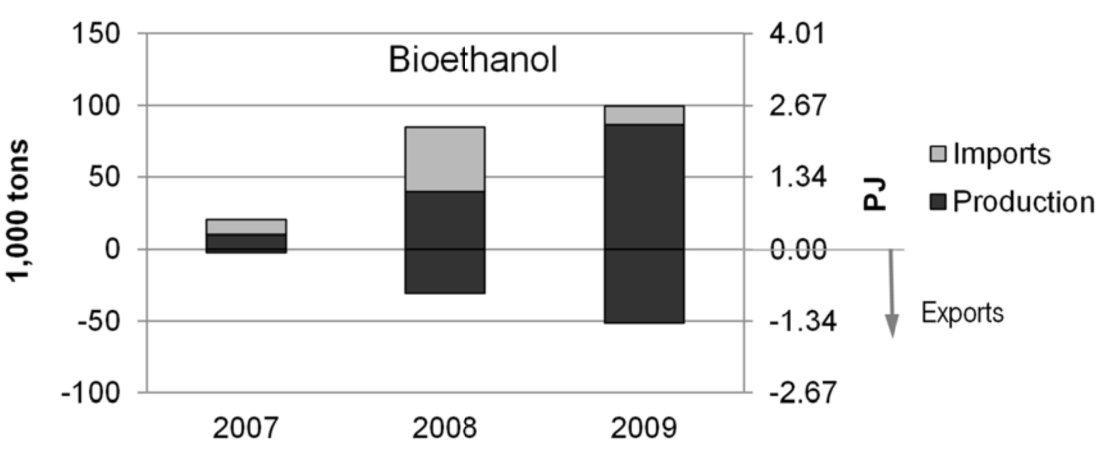

Figure 7-13. Austrian bioethanol supply from 2007 to 2009 according to the official biofuel report persuant Directive 2003/30/EC
Source: Winter (2010), own calculations

[30] In 2007 a test run was carried out but the final commissioning was postponed due to the high agricultural prices in the second half of 2007 and the first months of the year 2008 (see FAO, 2010c).

The self-sufficiency of cereals varied from 94 to 110% in the marketing years 2003/04 to 2008/09 (Statistik Austria, 2010f). Despite the additional demand for ethanol production (about 400,000 t), the self-sufficiency in 2008/09 was as high as 105%, because the production quantity in this marketing year surpassed the average of the previous five years by about 1 Mt. Hence, it is concluded that in contrast to the biodiesel supply, (i) the current feedstock demand for bioethanol production is relatively moderate, compared to the total cereal production (approximately 5.75 Mt in 2008/09), (ii) based on historical data, general conclusions about the impact of bioethanol production on international trade streams in Austria are not possible, but (iii) the data for 2008/09 suggest that at least in years with good crop yields, the feedstock demand for the current quantity of bioethanol production can basically be supplied from domestic production.

7.4.4 Indirect cross-border trade of wood-based fuels

Indirect imports of biomass include quantities which are originally imported for material uses but ultimately end up in energy generation. In order to assess the indirect biomass imports used for energy, it is essential to have an idea of the different utilization paths of the various wood fractions, as well as the flows between the wood processing industries.

Figure 7-14 shows an illustration of the wood flows in Austria in 2009. This illustration is the result of a comprehensive analysis based on production and consumption statistics of the wood-processing industries (sawmill industry: FAO, 2010a; paper and pulp industry: Austropapier, 2010; wood board industry: Schmied, 2011) as well as reports on timber felling (BMLFUW, 2010) and data on external trade of raw wood and (semi-)finished wood products (FAO, 2010b). Hence, the data required to gain a profound insight into indirect trade streams relevant for the bioenergy sector go far beyond energy statistics provided by Eurostat or national statistical institutes, respectively.

The figure shows that the bulk of raw wood is processed to sawnwood by the sawmill industry. (Raw wood for sawnwood production is denoted as “sawlogs” in Figure 7-14, whereas “industrial roundwood” (“IRW”) refers to raw wood used for paper, pulp and wood board production). The average share of imports in the consumption of the sawmill industry accounted for 43% (between 35% and 52%) during the period 2001 to 2009. Apart from industrial roundwood the wood supply of the paper and pulp industry and the wood board industry is based on residues of the sawmill industry (“sawmill by-products”). Therefore, the sawmill industry acts as an important raw material supplier for the other industry segments. The increasing production of the Austrian sawmill industry in the last years and decades provided favourable framework conditions for the growth of the paper and pulp and the wood board industry. However, the import quantities of these industries segments have also amounted to notable trade streams, as the utilization of wood residues for pellet production and energy generation has been growing rapidly in recent years.

The flow chart in Figure 7-14 shows that about one third of the total raw wood supply in 2009 was imported. Therefore, a significant share of wood residues, bark and other by-products of the wood processing industries being used for energy production in Austria actually originate from foreign countries. On the other hand, large quantities of finished and semi-finished wood products are exported, primarily in the form of sawnwood, paper and wood boards. Assuming that almost all wood products ultimately end up in energy production after their intended use (either in dedicated bioenergy plants utilizing waste wood, or in waste treatment plants), these trade streams could also be considered as indirect biomass trade for energy. However, due to insufficient statistical data on trade streams of wood products, substantial methodological challenges (including the consideration of recycling rates, uncertainties about the lifetime of wood products which range up to many decades in the case of construction wood, etc.) and the relatively small quantities compared to the major indirect trade streams, only the most important streams are taken into account here. Based on the wood flow chart, it was found that the following indirect trade streams are the most significant for the case of Austria: residues of the sawmill industry and further wood processing (sawmill by-products) as well as bark and off-cuts from imported sawlogs and industrial roundwood, and waste liquor of the paper and pulp industry.

The results of the assessment of these indirect imports of wood-based fuels are summarized in Figure 7-15. The annual fluctuations are partly due to weather conditions and storms, which had a significant impact on the domestic wood supply in recent years (especially the storms “Kyrill” and “Paula” in 2007 and 2008, respectively). With regard to waste liquor, the analysis of statistical data indicates that between 18 and 32% of the total quantity used for energy generation in Austria can be traced back to imported wood (directly imported roundwood and sawmill by-products as well as indirectly imported by-products). Hence, on an average about 6 PJ of indirectly imported waste liquor were used for energy production annually during 2001 to 2009.

Primarily due to the imports of the paper and pulp industry and the high net imports of bark and off-cuts in the form of roundwood, the indirect net imports have been clearly positive, and accounted for an average of 9.1% of the total biomass GIC during the period 2001 to 2009. However, this share has dropped to about 7% in 2007, as the indirect imports have remained relatively stable while the total biomass consumption has experienced a steep rise. Nevertheless, it is concluded that indirect imports of wood-based fuels are of high significance for the Austrian bioenergy sector.

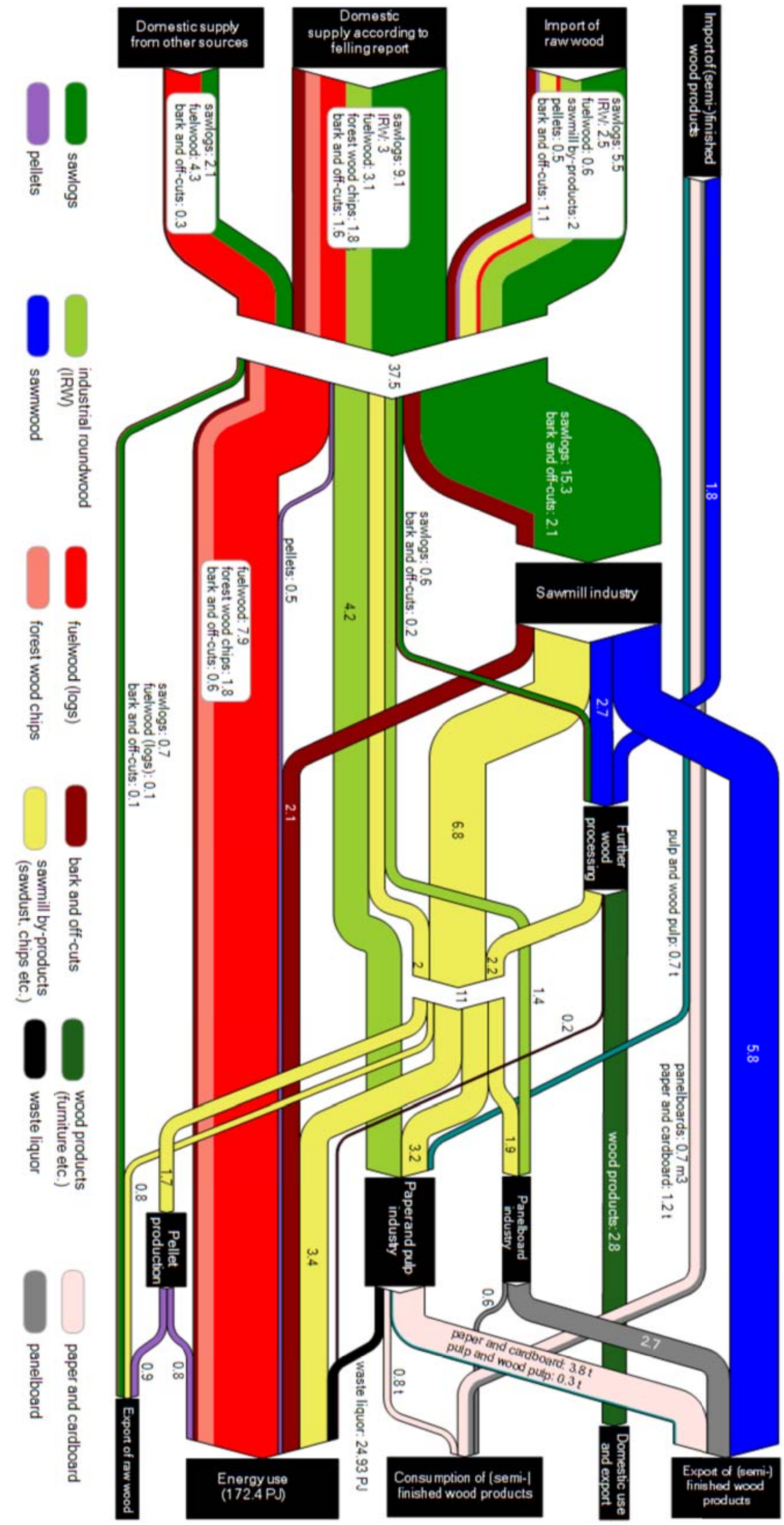

Figure 7-14. Wood flows in Austria in 2009

Sources: BMLFUW (2010), FAO (2010a), FAO (2010b), Eurostat (2011), Austropapier (2010) Schmied (2011), Hagauer et al. (2007b), Pellet@las (2010),Statistik Austria (2010a), own calculations and illustration

As mentioned above, a complete analysis of indirect biomass trade streams, comprising all kinds of wood products which end up in energy generation after their intended use is considered unfeasible due to insufficient statistical data. Therefore, the results of this assessment are to be considered as a best possible estimate, based on the most significant trade streams.

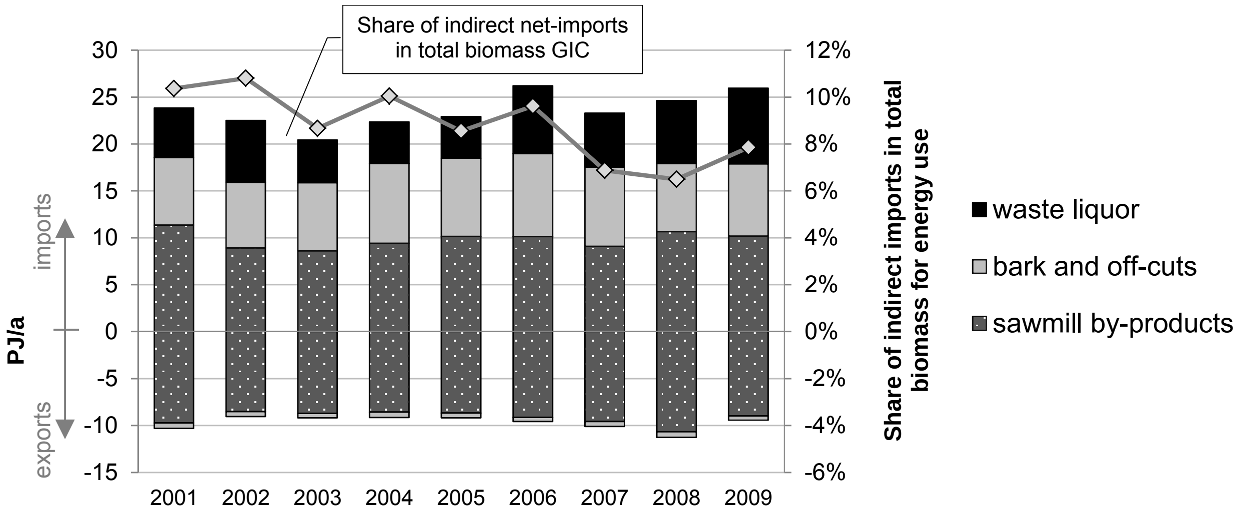

Figure 7-15. Development of indirect imports and exports for energy use, and the according share in the total biomass consumption in Austria
Sources: FAO (2010a), FAO (2010b), Austropapier (2010), BMLFUW (2010), Hagauer (2007b), Schmied (2011), own calculations

7.4.5 Summary

To sum up, with feedstock for biofuel production and indirect trade streams taken into account, cross-border trade of biomass is clearly more significant than energy statistics suggest. Based on the assessments described above, it is concluded that the share of imported biomass was more than 20% of the total biomass primary energy consumption in Austria in 2006 and 2009 (see Figure 7-16). Indirect imports of wood-based fuels are the most significant trade stream, but direct imports of wood fuels, liquid transport fuels and feedstock imports for biofuel production have also become increasingly important in recent years.
Furthermore, the results emphasize that there are strong interconnections between the wood processing industry and the energetic use of biomass in Austria, and that the high import and export activities of this branch of industry also have a strong impact on the bioenergy sector, and vice versa.

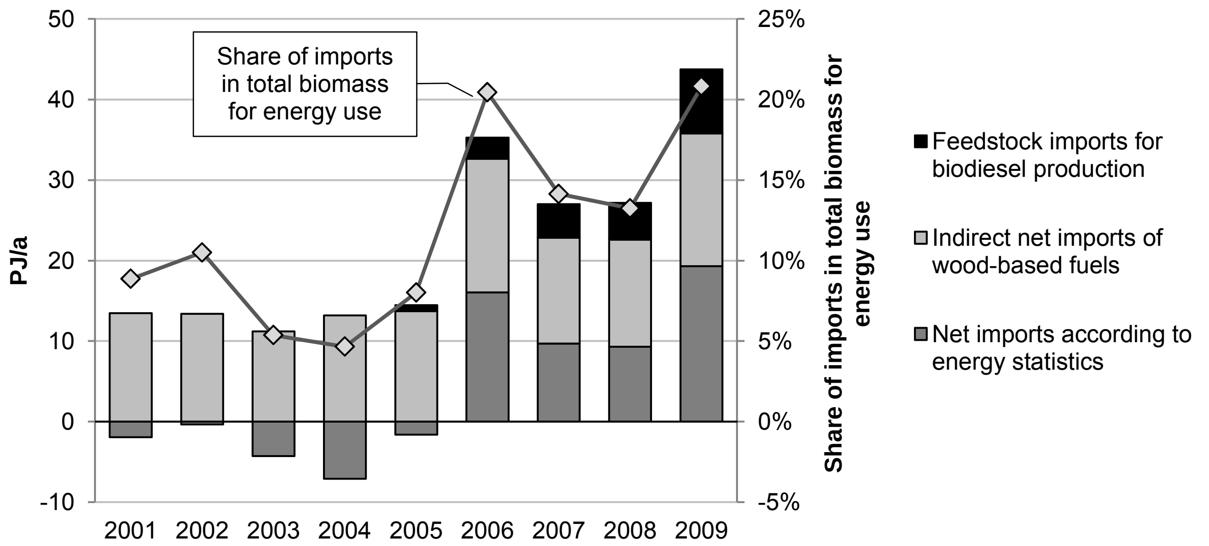

Figure 7-16. Development of biomass imports for energy use in Austria, including indirect imports and feedstock for biodiesel production, and the according share in the total biomass use

7.5 The impact of biodiesel production on international trade streams

A crucial issue in connection with the increasing demand for biofuels are possible indirect effects and spillover effects, especially on global land use and food markets. There has been growing concern about possible impacts of biofuel production from edible crops on global food security as well as sustainability issues like indirect land-use change (see EC, 2010c). For example, Fischer et al. (2010a) argue that "uncoordinated biofuels development can contribute substantially to short-term price shocks […] and may also result in a stable trend in rising food prices".

Vegetable oil and oilseeds are basically more suitable for long-distance transportation than wood biomass due to their higher specific calorific values. In section 7.2.4 it was shown that the rising consumption of biofuels was accompanied by increasing direct cross-border trade. The objective of this section is to analyse the impact of the increasing biodiesel production on trade streams of vegetable oil and oilseeds. The focus is on the countries which showed the most rapid development in biodiesel production and consumption among CE countries: Germany and Austria.

The basic approach is to convert production data of oilseeds, net imports of oilseeds and vegetable oil and data on the demand for biodiesel production on a common basis of comparison ("vegetable oil equivalents") and to qualitatively investigate correlations between the time series (see Table 7-1 for details on the commodities considered, references and CN Codes). Figure 7-17 shows the data for Germany and Figure 7-18 the data for Austria.

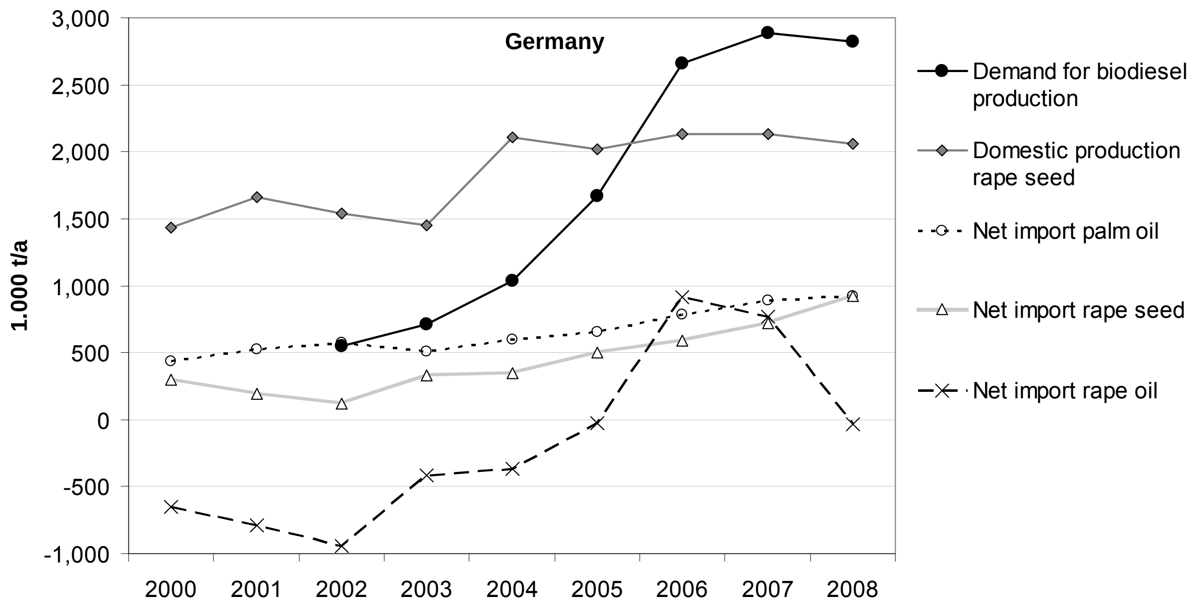

Figure 7-17. Development of vegetable oil demand for biodiesel production and provision of vegetable oil in Germany
(rape seed production and import converted to equivalent amount of vegetable oil).
Sources: UN Comtrade (2009), Eurostat (2010b), EBB (2011), own calculations

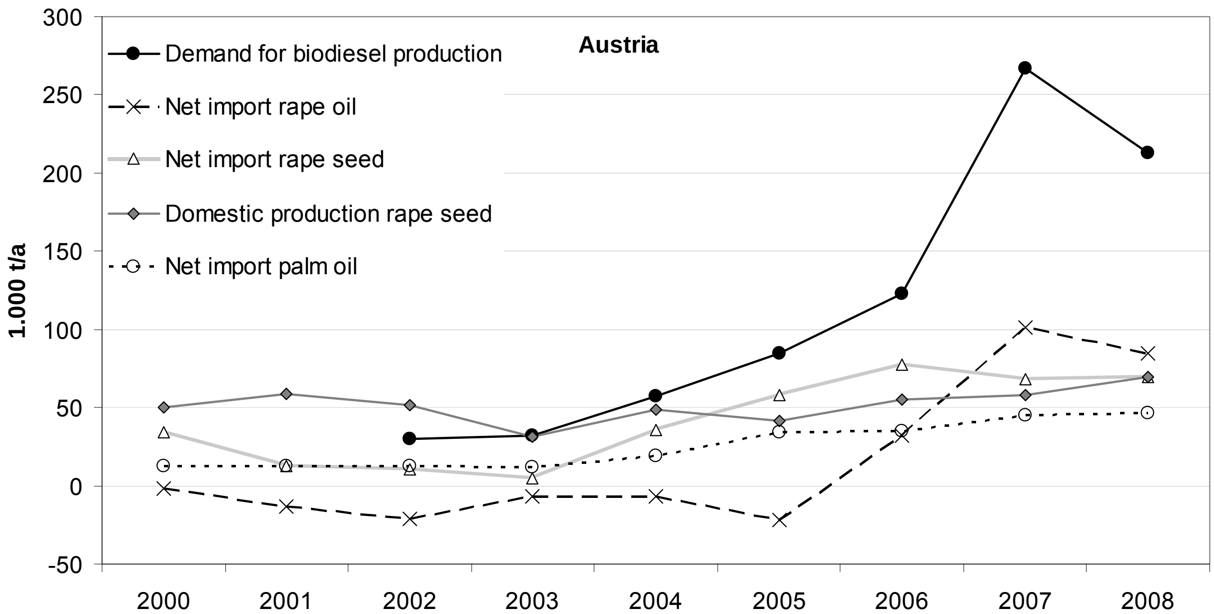

Figure 7-18. Development of vegetable oil demand for biodiesel production and provision of vegetable oil in Austria
Sources: UN Comtrade (2009), Eurostat (2010b), EBB (2011), own calculations

It is clear to see that in both countries, the growing vegetable oil demand for biodiesel production primarily resulted in an increase in rape oil net imports, rather than domestic production of rapeseeds. Furthermore, in both countries also a (compared to the rape oil imports moderate but still notable) increase in palm oil imports, primarily from Indonesia and Colombia, took place. Germany's total palm oil net imports increased from 0.44 Mt in 2000 to about 0.9 Mt in 2008 and Austria's net imports from 16,000 to 47,000 t during the same period. This supports the presumption by Rosillo-Calle et al. (2009), who argue that "increasing consumption of domestically produced rapeseed oil for biodiesel uses may have led to a considerable gap in EU food oil demand (which continues to increase), resulting in an increase on imports for other types of oil (mostly edible palm oil)".

It is concluded that the increasing biodiesel production in Germany and Austria led to significant shifts in international trade of vegetable oil and oil seeds. As shown in section 6.3.2, progress in the field of biofuels for transport was very uneven among CE countries. Therefore, the additional crop demand could initially be imported from neighbouring countries with favourable conditions for increasing energy crop production, especially Czech Republic and Hungary. However, recent data suggest that with the demand for energy crops also increasing in these countries, imports from other European, or especially Non-European countries seemingly become inevitable. In section 7.2.4 it was shown that the CE region recently turned from a net exporter of biofuels into a net importer. With regard to the supply of oilseeds, the data are even more striking: The total net imports of rape seed to CE increased from 0.76 Mt in 1996 to about 2 Mt in 2008.[31]

[31] Slovakia was excluded from this calculation due to highly implausible data for 2008 (UN Comtrade, 2009).

8 Potentials and prospects for an enhanced use of bioenergy in Central Europe

8.1 Bioenergy in the context of EU energy policy

With the implementation of the 2009-RES-Directive (EC, 2009a) an "overall binding target of a 20% share of renewable energy sources in energy consumption […] as well as binding national targets by 2020 in line with the overall EU target of 20%" have been established. The share of RES is calculated as the sum of final energy from RES consumed in the heat, transport and electricity sector, divided by the total final energy consumption, including distribution losses and consumption of the energy sector. In addition to the overall 20% target by 2020, a sub-target for the transport sector (including road and rail transport) in the amount of 10% was defined. Renewable electricity used in electric cars is also taken into account; in consideration of the higher efficiency of electric drivetrains, a factor of 2.5 is applied for electric cars. In order to promote advanced biofuels produced from non-food cellulosic materials and lignocellulosic materials, the amounts of "advanced" biofuels count twice towards the target. Still, the main contribution towards the sub-target is expected to come from biodiesel and ethanol.

In the European Biomass Action Plan (EC, 2005) it is recognized that bioenergy is of major importance for increasing the share of renewable energies and reducing dependence on energy imports. The projections made for the Renewable Energy Road Map (EC, 2006) suggest that the use of biomass can be expected to double and to contribute around half of the total effort for reaching the 20% target.

The "strengthened national policy scenario" in Resch et al. (2008a) gives an impression of to what extent bioenergy can contribute towards fulfilling the 2020-targets in CE.[32] The scenario is based on the following core assumptions: The implementation of "feasible" energy efficiency measures (leading to a moderate development of the future overall energy demand as projected in the PRIMES target case (Capros et al., 2008). Support conditions for RES are improved, leading to the fulfilment of the EU-wide 20%-target by 2020.

This simulation confirms that biomass is of crucial importance for meeting the 2020-targets. In all CE countries more than 50% of the growth in RES until 2020 is made up by bioenergy. In the Czech Republic, Hungary, Poland and Slovakia bioenergy even accounts for more than

[32] The scenarios have been compiled with the simulation tool *Green-X*. This model simulates future investments in renewable energy technologies for heat, electricity and transport fuel production, based on a myopic economic optimization. The availability of biomass resources, cost and price developments, the energy demand and its structure, diffusion and other influencing parameters as well as energy policy instruments are considered within the simulation runs.

75% of the growth. The consumption of biomass as share of the total GIC according to this scenario ranges from 7.6% in Italy to 25.3% in Denmark. Table 8-1 shows a summary of the share of biomass and all RES in the total energy consumption in the reference year 2005 and 2007 (the latest year available in statistics), the national targets according to the 2009-RES-Directive and the contribution of biomass according to the "strengthened national policy scenario" in Resch et al. (2008a).

Table 8-1. Summary of the current state, targets and prospects for the share of biomass and RES in CE countries (all values in %).

Concept	Reference	Fraction, year	AT	CZ	DE	DK	HU	IT	PL	SI	SK
Final energy consumption	EC (2009a)	RES, 2005	23.3	6.1	5.8	17.0	4.3	5.2	7.2	16.0	6.7
		RES Target, 2020	34.0	13.0	18.0	30.0	13.0	17.0	15.0	25.0	14.0
Gross inland consumption	Eurostat (2010a), own calculations	RES, 2005	21.7	4.0	5.1	16.4	4.4	6.5	4.8	10.6	4.3
		RES, 2007	23.8	4.7	8.3	17.4	5.3	6.9	5.1	10.0	5.5
		Biomass[a], 2005	11.1	3.5	3.4	12.4	3.9	1.9	4.6	6.5	2.1
		Biomass[a], 2007	13.3	4.2	5.7	13.2	4.6	2.2	4.8	6.2	3.2
	Resch et al. (2008a)	Biomass, scenario 2020	22.0	9.0	10.2	25.3	11.2	7.6	13.5	15.1	9.6

a) Non-renewable wastes have been deducted based on Eur'ObservER (2010)

8.2 Review and discussion of biomass potentials in literature

Assessments of biomass supply potentials are numerous and the results vary widely. There are different concepts of potentials like "theoretical", "technical" or "environmentally compatible" potentials (see Rettenmaier et al., 2008). Potentials in literature are usually qualified according to these definitions. Yet methodological approaches, assumptions and constraints of potential assessments differ from study to study.

The following analyses are based on three studies (EEA, 2006; Thrän et al., 2005 and de Wit and Faaij, 2010) which have been chosen for the following reasons: Uniform methodologies have been applied, they comprise all types of biomass resources (with the exception of non-agricultural residues not being considered in de Wit et Faaij, 2010) and results are available for all CE countries, broken down by country and biomass type. The main features of the methodological approaches applied and databases used are summarized in Table 8-2.

According to the Eurostat definition of “biomass consumption”, biofuels for transport are represented with the calorific value of the fuel (and not with the amount of biomass used to produce the fuel). Due to the relatively low conversion efficiencies (e.g. typically 55% for ethanol and 57% for biodiesel[33]; cp. AEBIOM, 2007) the energy content of the quantity of feedstock used for the production (primarily energy crops) is clearly higher than the consumption according to energy statistics (and shown in Figure 6-4). This needs to be taken into account when comparing statistical data with data on biomass supply potentials.[34]

The methodological approaches of the considered studies are basically quite similar. The most significant differences include environmental restrictions considered, scenario assumptions and influencing factors which are taken into account as well as assumptions about energetically usable fractions of certain biomass resources. Figure 8-1 shows a comparison of the results. The biomass production and consumption in the year 2007 are also included.

Basically it can be concluded that there are substantial unused biomass potentials in all CE countries. While forest biomass and biogenic wastes remain fairly constant, the potential of dedicated energy crop production is assumed to rise significantly. The potentials of biogenic wastes are the most consistent throughout the studies. This is unsurprising since they are based on current production statistics and often the same databases were used. However, it should be considered that the potentials of waste and residues are essentially based on estimated “use factors”. In the case of straw, this use factor is assumed 20% in EEA (2006) and 50% in de Wit et Faaij (2010). As the latter point out, the amount of straw which can be removed and used energetically without causing adverse environmental effects is actually site-specific and depends on numerous factors. Highly aggregated assessments of biogenic wastes can therefore only be seen as rough estimates. In order to derive profound data, detailed bottom-up approaches are required, carried out in the course of regional energy concepts, for example.

Another aspect to be considered in connection with the assessment of waste and residue potentials based on production statistics is that they sometimes include significant amounts of indirectly imported biomass. For example in Austria the potential of wood processing residues is to a large extent based on imported roundwood (see section 7.4.4). Strictly speaking, this fraction cannot be considered a domestic supply potential.

[33] The conversion efficiencies stated here are defined as the ratio of the energy content of the biofuel to the primary energy content of the feedstock used, with by-products (which can be used for energy recovery, for feed or material uses) not taken into account.

[34] That biofuels for transport are represented with the calorific value of the fuel and not with the primary energy required for the production of the biofuel is still justified by the following facts: First, this allows for a direct comparison of fossil fuel and biofuel consumption and second, the above mentioned by-products are thereby rightly excluded from the statistics.

Table 8-2. Summary of features, references/databases used and methodologies applied for assessing biomass potentials in Thrän et al. (2005), EEA (2006) and de Wit et Faaij (2010).

	Thrän et al. (2005)	EEA (2006)	de Wit et Faaij (2010)
Type of potential	Technical potential with consideration of structural and ecological restrictions	Technical potential with consideration of environmental criteria ("Environmentally-compatible potential")	"Supply potential" (forest biomass: sustainable potential)
Reference years	2000, 2010, 2020	2010, 2020, 2030	2030
Methodological approaches and main references/databases			
Methodology for assessing forest biomass potential	• Comprises potential from current use (felling residues) and potential from annual increment (annual growth minus fellings) • Base year: 2000 • 2010 and 2020: Increasing demand for wood products according to UNECE (2000) • Main databases: FAO (2010c), FAO (2005), UNECE (2000)	• Comprises "residues from harvest operations normally left in the forsest ("felling residues") and complementary fellings" • Complementary fellings describe difference between maximum sustainable harvest level and actual harvest needed to satisfy roundwood demand • Environmental considerations include biodiversity, site fertility, soil erosion, water protection • Criteria to avoid increased environmental pressure applied • Databases: FAO (2010c), OECD Europe (projections for wood demand)	• Comprises "difference between actual felling and felling residues and the net annual increment" (including stems) • Main database: Karjalainen (2005)
Methodology for assessing potential of biogenic wastes and residues	• Comprises only residues which are not usable for material uses • Exemplary proportions assumed to be available for energy recovery: sawmill residues 10%, bark 80%, waste wood 75% (estimated on basis of per capita production), straw 20% of total production • Other potentials based on scenarios and assessments in literature as well as estimates: e.g. manure based on livestock scenarios and assumptions about husbandry conditions, black liquor based on rough assessments and other studies, food processing industries also considered • Main databases: FAO (2010c), Eurostat (2010b)	• Comprises solid and other agricultural residues, manure, biogenic fraction of municipal solid waste (MSW), black liquor, wood-processing waste wood, construction and demolition wood, other waste wood, sewage sludge and food processing wastes • Environmental criteria assumed: waste minimization, no energy recovery from waste currently going to recycling or reuse (estimated proportions), production of timber and wood products declines, extensive farming practices etc. • Projections for waste fractions based on different scenarios in literature (e.g. FAO, 2005; Skovgaard et al., 2005)	• Comprises only agricultural residues obtained during production of food and feed • Crop-specific ratio of crop residue to crop main produce applied • Assumed "residue use factor": 50% • Main database: FAO (2010c)
Methodology for assessing potential of dedicated energy crops	• Base year: 2000 (average over 3 to 5 years) • Evaluation of surplus arable land and grassland available for dedicated energy crop production • Reduction of production surplus and related exports assumed • Considered influencing factors: population scenarios, reduction of agricultural land, yield increases, increasing efficiency in livestock breeding • Assumed distribution of energy crops • Databases: FAO (2010c), Eurostat (2010b)	• Evaluation of released and set-aside land under assumption of further reform of common agricultural policy (based on EuroCare, 2004) • Competition effect between bioenergy and food production are only taken into account for Germany • Assumption of site-specific environmentally-compatible crop mixes • Increase in crop yields according to EuroCare (2004) • Environmental criteria assumed: 30% of agricultural land dedicated to environmentally-oriented farming, 3% set aside land, extensively cultivated agricultural areas are maintained, bioenergy crops with low environmental pressure are used	• Evaluation of surplus arable land and grassland available for dedicated energy crops • Projected changes in land area requirements (population size, dietary habit, agricultural productivity, self-sufficiency ration of Europe) • Assumption: Europe maintains current food & feed self-sufficiency of about 90% • Different assumptions for yield increases and different sustainability criteria assumed • Databases: Fischer et al. (2010b)

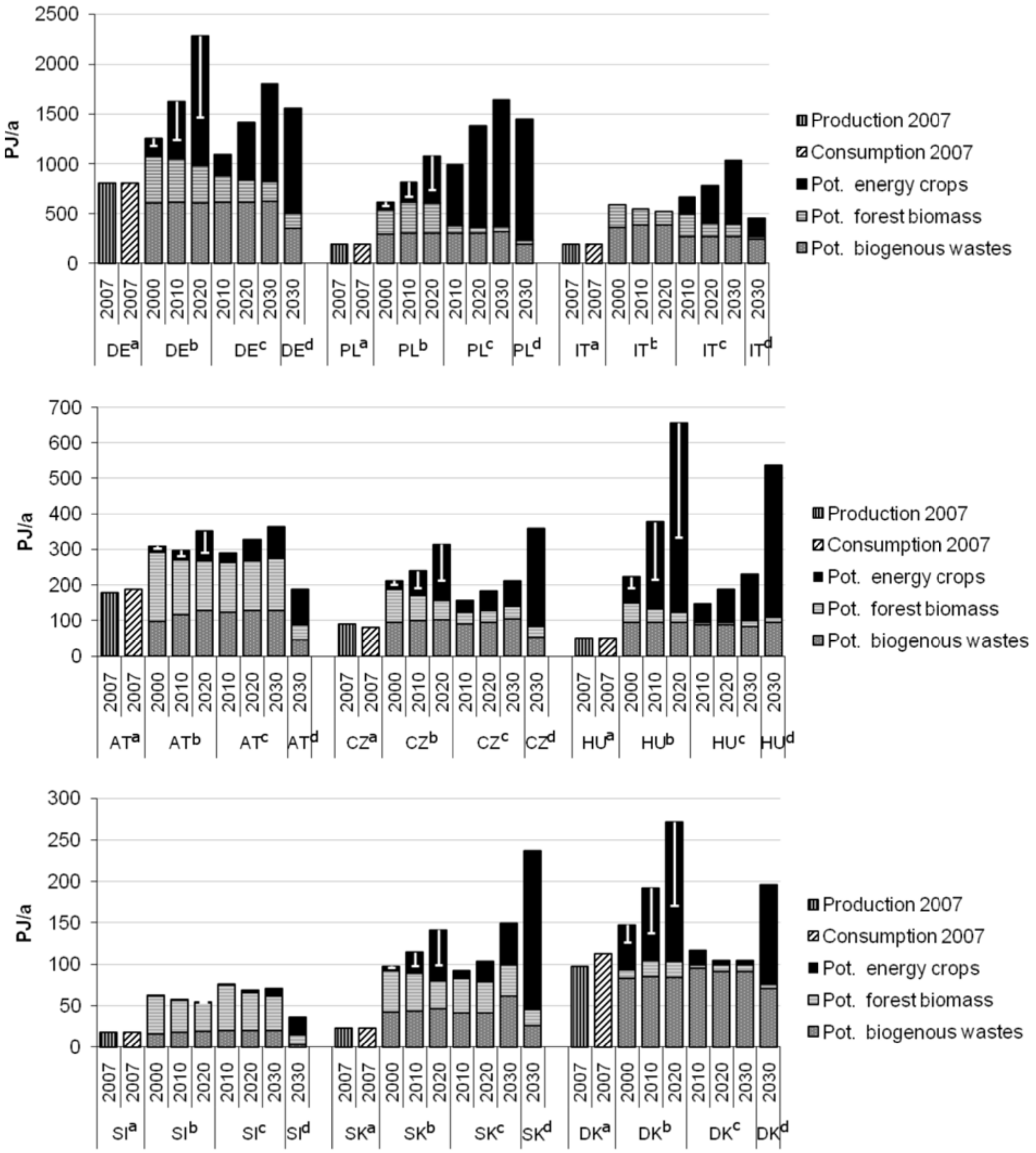

Figure 8-1. Comparison of biomass production and consumption in 2007 with biomass potentials ("Pot.") according to three studies.

Sources:

a) Eurostat (2010a)

b) Data obtained from Thrän et al. (2005) (error bars represent results for the environmentally-oriented scenario)

c) Data obtained from EEA (2006)

d) Data obtained from de Wit et Faaij (2010) (baseline scenario; biogenic wastes comprise only agricultural residues)

The increasing potentials of energy crops are on the one hand based on assumptions about yield increases in energy crop and food and feed production, and on the other due to scenario assumptions for the future development of agricultural production in Europe. Model-based simulations of the agricultural developments in the EU (e.g. of the CAPSIM model used in EEA, 2006) indicate that with continuing reforms of the common agricultural policy resulting in gradual liberalization of agricultural markets and a reduction in subsidized exports, agricultural productivity can be increased significantly and the current self-sufficiency for food and feed products maintained with clearly less agricultural land. Thus, surplus land is assumed to be made available for energy crop production.

To what extent the consideration of different environmental criteria influence the supply potentials of energy crops is illustrated by the e*nvironmentally-oriented scenario* according to Thrän et al. (2005), represented by the error bars in Figure 8-1. The and *High estimate* scenarios in de Wit et Faaij (2010) illustrate that assumptions about yield increases have a huge impact on energy crop potentials. Furthermore, especially with regard to the energy crop potentials in Poland, Italy, Hungary and Denmark, there are also inconsistencies which cannot be explained easily, indicating that there are substantial uncertainties connected with the future potential of energy crops.

The potential of forest biomass primarily depends on the currently unused annual growth. Furthermore, scenarios for the demand of wood products and the development of the wood-processing industries have a major impact. A comparison between EEA (2006) and Thrän et al. (2005) indicates that the additional environmental criteria considered in the former result in a significant reduction of the forest biomass potential.

Regardless of the uncertainties related to potential assessments, the following conclusions are drawn: Only in Germany, Austria and Denmark more than half of the biomass supply potential was actually utilized in 2007. The structure of biomass potentials is highly inhomogeneous. According to these studies, especially Germany, Poland and Hungary are capable of increasing the energy crop production substantially, while maintaining the current self-sufficiency for food and feed. The potential of forest biomass is generally rather limited, partly due to the increasing wood demand of the wood-processing industries.

Biogenic wastes and residues, including waste wood, wood processing and agricultural residues as well as residues from food processing are a considerable potential. The figures indicate that in several CE countries, the potential of wastes and residues even surpass the total biomass production in 2007.

Figure 8-2 shows the biomass potentials of the considered studies as shares of the GIC (projections according to Capros et al., 2008). A comparison with Table 8-1 (scenarios according to Resch et al., 2009) reveals that Poland could act as the main exporter of biomass in CE. Even if Poland's 2020-target is primarily achieved with biomass (as projected in Resch et al., 2009) the unused biomass potential accounts for approximately 500 PJ. In most other countries the domestic biomass potential needs to be utilized to a large extent to fulfil the 2020-targets. With regard to Germany, Italy, Denmark and Hungary no definite conclusions can be drawn due to big uncertainties as to what extent the supply potential of biomass can be extended with the production of energy crops.

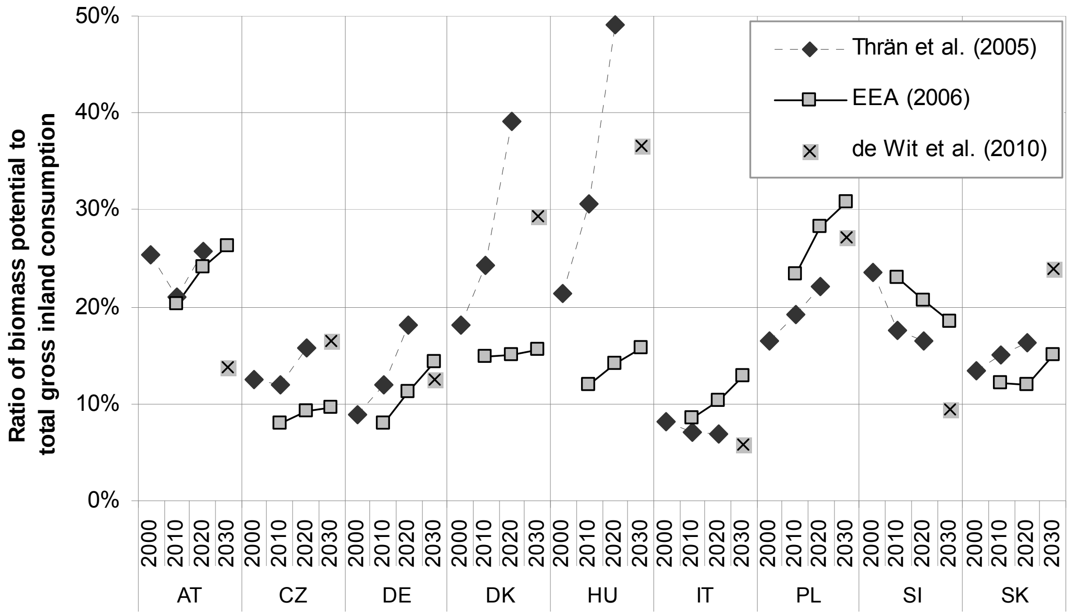

Figure 8-2. Ratio of biomass supply potential according to Thrän et al. (2005), EEA (2006) and de Wit et Faaij (2010) to total gross inland energy consumption (scenario according to Capros et al., 2008; “PRIMES target case”)

9 Discussion, conclusions and policy implications

9.1 Recent developments in bioenergy use in CE

Bioenergy is currently the most important source of renewable energy in CE. The contribution of biomass and wastes to the total energy supply (gross inland consumption) in CE countries ranges from 2.8% in Italy to 14.9% in Denmark (2008).

European directives and according national support schemes have already led to significant progress in recent years. Progress was very uneven in the considered countries. The CE countries with the highest growth of biomass as share of the GIC from 2000 to 2008 were Denmark (+6%), Germany (+4.8%), Austria (+4.5%) and Hungary (+3.9%). It is remarkable that the countries which already had the highest bioenergy shares in 2000, namely Austria and Denmark, are among these countries. It is therefore concluded that at least in recent years, the crucial barriers for an increase in bioenergy use was not the availability of biomass resources in the CE region but the typical barriers for upcoming technologies, such as know-how, capacity building of equipment etc.

In absolute numbers, Germany showed by far the highest increase in bioenergy use. In 2008 Germany was accountable for more than 50% of the total biomass consumption and production in the considered countries, and therefore dominates the structure of the energetic biomass use in CE.

Even though heat generation is the oldest and often most competitive utilization path for biomass (see Part I), EU Directives as well as national support schemes were focused on the electricity and transport sector in recent years. As a result, the annual increments in biomass-based heat generation have been relatively stable since 1990, whereas in the field of power and CHP generation and the production of transport fuels, growth rates increased considerably after the year 2000. It is assumed that as a consequence of the 2009-RES-Directive (EC, 2009a), in which national targets for the share of RES in the final energy consumption are defined, more attention will be paid to biomass use in the heat sector in the years to come.

9.2 International trade

The challenges related to mapping international trade streams of biomass for energy are numerous, and assessing the impact of the growing bioenergy use on trade streams is not straightforward. To this end, specific methodologies need to be developed, especially when it comes to assessing indirect effects like spillover effects or indirect land-use change.

Based on the approaches applied in this work, it is concluded that the main importers of wood fuels in CE are Italy, Denmark and Austria. Cross-border trade of wood pellets has been growing rapidly in recent years and is already of very high importance for the Danish bioenergy sector. (Pellets represent by far the most important fraction of biomass imports to Denmark.) Austria, being a net exporter of wood pellets, is importing considerable amounts of wood residues, primarily indirectly in the form of raw wood. On the other hand, Austria is exporting vast amounts of wood products.

The comprehensive assessment of biomass trade related to bioenergy carried out for the case of Austria indicates that indirect net-imports of wood-based fuels are in the same magnitude as direct trade, and that feedstock imports for biofuel production are roughly as important as direct biofuel trade. Hence, it is clearly insufficient to rely only on energy statistics (which do not include indirect trade streams and cross-border trade of feedstock used for biofuel production) when assessing international trade related to bioenergy use.

With regard to direct biofuel trade, Austria, Italy and Poland are the main importers (primarily biodiesel). Although growing rapidly, cross-border trade related to biofuels is still rather moderate compared to (indirect and direct) trade of wood fuels in CE. Still, as more and more (Central) European countries aim at achieving their biofuel targets, it is either necessary to mobilize domestic resource potentials or further increase imports from Non-European countries. There is strong evidence that the CE region is currently becoming increasingly dependent on imports of biofuels as well as feedstock for biofuel production.

There is also evidence that in Germany and Austria (which are most advanced in biofuel use), the growing demand for vegetable oil for biodiesel production primarily resulted in an increase in imports rather than the mobilization of domestic potentials. The trend of rising cross-border trade was not limited to European countries; palm oil imports have also gained in importance, albeit to a rather limited extent. Thus, in order to avoid adverse effects of the enhanced use of biomass (especially direct and indirect land-use change), the need for obligatory certification schemes for sustainably produced biomass is becoming increasingly urgent.

The enhancement of international biomass trade is often seen as a key factor for mobilizing the (global) biomass supply potential, avoiding short-term regional supply problems and providing the framework conditions required for steady growth of bioenergy use. However, concerns about sustainability issues of globally traded biomass resources have to be taken seriously, and in order to enhance the security of supply and facilitate domestic income, a main focus of national biomass action plans should be put on the mobilization and use of regional biomass resources.

9.3 Resource potentials

It is apparent that there are numerous aspects and barriers for an enhanced use of biomass, which cannot be considered in highly aggregated assessments of biomass potentials. Therefore, the assessment of locally available residues and wastes as well as specific measures for their utilization should be promoted in regional energy concepts and action plans. Increasing biomass imports to countries with a rapid growth of the bioenergy sector on the one hand, and evidence of unused domestic resource potentials on the other indicate that the supply with regional biomass has not been given enough attention within energy policy strategies, according support schemes and incentives. In particular, it should be investigated whether the cost of regional supply chains can be reduced with logistical improvements, the enhanced use of conversion technologies (e.g. pelletizing, torrefaction) and removal of organisational barriers.

Results of studies on biomass resource potentials indicate that there are vast unused potentials in most CE countries. According to EEA (2006) the environmentally compatible potential in the year 2010 in the considered countries was about two times higher than the actual utilization in 2007, and the potential in 2030 even three times higher. The results of other studies show even higher supply potentials. The consideration of different environmental criteria has a significant impact on the amount of agricultural and forest biomass potentials, indicating that there is a considerable risk that uncoordinated growth of bioenergy use results in additional pressure on the environment. The consideration of environmental criteria in the design of bioenergy support schemes (especially promoting the mobilization of biomass resources) is therefore of crucial importance.

To what extent the biomass potentials are already utilized is highly diverse among CE countries: In Denmark, Germany and Austria the currently unused resource potential is relatively small, whereas countries like Poland, Italy and Slovakia only use a very low proportion of their biomass potential. Especially agricultural resources (including energy crops as well as residues and wastes) are assumed to constitute a substantial potential that is hardly tapped yet. It is assumed that to some extent, the very uneven progress in biomass use (primarily resulting from diverging energy policies, support schemes and as a consequence diverging biomass price developments) encouraged cross-border trade between European countries. Increasing efforts in the field of bioenergy throughout all EU countries are likely to result in a further shift of trade flows towards international (trans-continental) biomass trade.

9.4 Towards the 2020-targets

The importance of bioenergy for reaching the 2020-targets defined to the 2009-RES-Directive is undisputed. Scenarios by Resch et al. (2008a) indicate that among the renewable sources of energy, biomass can be expected to bring the biggest contribution to the achievement of the 2020-targets. Special attention should therefore be attributed to the design of support schemes promoting bioenergy use. Aspects which should be considered within national biomass action plans include the following: Biomass can be used in all energy sectors (heat, electricity and transport) and the economic and environmental properties of the different bioenergy utilization paths often vary widely (see Part I). Clear strategies and targets for the development of the bioenergy sector, designed with consideration of technological, economic and ecological criteria are essential (see Kalt et al., 2010b).

Finally, it has to be taken into account that increasing competition for biomass resources between the different types of biomass use (both for energy and material uses) are expected with the progressing exploitation of biomass potentials. In order to facilitate the diffusion of the most efficient utilization paths, bioenergy policies should be designed to counteract resource competition as far as possible; both with supply-side measures and clear priorities for the most beneficial technologies and utilization paths.

Part III:

Modelling the bioenergy system – Scenarios for bioenergy use in Austria

10 Introduction

Due to the big variety of options to utilize biomass for energy, both concerning the primary energy resources (e.g. forest wood, industrial wood residues, energy crops, agricultural wastes, biogenic municipal solid wastes) and the technologies, it is considered essential to carry out profound systematic and strategic investigations about possible developments in the bioenergy sector. This section is dedicated to the question of how future developments can be modelled based on techno-economic approaches, in order to derive medium to long-term scenarios of bioenergy use. 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. The simulation model *SimBioSys*, which was developed in the course of this thesis, is a tool for handling the complexity of and interactions between these influencing factors and deriving well-founded scenarios of the bioenergy sector.

10.1 Outline

Part III of this thesis is organized as follows: After this introduction (section 10), which includes a description of the basic idea and objective of the modelling approach (10.2) and a brief overview of other energy models with focus on bioenergy (10.3), the model *SimBioSys* is introduced (section 11). The fundamental principles of the modelling approach are explained in section 11.1. In section 11.2 the model input data and data structures are described. The implementation of the basic simulation algorithms is described in section 11.3. In section 11.4 illustrative simulation results used for model verification are presented. The contents of chapter 12 are actual model applications: simulations of the development of the Austrian bioenergy sector up to 2030 and 2050, respectively. Section 12.1 presents simulations with a focus on agricultural bioenergy, and with the simulations presented in section 12.2, the possible impact of climate change on the Austrian bioenergy sector is assessed.

10.2 Objective and basic idea

The simulation model *SimBioSys* (an acronym for "simulation model for the bio-energy system") is designed for the purpose of deriving medium- to long-term scenarios for bioenergy use in a certain country or region and evaluate these scenarios with regard to various parameters. In the first place, the model results are to provide insight into the following aspects:

- What is the achievable contribution of bioenergy to the energy supply under certain framework conditions?

- To what extent can bioenergy contribute to reducing GHG emissions and dependence on fossil fuels?
- 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, and how should support schemes be designed to contribute to an efficient bioenergy use?

The core simulation algorithms are based on profitability analyses of the different biomass utilization paths. Economic framework conditions like subsidies or prices for fossil fuels as well as supply curves for biomass are the main influencing parameters. In each simulation period (each year), bioenergy plants (heat generation and combined heat and power plants as well as biofuel production plants) are deployed if they are competitive under the current framework conditions and if there are free demand-side and resource potentials available.[35] Hence, the energetic use of biomass is only extended if bioenergy plants are economic compared to the according fossil-fuelled reference systems. With the model it is possible to analyse the effects of different support schemes and price developments on the utilization of biomass resources, and assess the achievable contribution of biomass to the energy supply of the country or region under consideration.

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 the structure of the bioenergy sector. These factors include domestic biomass supply potentials and their costs, investment and operation costs of bioenergy technologies (which can be influenced by technological progress), fossil fuel price developments, energy policy framework conditions, energy demand trends (energy efficiency) as well as the initial situation (i.e. the stock of bioenergy plants which have been installed in preceding years). Within the scenario simulation, the future deployment of bioenergy plants is determined on a yearly basis, based on these influencing factors and deployment algorithms which have been developed specifically for this model (section 11.3).

Subsequently, the resulting scenario is evaluated with regard to numerous parameters, 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 technology.

[35] Demand-side potentials are the upper limits of energy required of a certain type (for example heat from small-scale boilers with a rated power of up to 15 kW); see section 11.2.1.

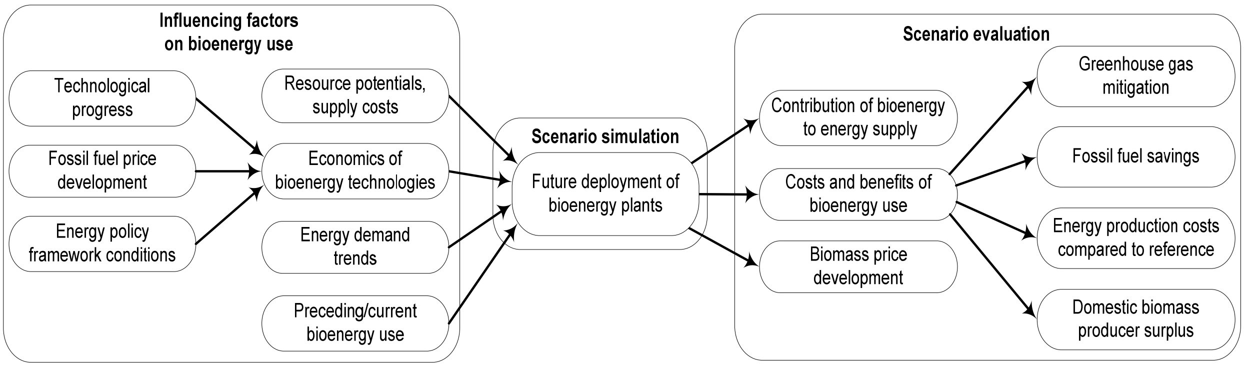

Figure 10-1. Illustration of the basic idea behind the modelling approach.[36]

10.3 Brief overview of energy models with bioenergy focus

This section gives a brief overview of selected energy models with a focus on bioenergy, with the intention of providing a rough comparison of the different modelling approaches and model features. With no claim to be exhaustive, this compilation of models is to illustrate the diversity and different focuses of (bio-) energy models.

10.3.1 MARKAL, MARKAL-MACRO, SAGE and TIMES

MARKAL (an acronym for "<u>mar</u>ket <u>al</u>location") is a dynamic bottom-up optimization model of the energy system of one or several regions that provides a basis for estimating energy dynamics over a multi-period horizon (Loulou et al., 2004a). *MARKAL* computes energy balances at all levels of an energy system: primary resources, secondary fuels, final energy, and energy services. Being an intertemporal partial equilibrium model, it identifies the least-cost pattern of resource use and technology deployment over time and calculates resulting environmental emissions. Further model assumptions include perfect foresight, price elastic energy demand and stepped fuel supply curves (see section 11.2.2).
By linking *MARKAL* with the neoclassical growth model *MACRO*, the model *MARKAL-MACRO* was created. This model calculates energy demands and prices endogenously through the interaction of the energy system with the rest of the economic system.
MARKAL is a widely applied energy system model. However, despite the large number of analyses using *MARKAL* at local, national and global scales, only few have a focus on bioenergy, although most have bioenergy included in an aggregated form (Jablonski et al., 2010).

[36] 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.

The model *SAGE* ("System for Analysis of Global Energy markets") is a myopic version of *MARKAL*. Hence, instead of an intertemporal optimization, the static partial equilibrium is computed for each time period separately (Loulou et al., 2005).

TIMES ("The Integrated *MARKAL-EFOM*[37] System") is an evolved version of *MARKAL* with additional functions and flexibilities (Loulou et al., 2004b). The additional features include time periods of variable length, investment and dismantling lead-times and costs and age-dependent parameters of facilities (i.e. availability factors and efficiencies). *TIMES* is also used specifically for deriving scenarios of the bioenergy sector (see König, 2010, for example).

10.3.2 Green-X

Green-X is a simulation tool for the future deployment of renewable energy technologies. The deployment is based on a myopic bottom-up least-cost approach. Prices for fossil fuels and according reference prices for heat, electricity and transport fuels are defined as exogenous scenario parameters, as wells as energy demand patterns and support schemes for renewables. Demand-side measures for reducing the electricity demand can also be simulated. Biomass supply potentials are represented by stepped cost-resource curves. The current *Green-X* database covers the 27 member states of the EU. The main simulation results include installed capacities of renewable energy technologies, their fuel demand and energy output, total costs of energy supply and support schemes as well as greenhouse gas emissions on an annual basis.

Green-X$_{Environment}$ is an evolved version of *Green-X* with a special focus on bioenergy (Resch et al., 2006), with a more detailed representation of bioenergy technologies and biomass resources. The latter, however, are still represented by stepped cost-resource curves. Furthermore, life-cycle greenhouse gas and air pollutant emissions of bioenergy technologies are evaluated by the model. An adapted version of *Green-X*$_{Environment}$, *Green-X*$_{Bio\text{-}Austria}$ was used to derive scenarios for the Austrian bioenergy sector in Kalt et al. (2010b)[38].

10.3.3 BioTrans

BioTrans is a myopic least-cost optimization model which was developed in the course of the *VIEWLS* project (Wakker et al., 2005). It was developed specifically for the purpose of computing an optimal mix of biofuels in the transport sector, given an externally defined biofuels consumption target. The model structure is described as being similar to a network

[37] *EFOM* (Energy Flow Optimization Model) is an energy optimisation model for the supply side of the energy model complex of the European Commission (Grohnheit, 1991).

[38] The work was published in Biomass and Bioenergy 34 (2010) under the title "Long-term strategies for an efficient use of domestic biomass resources in Austria".

flow model (Lensink et Londo, 2010), with biomass resources flowing from nodes representing biomass cultivation or collection to such representing conversion into biofuels, biofuels distribution and use. The nodes have specific costs associated with them, and transport costs are associated with the routes. The model is spatially differentiated in the 27 member states of the EU and Ukraine. Endogenous technological learning was introduced into the model for the *REFUEL* project (Refuel, 2010), in order to better account for emerging technologies which have to overcome the barrier of high capital costs during market introduction and become competitive to conventional biofuel technologies through technological learning.[39]

BioTrans minimizes the costs for a predefined biofuel target on a yearly basis. Neither competition with fossil fuels or alternative mobility options are considered, nor resource competition with bioenergy technologies for heat or electricity generation. Hence, the results are quite independent from fossil fuel price scenarios, and the biomass demand for applications other than the production of transport fuels needs to be considered in exogenous scenario assumptions.

10.3.4 BeWhere and other spatially explicit approaches

Spatially explicit models put a special focus on the regional distribution of biomass primary energy supply on the one hand and energy demand structures on the other. Furthermore, certain influencing parameters on the economics of bioenergy and conventional technologies, such as infrastructure (district heat or gas grids), transport costs etc. can be modelled in more detail than in the energy models described above. The results of spatially explicit models may provide insight into the optimal location of power plants, optimal deployment of infrastructure and other details.

An example for a spatially explicit modelling approach is the optimization model *BeWhere* (Schmidt et al., 2010a and Leduc et al., 2009). It is a spatially explicit mixed integer programming (MIP) model that minimizes the costs for supplying demand regions with energy (heat, power and transport fuels) from biomass or fossil-fuels. The energy system is optimized for one single year, with locations of bioenergy plants (technologies considered range from pellet production plants over ethanol to BIGCC plants), biomass transport, heat distribution grids etc. being modelled in a spatially explicit way. Spatially explicit models are usually coupled with GIS (Geographic Information System) data. Optimization or simulation models for spatially explicit biomass production (focusing on agriculture or forestry, for example) are sometimes used to provide input data for energy models. For example, the modelling framework presented in Schönhart et al. (2010) (which integrates a bio-physical process model (EPIC), an economic farm optimization model (FAMOS) and the crop rotation model CropRota) and

[39] In section 11.5 the fundamental principles of endogenous technological learning are described.

also applied in Kalt et al. (2010a) is capable of providing spatially explicit supply potentials of agricultural biomass.

The model *BSM* ("Bioenergy Siting Model") presented in Tittman et al. (2010) is another example for a GIS-based energy optimization model. Similar to *BeWhere*, *BSM* uses an MIP solving algorithm to determine the optimal location of bioenergy plants.

11 The model SimBioSys

The modelling approach of *SimBioSys* can be characterized as a myopic bottom-up least-cost approach. It is implemented in the numerical computing environment *MATLAB*. In contrast to most other energy models, a main focus of *SimBioSys* is on modelling the dynamics of the bioenergy system and interactions between different utilization paths, such as resource competition.

The core assumption of the modelling approach is that market actors attempt to minimize aggregate system costs. It is assumed that in each simulation period (each year) the decision-making structure of potential investors into bioenergy systems is based on a comparison of the total energy production costs (i.e. the long-run marginal costs) 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 respective simulation period and if there are free demand-side and resource potentials. A biomass utilization path is competitive if the price of the respective biomass fuel at the beginning of the simulation period is less than the price where the energy generation costs of the bioenergy system and the according reference technology are in equilibrium (see section 11.1.3). 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. (A "cluster" is a group of similar technologies.) The parameters of the cluster-specific diffusion curves are derived from developments observed in the past, or exogenous scenarios (e.g. gaseous transport fuels based on a projected market diffusion of gas-fuelled vehicles). Apart from this cost-based deployment approach, a demand-based deployment algorithm which determines the optimal deployment to achieve a certain energy output is implemented in the model.[40] This algorithm is used if obligatory quotas (being one of four optional support schemes which can be simulated in *SimBioSys*) are being simulated (for example quotas for biogenic fuels in the transport sector).

[40] This algorithm is comparable to the one applied in *BioTrans*.

11.1 Fundamental principles

11.1.1 Assumptions regarding markets and market actors

The modelling approach is based on several “perfect market assumptions”, the most important being:

- **Equal access to resources, no transaction costs**: Each actor in the bioenergy system under consideration is assumed to obtain commodities on the same single market and each commodity is assumed to have a single price. Transaction costs are assumed to be zero.[41]
- **Utility maximization and perfect rationality**: Market participants are assumed to act completely rational. Hence, investment decisions are assumed to be entirely based on economic profitability, and market participants do not have any preference for certain technologies, fuels or whatsoever.
- **Perfect competition and perfect information**: No participant is able to enforce market power and all agents dispose of all relevant information.

However, perfect market assumptions are deliberately dropped with regard to several aspects, in order to allow for simulation results which are closer to reality than results under strict perfect market conditions. The most important limitations are limits to technological penetration, speed of introduction of new technologies and the way resource competition between technologies or applications are modelled.

These principles and limitations are:

- Only the bioenergy sector is simulated in *SimBioSys*. Hence it is assumed that the energy demand which is not covered with bioenergy technologies is supplied with the according (fossil fuel-based) reference system.
- Other renewable energy sources are not explicitly taken into account. Competition between bioenergy and other renewable energy technologies is therefore not modelled. Scenarios for the market penetration of other RES (resulting in declining demand for bioenergy technologies) can be considered in the time-series of demand-side potentials (see section 11.3.1).
- Reference prices and costs are exogenous scenario parameters with fixed values, regardless of the demand and the extent, to which the reference system is substituted by bioenergy technologies.
- Bioenergy systems are deployed if and as long as they have lower energy production costs than the according reference systems. Deployment of bioenergy systems results in increasing demand and increasing prices of biomass resources, leading to

[41] Transaction costs are expenses related to an economic exchange, such as search and information costs.

equilibrium prices, where energy generation costs of bioenergy and reference systems are equal.[42]

- Market actors are not able to anticipate the consequences of additional demand (i.e. additional deployment of bioenergy plants) on biomass prices.
- It is assumed that once bioenergy plants have been installed, they stay in operation until the end of their technical life-time.
- Energy produced with bioenergy technologies is assumed to be consumed in the country/region where it is produced. Hence, imports and exports of energy commodities (electricity, transport fuels and of course heat) are not taken into account.
- The values of technology-specific depreciation periods used for investment decisions may be defined differently than the according technical life-times. This allows for the simulation of situations where a precondition for investments into bioenergy technologies is that they amortize during a period shorter than the actual life span of the plant.[43]

11.1.2 From biomass supply curves to bioenergy supply curves

Supply curves are a common concept used to model the relationship between quantities of commodities that are available on the market at certain prices. Under the assumption of perfect competition, marginal costs (i.e. the costs arising from the production of one more unit of the commodity) determine the supply, as market actors are willing to produce additional output as long as the price they receive is higher than the costs of producing one more unit.

Assuming that a single technology is used to convert a certain biomass feedstock, described by an inverse supply curve $p(q)$, to an energy output, an inverse bio*energy* supply curve $c^{be}(q)$ can be derived from the bio*mass* supply curve.[44] The energy output can be heat, electricity or a secondary energy carrier (such as liquid or gaseous transport fuels). The bioenergy supply curve can also be translated to a function of the quantity of energy output $c^{be}(y)$.[45]

[42] Strictly speaking, if a certain biomass fraction is utilized by more than one technology (which is usually the case), this is only true for the most competitive technology, as this technology determines to what extent a biomass fraction is utilized (and the resulting biomass price, respectively). This will be explained and discussed in more detail in the sections 11.3.1.

[43] For the model applications presented in section 12, the depreciation period is generally assumed 10 years, whereas the technical life-times of bioenergy plants range from 15 to 20 years.

[44] $p(q)$ and $c^{be}(q)$ are referred to as *inverse* supply curves, as supply curves are usually defined as quantity as a function of prices. However, with regard to the bioenergy supply curve, the adjunct “inverse” is usually left out in the following explanations.

[45] The list of symbols and default units used in this section can be found in section 14.3 in the Annex.

Figure 11-1 illustrates the fundamental relationships between biomass and bioenergy supply curves. For this figure a convex inverse biomass supply curve of the form

$$p(q) = p^{\min} + \gamma \cdot q^{\frac{1}{\varepsilon}} \qquad \textit{(11-1)}$$

is assumed, where p_{min} denote the minimum price, q the quantity, ε the supply elasticity and γ a constant influencing the shape of the curve. The total energy generation cost c^{be} of the assumed bioenergy technology are given by the following simplified formula for energy generation costs.[46]

$$c^{be}(p) = c^{fix} + \frac{p}{\eta} \qquad \textit{(11-2)}$$

where c^{fix} denote the fixed costs per unit of energy output (including capital, operation, maintenance costs etc.) and η the conversion efficiency.

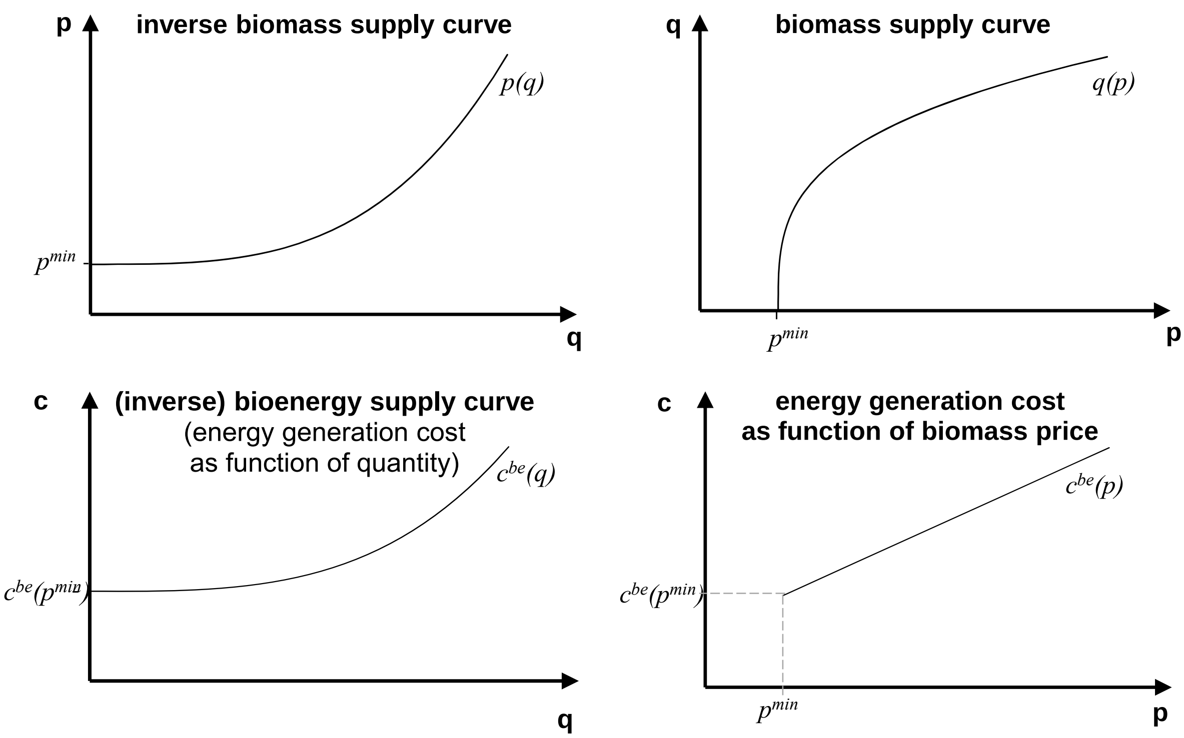

Figure 11-1. Illustration of the relationship between biomass and bioenergy supply curve.

11.1.3 Determining the economic potential of bioenergy

Based on biomass supply curves, the price and quantity at which the energy generation costs are equal to the reference price can be determined. This quantity of a biomass resource is equivalent to the primary energy potential which can be utilized economically by the

[46] To simplify matters, credits for by-products (which are considered within the model) are neglected here.

technology under consideration (assuming energy generation costs calculated according to Eq. (11-2)). Figure 11-2 illustrates the basic approach. The energy generation costs of the bioenergy technology c^{be} are less or equal to the reference price in the interval [p^{min}, $p*$]. $p*$ is the biomass price where $c^{be} = c^{ref}$, i.e. where an equilibrium is established between the bioenergy and its reference technologies (i.e. a partial market equilibrium).
The economically usable primary energy potential amounts to $q*$. The economically feasible energy output of the bioenergy technology is $y = (\eta q*)$, and the total economically feasible capacity is $P^{econ} = \frac{(\eta q*)}{T_{FL}}$, where T_{FL} denote the annual full load hours of the technology.

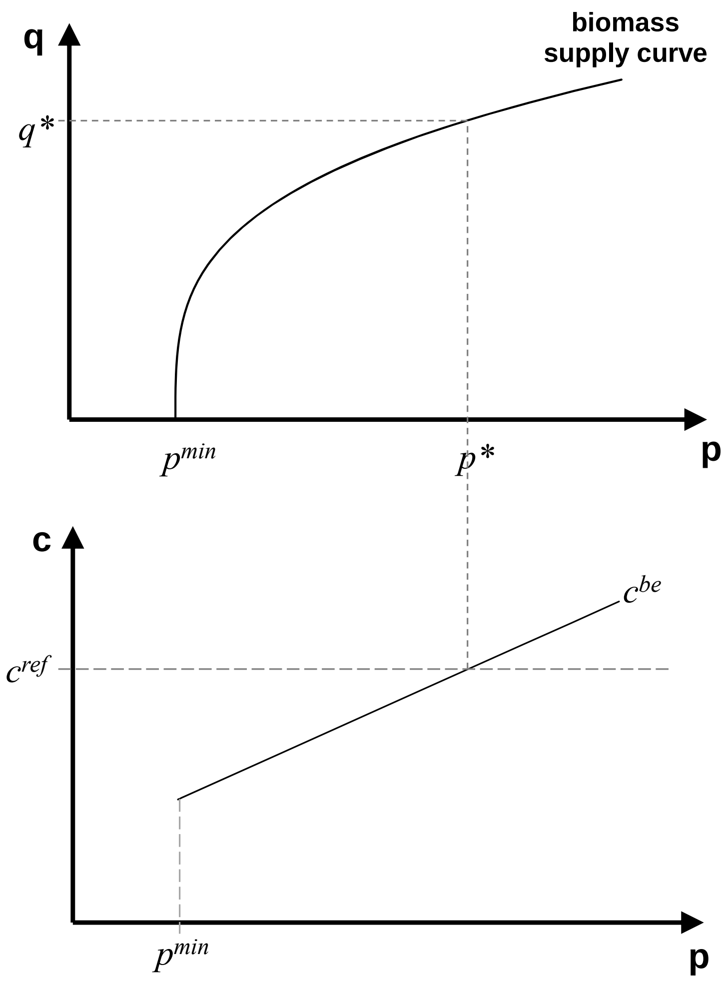

Figure 11-2. Schematic illustration for determining the economic potential of bioenergy, based on a biomass supply curve

11.1.4 Determining the producer surplus

With an increasing exploitation of biomass resources, the biomass prices and also energy generation costs of bioenergy technologies rise. From a plant operator's point of view, this is of course an adverse effect, but for biomass producers / suppliers, it is beneficial. The profit is usually expressed as the *producer surplus* in economics (see Samuelson et Nordhaus, 2009, for example).[47]

The producer surplus of an individual producer is defined as the difference between the price he is willing to supply a quantity for and the price he actually receives. It can be determined based on the supply curve and the equilibrium price $p*$ or the consumed quantity $q*$, respectively. Graphically speaking, the total producer surplus (PS) is the area between the horizontal line at the market price and the inverse supply curve (Figure 11-2).

Based on the supply curve, it is calculated as

$$PS = \int_{p^{\min}}^{p^*} q(p)dp \qquad (11\text{-}3)$$

and based on the inverse supply curve as

$$PS = \int_{0}^{q^*} (p^* - p(q))dq \qquad (11\text{-}4)$$

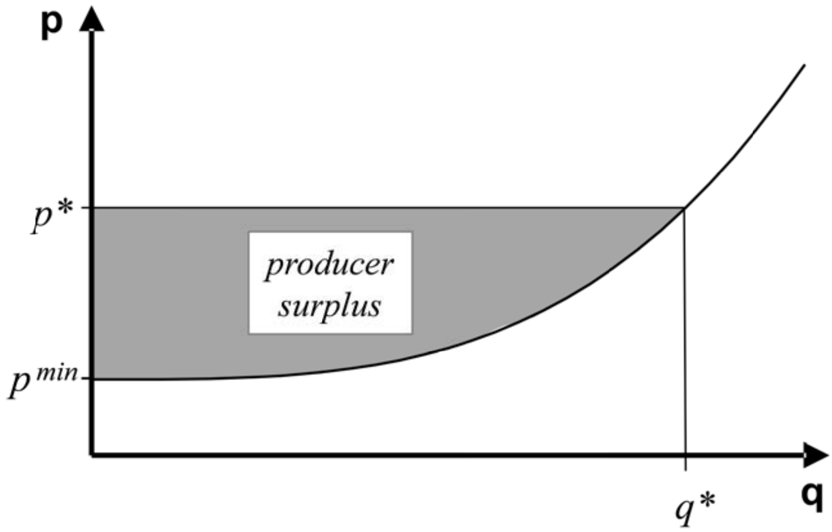

Figure 11-3. Illustration of the producer surplus at a market price p.*

11.1.5 Determining the optimal deployment to satisfy a given demand

Besides the cost-based approach to determine the economic potential of a certain bioenergy technology, it is also necessary to consider a situation where a given demand y^{demand} of a certain energy commodity (usually transport fuels or electricity) is to be covered with bioenergy. In *SimBioSys*, this is relevant if a quota for a certain energy commodity is simulated (see section 11.3.2). To simplify matters, for the following explanations it is assumed that there

[47] Being a benefit arising from the energetic use of biomass, the producer surplus is determined for each simulation period and each fuel type in *SimBioSys*.

are no existing bioenergy plants which may contribute to the fulfilment of the quota, and that biomass fuels are only utilized to fulfil the quota. These constraints of course do not apply to the actual implementation in the model.
As it is assumed that a given demand is satisfied in the most economic way possible, the “least-cost deployment of bioenergy plants” can be interpreted as an optimization problem with the following objective function, representing the total energy generation costs (Again, the simplified formula for energy generation costs, Eq. (11-2) is assumed.):

$$f(\vec{y}) = \overrightarrow{y^T}\left(\overrightarrow{c^{fix}} + R\vec{p}\right) \qquad (11\text{-}5)$$

The column vector $\vec{y} = [y_j]_{j=1,\dots,n}$ denotes the (annual) energy generation and $\overrightarrow{c^{fix}} = [c_j^{fix}]_{j=1,\dots,n}$ the specific fixed costs of the technologies j (1 to n). The vector $\vec{p} = [p_i]_{i=1,\dots,m}$ contains the prices of the fuels 1 to m. The matrix elements $\rho_{ji} = \frac{1}{\eta_{ji}}$ of the matrix $R = [\rho_{ji}]_{n\times m}$ are the reciprocal values of the conversion efficiencies of the technology j, converting the fuel i into the demanded energy commodity. The matrix $H = [\eta_{ji}]_{n\times m}$, containing the efficiencies, is defined analogously. By definition, all elements of the matrices R and H representing undefined conversion paths are zero. Hence, each row of these matrices, representing one utilization path (see section 11.2), contains exactly one value. In contrast, the columns may contain more than one non-zero value, as each fuel type may be utilized by several technologies.
The function $f(\vec{y})$ is minimized subject to the following constraints:

- The prices of the fuels are determined by the total demand (i.e. the sum of biomass demands of all technologies utilizing a certain biomass type), calculated as

$$\vec{q} = [q_i]_{i=1,\dots,m} = R^T\vec{y} \qquad (11\text{-}6)$$

  and the supply curves $p_i(q_i)$.
- Biomass prices are undefined for values q bigger than a maximum quantity q^{max}. Hence, the total demand for each fuel type may not exceed the maximum supply potential:

$$q_i \le q_i^{\max} \qquad (11\text{-}7)$$

- Minimum plant capacities $P_j^{\min}$ are to be considered, hence:

$$\left(\frac{y_j}{T_{FL,j}} = 0\right) \vee \left(\frac{y_j}{T_{FL,j}} \ge P_j^{\min}\right). \qquad (11\text{-}8)$$

- The total energy generation must be equal or larger than the given demand:

$$\sum_{j=1}^{n} y_j \geq y^{demand} \quad (11\text{-}9).$$

Based on this optimization problem, an algorithm was developed for *SimBioSys*, which is based on a stepwise approximation procedure. This approximation algorithm allows for the implementation of non-linear and piecewise concave supply curves, which are approximated by interpolation (see section 11.2.2), as well as for the consideration of minimum plant capacities, two aspects which are not easily considered in linear programming approaches. The fundamentals of this algorithm are illustrated in section 11.4.2.

11.2 Model input data and data structures

The main data structures of the model *SimBioSys* are shown in Figure 11-4. There are three technology categories: heat generation plants, electricity / combined heat and power (CHP) plants and conversion technologies (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 fuel demand). The data structure “technology type” contains technology-specific data such as efficiencies, power range, investment, operation and maintenance costs, other variable costs, technology-specific GHG emissions and fossil fuel demand (e.g. due to auxiliary energy consumption).

Biomass potentials are structured into “fuel types”. The input data for each fuel type include potentials and costs in the form of dynamic supply curves and import prices. Furthermore, in order to account for life-cycle emissions and fossil fuel consumption related to the production and supply of biomass, fuel types can be associated with embedded GHG emissions and data on the specific cumulated energy demand.

Each technology type is associated with one or more fuel types, as for example wood chip heating plants can be supplied with forest wood chips or industrial wood residues. 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 cumulated energy demand are also technology path-specific properties.

In the following sections the input data are described in more detail. In order to provide a better understanding, the data structures are explained on the basis of the default data set being compiled for the simulations of the Austrian bioenergy sector presented in section 12.

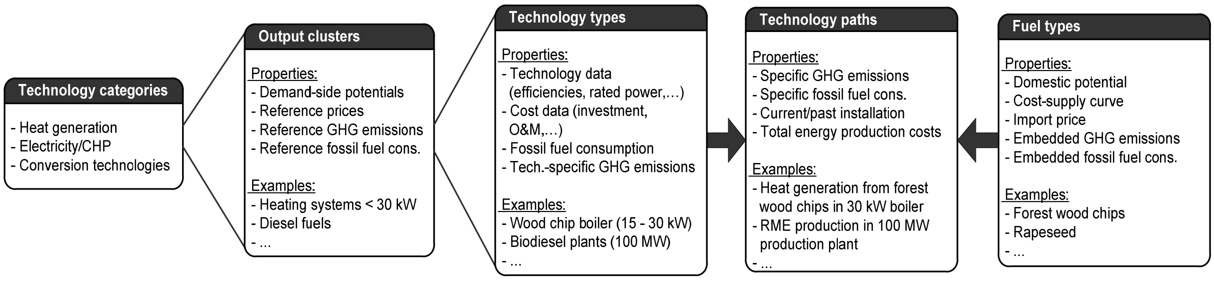

Figure 11-4. Data structures of the model SimBioSys.

11.2.1 Technologies, clusters and demand-side potentials

Table 11-1 shows a list and structuring of bioenergy technologies considered in the default data set of the model. For each technology category, the main output and optional secondary and tertiary outputs are specified, and each output is assigned to a certain output cluster, depending on parameters like plant type and size, or the type of by-product. For heating systems and plants, thermal energy is considered as the main output, for power plants and CHP plants electricity, and for conversion technologies the calorific value of the produced fuel. Technology data like rated power, main efficiencies or specific investment costs always refer to the main output. Optional secondary and tertiary outputs include heat from CHP generation, electricity from polygeneration plants[48] or non-energetic by-products like animal feed from ethanol plants. Generation costs, specific GHG mitigation etc. are also calculated related to the main output (for example in the case of a CHP plant, they are given in €/$MWh_{el.}$ or t CO_2-eq./$MWh_{el.}$), and additional outputs are considered via credits (see formulas in the Annex).

[48] The term "polygeneration" is used for facilities which produce fuels as well as heat and/or electricity.

Table 11-1. Structuring of bioenergy technologies and output clusters

Category	***Output clusters***	***Technology types***
Heat generation (main output: heat)	**Residential heat generation:** (wood log/general)[49] < 15 $kW_{therm.}$ 15 to 30 $kW_{therm.}$ 30 to 100 $kW_{therm.}$	Wood log boilers Wood chip boilers Pellet boilers Cereal grain boilers Plant oil boilers
	Centralized heat generation: 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:** <1 $MW_{el.}$ 1 to 5 $MW_{el.}$ > 5 $MW_{el.}$ **Heat:** < 100 $kW_{therm.}$ 100 $kW_{therm.}$ 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) Gasification CHP plants (BIGCC and other concepts)
Conversion technologies (main output: refined fuels, secondary/tertiary outputs: heat, electricity, non-energetic by-products)	**Fuels:** 1st generation liquid biofuels 2nd generation liquid biofuels Gaseous biofuels **Electricity:** <1 $MW_{el.}$ 1 to 5 $MW_{el.}$ > 5 $MW_{el.}$ **Heat:** < 100 $kW_{therm.}$ 100 kW to 1 $MW_{therm.}$ 1 to 5 $MW_{therm.}$ > 5 $MW_{therm.}$ **Non-energetic by-products:** DDGS, glycerol etc.	Oil press Biodiesel plant Bioethanol plant (by-product DDGS) Bioethanol plant (by-product biogas)
		Fischer-Tropsch plants Lignocellulosic ethanol plants
		Biomethane plants (anaerobic digestion and conditioning) Gasification plants
		Biorefineries Polygeneration plants

“Demand-side potentials” are the upper limits of a certain energy output. They are defined for each output cluster and are basically derived from the total heat, electricity and transport fuel

[49] In the simulations in section 12, small-scale heating systems are not only categorized 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.

demand. However, as the fields of application for bioenergy systems and biofuels are usually subject to further limitations, demand-side potentials need to be assessed for each output cluster individually. Limitations for the application of bioenergy systems, which can be captured in demand-side potentials, include the following:

- The structure of the demand for residential heating, i.e. the heat demand of all dwellings with a certain heat load in the region or country under consideration.
- The quantity of thermal energy obtained from biomass heat plants of a certain capacity is limited. (Estimates can be based on existing district heating systems, or scenarios for the future deployment of district heating.)
- Depending on the temperature level, industrial process heat demand can only partly be covered with solid biomass.
- The upper limit for the contribution of first generation biofuels (biodiesel and ethanol) to the transport fuel supply is defined by the number of vehicles suitable for operation with pure biofuels and legal framework conditions for blends with fossil fuels.
- The demand for gaseous transport fuels is limited by the number of gas-fuelled vehicles.

As most of these limitations are influenced by scenario-specific developments, demand-side potentials are defined as time series for each output cluster. As mentioned above, reference prices/costs are also defined for each output cluster.

Due to substantial *economies of scale*–effects in heat generation costs and the fact that demand-side potentials are considerable restrictions for heat generation from biomass, the residential heat demand is subdivided into three clusters, and another three heat clusters are defined for district heating networks of different sizes in the default data set. Additionally, there is a cluster for industrial process heat. Electricity generation is subdivided into three clusters for illustrative purposes only. All power generation technologies are assumed to be grid-connected, the reference prices of the three electricity cluster are identical and demand-side potentials are hardly relevant. Fuels produced by biomass conversion technologies are subdivided into gaseous and liquid transport fuels in the default data set. Further differentiations (e.g. into 1st and 2nd generation biofuels, to account for their different blending properties) were included due to demand-side limitations mentioned above, even though the reference prices of all liquid and all gaseous transport fuels are identical.

11.2.2 Biomass supply curves in SimBioSys

As mentioned before, the primary energy potentials of biomass resources are represented by supply curves within the model. Supply curves represent the quantity of a biomass type which is (ceteris paribus) supplied at various prices. In more detail, supply curves in *SimBioSys* are modelled as dynamic, continuous curves. The attribute “dynamic” indicates that in general, supply curves change over time. In contrast to the representation in other energy models (e.g. MARKAL, Green-X), biomass potentials are characterized by linearly interpolated, continuous curves rather than stepped curves. Hence, they are defined by two or more value pairs (for the price in currency units per energy unit and quantity in primary energy units per year). The number of value pairs and their location on the curve can be selected arbitrarily, in order to achieve a suitable approximation of the original supply curve.

Figure 11-5 (left) shows an exemplary supply curve based on Eq. (10-1) and approximations with a stepped and an interpolated curve with an equal number of partitions. It is apparent that the maximum error between the approximation and the original curve is clearly higher in the case of a stepped supply curve.

The main advantage of using continuous curves instead of stepped ones in *SimBioSys* is seen in the prevention of “penny-switching” effects[50]. This is illustrated is Figure 11-5 (right): The figures show exemplary bioenergy supply curves based on the continuous, the stepped and the interpolated biomass supply curves. Assuming that the reference price increases from c_I^{ref} to c_{II}^{ref}, the economic primary energy potential increases from q_I^* to q_{II}^*. It is clear to see that the error resulting from the use of a stepped supply curve is significant, whereas in the case of an interpolated curve, the error is negligible.

In the example shown in Figure 11-5, the values of the reference prices were in fact intentionally chosen to illustrate a worst-case example for the error resulting from approximated supply curves. In this specific example, the shift from c_I^{ref} to c_{II}^{ref} results in a deviation $\Delta q^* = \frac{q_{II}^* - q_I^*}{q_I^*}$, which amounts to the following values:

$$\Delta q^*_{continuous} = 3.7\%$$

$$\Delta q^*_{stepped} = 22.2\%$$

$$\Delta q^*_{interpolated} = 3.8\%$$

Furthermore, it is worth mentioning that linear supply curves can be modelled perfectly accurate and very comfortably with only two value pairs in *SimBioSys*, whereas the use of stepped supply curves is likely to result in significant penny-switching effects in such a case.

To conclude, the use of interpolated supply curves is considered a major improvement compared to energy models using stepped ones (such as the renowned models MARKAL or Green-X).

[50] “Penny-switching” describes the phenomenon that small changes in costs/prices can trigger big shifts in in model results, which can result in unrealistic scenarios.

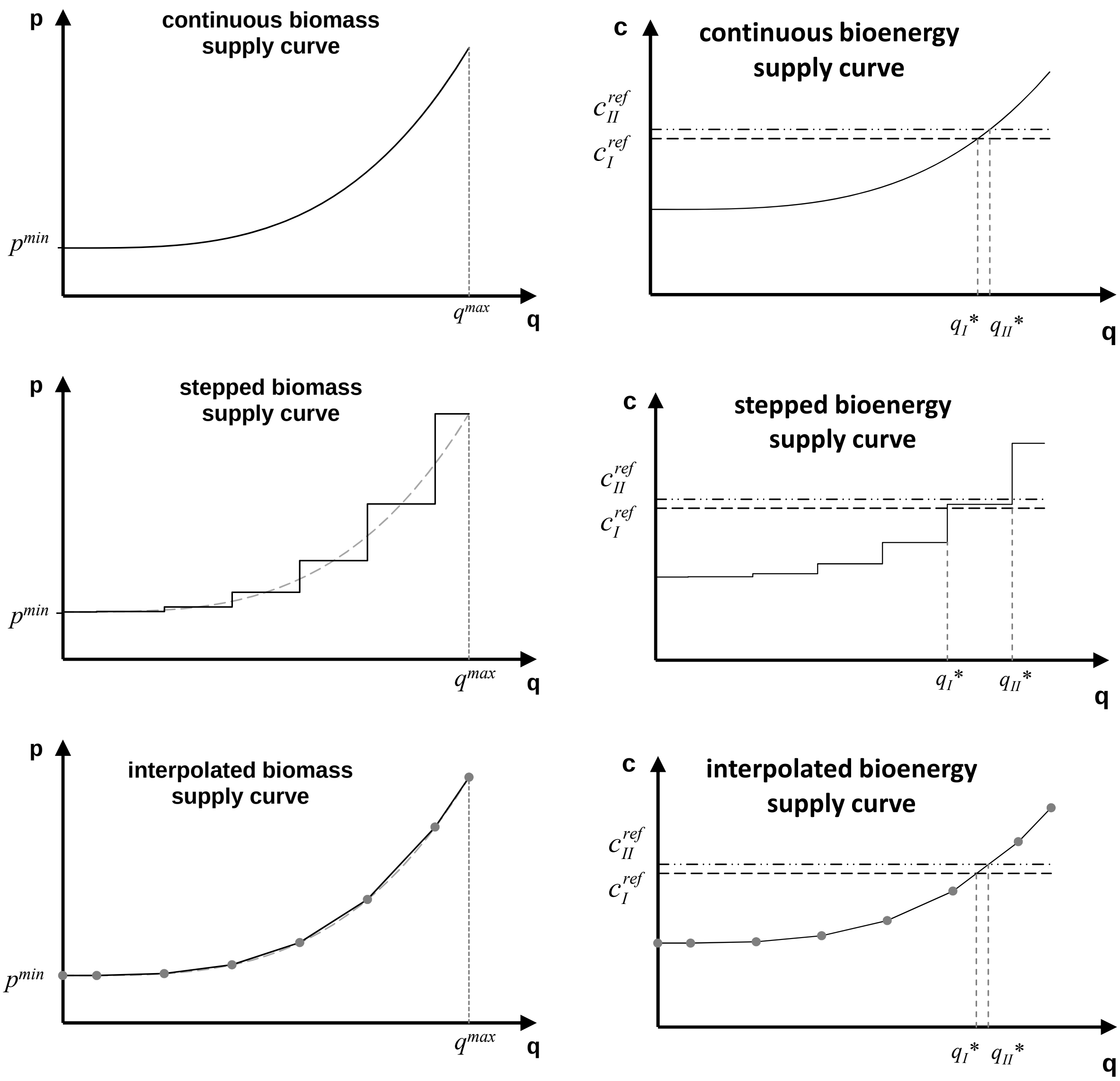

Figure 11-5. Illustration of an exemplary biomass supply curves as well as stepped and interpolated approximations (left) and according bioenergy supply curves (right).

11.2.3 Reference systems

For comparing energy production from biomass with conventional energy 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 (cp. Part I). Also, it is crucial that projections for the reference prices/costs of different technology types or clusters, respectively, are based on consistent scenarios.

Figure 11-6 illustrates the methodology which is applied for deriving consistent reference prices/costs for all technology clusters of the default data set. As discussed in Part I, reference systems need to be consistent with the initial situation of the energy system in the country or region under consideration. The reference systems assumed here refer to the situation in Austria, and the applicability to other countries or regions needs to be examined individually.

Based on general trends in fossil fuel price developments, consistent price scenarios for large and small consumer prices for oil products (heating oil, diesel and gasoline) and natural gas are derived. (For the simulations presented in section 12, price scenarios from literature are used.) The relationships between prices for crude oil and other wholesale prices with small consumer prices are derived from historic price developments. The reference prices for liquid biofuels are diesel and gasoline wholesale prices and those for biomass-derived substitute/synthetic natural gas (SNG) and biomethane are natural gas wholesale prices.

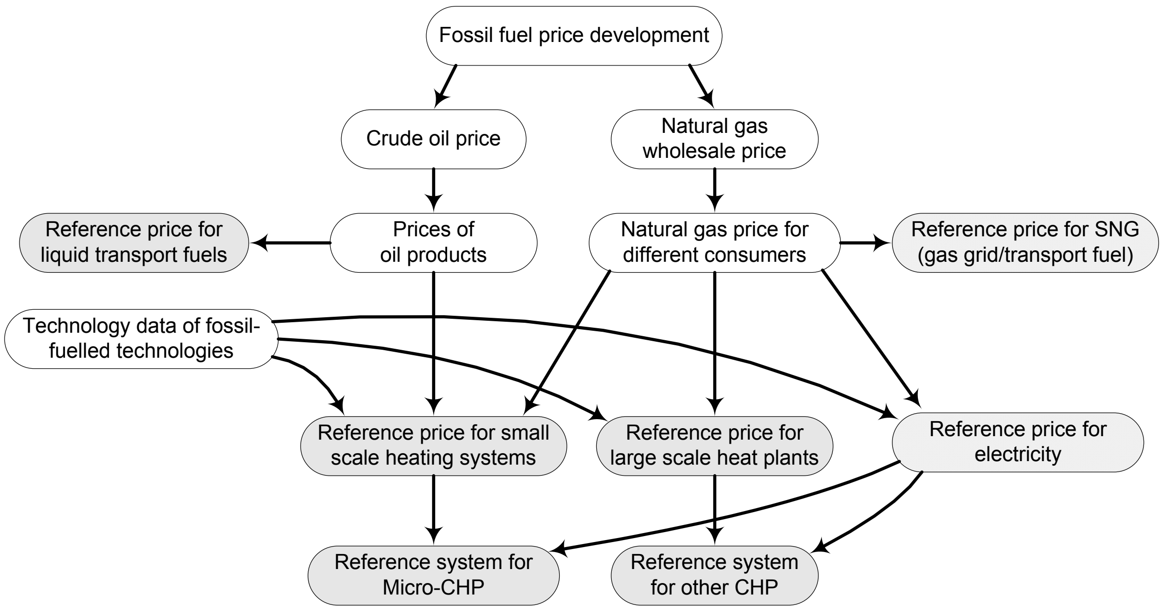

Figure 11-6. Default reference prices and costs: influencing parameters and interconnections.

The economics of heat, electricity and 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 costs of these technologies. The default reference systems for small-scale heat clusters are oil and/or gas boilers with according power ranges. Those of large-scale heat generation technologies are natural gas-fired heat plants. The default reference system for electricity is a modern combined cycle gas turbine (CCGT) (cp. section 4.2 and 4.6.3.2 in Part I).

11.2.4 Support schemes

The model allows for the simulation of different support schemes for bioenergy, including investment subsidies, premiums for energy from bioenergy plants, feed-in tariffs for electricity from bioenergy plants and obligatory quotas. All subsidies are defined as time series, i.e. support schemes may change over time. Table 11-2 gives an overview of the support schemes and their properties.

Table 11-2. Support schemes in SimBioSys 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 and are independent from reference price and fuel price developments
Premium	Subsidy on energy production in €/$MWh_{therm./el./chem.}$, 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 energy production in TWh/a; quotas can be defined for one technology cluster, but may also comprise several clusters (e.g. liquid and gaseous transport fuels). Based on the demand-based deployment algorithm (see section 11.3.2) quotas are fulfilled in the most cost-efficient way possible; support costs are based on prices of certificates, which are assumed to be equal to the energy generation costs of the most expensive plant which contributes to quota fulfilment; 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 for different fuel types (e.g. FITs for CHP plants utilizing waste wood can differ from the FIT for such using forest wood chips); FITs are implemented as being constant for the whole lifetime of plants; support costs incur annually and are influenced by reference and fuel prices developments

11.3 Model implementation

The deployment of bioenergy plants can be triggered either by economic profitability (cost-based deployment) or by a given demand, which needs to be satisfied due to an obligatory quota (demand-based deployment). The basic difference between the two mechanisms is illustrated in Figure 11-7, based on a bioenergy supply curve (generation costs c^{be} as a function of the quantity of energy output y). In the case of a cost-based approach, the economic energy output y^{econ} is determined by the intersection of the bioenergy supply curve with the reference cost/price. In the case of a demand-based approach, the energy quantity is determined by a given demand and the intersection with the bioenergy supply curve defines the price of a certificate:

$$p^{cert} = c^{db} - c^{ref} . \qquad (11\text{-}10)$$

With regard to the schematic illustration shown in Figure 11-7, it has to be noted that the one for the cost-based approach is defined by one single biomass supply curve, whereas the one for the demand based approach can be made up of several biomass types, as the demanded energy commodity (e.g. transport fuels) can be provided by different technologies (e.g. biodiesel production from oilseeds, ethanol from corn, Fischer-Tropsch-diesel from wood etc.).

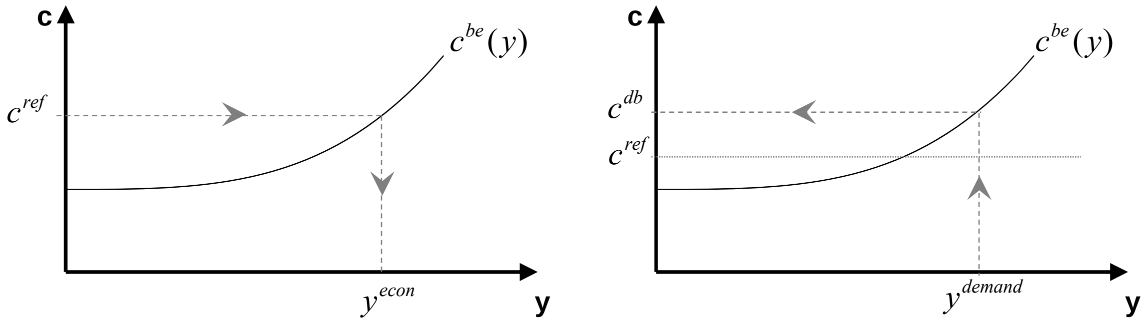

Figure 11-7. Illustration of the difference between a cost-based (left) and demand-based approach (right)

11.3.1 Cost-based deployment

The basic approach of the cost-based deployment algorithm is to determine the economic potential (or capacity) of bioenergy technologies. In addition to the methodology described above, there are several aspects which need to be considered. First a situation with only one bioenergy technology and only one biomass type is assumed.

The model calculates the economic capacities for each year successively, taking into account the plant capacities installed in previous years, i.e. the total existing capacity of bioenergy plants. It is differentiated between values at the beginning and at the end of a simulation period. The difference is explained in the following equations for the installed capacities at different times. P_t^{add} is the additional capacity installed in the simulation period t and LT the lifetime of the technology in simulation periods (years):

Total installed capacity at the beginning of period T: $$P_{B,T} = \sum_{t=T-LT+1}^{T-1} P_t^{add} \qquad (11\text{-}11)$$

Total installed capacity at the end of period T: $$P_{E,T} = \sum_{t=T-LT+1}^{T} P_t^{add} \qquad (11\text{-}12)$$

It is assumed that capacities are fully operational in the year of their installation. In the following, the simulation algorithm for one period is explained. First, the primary energy demand of existing capacities at the beginning (subscript B) of the simulation period T is determined

$$q_{B,T} = \sum_{t=T-LT+1}^{T-1} \frac{P_T^{add} T_{FL,t}}{\eta_t} . \qquad (11\text{-}13)$$

In this calculation it is taken into account that efficiencies and annual full load hours may be dynamic parameters (due to technological learning or changing energy demand structures, respectively). Based on the biomass supply curve, the fuel demand $q_{B,T}$ is translated to a biomass price at the beginning of the period $p_{B,T}$. Next, the bioenergy supply curve is used to determine the additional quantity of biomass primary energy which can be utilized economically (see Figure 11-8):

$$q_T^{add} = q_{E,T} - q_{B,T} . \qquad (11\text{-}14)$$

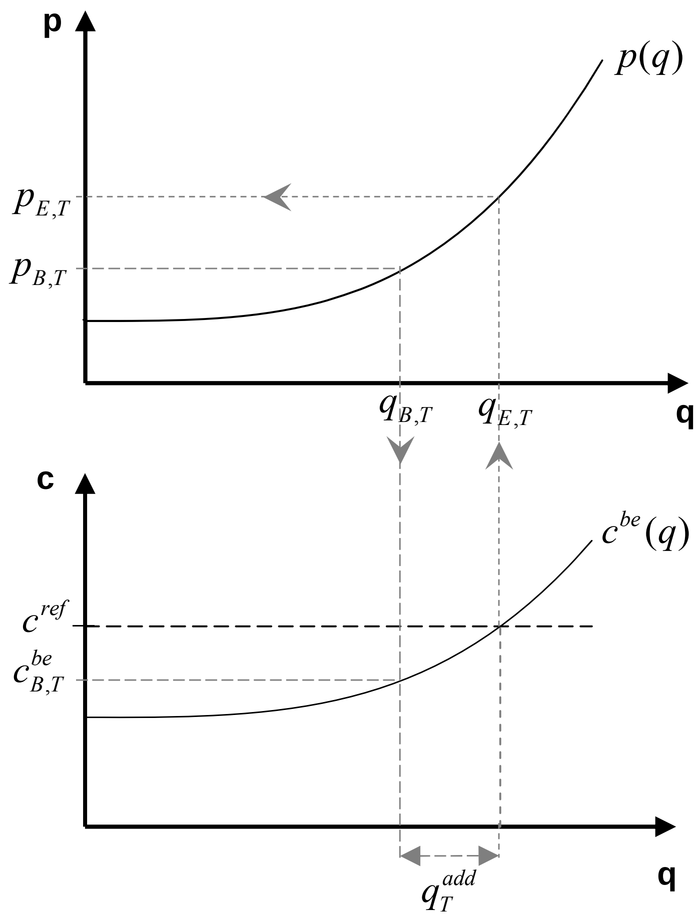

Figure 11-8. Illustration of the cost-based deployment algorithm for one simulation period, assuming one technology and one biomass type

Assuming that the economic capacity of the bioenergy technology in the period T

$$P_T^{add} = \frac{q_T^{add} \eta_T}{T_{FL,T}} , \qquad (11\text{-}15)$$

is actually deployed, the according energy generation is

$$y_T = \sum_{t=T-LT+1}^{T} P_t^{add} T_{FL,t} \qquad (11\text{-}16)$$

and the new equilibrium price for biomass is $p_{E,T}$.

11.3.1.1 Restrictions for cost-based deployment

The full capacity P_T^{add} is only deployed if (i) it is equal or bigger than the minimum plant capacity of the technology (which is specified in the technology input data) and (ii) if the demand-side potential for the according output clusters and the maximum diffusion rate for the cluster are not exceeded. Similar to the model *Green-X* (see Resch et al., 2006), this diffusion is modelled with an “S-curve approach” to emulate typical market diffusion. This diffusion is characterized by three stages: market introduction with moderate growth, increasing speed of market diffusion with a maximum growth at 50% of the full demand-side potential achieved, and increasing saturation against the end of the diffusion process. The diffusion curves are specified for each output cluster (index k) individually by the parameters δ_k and $\Delta y_k^{\max}$. The maximum additional energy generation y_k^{add} is calculated on the basis of these parameters, the generation at the beginning of the period $y_{k,B}$ and the demand-side potential $y_k^{\max}$ according to Eq. (11–17). Figure 11-9 shows the maximum additional generation as a function of the achieved demand-side potential for different parameter settings, as well as the according diffusion curves.

$$y_k^{add} = \delta_k \cdot y_{k,B} \left(1 - \frac{y_k}{y_k^{\max}} \right) \cdot \Delta y_k^{\max} \qquad (11\text{-}17)$$

It is a characteristic of this function that from $y_{k,B} = 0$ follows $y_k^{add} = 0$. In order to facilitate the start of a diffusion process, a “minimum deployment factor” $y_k^{\min}$ is defined. This factor is an exogenously defined, cluster-specific diffusion parameter, representing the value that is attributed to y_k^{add} if $y_k = 0$. This parameter is defined as percentage of the demand-side potential y_k^{add}. For example, a value of $y_k^{\min} = 5\%$ implicates that a maximum of five per cent coverage of the demand-side potential of the according demand cluster can be achieved, if $y_{k,B}$ equals zero at the beginning of this simulation period.

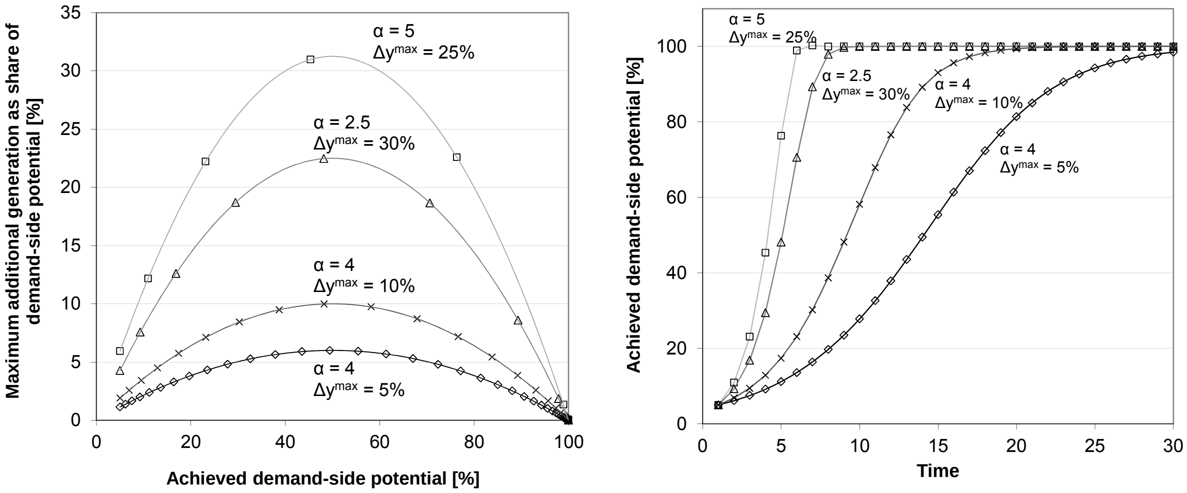

Figure 11-9. Maximum additional energy generation as function of the achieved demand-side potential for different parameter settings (left) and the according diffusion curves (right).

11.3.1.2 Modelling resource competition

In a more general situation than the one described in Figure 11-8, several bioenergy technologies compete for quantities of each biomass type. 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 fuel. The deployment algorithm of the model *SimBioSys* was designed in order to reflect these observations (see section 11.1). However, it is based on the assumption that the higher the relative difference between the energy production costs at the beginning of the simulation period and the according reference price $\left(\frac{c^{ref} - c^{be}}{c^{ref}}\right)$, the stronger is the incentive to switch from the reference system to a bioenergy technology.

Figure 11-10 shows an illustrative situation, where two bioenergy technologies, characterized by the bioenergy supply curves $c_1^{be}(q)$ and $c_2^{be}(q)$ compete for biomass in the interval [$q_{B,T}$, $q_{E,T}^I$]. It is assumed that resource allocation is determined by a profitability indicator a_j, which is calculated for each technology (subscript j):

$$a_j = \frac{1}{c_j^{ref}} \int_{q_{B,T}}^{q_{E,T}^I} \left(c_j^{ref} - c_j^{be}(q)\right) dq \ . \qquad \textit{(11-18)}$$

In Figure 11-10 the respective integrals are shown as shaded areas.

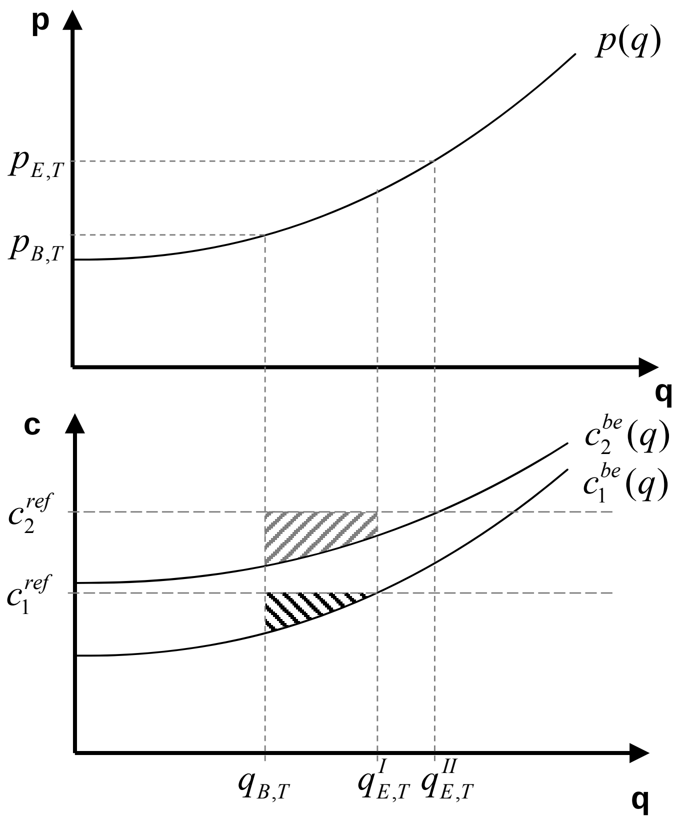

Figure 11-10. Explanatory illustration of the methodological approach for modelling resource competition

Next, the quantity $q_T^{add,I} = q_{E,T}^{I} - q_{B,T}$ is distributed among technology 1 and 2 (quantities $q_{1,T}^{add,I}$ and $q_{2,T}^{add,I}$) as follows:

$$q_{j,T}^{add,I} = q_T^{add,I} \frac{a_j}{\sum_j a_j} \qquad (11\text{-}19)$$

The quantity $q_T^{add,II} = q_{E,T}^{II} - q_{E,T}^{I}$ is fully allocated to technology 2, as $c_1^{be}(q) > c_1^{ref}$ in the interval $(q_{E,T}^{I}, q_{E,T}^{II}]$.

In the most general case, a multitude of technologies utilize numerous different biomass types. In this case, economically usable supply potentials are attributed to utilization paths according to the methodology described above, and for each fuel type successively. Consecutively, the additional installation of each technology is calculated on the basis of the biomass quantity assigned to this technology, with consideration of minimum plant sizes, demand-side potentials and diffusion curves.

11.3.2 Demand-based deployment

As already mentioned in section 11.2.4, quotas can be defined for output clusters or groups of output clusters (e.g. for transport fuels, or separately for liquid and gaseous biofuels). It is generally assumed that the fulfilment of quotas has priority against the cost-based deployment of bioenergy plants. If more than one quota is specified, quota priorities can be assigned.

The basic assumption for the quota algorithm (demand-based deployment) is that market participants aim at fulfilling the quota in the most cost-effective way possible. The according optimization problem was formally described in section 11.1.5. However, the demand-based deployment algorithm is an approximation procedure, which has been developed for the programming framework implemented in MATLAB, and has proven to be sufficiently accurate.

The modelling approach is based on the idea of deriving a "least-cost bioenergy supply curve" (*LCBSC*) for the energy output in demand, and determine the plant capacities required to reach the quota. In contrast to the bioenergy supply curves mentioned in previous sections, this supply curve is usually made up of several technologies and biomass types.

The following figures show an illustrative example of how a *LCBSC* is constructed from biomass and bioenergy supply curves: Figure 11-11 describes a situation where three technologies, utilizing two different biomass types are available to fulfil a given quota. The technologies *1* and *2* utilize biomass type a and technology *3* biomass type b. To simplify matters, linear biomass supply curves are assumed.

The *LCBSC* is constructed as follows (see Figure 11-12): Starting at c_0, technology *1* is the cheapest option for producing the quantity $\left(q^{II}\eta^{(1)}\right)$. The next segment of the *LCSC* is made up by technology *2* (which has a higher efficiency than technology *1*, resulting in a lower slope of the bioenergy supply curve). From c^{III} to c^{IV} both technology *2* and technology *3* contribute to the *LCBSC*, since they do not compete for the same fuel (as it is the case for technology *1* and *2*). At c^{IV} the maximum supply of fuel a is reached. The last segment of the *LCBSC* is therefore made up by technology *3* alone.

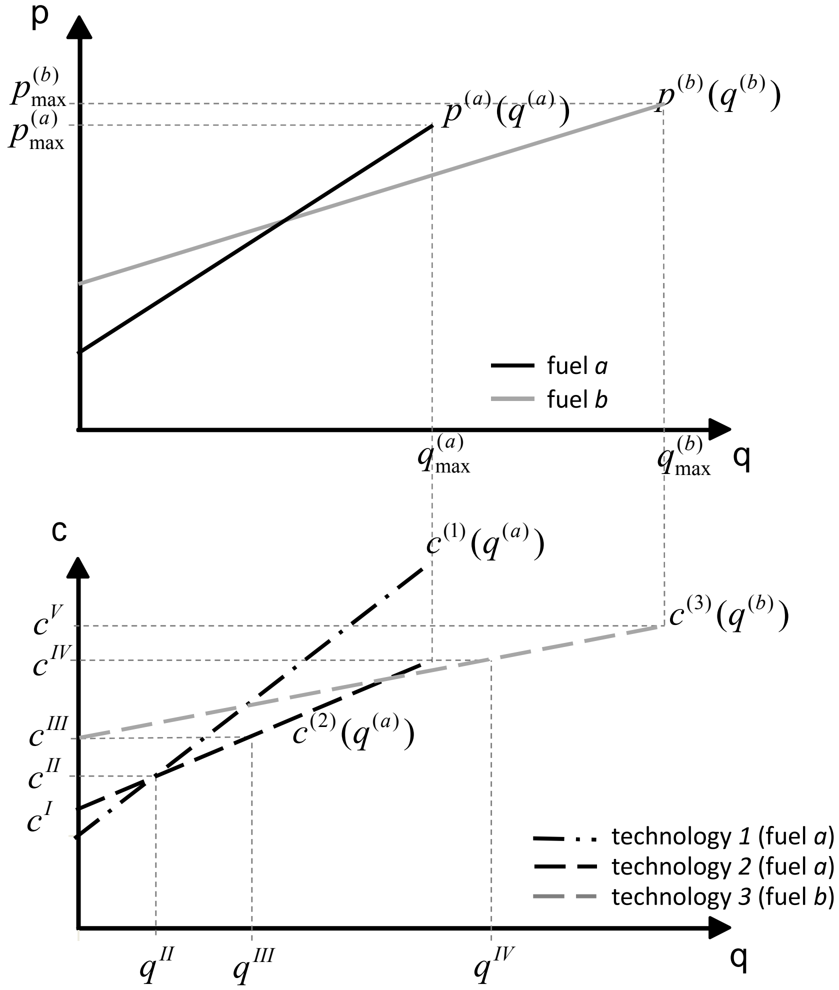

Figure 11-11. Illustrative example for the construction of a least-cost bioenergy supply curve (part 1): initial situation with biomass supply curves for two fuels (top) and according bioenergy supply curves of three technologies (bottom).

Consequently, the $LCBSC$ is used to determine the deployment required to fulfil a certain demand y^{demand} (corresponding to a given quota) in a most cost-effective way as follows: The intersection point of the horizontal line at y^{demand} with the $LCBSC$ determines the certificate price c^{cert} of energy commodities contributing to the fulfilment of the quota. This price is also used for calculating the support costs arising from an obligatory quota (see section 11.3). Assuming the simplified equation for the energy generation cost according to Eq. (11–2) and with the quantities $q_{cert}^{(a)}$ and $q_{cert}^{(b)}$ defined according to Eq. (10–20), the capacities $P^{(1)}$, $P^{(2)}$ and $P^{(3)}$ required to fulfil the quota in a most cost-effective way are determined according to Eq. (11–21).

$$c^{(2)}\left(q_{cert}^{(a)}\right) = c^{(3)}\left(q_{cert}^{(b)}\right) = c^{cert} \qquad (11\text{-}20)$$

$$P^{(1)} = \frac{q^{II}}{T_{FL}^{(1)}} \cdot \eta^{(1)}, \qquad P^{(2)} = \frac{\left(q_{cert}^{(a)} - q^{II}\right)}{T_{FL}^{(2)}} \cdot \eta^{(2)}, \qquad P^{(3)} = \frac{\left(q_{cert}^{(b)}\right)}{T_{FL}^{(3)}} \cdot \eta^{(3)} \qquad (11\text{-}21)$$

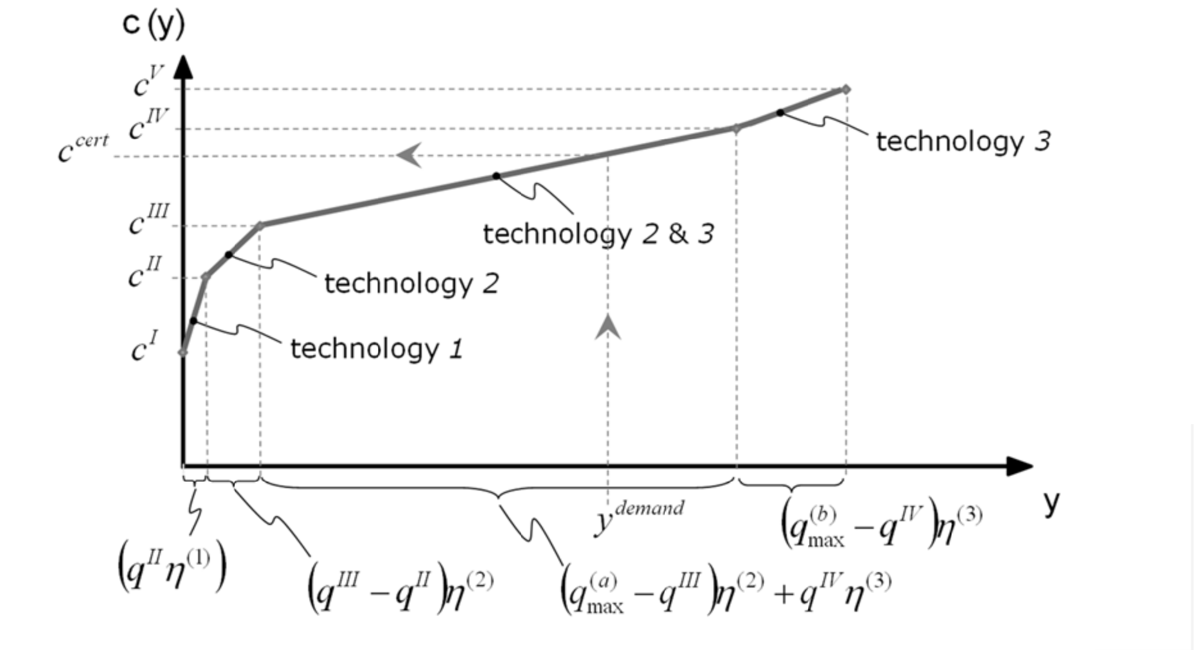

Figure 11-12. Illustrative example for the construction of a least-cost bioenergy supply curve (part 2): constructing the least-cost bioenergy supply curve

11.3.3 Biomass imports

The modelling approach of *SimBioSys* is basically focused on simulating the use of biomass potentials in the country or region under consideration. However, biomass imports need to be taken into account for three reasons: (i) In order to model the status quo of bioenergy use (i.e. the initial situation for scenario simulations) appropriately, cross-border trade needs to be considered.[51] (ii) In certain situations the domestic supply potential of a biomass type may decrease, for example due to exogenously assumed land-use trends, or exogenous scenarios for the wood processing industries. This may result in a supply shortage for existing bioenergy plants. In such a case it is assumed that these plants are supplied by imports. (iii) If an obligatory quota cannot be fulfilled with domestic resources, biomass imports are required.

Hence, imports of biomass from outside the region or country under consideration are taken into account in the simulation algorithms as follows:

- If there are not sufficient domestic biomass resources available to supply the demand of existing bioenergy plants, the shortage is covered with imports.

[51] For the case of Austria, biomass imports are especially relevant for the production of biodiesel (see section 7.4).

- The prices of imports are defined exogenously and are – contrary to domestic resources – not influenced by the demanded quantity.
- For the fulfilment of quotas, the use of domestic resources can either be prioritized to imported biomass or not. In the first case, imports are only used if there are not enough domestic resources available to fulfil the quota. In the second case, imports are used as soon as they allow for the quota to be fulfilled in a more cost-effective way.

Table 11-3. Overview of output data of the model SimBioSys.

broken down by… **Output data (time series)**	energy commodities [a]	utilization paths	technology clusters	biomass types	*Unit*
New capacity installation		X			[MW]
Total installed capacity		X			[MW]
Energy generation	X	X	X		[GWh/a]
Production of byproducts		X	X		[10^6 t/a]
Energy generation cost of new plants		X			[€/MWh]
Average energy generation cost of existing plants		X			[€/MWh]
Price of biomass fuels				X	[€/MWh]
Costs of support schemes [b]		X			[10^6 €/a]
Fuel demand		X		X	[GWh/a]
Fuel imports				X	[GWh/a]
Quantity of GHG emission reduction [c]		X	X		[t CO_2-eq./a]
Net GHG emission reduction [d]		X	X		[t CO_2-eq./a]
Quantity of fossil fuels replaced [e]		X	X		[GWh/a]
Net fossil fuel replacement [f]		X	X		[GWh/a]
Average cost of GHG mitigation		X	X		[€/t CO_2-eq.]
Average cost of fossil fuel replacement		X	X		[€/MWh]
Average specific producer surplus				X	[€/MWh]
Total producer surplus				X	[10^6 €/a]

a) heat / electricity / fuel

b) also broken down by the different types of support schemes

c) GHG emissions of replaced reference systems

d) GHG emissions of replaced reference systems minus GHG emissions of bioenergy systems

e) fossil fuel demand of replaced reference systems

f) fossil fuel demand of replaced reference systems minus fossil fuel demand of bioenergy systems

11.3.4 Model output data and scenario evaluation

Most output data are provided in disaggregation by various parameters. For example, data on GHG reduction are provided broken down by utilization paths and technology clusters. Table 11-3 gives an overview of the core model output data and the according forms of disaggregation in which they are available.

All output data are provided in the form of time series for the simulation period and an arbitrary number of preceding years. For these preceding years, the model only calculates certain output data on the basis of given data on installed capacities, which need to be provided exogenously.[52] The obvious advantage of this feature is that the model output data comprise the transition from exogenously given (historic) time series to simulated ones.[53]

11.4 Model verification

In the following sections, the results of exemplary simulation runs, carried out for model verification, are presented. Based on simple scenario assumptions, these simulation runs illustrate that the model algorithms have been implemented properly and that the model is working correctly. Moreover, these simulations are to provide further insight into the properties of the simulation algorithms.

11.4.1 Cost-based deployment

This exemplary simulation run is to illustrate the following aspects of the model:

- Deployment of competitive plants
- Market diffusion (S-curve approach)
- Decommissioning and replacement
- Formation of biomass prices
- Implications of myopic investment decisions

In this scenario, an illustrative market introduction of pellet boilers is simulated. The scenario is characterized by the following features:

- Three types of pellet boilers are considered (15, 30 and 50 kW).
- A pellet supply curve according to Eq. (11–1) is assumed. The assumed parameters describing the curve are: $a = 30, b = 0.03, \varepsilon = 0.45$.

[52] Therefore, it is also possible to use the model to just evaluate exogenously given scenarios with regard to GHG mitigation, fossil fuel replacement, biomass primary energy demand etc.

[53] For the model applications presented in section 12, the output parameters are evaluated on the basis of historic data for the period 2000 to 2010, and 2011 is the first actual simulation year. (In fact, the historic input data for the year 2010 are estimates, based on preliminary data and extrapolation.)

- There are no existing capacities at the beginning of the first simulation period.
- The reference prices, technology data as well as the pellet supply remain constant during the whole simulation.
- 26 years are simulated. The lifetime of pellet boilers is assumed 20 years.

The simulation results are illustrated in the following figures. Figure 11-13 shows the development of energy generation costs of pellet boilers and reference prices (top) and the heat generation broken down by types of pellet boilers (bottom). At $t = 0$, the heat generation costs of the 50 kW- and the 30 kW-pellet boilers are below the reference prices. Therefore, and because there are sufficient unused biomass and demand-side potentials, capacities of the two boiler types are installed. As the 15 kW-boiler is not competitive throughout the whole simulation period, no deployment of this boiler type occurs. In Figure 11-14 the development of annual installations and the cumulated capacities of 30 and 50 kW-boilers are depicted. The figures illustrate that as long as the pellet boilers are competitive, the deployment of the 30 kW- and the 50 kW-pellet boilers as well as the resulting heat generation follow the S-shaped diffusion curves. For illustrative purposes, the demand-side potential of the 50 kW-cluster is assumed clearly higher than the one of the 30 kW-cluster, and a higher diffusion speed is assumed for the 30 kW-cluster.

At $t = 14$, the pellet price has reached a level where the energy generation cost of the 30 kW-boilers are equal to the reference price. Therefore, the market diffusion of this cluster comes to a halt, whereas the 50 kW-boilers remain competitive until $t = 20$. Due to the increasing pellet demand during the period $t = [14,20]$, the pellet price and also the heat generation costs of all existing plants continue to rise until the fuel demand has reached a steady state at $t = 20$. With *SimBioSys* being a myopic simulation model, the fact that the heat generation costs of existing 30 kW- boilers are higher than the reference prices after $t = 14$ is the result of a fuel price development which was not anticipated by the market actors.

The reduction of the heat output (Figure 11-13) and the installed capacities (Figure 11-14) of 30 kW-boilers at $t = 20$ and the following simulation periods is due to the decommissioning of plants. In contrast, 50 kW-boilers going out of operation are replaced by new ones, which explains the installations after $t = 20$. As the replacement of old plants is not subject to diffusion restrictions, the new installation at $t = 20$ (being made up of old plants which are replaced and continuing market diffusion) is clearly higher than the one in previous years.

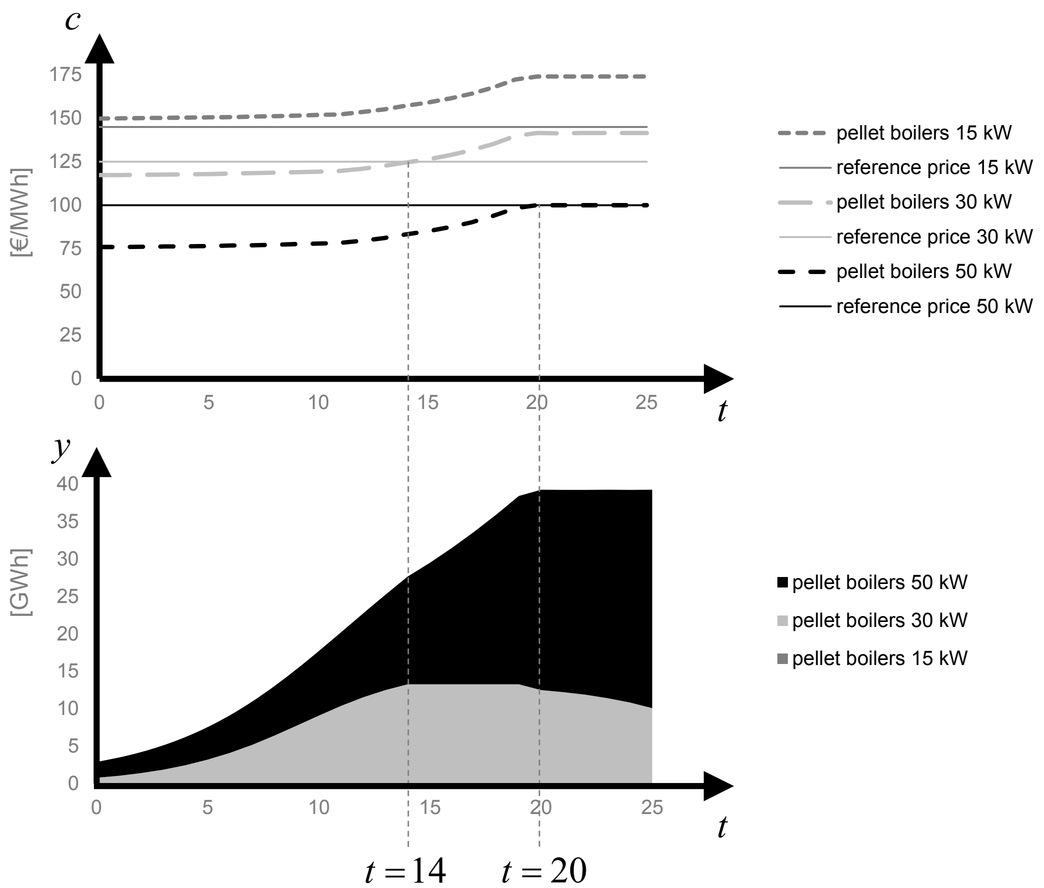

Figure 11-13. Development of energy generation costs of pellet boilers and reference prices (top) and development of energy output of installed pellet boilers (bottom) in the illustrative simulation.

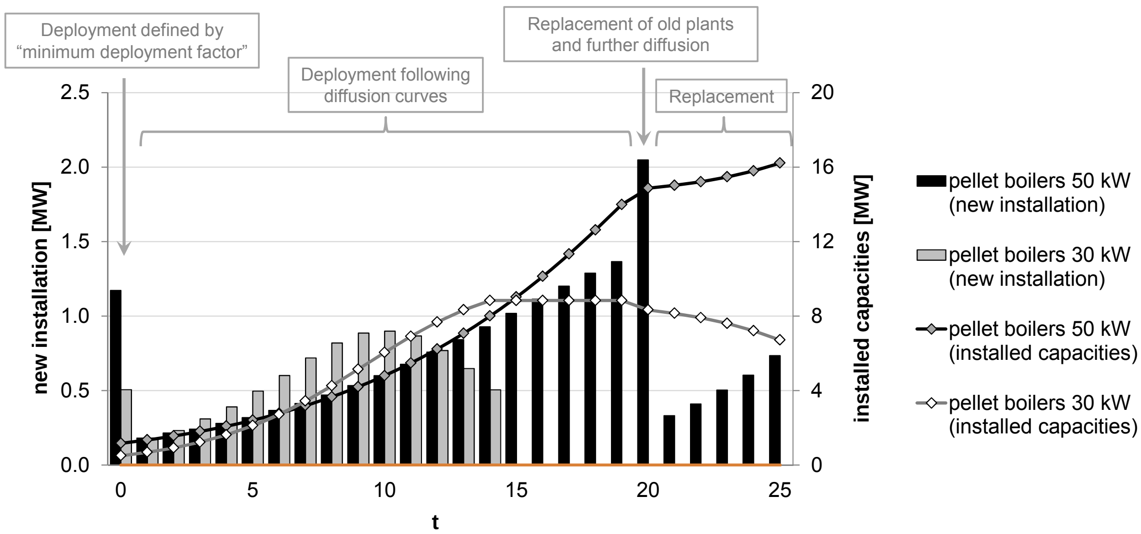

Figure 11-14. Development of annual installations of pellet boilers and total installed capacities in the illustrative simulation.[54]

[54] The relatively high installation at $t = 0$ result from "minimum deployment factors" assumed 3% for the 50 kW- and 5% for the 30 kW-cluster.

With regard to the total heat output of bioenergy plants (and the total fuel demand, respectively), the decreasing contribution of 30 kW-plants is compensated by additional installations of 50 kW-boilers, resulting in a steady heat output, as well as steady pellet demand and prices, as Figure 11-15 illustrates. This figure shows the connections between the developments of biomass demand, the supply curve and the price development as well as the producer surplus. It illustrates how the pellet demand continues to rise until it reaches a steady state at an equilibrium price of approximately 40 €/MWh. Hence, the figure provides evidence, that the simulation algorithms are consistent with the theoretical fundamentals.

With regard to the producer surplus, it can be seen that resulting from the shape of the supply curve and the price development, the producer surplus is very low during the first ten simulation periods or so. As steeper regions of the supply curve are reached, the producer surplus increases sharply.

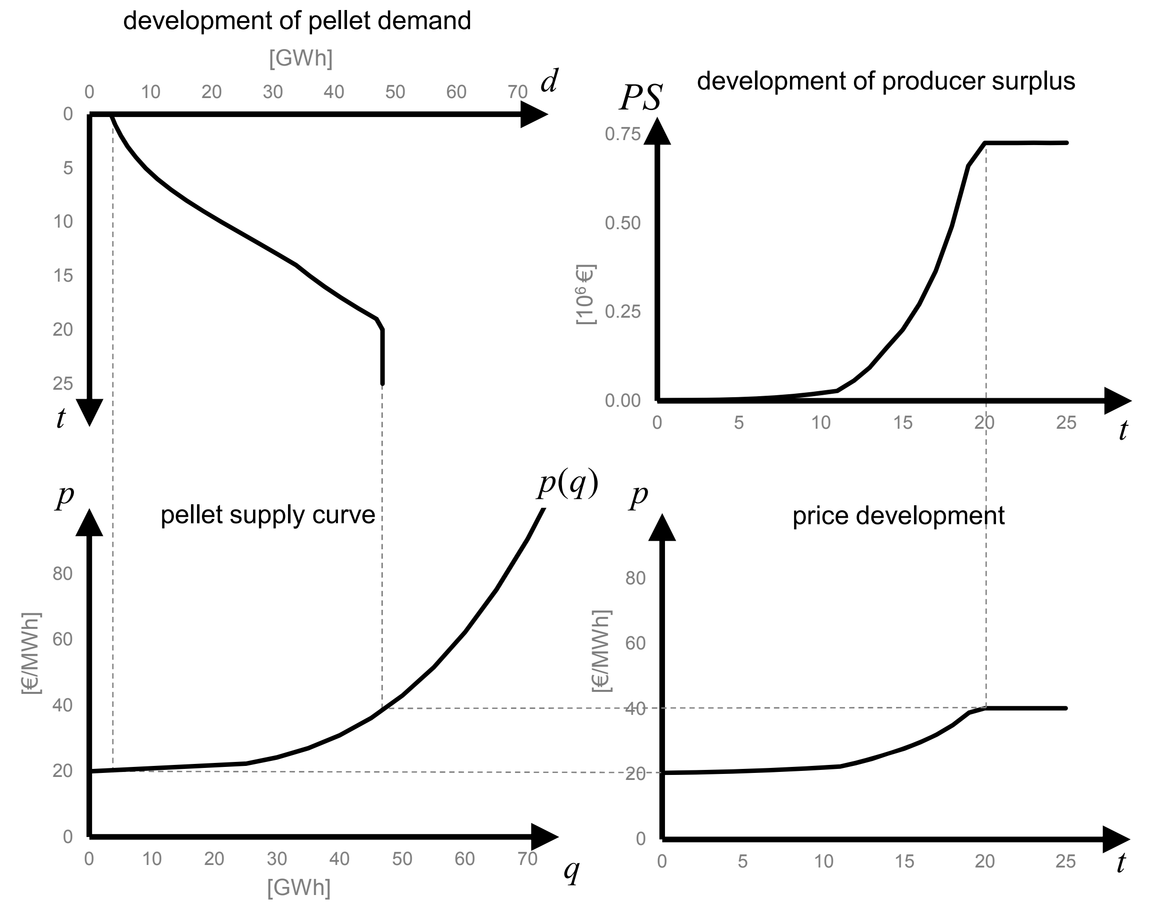

Figure 11-15. Connections between development of the demand, the supply curve and the price development as well as the producer surplus in the exemplary simulation run (cost-based deployment).

11.4.2 Demand-based deployment

This simulation run illustrates the results of the demand-based deployment algorithm. In contrast to the exemplary simulation presented in the previous section, only one period is simulated, but the obligatory quota which needs to be met with bioenergy technologies is varied from 0 to 5,000 GWh by steps of 100 GWh. Hence, 51 simulations are carried out. In order to increase the clarity of the exemplary simulation results, minimum plant capacities are assumed negligibly small, so they do not have an impact on the simulation results.

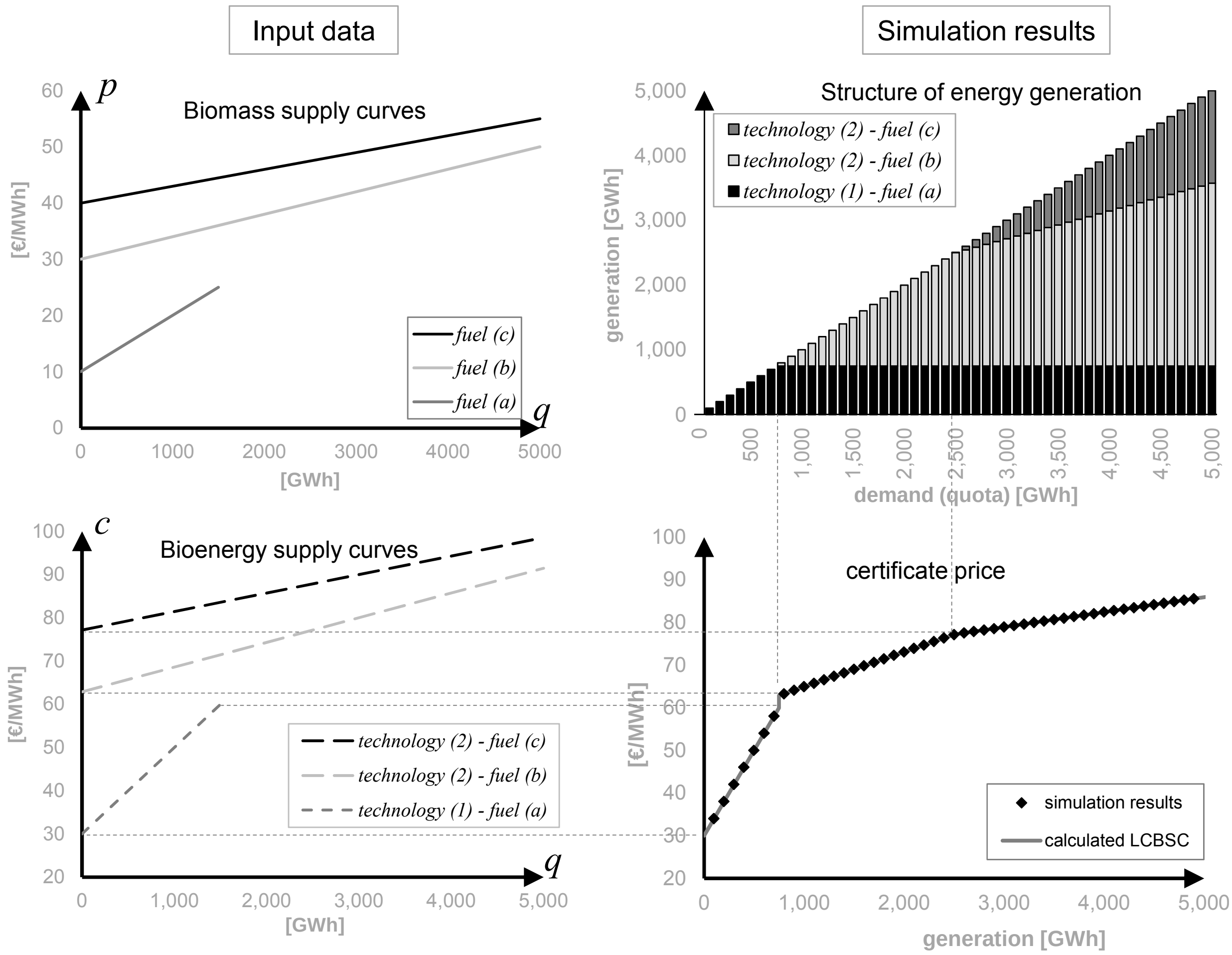

Figure 11-16. Input data and simulation results of the exemplary simulation run (demand-based deployment)

With regard to technologies and biomass supply curves, the assumed situation is similar to the one illustrated in section 11.3.2: There are three different biomass fuels available, characterized by linear supply curves. Two different technologies can be used to meet the demand. Technology *(1)* utilizes fuel *(a)* and technology *(2)* utilizes fuel *(b)* and *(c)*. Figure 11-16 (left) shows the assumed biomass and bioenergy supply curves. Figure 11-16 (right) illustrates the simulation results. The graph shown in the top right part of the figure depicts the structure of energy generation, and the one in the bottom right part shows a comparison of the calculated *LCBSC* with the maximum production costs depending on the quota. In the model these costs are interpreted as the certificate price resulting from the level of the quota. As the comparison shows, the model results correspond to the calculated *LCBSC*.

The figure illustrates that the simulation results are consistent with the theory presented in section 11.3.2: The output of technology *(1)* increases until fuel *(a)* is used exhaustively, since the maximum costs of the utilization path “technology *(1)* – fuel *(a)*” are lower than the minimum costs of technology *(2)*. As soon as fuel *(a)* is used exhaustively, the utilization path “technology *(2)* – fuel *(b)*” is deployed. For fulfilling quotas of more than 2,400 GWh, both fuel *(b)* and fuel *(c)* are used, because the most cost-efficient outcome is achieved when the marginal costs of both fuels are identical.

11.5 Conclusions, discussion and options for expansions

The core objective in the design of the model *SimBioSys* was to develop a software tool suitable for deriving medium to long-term scenarios for the bioenergy sector, based on biomass supply curves and different exogenous scenario parameters, such as fossil fuel price developments, energy demand trends etc.

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 large 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, as economic efficiencies of bioenergy options vary widely for different technologies, plant sizes and applications (as it is shown in Part I of this work).
- *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 (see section 11.2.3).
- *Taking into account numerous influencing parameters including different support schemes, technological progress, energy demand trends and their impacts on the demand-side potentials of bioenergy technologies* (see sections 11.2.1 and 11.2.4).
- *Deriving appropriate algorithms for simulating investment decisions*. For the modelling algorithms of *SimBioSys*, a special focus was given to avoiding penny-switching effects and modelling resource competition among bioenergy technologies (see sections 11.3.1 and 11.3.2).
- Biomass resource potentials and their provision costs 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 supply costs often vary over a wide range (see section 11.2.2).

- *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, fossil fuel savings and domestic biomass producer surplus on the other (see section 11.3.4).

There are several ideas for model expansions and additional features, for which conceptual designs have been developed but which have not yet been implemented into the model. Three of the most promising options for model expansions and the concepts for their implementation are described in the following paragraphs:

- **Implementation of cross-border trade**. Currently, the model is implemented for simulating one country or region, and biomass imports are modelled with constant import prices. A major step in the model applicability would be to allow for the parallel simulation of a number of countries or regions, and the incorporation of cross-border trade, based on the supply curves of the individual regions into the modelling algorithms.

  The basic concept for implementing this feature is to allow for each country/region to access the supply curves of potential trade partners. Transport costs can be implemented as surcharges on the supply costs, depending on the geographic location of the trade partners and the biomass type.
- **Endogenous technological learning**. In the current version of the model, all technical data are implemented as dynamic parameters, allowing for the implementation of exogenous cost reductions and increasing efficiencies through technological learning. This is basically considered an appropriate approach if the technological learning process primarily depends on developments in other countries or regions than the one which is simulated. (For example, the development of the Austrian bioenergy sector is hardly relevant for cost reductions through technological learning in the field of advanced conversion technologies, as technological progress in this field is dominated by global developments.) However, if the model is used for developing scenarios for larger regions (e.g. the EU-27), the implementation of endogenous technological learning could be a substantial improvement.

  Based on the concept of learning curves, endogenous learning means that with each unit of a certain technology installed, experience in the production and deployment process is gained, resulting in reduced investment costs (and eventually also reduced operation and maintenance costs) in the next simulation period $(T+1)$. The basic approach for implementing endogenous learning is to replace an exogenously given time series for technology data with a single value for the first simulation period, and calculate the data for each successive period on the basis of the original cost data, the cumulative plant capacities installed in all preceding years and an exogenous parameter referred to as “learning index”. The calculation is based on the common relationship describing learning curves (or experience curves, as they are sometimes called in the context of energy systems; cp. Junginger et al., 2006, for example)

$$C_{T+1} = C_T \left(\sum_{i=0}^{T} P_i \right)^b \text{ or} \tag{11-22}$$

$$\log(C_{T+1}) = \log(C_T) + b \cdot \log\left(\sum_{i=0}^{T} P_i \right), \tag{11-23}$$

where C_T and the C_{T+1} denote the cost data in the year T and $(T+1)$, respectively, and P_i the production (or capacity installed) in the year i. The parameter b is the learning index (or experience index), which is often translated to the progress ratio PR, defined as

$$PR = 2^b \tag{11-24}$$

The progress ratio describes the rate of unit cost decline with each doubling of cumulative production.

In general, it is appropriate to assume that technological learning does not occur for each technology type individually, but for certain groups of technologies (e.g. biogas technologies, including all plant sizes of biogas CHP plants and biomethane plants). Therefore, the implementation of endogenous learning implies the definition of “learning clusters”, so that the cost reductions of a certain technology type are not only influenced by the cumulative installation of this specific type but all technologies within the according learning cluster.

- **Simulation of other renewable energy technologies and energy efficiency measures**. Even though *SimBioSys* was designed for simulating scenarios of the bioenergy sector, the implementation of other renewable energy technologies is basically possible. The most important benefit would be that the competition between bioenergy and other renewable energy technologies with regard to demand-side potentials and subsidies could be assessed. Similarly, the implementation of energy efficiency measures (which reduce the total energy demand and demand-side potentials by investments in building insulation, for example) could improve the quality of the model results. It is, however, recognized that these additional features would result in significant extensions of input data requirements.

12 Model applications

Applications of the model *SimBioSys* are presented in this section. The focus is on the description and interpretation of the simulation results, as methodological aspects of the model were described in the previous chapter. Furthermore, the simulation results serve as basis for a discussion on the prospects of bioenergy use in Austria. This discussion is augmented by supplementary analyses, which are partly not based on the simulation model (section 12.1.3.4).

The model application presented in section 12.1 is focused on agricultural bioenergy. In section 12.2 simulations for the Austrian bioenergy sector under different climate scenarios are described.

12.1 Agricultural bioenergy in Austria – Simulations up to 2030

12.1.1 Motivation and objective

The enhanced use of bioenergy in Austria in recent years was partly based on an increasing use of agricultural resources, such as rapeseed for biodiesel and cereal grain for bioethanol production, as well as biogas production from agricultural feedstock. With regard to energy policy objectives in the field of greenhouse gas mitigation and renewable energy sources (Kyoto Protocol, Renewable Energy Action Plan, "2020 targets" etc.), it is often expected that agricultural biomass will play a crucial part in establishing a sustainable energy system in Austria.

The analyses presented in this section have been carried out within the project “ALPot – Strategies for a sustainable mobilization of agricultural bioenergy potentials” (Kalt et al. 2010a). The core objective is to gain insight into the achievable contribution of agricultural biomass in the Austrian energy system under different framework conditions, as well as into costs and benefits of different support policies. However, as the availability and use of forest biomass and biogenic residues and wastes has an influence on the demand for agricultural resources, these fractions are also taken into account within the simulations.[55]

12.1.2 Input data and exogenous scenario parameters

In the following sections, the input data and exogenous scenario parameters for the model simulations are summarized: the price and energy demand scenarios are presented in section 12.1.2.1 and 12.1.2.2, respectively, and the biomass supply curves in 12.1.2.3. Section

[55] Waste liquor and the biogenic fraction of municipal solid waste, which are usually also included in energy statistics on biomass use, are not taken into account here.

12.1.2.4 gives an overview of the different scenarios and the support schemes assumed. The assumed technology data and assumptions on technological learning correspond to the data used in Part I (see Annex).

12.1.2.1 Price scenarios

The following figures show the fossil fuel price developments assumed for the simulations in this section. The scenario *FAO/Primes* is based on price scenarios according to OECD/FAO (2008) and Capros et al. (2008). In this scenario the real crude oil price is assumed to increase to slightly more than 100 $\$_{2007}$/bbl until 2020 and 113 $\$_{2007}$/bbl until 2030.[56] The price scenario *Level 2006* is based on the assumption that the real prices remain constant at the level of the year 2006. In fact, this scenario is considered rather unlikely, but it serves as a reference scenario for the *FAO/Primes scenario*, in order to illustrate the impact of increasing fuel prices. (With regard to the high price volatility in recent years, the price level in 2006 is considered a reasonable assumption.)

Figure 12-1 shows the historic price developments since the year 2000 and the price scenarios up to 2030 for crude oil and the transport fuels diesel and gasoline (wholesale prices per MWh_{HHV}; taxes not included). Figure 12-2 and Figure 12-3 show the price scenarios for the fuels natural gas (small and large consumer prices) and domestic fuel oil, and electricity, respectively. With regard to the latter, it is assumed that a modern natural gas CCGT power plant is the price setting technology. Hence, the reference price for electricity corresponds to the power generation costs of this technology and is based on the assumed price scenario for natural gas and projected technology costs according to Cosijns et al. (2007). Prices for CO_2 emissions are not taken into account here, as support schemes are defined for each scenario individually (see section 12.1.2.4). For the period from 2000 to 2008, the historic development of the representative electricity price (base load price index EEX Phelix Base) as well as the calculated power generation costs of the reference technology is shown in Figure 12-3.

[56] All monetary data in this section are real prices or costs with the base year 2007.

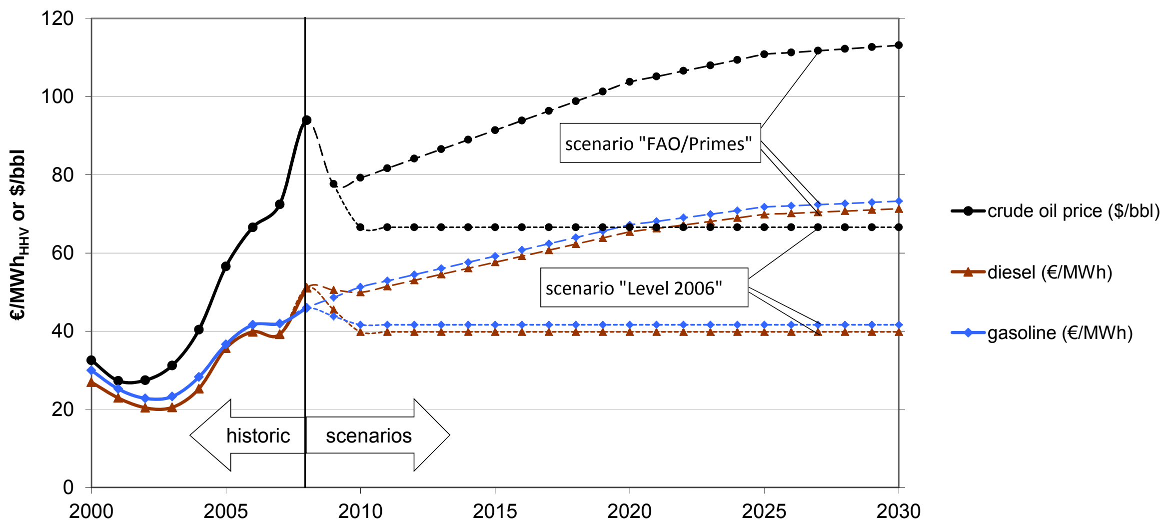

Figure 12-1. Historic price development of crude oil and fossil fuels from 2000 to 2008 and scenarios up to 2030

Sources: Mineralölwirtschaftsverband e.V. (2010) according to OPEC Bulletin, Petroleum Intelligence Weekly, Statistik Austria (2010c), Eurostat (2010a): historic developments, Capros et al. (2008): relative price increase in the scenario FAO/Primes, own calculations and illustration

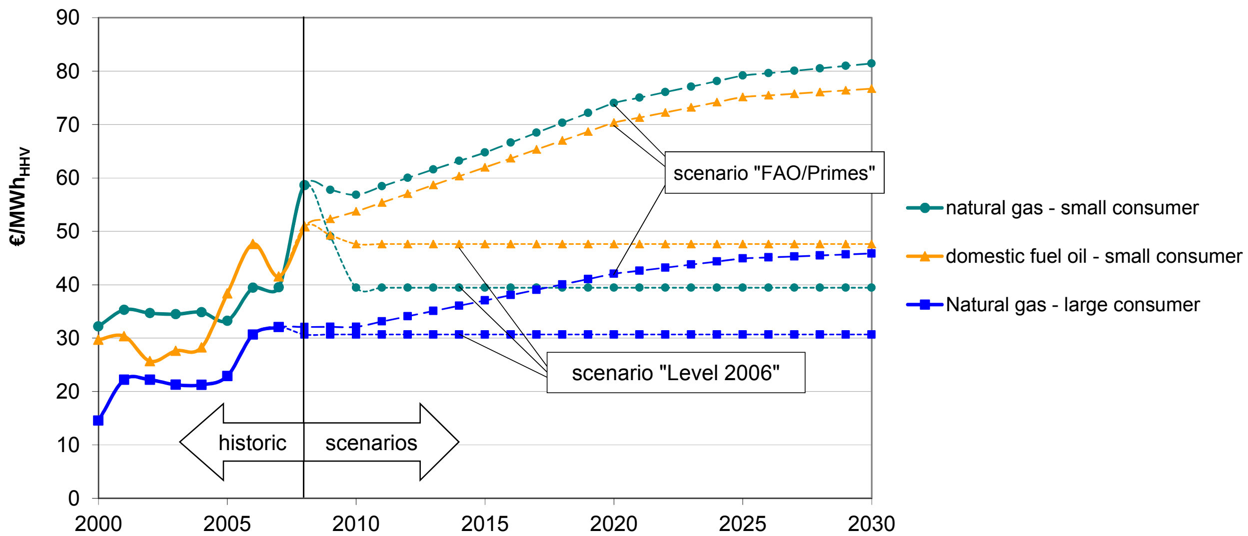

Figure 12-2. Historic price development of fossil energy carriers from 2000 to 2008 and scenarios up to 2030

Sources: Statistik Austria (2010c), Eurostat (2010a): historic developments, Capros et al. (2008): relative price increase in the scenario FAO/Primes, own calculations and illustration

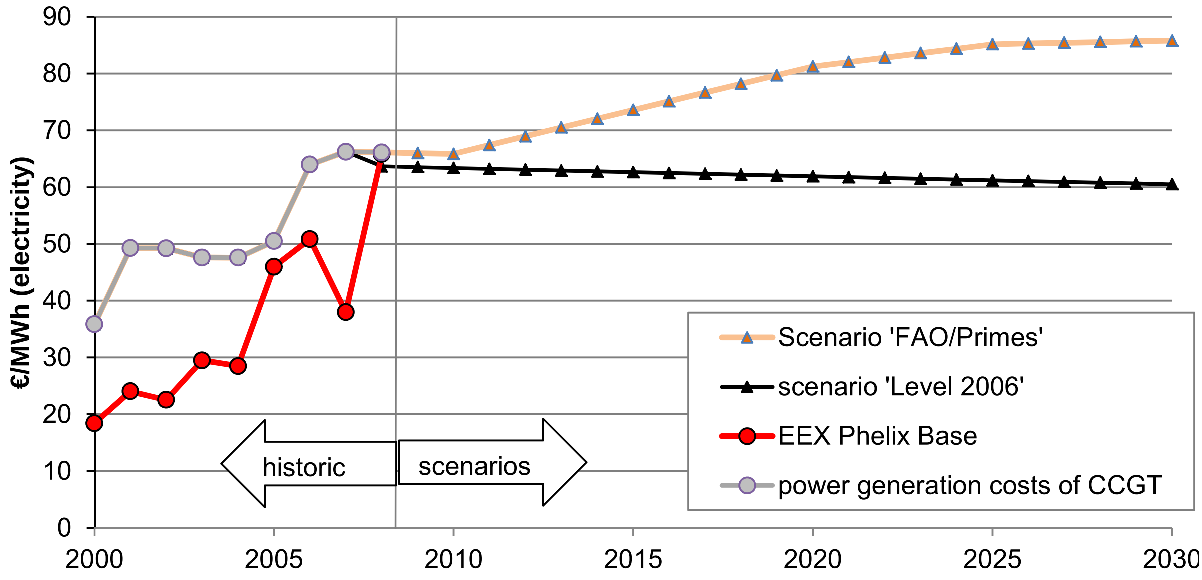

Figure 12-3. Historic electricity price development from 2000 to 2008 (base load price index EEX Phelix Base) and electricity generation costs of a modern CCGT plant from 2000 to 2030 (based on historic natural gas price development and price scenario up to 2030)
Sources: EEX (2010), Cosijns et al. (2007): technology data of CCGT plant, Capros et al. (2008): relative price increase in the scenario FAO/Primes, own calculations and illustration

12.1.2.2 Energy demand

The future development of the energy demand assumed for the simulations in this section are based on scenarios and model results in literature as well as own assumptions. The basic assumption is that the total energy demand shows a moderate decrease up to 2030.[57]

With regard to the sectoral developments, the scenarios are based on the following references: The growth rate of the electricity demand is based on Capros et al. (2008) (28% increase from 2008 to 2030). The assumed development of the annual transport fuel consumption is also based on Capros et al. (2008) and shows an almost constant value up to 2030.[58] The annual industrial heat demand (process heat, steam generation and industrial ovens) is also assumed to remain constant at the average level of the years 2005 to 2008. With regard to the low temperature heat demand (residential heating and water heating), an ambitious scenario according to Kranzl et al. (2010) is assumed. This scenario is based on simulation results of the model *ERNSTL*, which is used to simulate the energy demand for

[57] This assumption is basically in line with objectives according to the *Austrian Energy Strategy* (BMLFUW et BMWFJ, 2010).

[58] With regard to the technological options for increased efficiency in the electricity and transport sector, these scenarios appear as business-as-usual scenarios rather than ambitious ones. However, in consideration of the historic developments and the objectives according to the *Austrian Energy Strategy* (BMLFUW et BMWFJ, 2010), they are deemed reasonable assumptions.

heating based on the existing building stock and economic assessments for building refurbishment. In the scenario assumed here, the annual rate of refurbishment increases to 2.4%. Figure 12-14 illustrates the development of the heat demand according to this scenario, broken down by their location in rural or urban areas as well as heat loads. Due to continual building refurbishment, not only the total residential heat demand decreases, but there is also shift from dwellings with high heat loads (> 30 kW) to such with lower ones (15 to 30 kW and < 15 kW).

The structure of the heat demand is a main influencing factor for the demand-side potentials of biomass heating systems and heat plants. The main barriers and limiting factors for the applicability of bioenergy technologies include temperature levels, the structure of residential buildings as well as the location of the plant. As biomass heating systems are more likely to be installed in rural regions, it is simplistically assumed that the demand-side potential includes only buildings in rural areas. Urban areas can only be supplied with heat from biomass via district heating networks. Moreover, a continuing diffusion of solar thermal heating systems and heat pumps is assumed, resulting in a further reduction of the demand-side potential of biomass heating systems. All in all, the resulting demand-side potential of biomass heating systems is considered a rather conservative estimate. With regard to the demand-side potentials of biomass heating plants supplying district heating networks, it is assumed that existing heating plants fired with fossil fuels can successively be replaced with biomass plants.

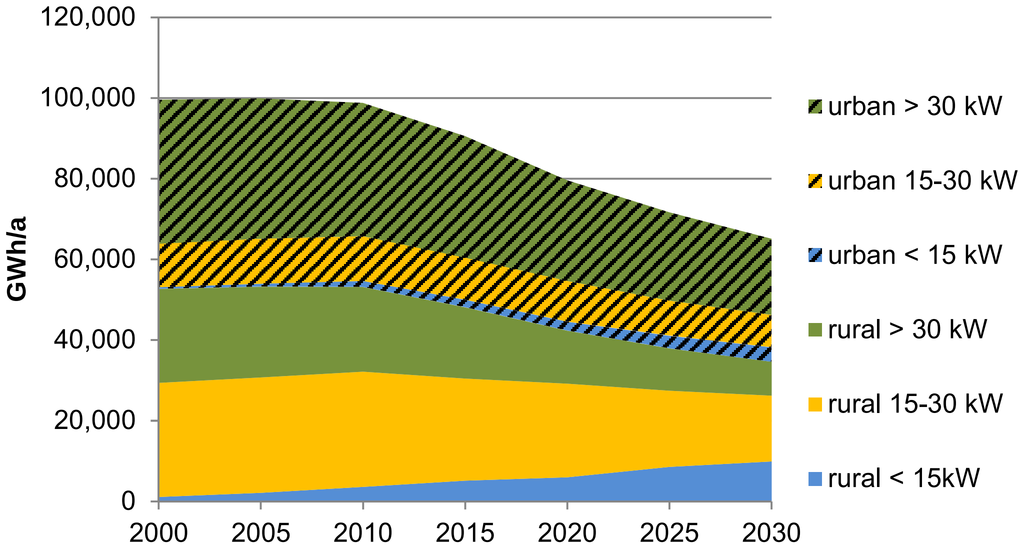

Figure 12-4. Development of the demand for low temperature heat broken down by rural and urban areas and heat loads.

Source: Kranzl et al. (2010)

12.1.2.3 Biomass supply curves

The supply curves for agricultural biomass are based on a the results of an integrated spatially explicit land use modelling framework (see Schönhart et al., 2010 for a description of the modelling framework and Kalt et al., 2010a for the actual application). In this modelling approach, specific focuses on different crop types were assumed ("energy crop scenarios"). Hence, it was assumed that energy crop production in Austria is either focused on conventional crops (oilseeds, common types of cereals, sugar beet etc.), biogas plants (maize silage and other types of silage) or short rotation forestry (primarily poplar). The following figures show the supply curves for the energy crop scenarios "conventional", "biogas" and "lingocellulose". Each figure shows the supply curves for the base year 2006 and 2030. The time dependence of the supply curves result from the underlying scenarios concerning prices for agricultural commodities (OECD/FAO, 2008), agricultural policies[59] and production costs, which are influenced by energy and fuel prices.

The supply curves basically refer to the energy content (lower heating value) of the energy crops, with the exception of biogas substrates, for which both prices and potentials refer to the energy content of the crude biogas yield after co-fermentation with 10% manure (percentage by energy content).

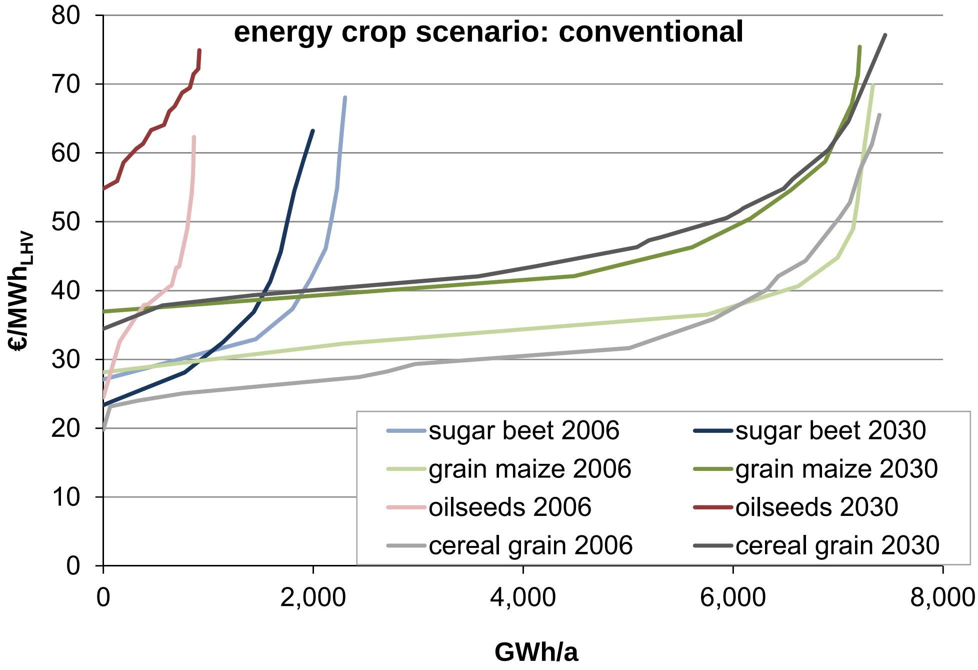

Figure 12-5. Supply curves in the energy crop scenario "conventional crops" (VAT not included)

[59] The reforms in the Common Agricultural Policy (CAP) which have been agreed on within the "Health Check" in November 2008 and are to be implemented by the EU member states until 2013 include the following: (i) Phasing out of milk quotas until 2015, (ii) "decoupling" of direct aid to farmers from production and increased modulation, (iii) the abolition of set-aside (requirement for farmers to leave 10% of their land fallow) and (iv) the introduction of additional support schemes in the field of risk management, animal husbandry and health etc (EC, 2009c).

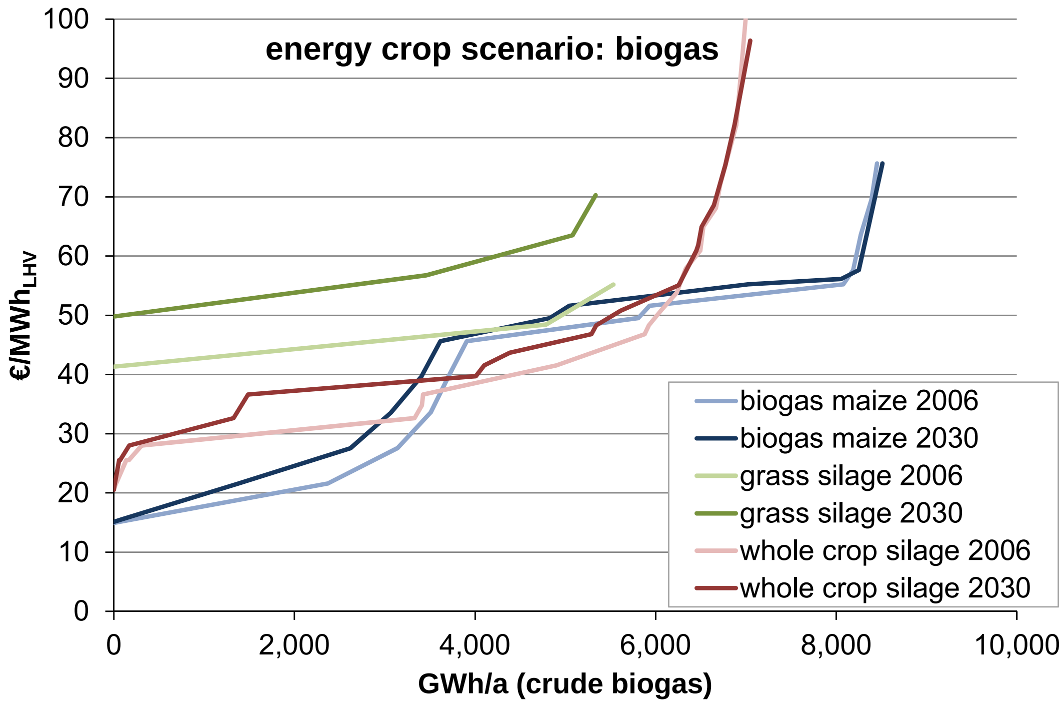

Figure 12-6. Supply curves in the energy crop scenario "biogas"
(VAT not included; energy units refer to the lower heating value of the crude biogas yield after co-fermentation with 10% manure)

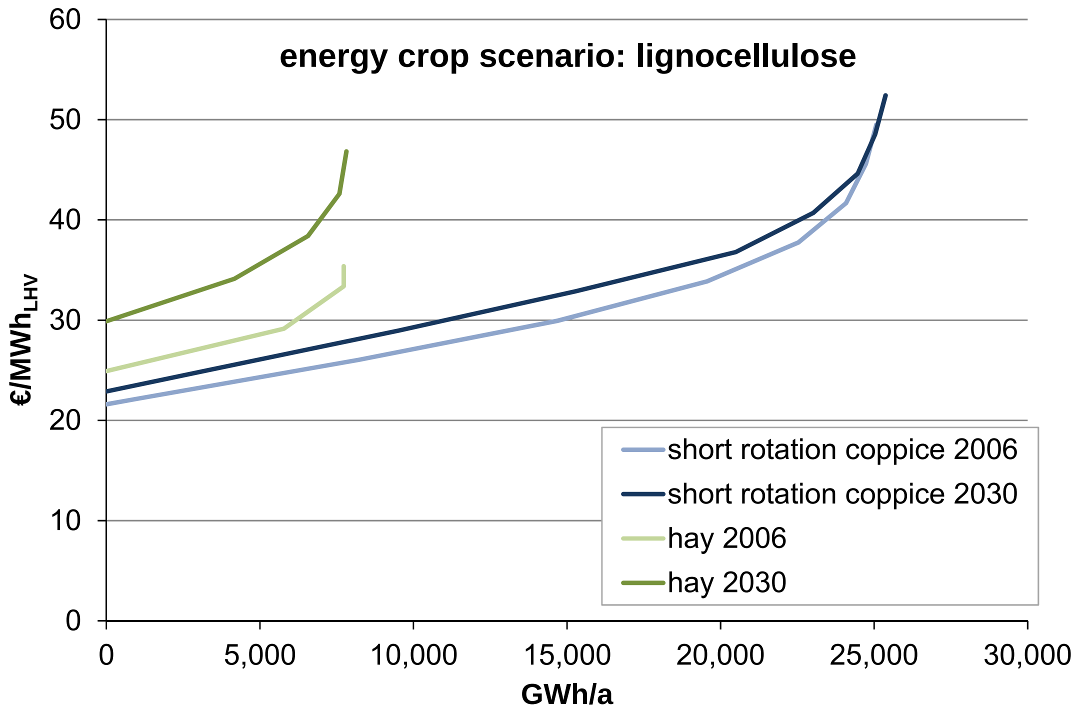

Figure 12-7. Supply curves in the energy crop scenario "lignocellulose"
(VAT not included)

For the potential of cereal straw it is assumed that up to 30% of the total production (including straw from energy crops as well as from food and feed crops) can be used energetically (cp. assumptions in other studies, summarized in Table 8-2). The costs of straw are assumed to range from 60 to 70 €/t (cp. FNR, 2007), with the supply potential being equally distributed in this range (i.e. a linear supply curve is assumed).
The supply curve assumed for forest biomass is based on Kranzl et al. (2010). According to this study, the forest biomass potential in Austria amounts to approximately 23 TWh/a in the baseline scenario, where climate change is not taken into account. The costs of the supply potential range from about 13 to 23 €/MWh (see section 12.2.1.3).
The supply potential of industrial wood residues and waste wood highly depends on the development of the wood processing industries. As a conservative approach, it is assumed that the production of the sawmill industry as well as distribution patterns of wood residues remain constant at the average level of the period 2004 to 2008 (see section 7.4.4).[60] The resulting biomass potential amounts to 23 TWh/a. It is assumed to be equally distributed in a cost range from 10 to 18 €/MWh, which corresponds to historical price data of different fractions of wood residues like bark, sawdust, wood chips etc.

12.1.2.4 Scenarios

Table 12-1 gives an overview of the different scenarios and the according settings and exogenous parameters. The following groups of scenarios are analysed: *No Policy* scenarios (no subsidies or tax incentives for bioenergy), *Current Policy* scenarios (current subsidies and tax incentives) und *Specific Support* scenarios (increasing levels of financial incentives for certain utilization paths). The results of the *No Policy* and *Current Policy* scenarios are evaluated primarily with regard to the importance of agricultural biomass to the energy supply. The main purpose of the *Specific Support* scenarios is to illustrate the support costs vs. benefits (greenhouse gas mitigation, substitution of fossil fuels) of different utilization paths and to derive conclusions regarding favourable focal points for funding. The *No Policy* and *Current Policy* scenarios include the whole bioenergy sector (i.e. agricultural, forest and industrial biomass) with the exception of biogenic wastes being utilized energetically in waste management plants and waste liquor of the paper and pulp industry. Within the *Specific Support* scenarios only certain (scenario-specific) types of agricultural biomass are considered.
With regard to the fossil fuel price developments, the two scenarios described above are distinguished: *Level 2006* (real prices remain constant at the level of the year 2006) and

[60] Just like in energy statistics, no differentiation is made between wood residues originating from domestic forests and such being indirectly imported.

FAO/Primes (increasing real prices for fossil fuel with a crude oil price of more than 100 $\$_{2007}$/bbl in 2020).

Alternative scenarios and supplementary analyses are presented in section 12.1.3.4.

Table 12-1. Overview oft the simulation runs and the corresponding scenario assumptions

		Price scenario		Biomass potentials				Support schemes and tax incentives for bioenergy						
Nr.	Title	*Level 2006*	*FAO/ Primes*	non-agri. biomass	con-ventional energy crops	biogas plants	ligno-cellulosic	Taxes: energy tax / mineral oil tax on fossil fuels	Small-scale heating systems	Heat plants	Electricity generation	Transport fuels	Feed-in of biomethane/ SNG	Section
	No Policy-Scenarios													12.1.3.1
1-1	No Policy - Level 2006	x	-	x	x	x	x	-	-	-	-	-	-	
1-2	No Policy - FAO/Primes	-	x	x	x	x	x	-	-	-	-	-	-	
	Current Policy-Scenarios (CP)													12.1.3.2
2-1a	CP - Level 2006 - no agri. biomass	x	-	x	-	-	-	current taxes, biogenous transport fuels exempt from mineral oil tax	20 % investment subsidy		current feed-in tariffs (see E-Control, 2009)	Quota[a] 2010: 5.75 % 2020: 10%	-	
2-1b	CP - Level 2006 - conventional energy crops	x	-	x	x	-	-						-	
2-1c	CP - Level 2006 - Biogas	x	-	x	-	x	-						-	
2-1d	CP - Level 2006 - lingocellulose	x	-	x	-	-	x						-	
2-2a	CP - FAO/Primes - no agri. Biomass	-	x	x	-	-	-						-	
2-2b	CP - FAO/Primes - konv. Ackerfrüchte	-	x	x	x	-	-						-	
2-2c	CP - FAO/Primes - Biogas	-	x	x	-	x	-						-	
2-2d	CP - FAO/Primes - lingocellulose	-	x	x	-	-	x						-	
	Specific Support Scenarios (SSS)													12.1.3.3
3-1a	SSS transport fuels - conventional energy crops	-	x	-	x	-	-	-	-	-	-	x[b]	-	
3-1b	SSS transport fuels - biogas (biomethane)	-	x	-	-	x	-	-	-	-	-	x[b]	-	
3-1c	SSS transport fuels (liquid) - lingocellulose	-	x	-	-	-	x	-	-	-	-	x[b]	-	
3-1d	SSS transport fuels (gaseous) - lingocellulose	-	x	-	-	-	x	-	-	-	-	x[b]	-	
3-2a	SSS heat generation- conventional energy crops	-	x	-	x	-	-	-	x[b]	x[b]	-	-	-	
3-2b	SSS heat generation- biogas (biomethane-into-g	-	x	-	-	x	-	-	-	-	-	-	x[b]	
3-2c	SSS heat generation - lingocellulose (solid fuels)	-	x	-	-	-	x	-	x[b]	x[b]	-	-	-	
3-2d	SSS heat generation- lingocellulose (SNG-into-g	-	x	-	-	-	x	-	-	-	-	-	x[b]	

a) Electric vehicles not considered

b) Simulation of several support levels for the according technology types (virtual premia on energy output)

12.1.3 Simulation results

12.1.3.1 No Policy scenarios

The purpose of the *No Policy* scenarios is twofold: First, they illustrate to what extent bioenergy use is competitive to the reference technologies and to what extent historic developments have been influenced by direct or indirect support for bioenergy use.[61] Second, they can be regarded as reference scenarios. That is, by comparing other scenarios with the *No Policy* scenarios, the effect of support schemes can be assessed.

The two *No Policy* scenarios differ with regard to the price scenarios assumed. Furthermore, the effects of presumed changes in agricultural policy and price developments of agricultural commodities are considered in the *FAO/Primes* scenario[62], whereas no such changes are considered in the *Level 2006* scenario. In fact, these effects are incorporated in the biomass supply curves for agricultural biomass. For the *Level 2006* scenarios static supply curves are assumed, whereas the supply curves in the *FAO/Primes* scenario change over time, as described above.

A core assumption which needs to be considered in the interpretation of the *No Policy* scenarios is that existing bioenergy plants remain operational until the end of their technical life-time, regardless of the economic framework conditions in the years after their commissioning. More specifically, existing biofuel production plants are not affected by the assumed abolishment of the obligatory biofuel quota which is currently in place. However, bioenergy plants which are not economic under the “no-policy-assumption” are not replaced after they have gone out of operation, and at the end of the simulation period in 2030, only plants which are competitive under the assumed framework conditions are in operation.

Figure 12-8 shows the development of the biomass share in primary energy consumption and in the sectors heat, electricity and transport in the *No Policy* scenarios. The main difference resulting from the different price scenarios is the development in the heat sector. Due to the increasing fossil fuel prices in the price scenario *FAO/Primes*, the share of biomass in heat consumption increases to approximately 30% in 2030. The decreasing trend in low temperature heat demand (see section 12.2.1.2) is also a significant influencing parameter, as will be shown below. However, the share of biomass in the total energy consumption decreases in both *No Policy* scenarios.

[61] It is generally assumed that investment decisions are based on a depreciation period of 10 years.

[62] Strictly speaking, the title “No Policy” therefore only refers to the assumed energy policy framework conditions, not to agricultural policies.

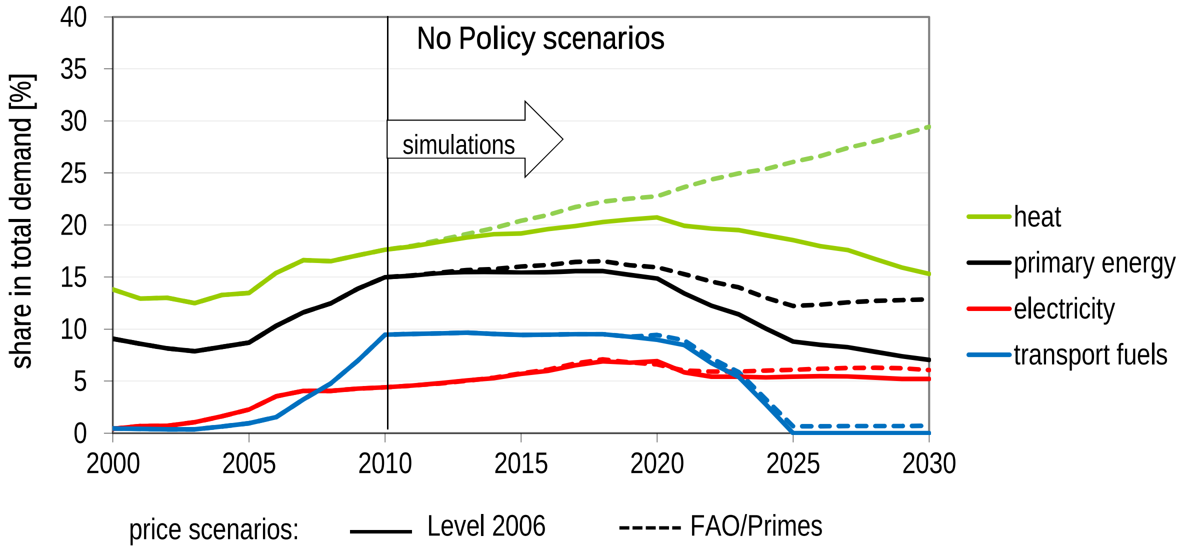

Figure 12-8. Simulation results of the No Policy scenarios (scenarios 1-1 and 1-2 in Table 12-2): Share of bioenergy in the heat, electricity and transport sector as well as in the total primary energy consumption

No Policy* – price scenario *Level 2006

The following figures show the development of bioenergy use with regard to the biomass primary energy consumed and the quantity of energy produced (output of bioenergy technologies). The figures illustrate that under the no-policy-assumption and the price scenario *Level 2006*, practically no utilization paths of energy crops are competitive to a significant degree. Until 2030, the only notable contribution of agricultural biomass originates from the use of straw in large scale CHP plants (IGCC technology) and, to a very moderate extent, plant oil in CHP plants. However, in this scenario the bioenergy sector is dominated by the use of forest biomass and wood processing residues for residential heating and process heat.

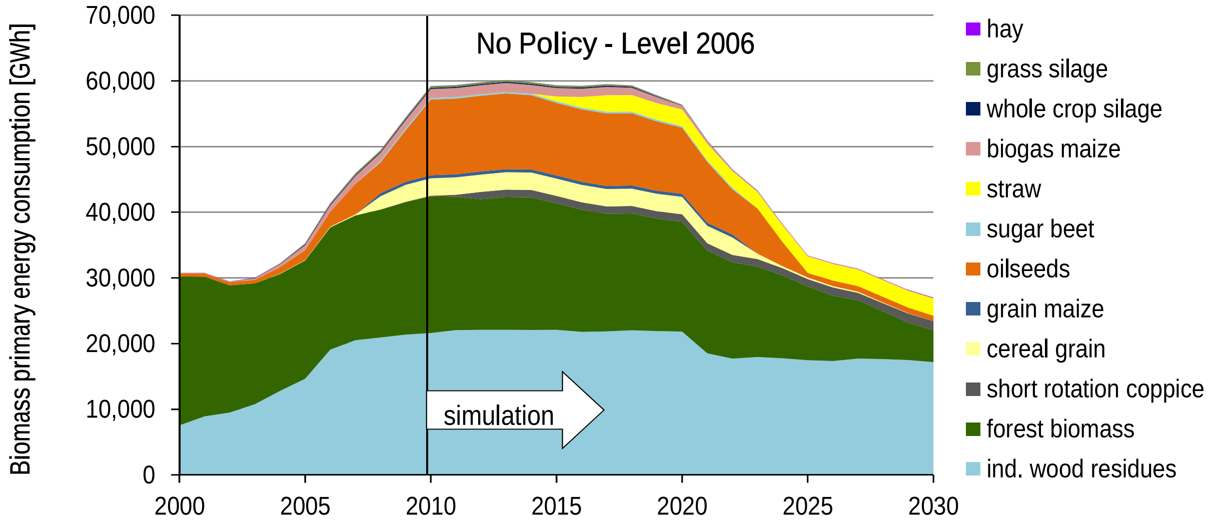

Figure 12-9. Simulation results of the No Policy-Level 2006 scenario (1-1): Primary energy consumption of biomass

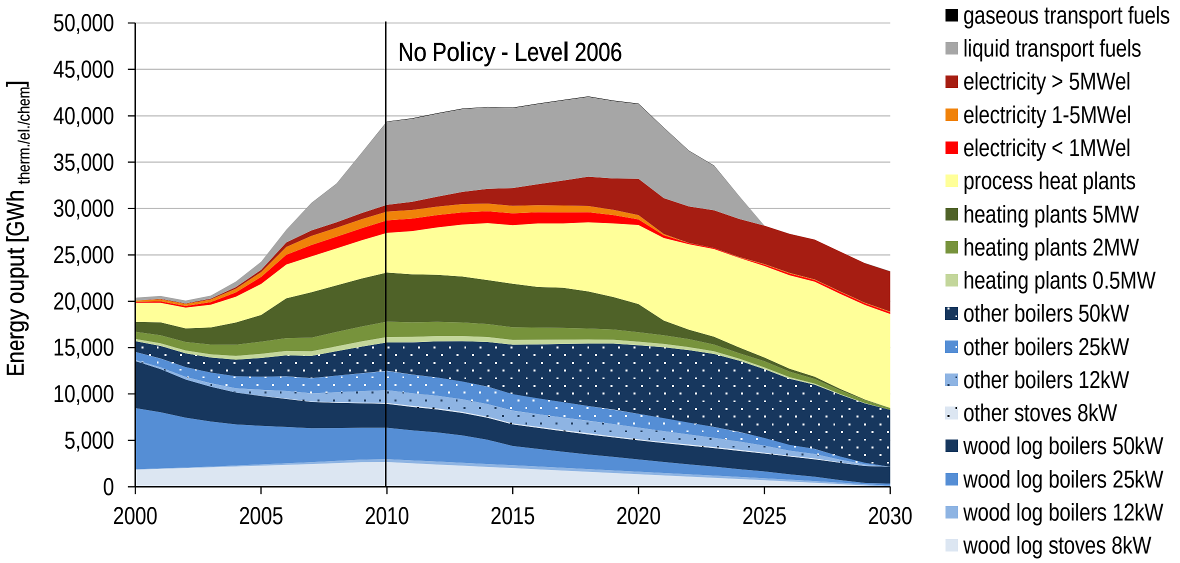

Figure 12-10. Simulation results of the No Policy-Level 2006 scenario (1-1): Output of bioenergy plants

No Policy* – price scenario *FAO-Primes

The main difference arising from the assumption of the price scenario *FAO/Primes* instead of *Level 2006* is the clearly higher exploitation of forest biomass supply potentials for heat generation (cp. Figure 12-9 and Figure 12-11, illustrating the consumption of biomass in the two scenarios). Figure 12-12 shows that the output of heating systems in the categories 12 and 25 kW as well as of heating plants is clearly higher than in the *Level 2006* scenario (Figure 12-10). Apart from that, heating plants are being deployed after 2020. With regard to the output of heating systems in the category 50 kW, there is hardly any difference, as the shrinking demand-side potential is the limiting factor in both scenarios. Apart from the use of straw in CHP plants, electricity generation in large biogas plants (with a power of 500 kW_{el} and more) using maize silage is competitive, albeit only to a very limited extent. The electricity generation in the *FAO/Primes* scenario is only slightly higher than in the *Level 2006* scenario, as biomass resources which are used in CHP plants in the latter (primarily straw and industrial residues) are partly utilized for heat generation in the former. In other words, between the two scenarios there is a shift from electricity to heat generation, resulting from increased resource competition at higher fossil fuel prices. With regard to the utilization of agricultural biomass, the higher reference prices in the *FAO/Primes* scenario have a very moderate effect.

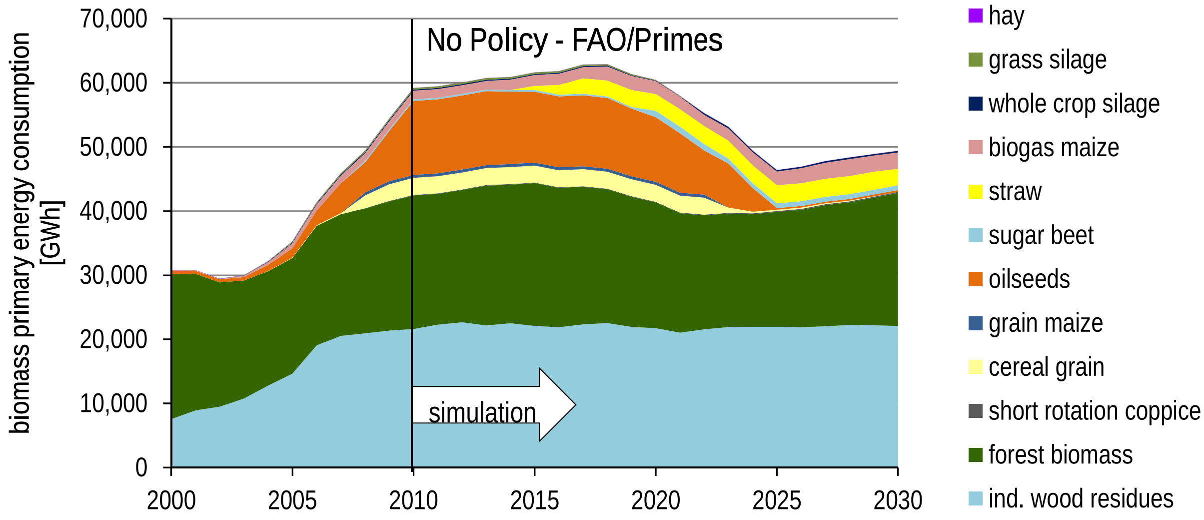

Figure 12-11. Simulation results of the No Policy-FAO/Primes scenario (1-2): Primary energy consumption of biomass

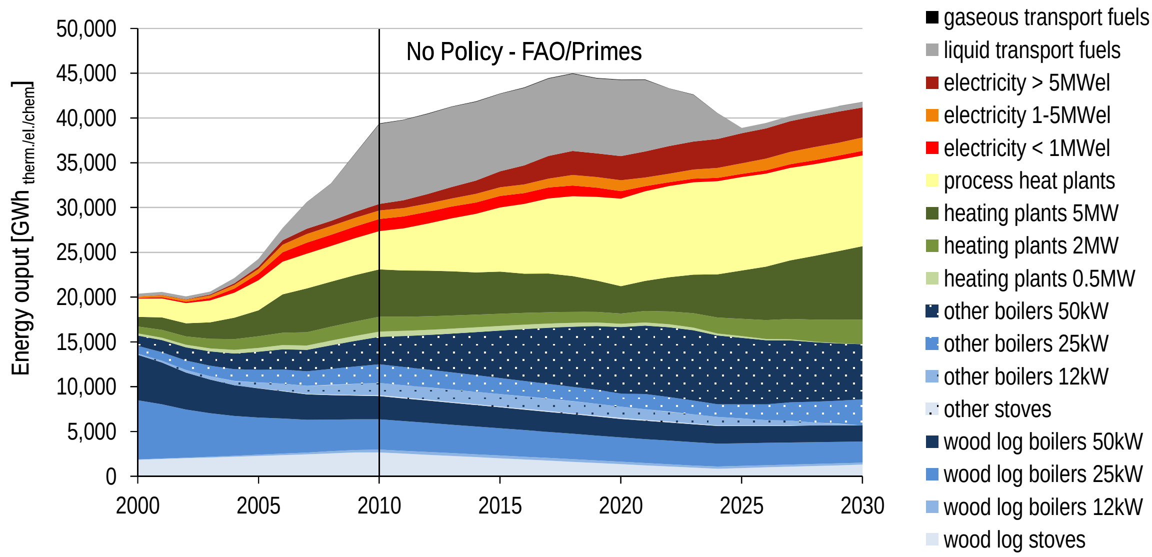

Figure 12-12. Simulation results of the No Policy-FAO/Primes scenario (1-2): Output of bioenergy plants

12.1.3.2 Current Policy scenarios

The *Current Policy* scenarios illustrate to what extent agricultural biomass could be utilized for energy generation in a profitable way, if the current support schemes and tax incentives are maintained. In contrast to the *No Policy* scenarios, these scenarios show a substantial increase in the demand for energy crops, and the question of what type of energy crops are preferred, gains in importance. Therefore, three scenarios with different focuses of energy crop production are assessed: *Conventional crops*, *biogas plants* and *lignocellulosic feedstock*.

This approach is applied for two reasons: First, a core objective is to illustrate the specific costs and benefits of the different utilization paths of agricultural bioenergy. Second, it was found that there are significant non-economic barriers to a widespread production of certain energy crops. For example, short rotation forestry requires a long-term commitment of farmers, and means a higher risk than conventional energy crops (see Kalt et al., 2010a). By exogenously assuming different energy crop scenarios, the necessity to consider these barriers, which cannot be implemented appropriately in a cost-based simulation model like *SimBioSys*, is shifted to the interpretation of the simulation results.

In addition to the six energy crop scenarios (three for each price scenarios), the *Current Policy* scenarios are also simulated under the assumption that no agricultural biomass is available for energy uses, in order to obtain reference scenarios.

Current Policy* – price scenario *Level 2006

Figure 12-13 shows the aggregated simulation results for the price scenario *Level 2006*. Compared to the scenario without any agricultural biomass, the availability of energy crops and straw results in an additional contribution of bioenergy to electricity supply, regardless of the type of energy crops which are utilized. In the year 2030, the additional electricity production in the energy crop scenarios exceeds the power generation in the reference scenario without agricultural biomass by at least 3.5 TWh, which is equal to about 4% of the total electricity demand. In the *biogas* scenario the electricity generation from agricultural biomass amounts to close to 4 TWh in 2030, i.e. it is about 10% higher than in the other energy crop scenarios. Furthermore, the heat output of CHP plant results in an additional contribution to the heat supply. The production of biogenic transport fuels is dominated by existing biodiesel plants until 2020 or so. Thereafter, the 10%-biofuel quota assumed in all *Current Policy* scenarios is fulfilled in a slightly different way in each scenario. However, SNG from thermochemical gasification of wood and straw plays an important part, regardless of the energy crop scenario assumed. The rest is made up of first generation biofuels (scenario *conventional energy crops*), biomethane (*biogas* scenario) or gaseous and liquid 2nd generation biofuels from short rotation coppice (scenario *lignocellulosic*).

Hence, a relatively high contribution of gaseous transport fuels from biomass is a robust result of the simulations. This result certainly depends on a trend towards gas-fuelled vehicles. However, regardless of which types of biofuels are produced to fulfill the 10% quota, it is obvious that the quota cannot be fulfilled with biomass from domestic agricultural production only. To what extent imported feedstock or imported biofuels are going to be utilized is certainly also a question of political framework conditions, especially with regard to sustainability criteria imposed on renewable transport fuels, as well as certification schemes applied.

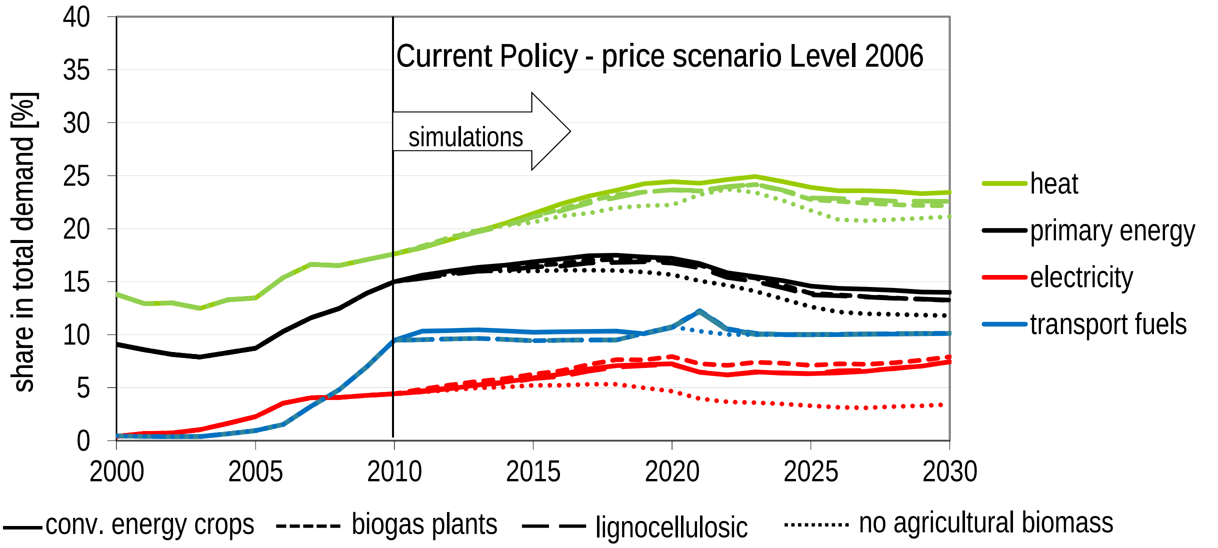

Figure 12-13. Simulation results of the Current Policy-Level 2006 scenarios (2-1a to 2-1d): Share of bioenergy in the heat, electricity and transport sector as well as in the total primary energy consumption[63]

The diffusion of small scale biomass heating systems is similar in all *Level 2006* scenarios: Until 2020 the demand-side potentials of 50 kW-systems are increasingly realised. Thereafter, the importance of biomass heating systems decreases, as the demand-side potentials decrease and the structure of the heat demand shifts towards lower heat loads due to improving thermal quality of residential buildings. In the categories 12 and 25 kW, biomass heating systems are hardly becoming competitive, partly due to the increasing biomass demand for the production of transport fuels, which results in notable price increases.

Current Policy – price scenario “FAO/Primes“

Figure 12-14 shows the development of bioenergy use under the *Current Policy*-assumptions and the price scenario *FAO-Primes*. Compared to the *Level 2006* scenarios, the differences between the different energy crop scenarios are clearly more pronounced. The highest contribution to the primary energy consumption is achieved in the energy crop scenario *lignocellulosic*, due to a significantly increasing share of bioenergy in the heat sector. The main reason is that biomass heating systems in the 12 and 25 kW-category are becoming competitive in the price scenario *FAO/Primes*.

[63] The temporary exceedance of the 10%-quota in the year 2021 is due to (technology-specific) minimum plant sizes.

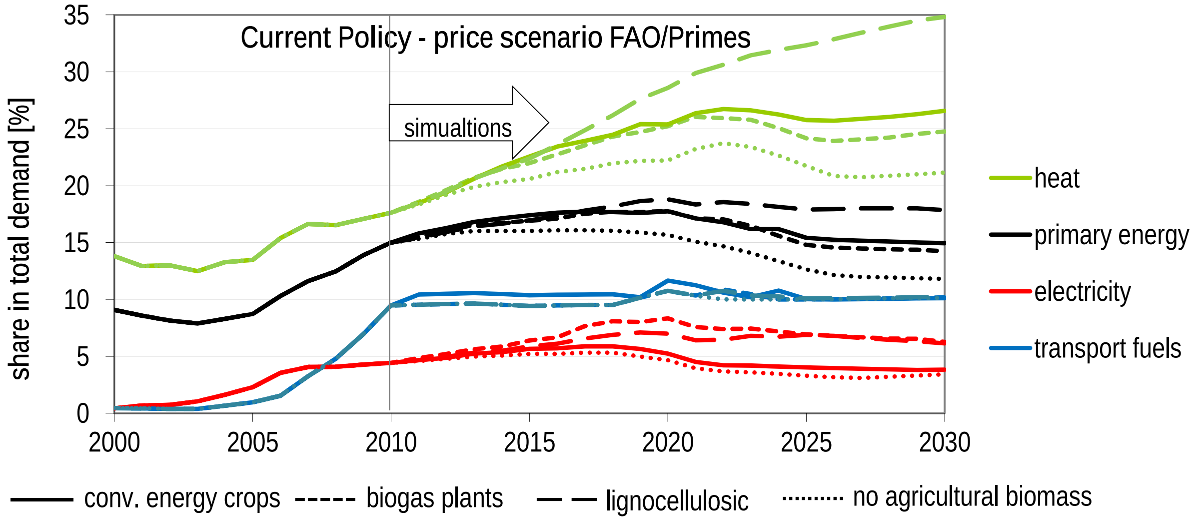

Figure 12-14. Simulation results of the Current Policy-FAO/Primes scenarios (2-2a to 2-2d): Share of bioenergy in the heat, electricity and transport sector as well as in the total primary energy consumption

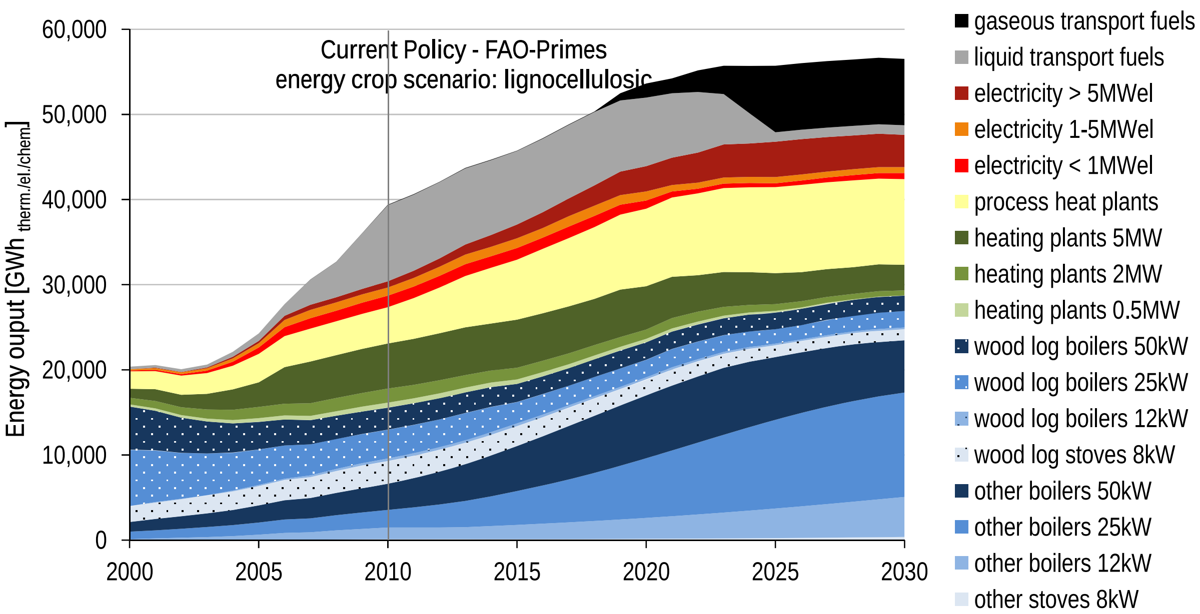

Figure 12-15. Simulation result of the Current Policy-FAO/Primes scenario with focus on lignocellulosic energy crops (scenario 2-2d): energy output of bioenergy plants

Figure 12-15 illustrates the development of bioenergy production in the scenario *lignocellulosic.* Apart from the diffusion of biomass systems in residential heating, the figure illustrates the shift (which was already mentioned in the previous section) from liquid biofuels primarily produced from imported oilseeds and plant oil to gaseous transport fuels produced from domestic biomass. With regard to the share of bioenergy in electricity supply, it is clear to see that this shift has a strong negative impact on the use of bioenergy for other applications.

The obligatory biofuel quota results in increased competition for the limited biomass resources, inhibiting a further diffusion of CHP plants after 2020 (especially in the *biogas* scenario).

Figure 12-16 shows the development of GHG mitigation and fossil fuel replacement resulting from the use of bioenergy. In the scenario *lignocellulosic*, the GHG savings in 2020 amount to approximately 15 Mt CO_2-eq. and the fossil fuel replacement to about 70 TWh. Compared to the reference scenario without agricultural biomass, the additional savings resulting from the use of agricultural biomass are about 3 Mt CO_2-eq. and 15 TWh. In the scenarios *biogas* and *conventional energy crops* the additional benefits are clearly lower: 1.72 Mt CO_2-eq. and 10 TWh (*biogas*), and 1.43 Mt CO_2-eq. and 7.3 TWh (*conventional energy crops*) in 2020. Until 2030, the additional benefits in the *lignocellulosic* scenario increase to 5.7 Mt CO_2-eq. and 27 TWh, whereas in the other energy crop scenarios they remain almost constant.

On the other hand, the arable land dedicated to energy crop production is also significantly higher in the *lignocellulosic* scenario than in the other scenarios. In 2020 it amounts to 300,000 and in 2030 to 600,000 ha (close to one fourth/half of the total arable land in Austria), whereas in the other scenarios it is less than 250,000 ha throughout the period 2020 to 2030. Whether it is politically desired that the arable land in Austria is used for bioenergy production to such a high degree is open to question. However, the support costs are also highest in the *lignocellulosic* scenario, albeit only slightly higher than in the *biogas* scenario.

One utilization path which is not given due attention under the *Current Policy*-assumptions is the substitution of natural gas via the feed-in of biomethane into existing gas networks. Since there are currently no clear framework conditions and support schemes in place, this utilization path is not subsidized in the *Current Policy* scenarios.

However, the results of the *Current Policy* scenarios illustrate that in case of a continuing increase in fossil fuel prices, lignocellulosic energy crops (short rotation coppice) is the most promising option for agricultural biomass production. This is primarily due to the improving competitiveness of wood-fired small-scale heating systems with a rated power of 25 kW or less.

A major advantage of a focus on conventional energy crops is that there is no necessity for farmers to adapt to new production and harvesting methods. Especially a focus on short rotation coppice requires a long-term commitment of farmers to energy crop production as well as the acquisition of new agricultural machines. Another aspect that has so far not been taken into account is the production of non-energetic byproducts. In the *Current Policy* scenario with a focus on conventional energy crops (price scenario *FAO/Primes*), a quantity of 140,000 tons of rape meal and 350,000 t of DDGS ("Dried Distillers Grains with Solubles") are produced in the year 2020 as by-products of biodiesel and ethanol production, respectively. Based on the nutritive value, more than 50% of the current imports of protein animal feed could be replaced with these quantities (BMLFUW, 2010; Url et al., 2005). Until 2030, the production of DDGS increases by another 20%. In the price scenario *Level 2006* the quantity of non-energetic by-products is about 30% lower than in the *FAO/Primes* scenario, as advanced biofuels produced from wood play a more important part in fulfilling the biofuel quota. This is due to a lower demand for wood biomass for heat and power generation at moderate fossil fuel prices.

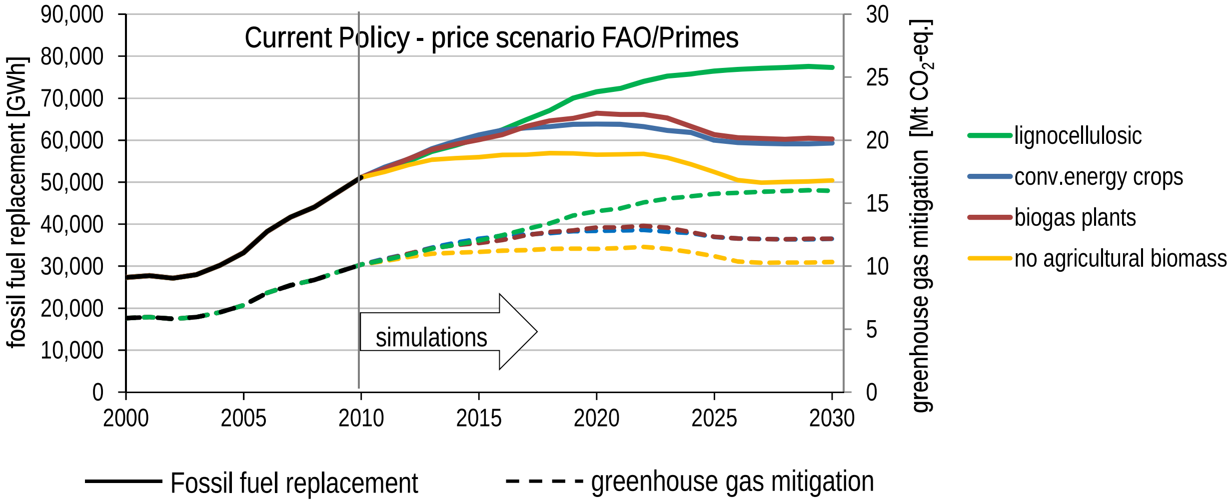

Figure 12-16. Simulation results of the Current Policy-FAO/Primes scenarios (2-2a to 2-2d): Greenhouse gas reduction and fossil fuel replacement under different energy crop scenarios (Non-energy by-products like animal feed are not considered here; see section 12.1.3.4)

12.1.3.3 Specific Support scenarios

The scenarios presented in the previous sections illustrate the development of the bioenergy sector under the assumption of nonexistent (*No Policy)* and currently implemented (*Current Policy*) bioenergy support schemes. The *Specific Support* scenarios are to illustrate the effect of different support levels for certain utilization paths of agricultural biomass. The simulation results provide insight into the cost-benefit ratio (GHG mitigation and fossil fuel replacement vs. support costs) of different options for agricultural bioenergy production. The support schemes assumed (virtual premiums on the energy output of bioenergy plants) are not to be considered as actual options for support policies, and the resulting developments of the bioenergy sector not to be seen as realistic developments, as these highly focused support strategies result in fairly distinctive scenarios. *Specific Support* scenarios are presented for the heat and the transport sector.[64] For all *Specific Support* scenarios the price scenario *FAO/Primes* is assumed.

[64] No *Specific Support* scenarios for the electricity sector are presented because the available data on demand-side potentials of biomass CHP, which are highly relevant for these simulations, are considered insufficient.

In contrast to the presentation of the previous scenarios, which was focused on the dynamic development of the bioenergy sector, the simulation results of the *Specific Support* scenarios are illustrated on the basis of the cost-benefit ratio in the year 2030 only, and only the costs and benefits resulting from the particular utilization paths of agricultural biomass are taken into account.

Specific Support* scenarios: *Transport fuels

In Part I of this thesis it was already demonstrated that the use of biomass in the heat and the electricity sector usually results in lower costs of GHG mitigation and fossil fuel replacement than in the transport sector (see also Kalt et al. 2010b). Nonetheless, the substitution of fossil transport fuels is a central aim of the European Union's energy policy agenda (see EC, 2009a). The current Austrian biofuel supply is highly dependent on imports (see section 7.4). The enhanced production of energy crops could help reduce this import dependence. A core issue is the question of what types of energy crops should be promoted, and which transport fuels are to be favoured on a longer term.

In order to answer this question, the following methodology was applied: Starting with the *No Policy*-assumption, a premium for the production of a certain type of biofuels (conventional biofuels, biomethane as well as SNG and liquid biofuels from lignocellulosic feedstock) is assumed. The premium is increased in equal steps, until either one third of the total arable land in Austria is used for energy crop production in 2030, or pronounced saturation effects become obvious in the deployment of bioenergy plants. Consecutively the cost-benefit ratio is evaluated for each level of support in the year 2030.

Figure 12-17 and Figure 12-18 show the results for the *Specific Support* scenarios for *Transport fuels.* Each bubble in the diagrams represents the result of one simulation run in the year 2030. The location of the bubbles provide information about the cost-benefit ratio in the considered scenario, i.e. the support costs (in 10^6 €) and the GHG mitigation (in t CO_2-eq.; Figure 12-17) or the fossil fuel replacement (in GWh; Figure 12-18). The data labels and the sizes of the bubbles represent the arable land used for energy crop production (data labels in 1,000 ha).

The figures show that the cost-benefit ratios of the various utilization paths differ significantly. Furthermore, the average costs of GHG mitigation and fossil fuel replacement, which can be derived from the figures, depend on the support level, and the quantity of biofuels produced, respectively. The determinants for this aspect are the biomass supply curves.[65] The best performance with regard to GHG mitigation is achieved with gaseous fuels (SNG) followed by

[65] Note that this aspect is the main advantage of the methodology applied here, compared to the analyses presented in Part I, were fixed feedstock prices were assumed and no statements about the sensitivity of mitigation costs to production volumes could be derived.

liquid fuels from lignocellulosic energy crops. The performance in the support scenarios *biomethane* and *conventional energy crops* are quite similar with regard to the costs of GHG mitigation, but due to higher biofuel yields per hectare, less land is required in the *biogas* scenarios, especially at high support levels.

The reason for the relatively good performance of the scenario focused on *conventional energy crops* at low support levels is the higher availability of cereal straw, which can be utilized economically at relatively low support levels. In the *Specific Support* scenarios based on *biogas* and *lignocellulosic energy crops,* land which has originally been used for cereal production is increasingly used for energy crops. Therefore, the enhanced cultivation of these energy crops has an adverse effect on the supply potential of straw from food and feed production.

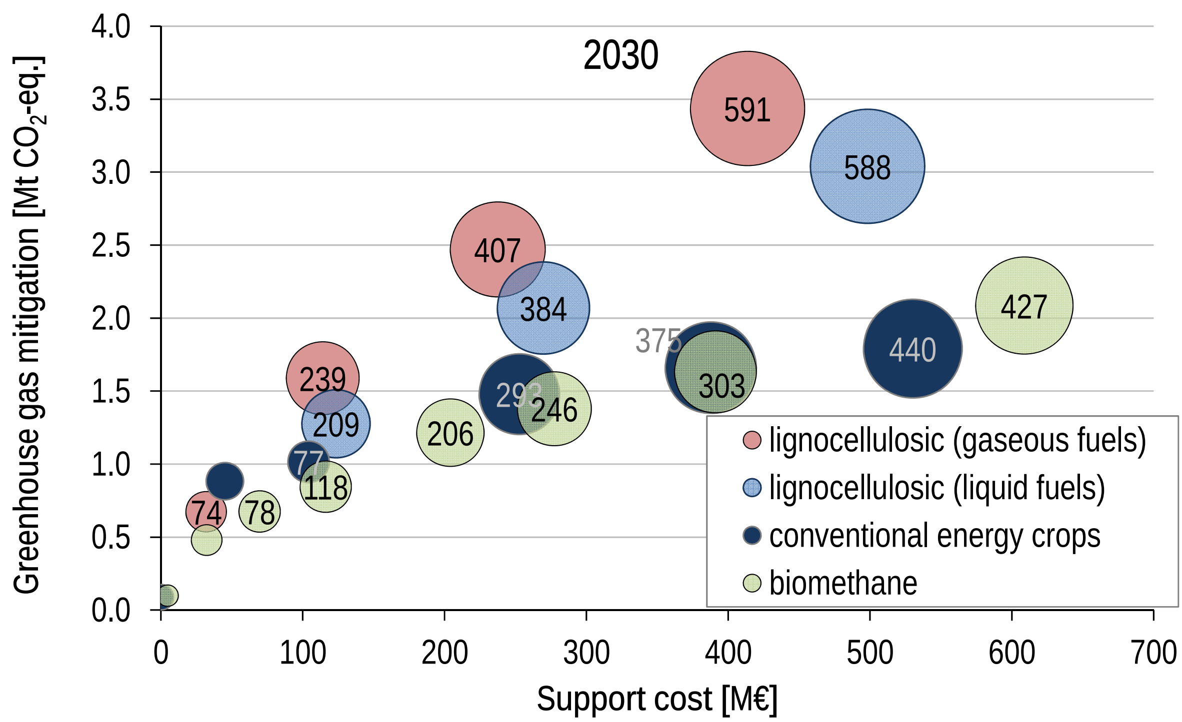

Figure 12-17. Simulation results of the Specific Support scenarios "Transport fuels" (3-1a to 3-1d) [66]*: Support costs vs. greenhouse gas reduction in the year 2030.*

(Data labels and size of bubbles: arable land occupied with energy crops in 1.000 ha)

[66] Non-energetic by-products from the production of 1st generation biofuels are not taken into account here (see section 12.1.3.4).

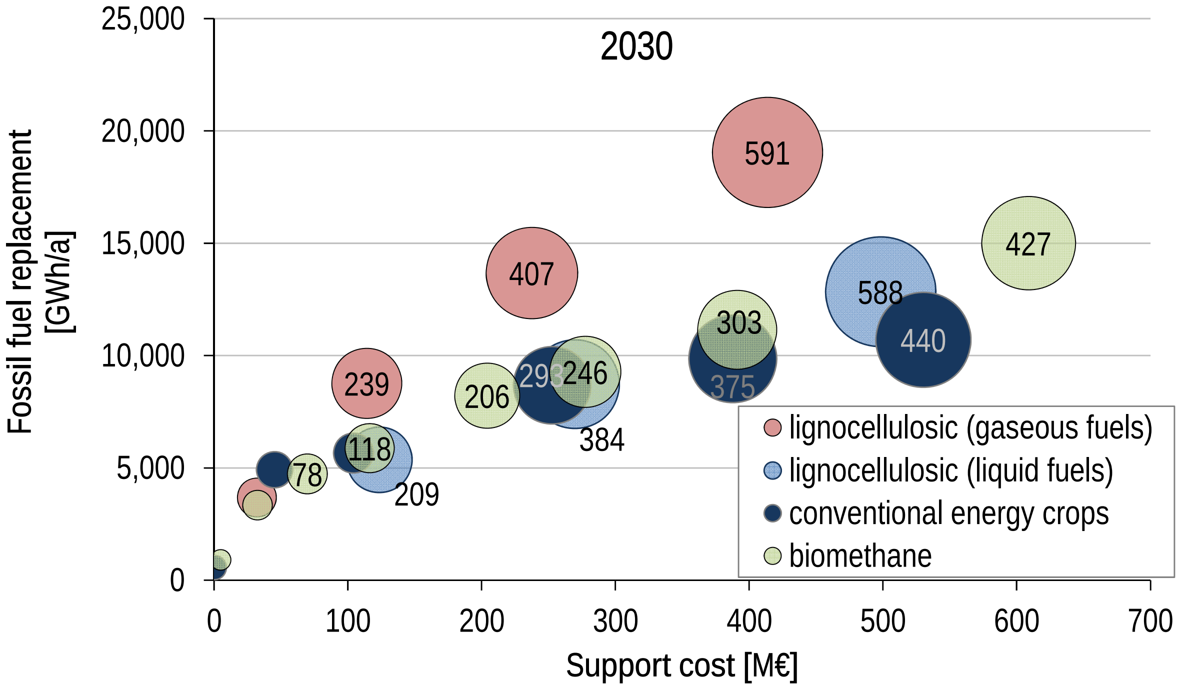

Figure 12-18. Simulation results of the Specific Support scenarios "Transport fuels" (3-1a to 3-1d): Support costs vs. fossil fuel replacement in the year 2030.
(Data labels and size of bubbles: arable land occupied with energy crops in 1.000 ha)

The average cost of GHG mitigation in the *SNG-scenario* are approximately 50 €/t CO_2-eq. at a biofuel share of 3.7% (the premium which results in this share is 10 €/MWh_{HHV}), and 120 €/t CO_2-eq. at a share of 20% (25 €/MWh_{HHV} premium).[67] In the *biomethane-scenario* they amount to 67 €/t CO_2-eq. at a share of 3.7% (10 €/MWh_{HHV} premium) and approximately 200 €/t CO_2-eq. at a share of 10% (30 €/MWh_{HHV} premium).

With regard to fossil fuel replacement (Figure 12-18), the cost-benefit ratio of liquid transport fuels from lignocellulosic crops does not differ much from the one of biomethane and conventional energy crops, and the land required for achieving a certain quantity tend to be even higher. The focus on SNG also shows the clearly best performance with regard to fossil fuel replacement.

[67] Compared to the results presented in Figure 4-13, the costs of GHG mitigation with SNG are clearly higher. The reasons for this discrepancy are that the calculations in Part I are based on current typical feedstock prices, whereas here agricultural resources (short rotation coppice, in this case) are assumed as feedstock. Furthermore, the endogenously modeled biomass price development applied in *SimBioSys* results in significant biomass price increases at rising reference price levels and increasing support levels (as it is the case here).

Specific Support* scenarios: *Heat

This second group of *Specific Support* scenarios is focused on the heat sector. Apart from solid wood fuels (primarily wood chips and pellets from short rotation coppice), agricultural biomass can be used for heat generation in the form of vegetable oil, straw, hay and cereal corn, as well as gaseous biomass from anaerobic digestion (biomethane) or thermo-chemical gasification processes (SNG). After being cleaned and conditioned, gaseous fuels are assumed to be fed into gas distribution networks. Hence, the production of gaseous fuels from biomass allows for a direct substitution of natural gas.

Figure 12-19 and Figure 12-20 show the results of the *Specific Support* scenarios for heat generation. In contrast to the *Transport fuel* scenarios, the diffusion of biomass heating systems fuelled with solid biomass is limited by demand-side potentials (i.e. the structure of heat demand and the applicability of biomass heating systems), which partly shrink significantly up to 2030. Apart from that, a considerable share of the demand-side potentials is covered with forest biomass.[68] With regard to gaseous fuels, the assumed energy demand scenarios suggest that demand-side potentials are sufficiently high as not to limit the diffusion of biomethane/SNG-plants in the period 2010 to 2030. (The main reason for this is the high share of gas heating systems in urban areas, which is unlikely to be replaced with solar thermal or other renewable heating systems.) Furthermore, decreasing average heat loads due to enhanced building refurbishment do not influence the economics of the according utilization paths, as it is the case for biomass heating systems.

However, the simulation results suggest that a focus on solid lignocellulosic fuels results in the best cost-benefit ratio. For the above-mentioned reasons, the ratio deteriorates significantly at higher support levels (i.e. the gradient of the imaginary connecting line of the bubbles for “lignocellulosic – solid fuels” decreases), but still this focus is always superior to the second-best support focus “lignocellulosic – SNG feed-in”. Especially with regard to the quantity of GHG mitigation per hectare of arable land used for energy crop production, the results for this focus are clearly better than all other *Specific Support* scenarios (including the *biofuel*-scenarios).

The focus “conventional energy crops” shows a relatively good performance at low support levels because of a high availability of straw. However, the maximum GHG mitigation is reached at approximately 1.5 Mt CO_2-eq. with a premium of 30 €/$MWh_{therm.}$. A further increase of the premium does not result in further deployment or increasing GHG mitigation.

68 To be specific, the demand-side potentials for biomass heating systems fuelled with agricultural biomass are assumed as the total demand-side potentials reduced by the heat generation from non-agricultural resources in the *Current Policy* scenario.

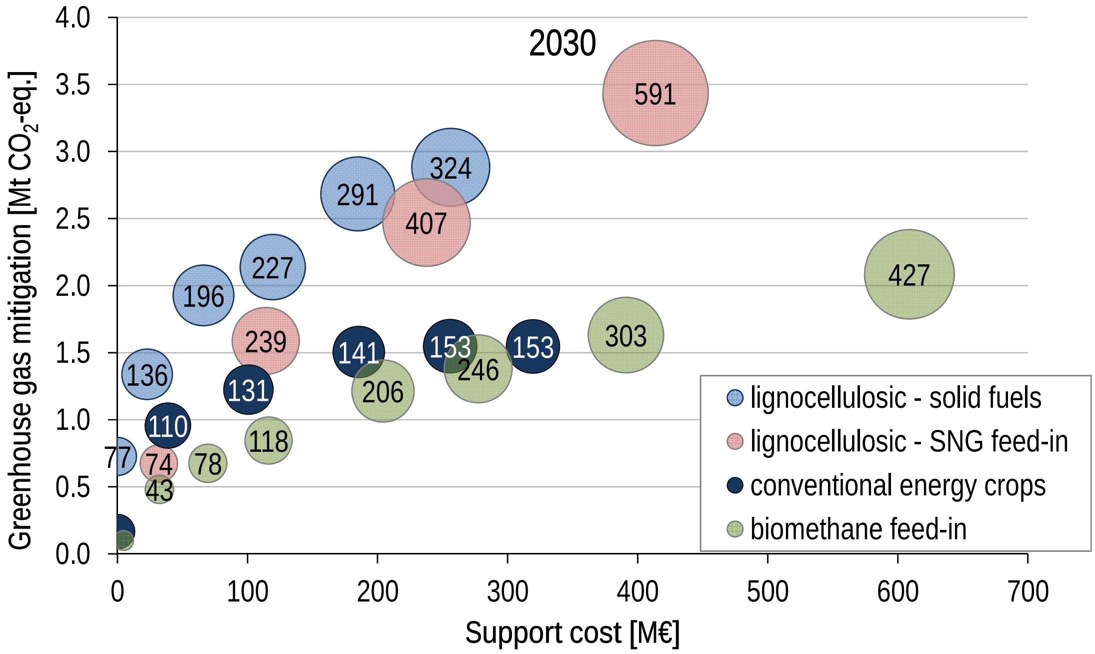

Figure 12-19. Simulation results of the Specific Support scenarios "Heat" (3-2a to 3-2d) [69]*:*
Support costs vs. greenhouse gas reduction in the year 2030.
(Data labels and size of bubbles: arable land occupied with energy crops in 1.000 ha)

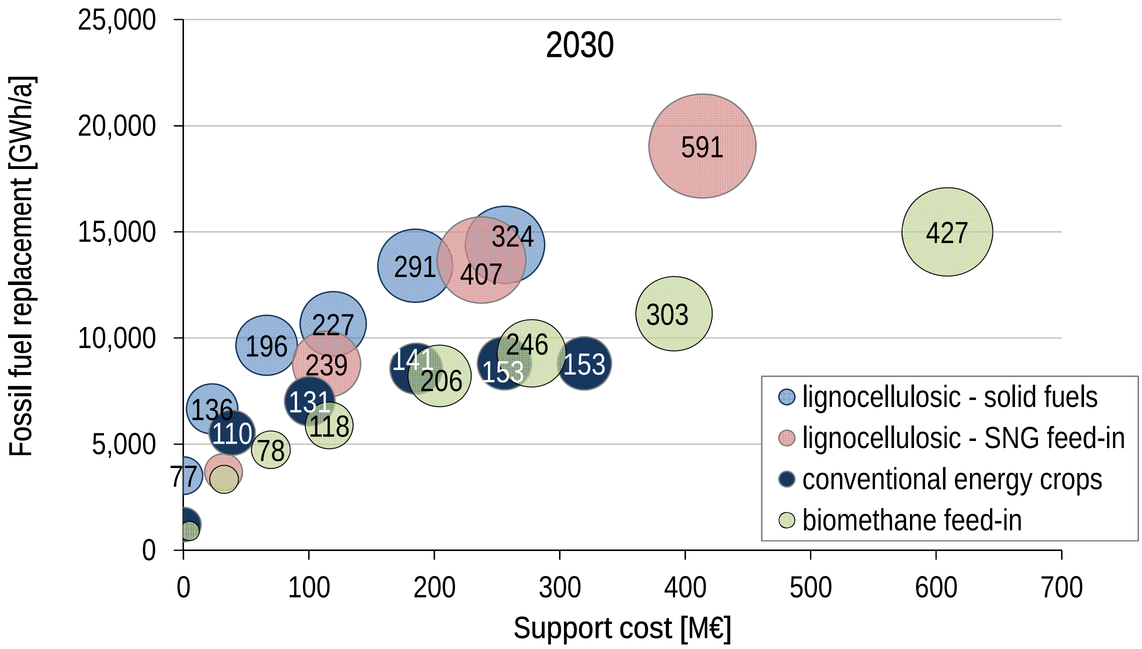

Figure 12-20. Simulation results of the Specific Support scenarios "Heat" (3-2a to 3-2d):
Support costs vs. fossil fuel replacement in the year 2030.
(Data labels and size of bubbles: arable land occupied with energy crops in 1.000 ha)

[69] By-products from the production of biofuels are not considered here (see section 12.1.3.4).

With regard to fossil fuel replacement (Figure 12-20), the differences between the various utilization paths are clearly less pronounced. The *biomethane-* and *SNG*-scenarios show a slightly better performance compared to the other scenarios, than with regard to GHG mitigation. However, the *solid fuels*-scenario remains to be the most beneficial, followed by the *SNG*-scenario.

12.1.3.4 Alternative scenarios and supplementary analyses

In the following sections, alternative scenarios and supplementary analyses to the simulation results presented above are described. The core aim is to quantify the sensitivities of the results to data uncertainties (future yields of energy crops, GHG balances of biogas production) and illustrate the impact of different methodological approaches (credits for by-products).

Alternative scenario: Increasing yields

Agricultural statistics indicate that the average yields of most crops have increased substantially in Europe and most other regions during the last decades (see FAO, 2010c). This was achieved with the enhanced use of fertilizers and plant protection agents as well as improvements in cultivation methods and breeding progress.

Expert opinions about the future development of crop yields are somewhat controversial. Some experts argue that the further progress which can be expected for the future is rather moderate, whereas others believe that there are still vast potentials for improvements, especially with regard to maize and “new” types of energy crops (Miscanthus, poplar etc.). In EEA (2006) it is assumed that the yields of such energy crops increase by 1.5% per year in the period from 2010 to 2020 and by 2% per year from 2020 to 2030. For conventional crops, an annual increase between 1 and 1.5% is assumed for the period 2010 to 2030. Based on KTBL (2006), the following yield increases up to 2020 are assumed in Thrän et al. (2009): 3% per year for maize silage, 0.6% for whole-plant-silage, rapeseed and sugar beet, 2% for intercrops and Miscanthus and 2.5% for short rotation forestry.

For the supply curves shown in section 12.1.2.3 as well as for all scenarios presented above, constant per-hectare-yields have been assumed for the whole period 2010 to 2030. In the following, the default *Current Policy* scenarios (section 12.1.3.2) are compared to the results of simulations under the assumption of yield increases of 2% per year for *biogas* and *lignocellulosic* crops and 1% for *conventional* energy crops. The production costs per hectare

are assumed to remain constant, resulting in reduced specific production costs of energy crops.[70]

The following core conclusions are drawn from the simulation results of the alternative scenarios with increasing yields. Up to 2020, there are hardly any differences compared to the default *Current Policy* scenarios, but up to 2030 they tend to be considerable. Figure 12-21 illustrates the differences in the year 2030, on the basis of the share of bioenergy in energy consumption. Especially in the *biogas*- and the *lignocellulosic*-scenario, biogenic transport fuels become competitive and the share of biofuels in the transport sector increases beyond the obligatory 10%-biofuel quota. Apart from that, the use of biomass for heat generation slightly increases in the *conventional* and the *lignocellulosic*-scenario. All in all, the *lignocellulosic*-scenario benefits most from the assumed yield increase, which is unsurprising, considering that agricultural biomass is used most extensively in this scenario. Compared to the default scenario, the additional share of biomass in the primary energy consumption is close to 4% in 2030.

Hence, it is concluded that increasing yields could have a substantial and very positive effect on the profitability of agricultural bioenergy – at least as long as the increases are achieved trough breeding progress, and not additional use of fertilizers and plant protection agents, which would cause additional costs and possibly deteriorate the GHG and energy balances.

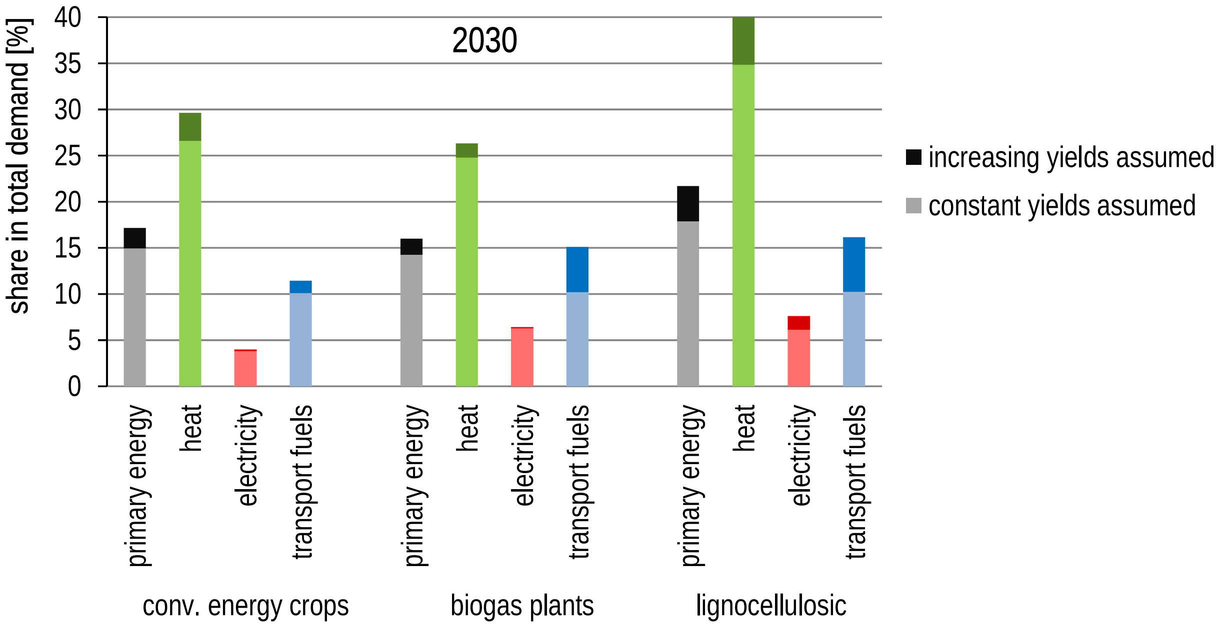

Figure 12-21. Comparison of the alternative scenarios “increasing yields” with the default Current Policy-FAO/Primes scenarios with constant yields assumed

[70] In fact, the resulting changes on the economics of energy crop production would have an impact on the crop distribution on arable land, i.e. on the supply curves for energy crops. This aspect is not taken into account here.

Alternative scenario: Greenhouse gas balance of biogas

The GHG balances for biogas assumed by default (see Annex) differ somewhat from the default values stated in EC (2010d). If the values according to EC (2010d) are assumed, the results of the *Specific Support* scenarios for *biogas* improve, as shown in Figure 12-22. It is interesting to note that especially at higher support levels, the *biogas*-scenarios show a better cost-benefit ratio than the *conventional*-scenarios in this case. It is therefore concluded that uncertainties concerning GHG balances of biogas (which are not only due to methodological approaches and general assumptions in life-cycle assessments but are also due to varying agricultural practices) are in a range that does have an impact on the conclusions to be derived from the simulation results.

Supplementary analysis: Credits for by-products

By-products of biodiesel and ethanol production have so far not been taken into account in the data about arable land required. Hence, the land used for the production of oilseeds and ethanol crops was entirely attributed to biofuel production, regardless of the non-energetic by-products. One option to take by-products into account is via credits. Assuming that the by-products from biodiesel and ethanol production substitute imports of animal feed, the area required for growing energy crops is reduced by the area which would be required to produce the equivalent amount of animal feed which is substituted. Hence, in this case only the "net area requirement" is attributed to bioenergy production.[71]

For the calculation of the net area requirement, it is assumed that rapeseed meal and DDGS (from plant oil or biodiesel production, and ethanol production, respectively) substitute imports of soya meal. Based on Thomet et al. (2008), an average yield of 4.5 t/ha is assumed for soya meal. Furthermore, the lower nutritive value of DDGS compared to soya meal is taken into account (cp. BMLFUW, 2009).

Figure 12-22 compares the resulting values for the *Specific Support* scenario *Transport fuels* with the default scenario without credits for by-products. With by-products taken into account, the area required at the higher support levels is about 35% lower than in the default case. Hence, the use of by-products improves the overall balance of biofuels from conventional energy crops quite significantly.

[71] The drawback of this approach is that the net area does not correspond to the area which actually needs to be dedicated to energy crop production. This can be quite misleading, and therefore credits for byproducts have by default not been taken into account.

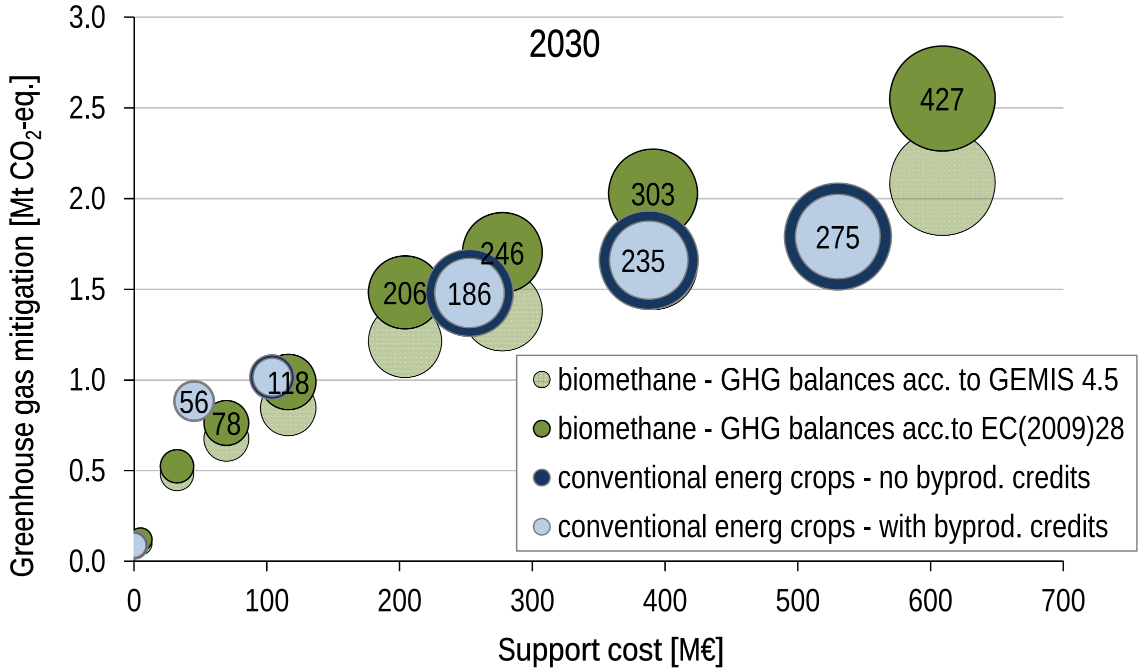

Figure 12-22. Comparison of the alternative scenarios "credits for by-products" and "greenhouse gas balance of biogas" with the according default scenarios (cp. Figure 12-17)

Supplementary analysis: Intercrops

Intercrops, which are often considered as favourable feedstock for biogas plants have so far not been taken into account. This supplementary analysis provides a rough assessment of the achievable contribution of intercrops to the Austrian (bio-)energy system.

With crop rotations and the regionally different amounts of precipitation in August and September (which are decisive for the yields of intercrops) taken into account, the arable land which is suitable for growing energy crops for energy generation in Austria is estimated 110.000 ha in Kalt et al. (2010a). Based on crop trials carried out by Aigner et Sticksel (2010), 3.5 tons of dry matter per hectare (corresponding to 800 m^3CH_4/ha) are considered as representative yields. Based on these data, the primary energy potential of raw biogas from intercrops is estimated 3.2 PJ/a. Assuming a utilization in medium-sized biogas plants, the electricity output accounts for about 0.5% of the projected electricity demand in the year 2020 and about 30% of the total electricity produced in biogas plants in the *Current Policy* scenario *Biogas.*

However, due to the comparatively low yields of intercrops, agricultural subsidies (within the Austrian Rural Development Programme "ÖPUL") are essential for the profitability of biogas production from intercrops. Without such additional incentives, this utilization path is considered economically inefficient and not feasible under current support schemes.

12.1.4 Summary, discussion and conclusions

Under the support scenario *No Policy* and the price scenario *Level 2006* practically no utilization paths of energy crops are competitive. Until 2030, the only notable contribution of agricultural biomass to the energy supply originates from the use of straw and (to a very moderate extent) plant oil in CHP plants. In this scenario the bioenergy sector is dominated by the use of forest biomass and wood processing residues for residential and district heating as well as industrial heat generation. The main difference in the price scenario *FAO/Primes* is the clearly higher exploitation of forest biomass potentials for heat generation. Apart from that, electricity generation in large biogas plants (with a power of 500 kW_{el} and more) using maize silage is to some extent competitive. Still, agricultural biomass plays a rather insignificant role.

The *Current Policy scenarios* illustrate to what extent agricultural biomass could be utilized in a profitable way if the current support schemes and tax incentives are maintained. In contrast to the *No Policy scenarios*, these scenarios show a substantial increase in the demand for energy crops, and the question of what type of energy crops are preferred, gains in importance. The best cost-benefit ratio as well as the highest expansion of agricultural bioenergy is achieved with a focus on lingocellulosic biomass (short rotation coppice). The GHG reduction from agricultural bioenergy in this scenario accounts for 3 Mt CO_2-eq. in the year 2020 und 5.7 Mt in 2030. The savings of fossil fuel consumption amount to 15 TWh in 2020 and 27 TWh in 2030. However, the arable land used for energy crop production accounts for about 300,000 ha in 2020 and 600,000 ha in 2030 (close to one fourth/half of the total arable land in Austria). The savings achievable with a focus on conventional crops and biogas plants are clearly lower. Figure 12-23 gives an overview of the simulation results: the primary energy consumption of biomass in the *No Policy* and the *Current Policy scenarios* in 2020 and 2030, subdivided into agricultural and other biomass.

The *Specific Support* scenarios illustrate the effect of different support levels for specific utilization paths of agricultural biomass. The simulation results show that the cost-benefit ratios differ significantly, depending on which utilization paths are promoted. If only transport fuels are promoted, the best performance with regard to GHG mitigation is achieved with gaseous fuels (SNG), followed by liquid fuels from lignocellulosic energy crops. However, the best cost-benefit ratio (with regard to GHG mitigation as well as fossil fuel replacement) among all *Specific Support scenarios* is achieved with a focus on solid fuels used for heat generation.

It is concluded that in the case of a continuing increase in fossil fuels prices, agricultural biomass of domestic origin could be of some significance for the Austrian bioenergy sector. However, the production of large quantities of energy crops entails a reduction of the self-sufficiency in food and feed crops, unless increases in crop yields are achieved or the demand for food and feed crops declines (e.g. through changes in nutritional behaviour; see section 13). Intercropping may be an option for producing biogas feedstock without interfering with food and feed production, but under the current framework conditions the potentials are found to be rather moderate. However, the longer-term potentials might prove to be clearly higher, as research in this field may lead to optimized crop rotations and cultivation methods. Apart from energy crops, straw, other plant residues and manure represent a limited but (with regard to ecological issues) favourable and yet hardly used potential for agricultural energy generation.

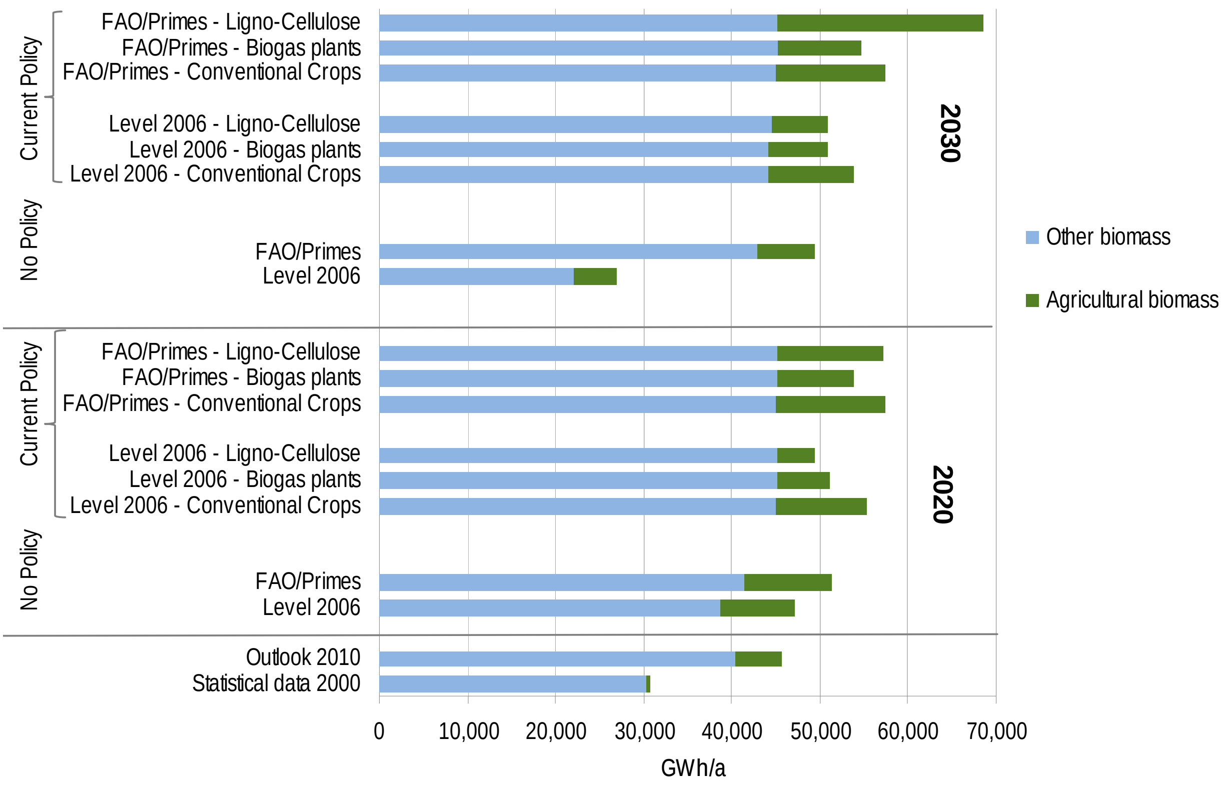

Figure 12-23. Summary of simulation results: primary energy consumption of domestic biomass in the No Policy and the Current Policy scenarios in 2020 and 2030.

12.2 Climate-sensitive scenarios of the Austrian bioenergy sector

The simulations presented in this section illustrate the development of the Austrian bioenergy sector under different climate scenarios. The core question to be assessed is: To what extent do climate change and different mitigation policies influence the development of bioenergy use in Austria? Furthermore, it is assessed if it is possible to derive adaptation measures for the bioenergy sector.

The analyses presented in this section have been carried out within the project "KlimAdapt - Priority measures for adapting the energy system to climate change" (Kranzl et al. 2010), and are based on impact assessments of climate change on heating and cooling, hydroelectric power generation and electricity generation in Austria in general, as well as on the availability of forest resources.

The climate-sensitive input data are based on the "SRES-scenarios" *A2*, *A1B* and *B1* (IPCC, 2000) (SRES: Special Report on Emissions Scenarios). For each scenario, two simulations are carried out: with and without consideration of the climate-sensitivity of influencing parameters. By comparison of the climate-sensitive with the baseline scenarios, conclusions about the climate sensitivity of the bioenergy sector are derived.

12.2.1 Input data and exogenous scenario parameters

For the following input data, climate-sensitive datasets are taken into account:

- Price scenarios for fossil fuels
- Supply curves for forest biomass
- Residential heating demand
- Electricity demand (with regard to additional power demand for cooling)

Apart from that, different energy policy framework conditions (support schemes for bioenergy) are assumed for each climate scenario, in order to fit into the general design of and assumptions for the SRES-scenarios according to IPCC (2000). These scenarios cover a wide range of demographic, economic and technological driving forces and resulting global GHG emissions, and are widely used in the assessments of future climate change. The scenario *A2* describes a very heterogeneous world with high population growth, slow economic development and slow technological change. In *A1B* a world of rapid economic growth is assumed, with a global population that peaks in mid-century and fast introduction of new and more efficient technologies, balanced across fossil and non-fossil energy resources. *B1* describes a convergent world (i.e. income and way of life converge globally), with the same global population as *A1B*, but with more rapid changes in economic structures toward a service and information economy (Bernstein et al., 2007).

Apart from the scenario specific data mentioned above, all further input data are assumed invariant to climate scenarios, including agricultural biomass supply potentials. In fact, it is commonly accepted that climate change will have an impact on agricultural production, and therefore also on the prospects of agricultural bioenergy use (EC, 2009d; EC, 2009e; EC, 2009f; Eitzinger et al., 2009; Iglesias et al., 2007; EEA, 2008). However, due to considerable uncertainties, this aspect of climate change is not taken into account here.

12.2.1.1 Price scenarios

Figure 12-24 illustrates the developments for wholesale prices of fossil fuels and electricity assumed in the different scenarios. The scenarios for oil and natural gas have been determined endogenously in the modelling framework presented in Riahi et al. (2007). The scenarios for the electricity price are based on a simulation model for the Austrian electricity sector presented in Kranzl et al. (2010), where also the fossil fuel price developments according to Riahi et al. (2007) have been assumed.[72]

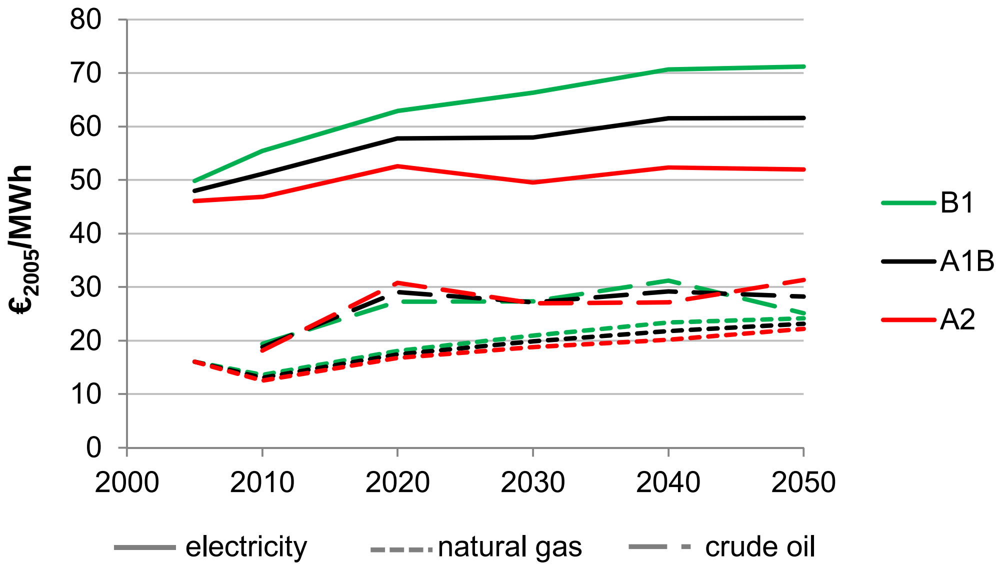

Figure 12-24. Energy price developments assumed in the climate scenarios (wholesale prices).[73]

Source: Riahi et al. (2007) (oil and natural gas), Kranzl et al. (2010) based on Riahi et al. (2007) (electricity)

12.2.1.2 Energy demand scenarios

The climate-sensitive parameters of the energy demand include developments in residential heating and electricity consumption according to Kranzl et al. (2010). For the transport sector and high temperature heat demand, climate-invariant developments are assumed. The scenario for the transport sector is based on the “target case-scenario” according to Capros et al. (2008), and shows a slight reduction (approximately 10%) of the transport fuel consumption (currently about 90 TWh/a) until 2050, compared to the average of the years 2005 to 2008. The consumption of high temperature heat is assumed to remain constant at the average level of 2005 to 2008. Figure 12-25 shows the resulting scenarios for the GIC (primary energy) as well as the development of the total heat demand and electricity consumption.[74]

[72] Compared to the price developments assumed in section 12.1, these scenarios are clearly more conservative. Furthermore, it is recognized that compared to more recently published scenarios for fossil fuel price developments (e.g. IEA, 2009a), the increases assumed here are very low.

[73] The historic prices for electricity and natural gas are interpolations from the average price level in 2005 to the scenario-specific values for 2010. Hence, the price peaks during this period are not shown.

[74] Even scenario *B1* can be described as rather conservative, especially with regard to the transport fuel and high temperature demand.

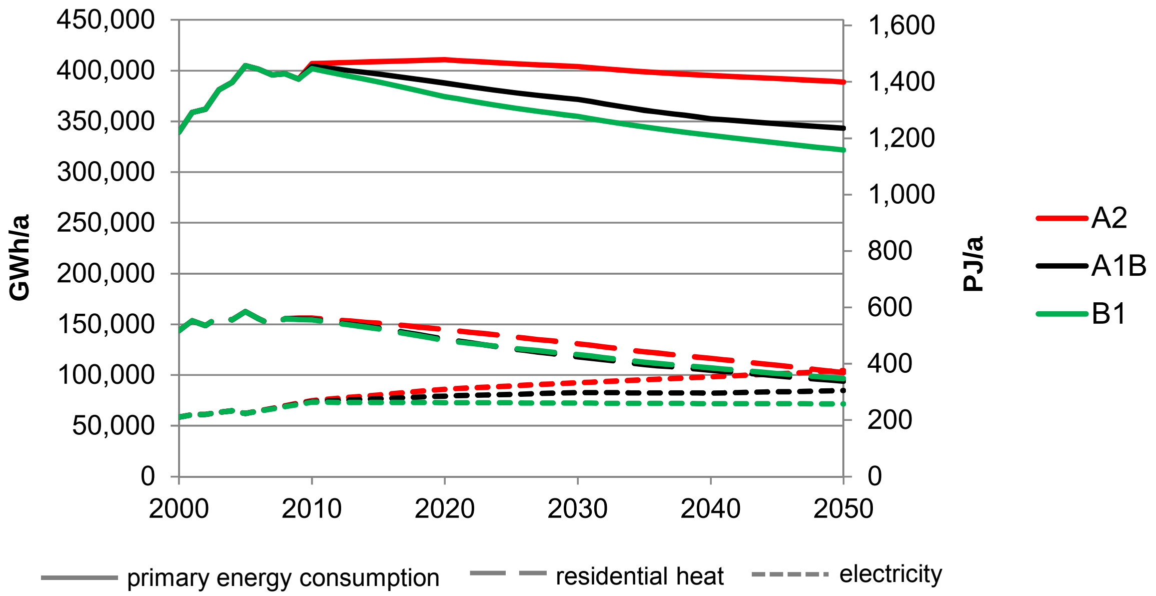

Figure 12-25. Assumed developments for primary energy consumption, electricity and residential heat demand in the three scenarios.
Source: based on Kranzl et al. (2010), own calculations

12.2.1.3 Biomass potentials and supply curves

In Kranzl et al. (2010) the climate-sensitivity of biomass supply potentials from Austrian forests up to 2100 have been assessed based on forest simulation models[75]. The simulated supply potentials are influenced by precipitation, temperature, radiation and other environmental parameters. Figure 12-26 shows the difference of the environmentally-compatible supply potentials for energy generation in the climate change scenarios compared to a baseline scenario without climate change, broken down by 30-year-periods. Apparently, the impact of climate change on the dynamics of forest growth highly depends on the characteristics of the climate scenario, and differs significantly for the three scenarios. However, there is a general trend towards increased growth in alpine regions, whereas in low-lying regions climate change has a negative impact on forest growth. For the whole period 2011 to 2100, the differences in the total supply potential compared to the reference scenario amount to 279,000 t/a (+5.3%) in the *A2*-scenario, 164,000 t/a (+3.1%) in the *A1B*-scenario and 97,000 t/a (+1.9%) in the *B1*-scenario.

Based on the assessment of potentials, climate-sensitive supply curves have been derived in Kranzl et al. (2010) (Figure 12-27). The shapes of the curves are determined by the cost of

[75] More specifically, the approach is based on climate-sensitive simulations of the net primary production, carried out with the forest ecosystem model *PICUS 3G* (an adaptation of the model *PICUS* 1.4; see Seidl et al., 2005) and the model *G4M* – Global Forest Model (Kindermann et al. 2006, Kindermann et al. 2008), which was used to derive supply potentials from the net primary production.

wood extraction, which are influenced by topography, composition of tree species as well as the methods of wood extraction applied. Due to the large time constants of forest growth processes, the shapes of the supply curves do not change substantially during the considered period up to 2050.

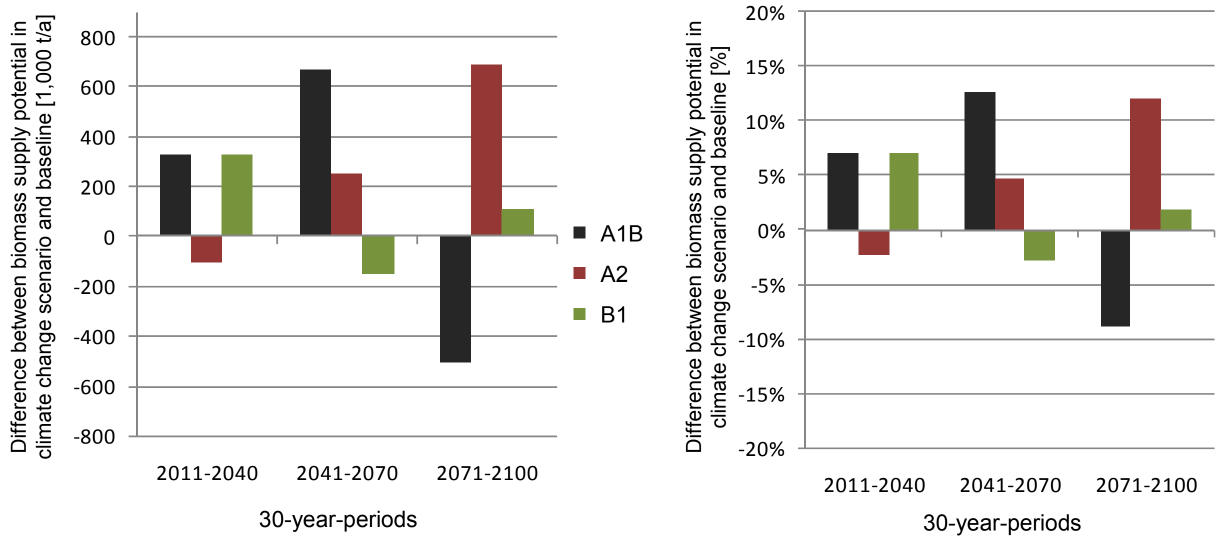

Figure 12-26. Difference between forest biomass supply potential (stock wood for energy use) in climate change scenarios and baseline
Source: Kranzl et al. (2010)

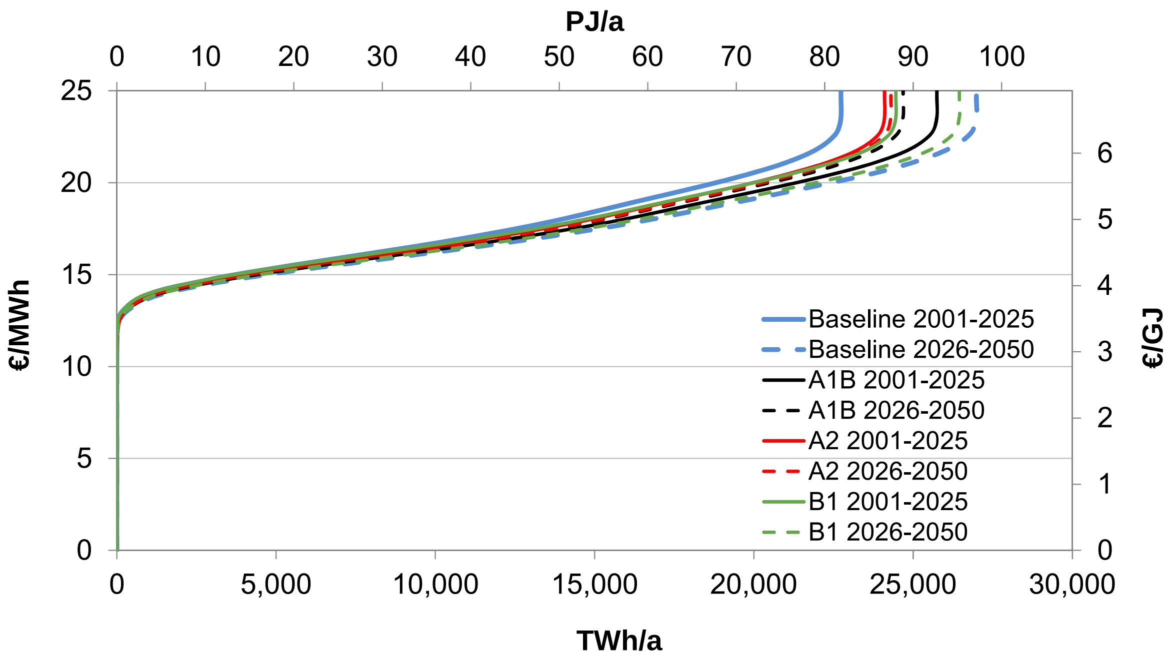

Figure 12-27. Supply curves for forest biomass for energy use for the different climate scenarios and time periods (averages over 25-year periods).
Source: Kranzl et al. (2010)

Apart from these climate-sensitive biomass supply curves, the supply potentials of agricultural and other biomass types are taken into account. The according supply curves are assumed invariant to climate change and correspond to the ones described in section 12.1.2.3.

12.2.1.4 Support schemes

As mentioned above, different support schemes are assumed for the scenarios *A2*, *A1b* and *B1*, in order to be in line with the general trends in the according SRES-scenarios. Table 12-2 gives an overview of the bioenergy support schemes assumed. In scenario *A2* it is assumed that the political effort to increase the share of renewable energy technologies is widely cancelled. Therefore, this scenario corresponds to a “No Policy-scenario” with regard to bioenergy support policies. For the scenario *A1B* it is assumed that support schemes currently in place are maintained, and for scenario *B1* the support for heat and electricity generation from biomass is slightly increased. The tax exemption for pure biofuels is assumed to be maintained in all scenarios.

Table 12-2. Support schemes assumed in the different climate scenarios

		Heat generation	Electricity generation	Transport fuels
Type of support scheme		investment subsidy	feed-in tariff	quota
Amount	A2	-	-	-
	A1B	20%	current tariffs	10% from 2020 on
	B1	30%	current tariffs + 20%	10% from 2020 on

12.2.2 Simulation results

The simulation results presented in the following sections are primarily illustrated on the basis of the share of biomass in total energy consumption (primary energy) and in the sectors heat (useful energy), electricity (final energy) and transport fuels (final energy).

12.2.2.1 Scenario A2

Figure 12-28 shows the simulation results for the scenario *A2*. The underlying scenario for fossil fuel prices and energy policy framework conditions leads to a steep decline of bioenergy use in all sectors. Due to the historic development of bioenergy plant deployment (especially the deployment of CHP plants around 2005 and of biofuel production plants during the period 2005 to 2010) the most rapid decline takes place from 2020 to 2025. During this period, the share of biomass in the total primary energy consumption drops from about 12.5% to 5%.

The only substantial deployment of bioenergy plants takes place in the cluster of small-scale heating systems around 50 kW, but because of the decreasing heat demand, the installed capacities in this category also decline after 2025. The decreasing consumption of biomass fuels implies that biomass prices also decline. Furthermore, as a consequence of the assumed technological development in the field of advanced biofuel production (Hamelinck et Faaij, 2006) and the assumption of a tax exemption for biogenic transport fuels, the production of lignocellulosic ethanol becomes economic after 2040, resulting in a biofuel share in the transport sector of about 4%.

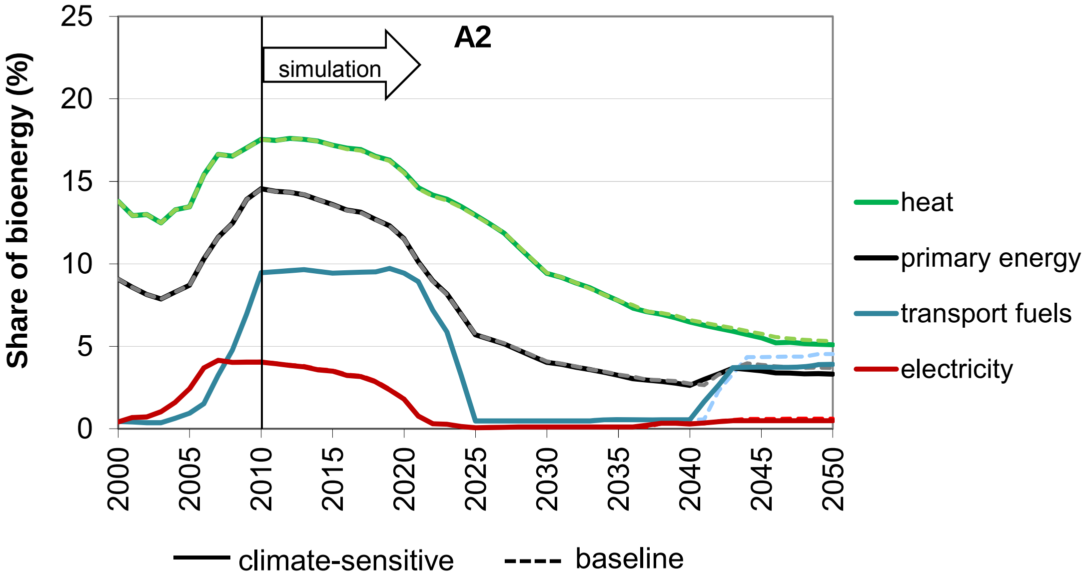

Figure 12-28. Simulation results of scenario A2 in the climate-sensitive and the baseline case: share of bioenergy in the different sectors and in the primary energy consumption

As Figure 12-28 shows, the differences between the climate-sensitive and the baseline scenario are negligible. In view of the uncertainties regarding technological progress up to 2040, the fact that the production of biofuels starts one year later in the baseline scenario is considered a model artefact, resulting from the slightly lower demand-side potential of residential heating in the climate-sensitive scenario.

12.2.2.2 Scenario A1B

The scenario *A1B* is based on the assumption that current support schemes for bioenergy are largely maintained. On the long term, this results in a strong shift from heat-only generation towards CHP. The following figures show the simulation results in relative and absolute numbers.

The contribution of bioenergy in this scenario (and specifically the share of bioenergy in the heat sector) is characterized by the following trends: (i) The initially strong deployment of small-scale heating system comes to a halt around 2020, due to the rapidly declining residential heat demand in the demand 50 kW-category. Biomass heating systems in the other heat clusters (12 and 25 kW) are initially not economic under the given fossil fuel price scenario. (ii) Biomass is increasingly used for combined heat and power generation after 2020. Until 2050 the contribution to the electrical power supply increases to about 10%. (iii) On the long term, rising fossil fuel prices result in improved economic efficiency of bioenergy in industrial and district heat generation, causing a distinctive increase in heat generation from 2040 to 2050.[76]

With regard to the impact of climate change, there are slight differences between the climate-sensitive and the baseline scenario. These differences result from the lower residential heat demand and the additional electricity demand for cooling in the climate-sensitive scenario, as well as differences in forest growth. Based on the results in relative (Figure 12-29) and absolute numbers (Figure 12-30), it is concluded that the different share in the electricity sector as well as the deviation in the heat sector from 2025 to 2040 primarily result from the climate-sensitivity of the energy demand for heating and cooling. On the other hand, the higher heat generation in the baseline scenario towards the end of the simulation period is a consequence of a climate-related reduction of forest productivity (cp. Figure 12-27). The production of biofuels is determined by the assumed 10%-quota, and is therefore not influenced by climate-sensitive parameters.[77]

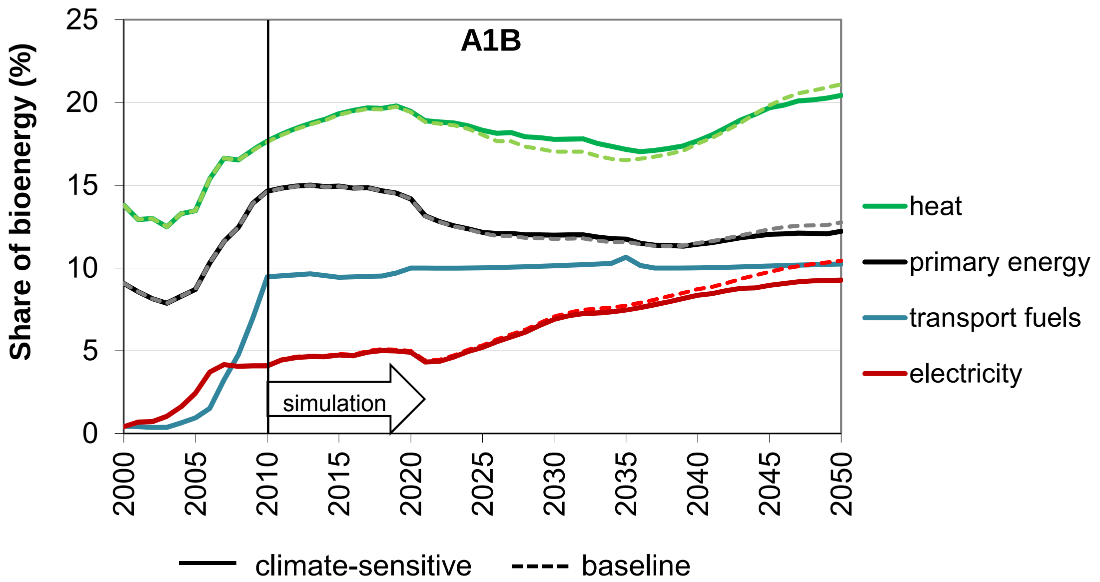

Figure 12-29. Simulation results of scenario A1B in the climate-sensitive and the baseline case: share of bioenergy in the different sectors and in the primary energy consumption

[76] That is to say that the reference system for biomass district heat is fossil-fuel-based district heat generation, and that the demand for district heat is given exogenously. Hence, to what extent a significantly reduced residential heat demand has an impact on the profitability of district heating networks compared to decentralized heat generation is not explicitly taken into account here.

[77] The temporary exceedance of the 10%-quota in 2035 is a result of minimum plant capacities.

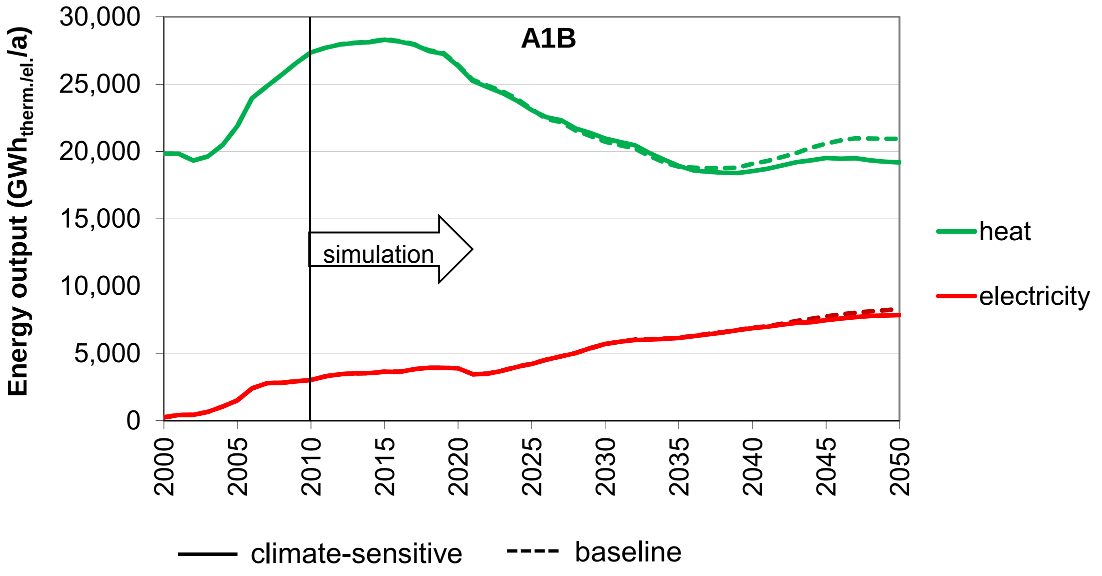

Figure 12-30. Simulation results of scenario A1B in the climate-sensitive and the baseline case: heat and electricity generation of bioenergy plants

12.2.2.3 Scenario B1

Scenario *B1* is characterised by the highest support for bioenergy use, resulting in a significantly higher deployment than in the previous scenarios. Furthermore, this scenario shows the highest climate-sensitivity. The following figures illustrate the development of bioenergy use in the climate-sensitive and the baseline scenario.

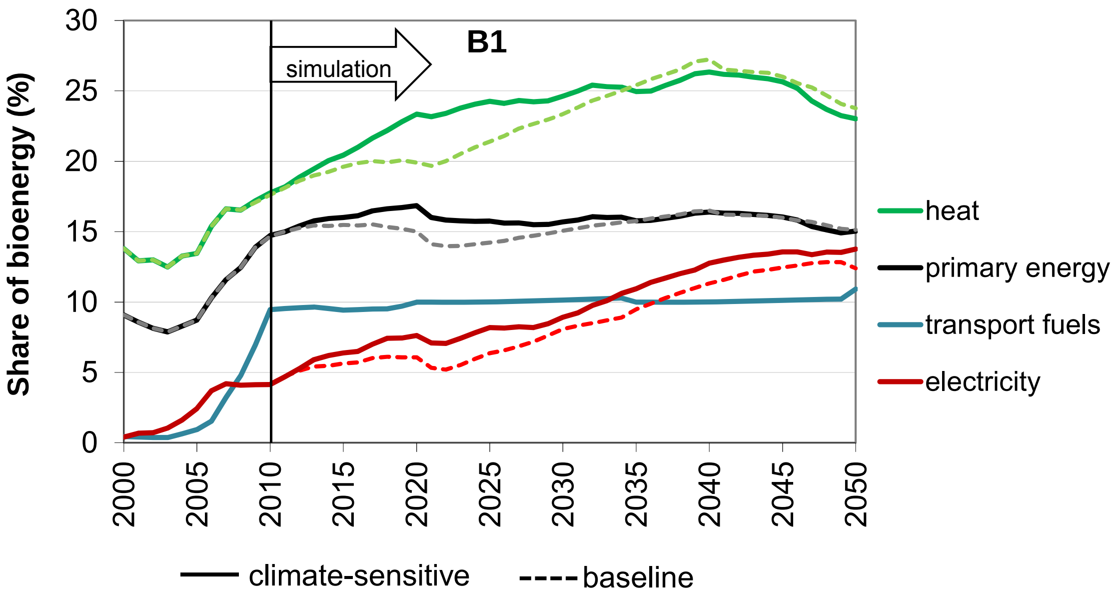

Figure 12-31. Simulation results of scenario B1 in the climate-sensitive and the baseline case: share of bioenergy in the different sectors and in the primary energy consumption

With regard to the heat sector, the mechanisms explained in the description of scenario *A1B* are clearly more pronounced. Apart from that, the initially higher forest productivity in the climate-sensitive case allows for a faster diffusion of bioenergy in the heat and the electricity sector. As a result of the high feed-in tariffs (20% higher than in the *A1B*-scenario), the contribution of biomass CHP increases to about 14% of the total electricity demand.

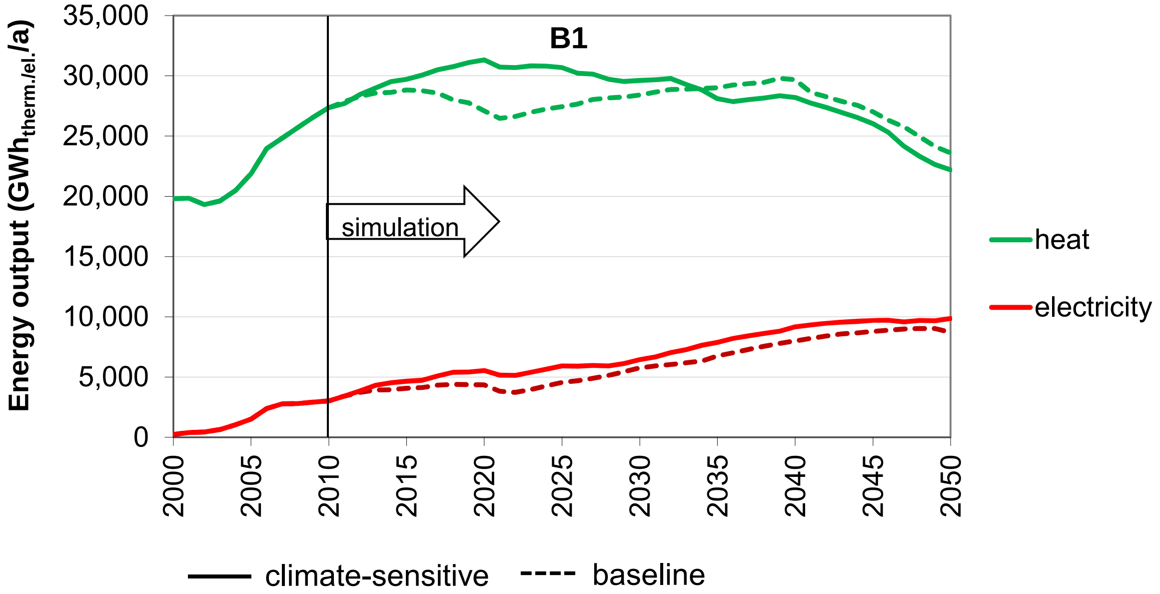

Figure 12-32. Simulation results of scenario B1 in the climate-sensitive and the baseline case: heat and electricity generation of bioenergy plants

Figure 12-33 shows the energy generation in the climate-sensitive case broken down by technology clusters. The figure illustrates the initial deployment of heating systems in the 50 kW-category, followed by a gradual shift towards the 25 kW-category.[78] Nevertheless, the heat output of small-scale heating systems decreases towards the end of the simulation period, as demand-side potentials decline and biomass systems do not become competitive in the 12 kW-category under the given price scenario. The figure also shows that the increasing electricity generation is primarily due to the deployment of large-scale CHP plants above 5 MW_{el}.[79]

[78] The general trend from wood log systems towards other (primarily wood chip and pellet) heating systems is due to an exogenous assumption, implemented via demand-side restrictions.

[79] The peculiar fluctuations in the simulation results of scenario B1 result from variations in the supply potentials of forest biomass, caused by the forest growth model.

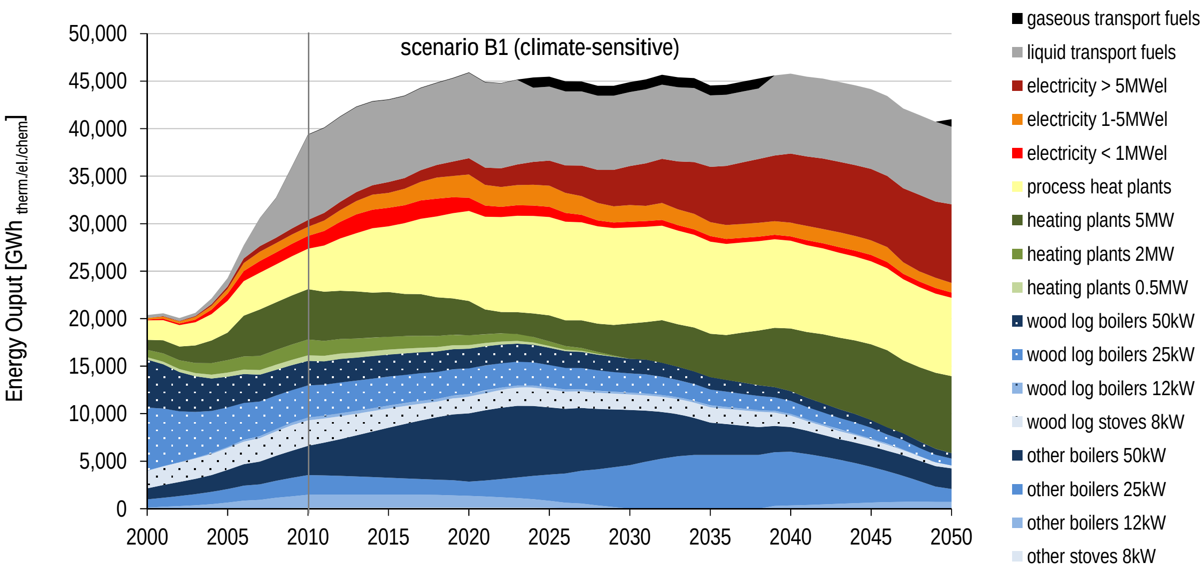

Figure 12-33. Simulation results of scenario B1 in the climate-sensitive case: energy generation of bioenergy plants

12.2.3 Summary, discussion and conclusions

Figure 12-34 shows a comparison of the simulation results for the climate-sensitive scenarios. The developments range from a drastic reduction of bioenergy use (scenario *A2*) to a significant increase (especially scenario *B1*). These differences, caused by the support policies assumed, are far beyond the influence of the considered climate-sensitive parameters. Despite the fact that not all climate-sensitive influencing factors could be taken into account in this analysis (e.g. the impact on agricultural supply potentials, or the risk of increasingly frequent extreme weather events), it is concluded that a strategic and targeted promotion of bioenergy use has priority over climate change adaptation measures. Furthermore, adaptation measures in the field of forestry are primarily dictated by the needs of the wood processing industries rather than the bioenergy sector. Similarly, adaptation measures in agriculture are considered more important with regard to securing food supply than with regard to agricultural bioenergy production. Of course, most agricultural adaptation measures apply for energy crops as well as for food crops, such as the use of drought-resistant crops, improved soil management or pest and disease control (EC, 2009d).

Apart from that, the following conclusions are derived from the application of the model *SimBioSys* presented in this section: Uncertainties related to several model input data, such as technological progress, fossil fuel price developments and current (climate-insensitive) biomass supply potentials are at least as significant as the impact of the considered climate-sensitive influencing parameters on the simulation results. These uncertainties, together with uncertainties related to climate scenarios raise the question of whether it is actually possible to draw concrete conclusions about the climate-sensitivity of the bioenergy sector.

However, the simulation results suggest that the climate-sensitivity of forest growth does have an impact on the development of the Austrian bioenergy sector, at least in scenarios with a high share of bioenergy. The more of the supply potentials is utilized, the more the bioenergy sector is affected by climate-related changes in productivity. Compared to a baseline scenario, the underlying climate scenarios indicate to increased forest growth in the first three decades of the century. Still, the overall impact of climate change could be adverse, as extreme weather events like droughts and storms are expected to occur more frequently in the wake of global warming (EEA, 2008).

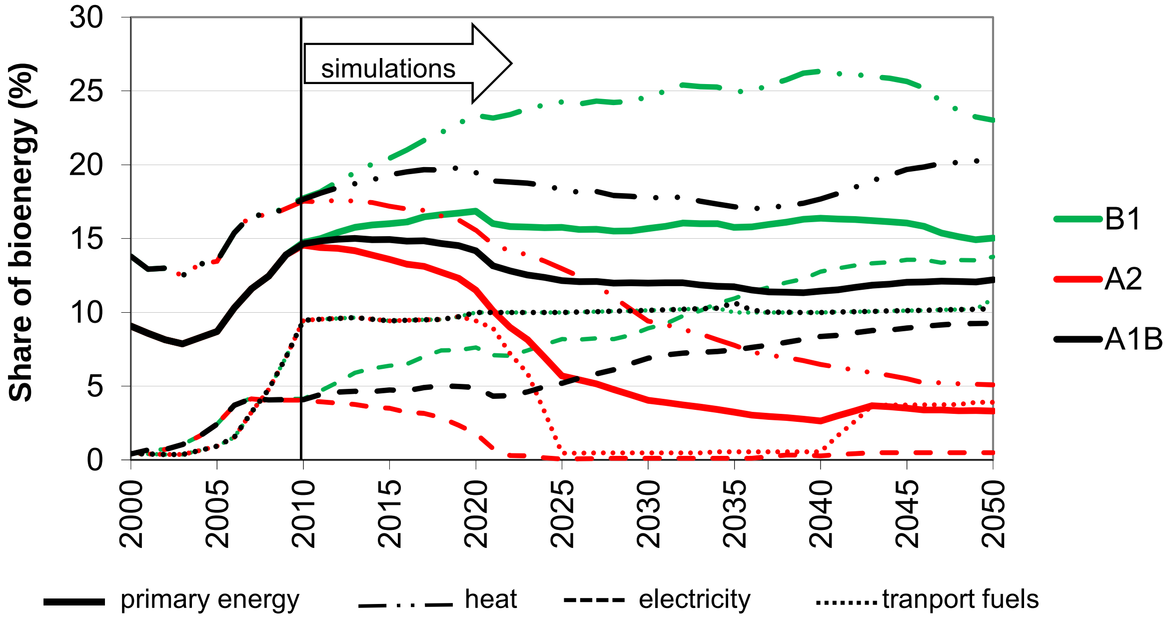

Figure 12-34. Comparison of the climate-sensitive scenarios: share of bioenergy in the different sectors and in the primary energy consumption

13 Synthesis, discussion and further aspects

Within this final section, the main findings of the thesis are summarized and discussed, and further aspects, which have not been taken into account in the main sections but are considered highly relevant, are pointed out.

With an estimated share of 10% in the global primary energy consumption (WBGU, 2009), bioenergy is already today making a substantial contribution to supplying the global energy demand. Due to a long tradition in residential heating with biomass and the high importance of the wood-processing industries, the share of biomass in Austria's primary energy consumption is above the international average (about 15% in 2009), and clearly higher than the biomass share in the energy consumption of the EU-27 (5.8% in 2008) as well as the average share in other Central European countries (about 6.3% in 2008). The fact that Austria is a heavily wooded country undoubtedly contributed to the historic growth of the bioenergy sector, but a close investigation of biomass use reveals that a large proportion is actually based on imported resources. Indirect trade of wood-based fuels is highly relevant for the Austrian bioenergy sector, as large quantities of raw wood are imported for the production of wood products, and a significant share of these quantities actually ends up in energy generation.[80] With indirect trade streams and feedstock imports for biofuel production taken into account, the share of imported biomass in the total biomass consumption accounted for up to 20% during 2006 to 2009; about two times higher than energy statistics suggest.

The recent growth in bioenergy use in Austria (since 2004) resulted in a rapid increases in biomass cross-border trade, especially in the field of biofuels for transport. Furthermore, there is evidence that not only Austria, but the whole Central European region is becoming increasingly dependent on imports of biofuels and feedstock for biofuel production. For Austria, this implies that biofuel and feedstock will probably have to be imported over larger distances in the future. Taking into account that the European Union aims at further increasing the use of biofuels (at least until 2020), it is most likely that the according trade streams towards Central Europe and the EU are going to rise significantly. With regard to issues like deforestation of tropical rainforests, land-use change and food shortages in some world regions, as well as increasing prices for agricultural commodities, increasing imports of the EU imply that concerns about the sustainability and global impacts of the European biofuel policy have to be taken seriously. Sustainability criteria and certification schemes for biofuels may be a step into the right direction, but it is also obvious that there are limits and weaknesses to such schemes. To put it in the words of Doornbosch et Steenblik (2008), as long as the EU

[80] On the other hand, the Austrian wood-processing industries export large quantities of (semifinished) wood products; Austria is a net exporter of sawnwood, paper and wood boards.

sticks to its biofuel policy, the question of whether “the cure is worse than the disease" will have to remain a core issue of the EU’s environmental and energy policy research agenda.

However, biofuels used in the transport sector are still only a small fraction of the total biomass use for energy. On a global scale, solid biomass accounts for as much as 97% of the total biomass use, 71% of which is used for heating and cooking in the residential sector, and most of the biomass is produced locally (WBGU, 2009). Despite the rapid development in the Central European region in recent years, biofuels for transport accounted for only 11% of the biomass primary energy use in 2008; clearly less than the quantities used for heat generation (46%) and electricity/CHP generation (39%), but more than the quantity used for district heating (4%).

The importance of bioenergy for reaching the European Union’s 2020-targets (defined in the 2009-RES-Directive; EC, 2009a) is undisputed. There is no doubt that an even larger contribution of biomass to the global, European and Austrian energy supply is possible (cp. WBGU, 2009 and EC, 2006), and that bioenergy has a crucial role to play in enhancing energy security, reducing GHG emission and substituting fossil fuels. This needs to be achieved through sustainable mobilisation of currently unused primary energy potentials on the one hand, and increasing the efficiency of biomass use on the other. Furthermore, sooner or later a transition from a fossil-based to a bio-based economy is considered inevitable. This shift from depletable to renewable resources is one of the core challenges in order to achieve sustainable economic development; especially with regard to a growing world population, which needs to rely on limited productive land to cover its increasing demand for food, water, energy, space and materials.

A major factor influencing the land required to meet the global food demand, and one of the main reasons for anthropogenic environmental degradation is the excessive consumption of animal products in developed countries. To make things even worse, the livestock sector in some developing countries, especially China and other East Asian countries, is expanding at a rapid rate (LEAD, 2006). The annual per capita consumption of meat in developing countries has already doubled from 1980 to 2002, and this trend is expected to continue for another ten to twenty years before slowing down (Delgado et al., 1999). Still, the average per capita meat consumption in developing countries is expected to amount to less than half of the one in developed countries in 2030 (LEAD, 2006). Up to 2050, global production of meat is projected to double, compared to the production around the year 2000.

Due to the wide-ranging environmental impacts of the livestock sector, it “should rank as one of the leading focuses for environmental policy” (LEAD, 2006). Most surprisingly, it receives very little attention in today’s environmental policy agendas (Stehfest et al., 2009). Therefore, and because of the tremendous impact of dietary patterns on the global potentials of bioenergy production (cp. WBGU, 2009; Bauen et al., 2010; Kalt et al., 2010c), some of the most striking facts about livestock production shall be mentioned here:

- Livestock production accounts for 70% of all agricultural land and 30% of the land surface of the planet. The total area dedicated to the production of crops for feed use amounts to 33% of total arable land (LEAD, 2006).
- The livestock sector is responsible for some of the most serious environmental problems. According to LEAD (2006), livestock production "is probably the largest sectoral source of water pollution, contributing to eutrophication, dead zones in coastal areas, degradation of coral reefs, human health problems, emergence of antibiotic resistance and many others". Furthermore, the expansion of livestock production is "a key factor in deforestation" and probably "the leading player in the reduction of biodiversity".
- The livestock sector is responsible for 18% of global GHG emissions, which is more than the share of the transport sector (LEAD, 2006).
- According to Stehfest et al. (2009), dietary changes could create substantial benefits for global land use and play an important role in future climate change mitigation policies, while significantly improving human health.[81] More specifically, Stehfest et al. (2009) show that a global transition to a low meat-diet (as recommended for health reasons) would reduce the global mitigation costs to achieve a stabilisation target of 450 ppm CO_2-eq. by about 50% in 2050, compared to the reference case.

These facts indicate that changing dietary habits is one of the key aspects towards global sustainable development, and that a transition to "low meat diets" pays off in many ways, especially with direct environmental benefits, positive effects for human health and improved prospects for establishing a sustainable energy system largely based on bioenergy (see Bauen et al., 2010).

While dietary habits are usually not explicitly taken into account in (bio-)energy scenarios (as in this work), normative scenarios for energy, material and food autonomy up to 2050 are derived for Austria within the study "Safe our Surface" (see SOS, 2011). The preliminary results of this project (Altvater et al., 2010) illustrate the close interconnections between the different sectors of consumption and indicate that a reduced consumption of animal products is essential for establishing autonomous supply structures in Austria.

[81] According to Leitzmann (2005), there is growing scientific evidence that "wholesome vegetarian diets offer distinct advantages compared to diets containing meat and other foods of animal origin." Leitzmann (2005) stresses that vegetarian diets are beneficial in the prevention and treatment of many diseases, including some of the most common causes of death, like cardiovascular diseases, cancer and diabetes. Sabaté (2003), for example, also points out that "advances in nutrition research […] have changed scientists' understanding of the contribution of vegetarian diets to human health", and "that well-balanced vegetarian diets could best prevent nutrient deficiencies as well as diet-related chronic diseases".

Regardless of the framework conditions and biomass supply potentials, all resources should be utilized as efficiently as possible. In order to facilitate the design of energy policy framework conditions which foster an optimal use of the limited biomass potentials, scientific investigations about the implications, costs and benefits of the different options of bioenergy are essential. The techno-economic assessments and modelling approaches presented in this work primarily aim at serving as aid for scientists, political decision-makers and local authorities in designing reasonable medium- to long-term strategies and establishing cost-efficient support schemes for the bioenergy sector. In the approaches presented in this study, cost-efficiency, reducing greenhouse gas emissions and increasing energy security by replacing fossil fuels are considered as the main objectives.

The technology-specific analyses presented in Part I show that the efficiencies of different bioenergy technologies and applications vary widely with regard to these objectives. Biomass heating systems in a medium and high capacity range have been identified as efficient applications, as long as their utilization results in the replacement of fossil-based heating systems. A comparable performance is achievable with certain CHP technologies under favourable conditions; the production and use of currently established biofuels for transport is generally clearly less efficient. However, it is necessary to recognise that these conclusions are only true for the assumed reference systems, and that the results of the techno-economic assessment show a high sensitivity to certain parameters, like for example typical annual load hours of heating systems. On the medium to long term, structural changes in the energy supply as well as technical innovation and cost reductions through technological learning (in bioenergy as well as other renewable and conventional technologies) result in changing framework conditions for bioenergy systems. Therefore, not only technological research and development but also accompanying economic research and evaluation of support schemes and energy strategies is considered essential.

Apart from technology-specific economic and technological aspects of bioenergy systems, it is also necessary to take structural and systemic aspects into account in the assessment of prospects, costs and benefits of bioenergy. Such aspects include demand-side potentials of different application, supply potentials of various types of biomass and according costs, and many more. Simulation models are a means of handling the complexity and interactions between the numerous parameters influencing developments in the bioenergy sector, and deriving well-founded scenarios. It was shown that the simulation model *SimBioSys*, which was developed in the course of this thesis, is a suitable tool for simulating future developments of the bioenergy sector. The simulation results illustrate the impact of different support schemes on the efficiency of the bioenergy sector and emphasize the importance of well-planed and targeted energy strategies. For the case of Austria, it was shown that if we aim at establishing a sustainable energy supply, bioenergy will most likely constitute a central pillar of the energy system.

14 Annex

14.1 Abbreviations

(B)IGCC........... (Biomass) Integrated gasification and combustion
CAP................. Common Agricultural Policy (of the European Union)
CCGT.............. Combined cycle gas turbine
CE.................... Central Europe
CHP................. Combined heat and power
CPP................. Condensing power plant
CCS................. Carbon capture and storage
DDGS.............. Dried Distillers Grains with Solubles (livestock feed)
EC.................... European Commission
EU.................... European Union
(EU) ETS......... European emission trading schems
FBG................. Fluidized bed gasifier
FT..................... Fischer-Tropsch
GEMIS............. Global Emission Model of Integrated Systems (see Oeko-Institut, 2010)
GHG................ Greenhouse gas(es)
GIS.................. Geographic information system
GIC.................. Gross inland (energy) consumption
HHV................. Higher heating value (gross calorific value)
IRW................. Industrial roundwood
LHV................. Lower heating value (net calorific value)
LRMC.............. Long run marginal cost
MCFC.............. Molten carbonate fuel cell
MIP.................. Mixed integer programming
ORC................ Organic Rankine cycle
RES................. Renewable energy source(s)
SNG................. Synthetic natural gas
SRES............... Special Report on Emissions Scenarios (IPCC, 2000)
SRMC.............. Short run marginal cost

14.2 Technology data

Table 14-1. Technology data for heating systems and heating plants

	annual use efficiency[a]	annual full load hours	total capital investment[b]	capital investment (components): boiler/ stove	capital investment (components): additional heat storage	capital investment (components): peripheral equipment	capital investment (components): fuel storage	capital investment (components): installation, commissioning	operation and maintenance	specific GHG emissions[c, d, f]	fossil fuel consumption[c, e, f]	references (based on)
unit	%	h·a^{-1}	€kW^{-1}	€kW^{-1}	€kW^{-1}	€kW^{-1}	€kW^{-1}	€kW^{-1}	€(kW·a)$^{-1}$	kg CO_2-equ·MWh$_{therm}^{-1}$	MWh$_{HHV}$·MWh$_{therm}^{-1}$	
single stoves 8 kW												
oil stove	80%	500	200.00	200.00	-	-	-	-	4.00	366.86	1.435	Kranzl et al. (2009),
wood log stove	70%	500	300.00	300.00	-	-	-	-	8.00	24.75	0.020	Hansen et al. (2007)
pellet stove	82%	500	400.00	400.00	-	-	-	-	8.00	36.97	0.078	Hartmann et al. (2007)
boilers 12 kW												
oil-fired boiler	85%	1500	746.53	300.00	-	188.94	200.00	57.59	14.93	346.04	1.350	Hartmann et al. (2007)[h]
gas-fired boiler	85%	1500	546.53	300.00	-	188.94	-	57.59	10.93	265.96	1.390	Erdgas OO (2006)
wood log boiler	75%	1500	1130.35	650.00	150.00	253.56	-	76.79	22.61	27.77	0.044	
pellet boiler	84%	1500	1423.41	1000.00	30.00	292.48	-	100.93	28.47	27.15	0.095	Hartmann et al. (2007)
plant oil-fired boiler	91%	1500	846.53	400.00	-	188.94	200.00	57.59	16.93	229.94	0.462	
boilers 25 kW												
oil-fired boiler	85%	1500	541.28	200.00	-	105.28	200.00	36.00	10.83	346.04	1.350	Hartmann et al. (2007)[h]
gas-fired boiler	85%	1500	311.28	170.00	-	105.28	-	36.00	6.23	265.96	1.390	Erdgas OO (2006)
wood log boiler	75%	1500	727.00	350.00	150.00	167.00	-	60.00	14.54	27.77	0.044	
pellet boiler	84%	1500	961.38	600.00	30.00	158.08	100.00	73.29	19.23	27.15	0.095	Hartmann et al. (2007)
plant oil-fired boiler	91%	1500	591.28	250.00	-	105.28	200.00	36.00	11.83	229.94	0.462	
wood chip boiler	80%	1500	1190.00	950.00	30.00	165.00	-	45.00	23.80	24.14	0.066	
boilers 50 kW												
oil-fired boiler	85%	1800	242.14	83.33	-	40.81	100.00	18.00	4.84	346.04	1.350	Hartmann et al. (2007)[h]
gas-fired boiler	85%	1800	158.81	100.00	-	40.81	-	18.00	3.18	265.96	1.390	Erdgas OO (2006)
wood log boiler	75%	1800	449.00	200.00	150.00	77.00	-	22.00	8.98	27.77	0.044	
pellet boiler	84%	1800	447.66	300.00	30.00	58.95	38.33	20.38	8.95	27.15	0.095	Hartmann et al. (2007)
plant oil-fired boiler	91%	1800	258.77	99.97	-	40.81	100.00	18.00	5.18	229.94	0.462	
wood chip boiler	80%	1800	489.00	370.00	30.00	67.00	-	22.00	9.78	24.14	0.066	
heating plants 0.5 MW												
oil-fired	85%	3000	200.00	-	-	-	-	-	6.00	382.52	1.406	
gas-fired	85%	3000	200.00	-	-	-	-	-	6.00	278.03	1.440	Karl (2006), FNR (2007)
wood chip-fired	85%	3000	750.00	-	-	-	-	-	22.50	24.50 (+27.80)	0.089 (+0.144)	
straw-fired	85%	3000	1125.00	-	-	-	-	-	28.80	21.76 (+27.80)	0.072 (+0.144)	Karl (2006), FNR (2007)[g]
heating plants 2 MW												
oil-fired	85%	3000	150.00	-	-	-	-	-	4.50	382.52	1.406	
gas-fired	85%	3000	150.00	-	-	-	-	-	4.50	278.03	1.440	Karl (2006), FNR (2007)
wood chip-fired	85%	3000	510.00	-	-	-	-	-	15.30	24.50 (+27.80)	0.089 (+0.144)	
straw-fired	85%	3000	765.00	-	-	-	-	-	19.58	21.76 (+27.80)	0.072 (+0.144)	Karl (2006), FNR (2007)[g]
heating plants 5 MW												
oil-fired	85%	3000	130.00	-	-	-	-	-	3.90	382.52	1.406	
gas-fired	85%	3000	130.00	-	-	-	-	-	3.90	278.03	1.440	Karl (2006), FNR (2007)
wood chip-fired	85%	3000	470.00	-	-	-	-	-	14.10	24.50 (+27.80)	0.089 (+0.144)	
straw-fired	85%	3000	705.00	-	-	-	-	-	18.05	21.76 (+27.80)	0.072 (+0.144)	Karl (2006), FNR (2007)[g]
process heat plant 5 MW												
gas-fired	85%	6000	175.00	-	-	-	-	-	5.25	265.92	1.390	Karl (2006)
wood chip-fired	85%	6000	634.50	-	-	-	-	-	19.04	11.81	0.007	

a) Efficiencies refer to LHV for bioenergy systems and HHV for fossil oil and gas systems
b) For heating plants and process heat plants, total capital investment include all costs for building, peak load boiler, peripheral equipment, commissioning etc.
c) Data on GHG emissions and fossil fuel consumption all based on GEMIS-datasets (Oeko-Institut, 2010)
d) Cumulated non-renewable GHG emissions
e) Cumulated fossil fuel demand
f) Data in parenthesis: additional GHG emissions of peak load coverage at assumed operation time of 300 h·a
g) Boilers of straw-fired plants are assumed to have 50% higher investment costs than according wood-chip-fired plants (see Leuchtweis, 2008)
h) Investment costs have been adapted based on AEA (2004) and Konsument (2008)

Table 14-2. Technology data for biomass CHP technologies and reference power plants

	typical rated power	efficiency electricity	efficiency heat	annual full load hours	investment cost CHP plant	additional investment cost for peak load boiler (mode 2 only)	operation and maintenance	specific GHG emissions[a]	fossil fuel consumption[a]	additional GHG emissions from peak load boiler (mode 2 only)[e]	additional fossil fuel consumption from peak load boiler (mode 2 only)[e]	references (based on)
unit	MW_{el}	%	%	$h \cdot a^{-1}$	$€ \cdot kW_{el}^{-1}$	$€ \cdot kW_{el}^{-1}$	$€ \cdot (kW_{el} \cdot a)^{-1}$	$kg\ CO_2\text{-equ} \cdot MWh_{el}^{-1}$	$MWh_{HHV} \cdot MWh_{el}^{-1}$	$kg\ CO_2\text{-equ} \cdot MWh_{el}^{-1}$	$MWh_{HHV} \cdot MWh_{el}^{-1}$	
Bioenergy plants												
Biogas CHP plants[b]	0.050	22%	32%	8000	6,000	218	300.00	279	0.628	9.80	0.051	
	0.200	23%	32%	8000	4,515	136	224.00	262	0.589	9.41	0.049	Walla et al. (2008), Walla (2006)
	0.500	24%	32%	8000	3,833	132	179.00	255	0.572	9.22	0.048	
	1.500	26%	32%	8000	2,700	122	135.00	234	0.627	8.71	0.045	Hagauer et al. (2007a)
Plant oil CHP plant[c]	0.015	31%	61%	7000	2,567	197	77.00	505	0.619	12.72	0.066	Prankl et al. (2006)
	0.200	31%	61%	7000	1,120	197	34.00	505	0.619	12.72	0.066	
	1.000	31%	61%	7000	949	197	28.47	505	0.619	12.72	0.066	
Wood chip boilers, Stirling engine	0.035	11%	76%	7000	14,001	719	314.11	99	0.293	20.99	0.109	Obernberger et Thek (2006)
	0.070	11%	76%	7000	11,143	719	250.83	99	0.293	21.07	0.184	
Wood chip boilers, ORC plant	0.650	14%	72%	7000	8,120	514	273.74	74	0.228	19.13	0.099	
	1.600	14%	72%	7000	5,443	514	229.17	74	0.228	19.13	0.099	
Steam turbine plant (wood chips)	1.000	11%	74%	7000	6,056	673	302.80	85	0.262	20.64	0.107	Kirjavainen et al. (2004)
	5.000	18%	65%	7000	3,992	360	190.55	57	0.169	16.87	0.087	Obernberger et Thek (2006)
	10.000	24%	62%	7000	3,033	256	148.01	45	0.14	14.55	0.075	Wahlund et al. (2000)
Straw boilers, ORC plant	0.650	14%	72%	7000	9,329	514	466.45	67	0.226	19.13	0.099	Obernberger et Thek (2006)[d]
	1.600	14%	72%	7000	6,600	514	330.02	67	0.226	19.13	0.099	
Steam turbine plants (straw)	1.000	11%	74%	7000	7,070	673	353.48	89	0.305	20.64	0.107	Kirjavainen et al. (2004)[d]
	5.000	18%	65%	7000	4,712	360	235.60	59	0.195	16.87	0.087	Obernberger et Thek (2006)[d]
DDG, gas engine (wood chips)	0.600	28%	36%	7000	6,734	132	383.45	94	0.309	10.03	0.052	Obernberger et Thek (2006)
FBG, gas engine, ORC (wood chips)	5.000	34%	37%	7000	5,159	110	388.10	72	0.235	8.93	0.046	
BIGCC (wood chips)	50.000	43%	47%	7000	2,300	109	57.50	57	0.186	8.87	0.046	Wetterlund et al. (2010)
Reference technologies												
CCGT (natural gas)	500.000	58%	-	7500	498	-	29.25	432	2.260	-	-	Cosijns et al. (2007)
CPP (hard coal)	500.000	46%	-	7500	959	-	54.00	888	2.431	-	-	
CCGT (natural gas) with CHP	500.000	47%	33%	7500	605	-	62.25	532	2.788	-	-	
CCGT (natural gas) 2030	500.000	62%	-	7500	435	-	29.25	417	2.185	-	-	
CPP (hard coal) 2030	500.000	50%	-	7500	989	-	54.00	786	2.151	-	-	
IGCC (hard coal) 2030 with CCS	1000.000	48%	-	7500	1,652	-	90.75	113	2.217	-	-	
CCGT (natural gas) 2030 with CCS	500.000	56%	-	7500	1,046	-	65.25	46	2.341	-	-	

a) Data on GHG emissions and fossil fuel consumption all based on GEMIS-datasets (Oeko-Institut, 2010)
b) GHG emissions and fossil fuel consumption refer to a feedstock mix of 90% maize and 10% manure
c) GHG emissions and fossil fuel consumption refer to the use of rapeseed oil
d) Boilers of straw-fired plants are assumed to have 50% higher investment costs than according wood-chip-fired plants
e) Additional GHG emissions of peak load coverage are based on assumed operation time of 300 $h \cdot a^{-1}$
Abbreviations: DDG = downdraft gasifier, FBG = fluidized bed gasifier, CCGT = combined cycle gas turbine, CPP = condensing power plant, IGCC = Integrated gasification and combustion, CCS = Carbon capture and storage

Table 14-3. Technology data for biofuel production technologies

	typical rated power	input feedstock	efficiency fuel	efficiency electricity	byproduct output	type of byproduct	Annual full load hours	Total capital investment	operation and maintenance	specific GHG emissions [a,b]	fossil fuel consumption [a,c]	references (based on)
unit	MW_{LHV}	-	%	%	$t/MWh_{LHV,fuel}$	-	$h \cdot a^{-1}$	$€kW_{LHV}^{-1}$	$€(kW_{LHV} \cdot a)^{-1}$	$kg\ CO_2\text{-equ} \cdot MWh_{LHV}^{-1}$	$MWh_{HHV} \cdot MWh_{LHV}^{-1}$	
biofuel production plants												
decentralized plant oil press	0.5	rapeseed	66%	0.00%	0.146	press cake	5000	329.23	49.69	138.74	0.163	Remmele (2007)
centralized plant oil press	250.0		83%	0.00%	0.116	press meal	8000	49.90	1.50	138.74	0.163	Diesenreiter (2008)
decentralized biodiesel plant	12.0	plant oil	100%	0.00%	0.011	crude glycerol	8000	360.00	52.46	165.51	-0.018	Toro et al. (2009), Berger (2004)
centralized biodiesel plant	150.0		100%	0.00%	0.011	crude glycerol	8000	122.70	23.86	165.51	-0.018	Berger (2004)
bioethanol plant (starch)	100.0	wheat grain	46%	0.00%	0.153	DDGS	8000	645.00	110.08	132.12	0.668	Friedl et al. (2005)
bioethanol plant (sugar)	60.0	sugar beet	57%	0.00%	-	-	8000	474.58	23.14	117.11	0.747	Toro et al. (2009)
biomethane plant	0.3	90% maize, 10% manure	68%	0.00%	-	-	8000	3520.01	332.11	85.35	0.229	Klinski (2006), Urban et al. (2008)
	1.5		68%	0.00%	-	-	8000	1298.58	139.82	85.35	0.229	
	3.0		68%	0.00%	-	-	8000	967.73	114.75	85.35	0.229	
Fischer-Tropsch-plant	150.0	wood chips	42%	3.20%	-	-	8000	2176.68	95.77	17.04	0.069	Hamelinck et Faaij (2006)
bioethanol plant (cellulose)	125.0		35%	4.10%	-	-	8000	2616.75	167.47	31.76	0.103	
SNG plant	14.0		74%	1.58%	-	-	8000	1388.23	76.51	44.07	0.152	Gassner et al. (2009), Klinski (2006)
	110.0		74%	1.60%	-	-	8000	993.66	44.35	43.99	0.152	
reference fuels												
fossil diesel	-	-	-	-	-	-	-	-	-	50.62 (+250.31)	1.157	
fossil petrol	-	-	-	-	-	-	-	-	-	53.03 (+247.25)	1.195	
natural gas	-	-	-	-	-	-	-	-	-	43.63 (+179)	1.142	

a) Data on GHG emissions and fossil fuel consumption all based on GEMIS-datasets (Oeko-Institut, 2010), except for GHG emission data for biodiesel, ethanol and FT diesel which are based on (EC, 2009a)

b) Values in parentheses: non-renewable GHG emission for combustion

c) Negative values result from credits for the byproducts press meal and glycerol

14.3 Nomenclature and formulae

The following sections provide the nomenclature and formulae for Part I and Part III. The ones used in both sections are:

α .... Capital recovery factor $\alpha = \frac{(1+i)^n \cdot i}{(1+i)^n - 1}$ (14-1)

n .... Depreciation period / lifetime (in years)[82]

i .... Interest rate, %

$SRMC$ .... Short run marginal cost, € MWh^{-1}

$LRMC$ .... Long run marginal cost (energy generation costs), € MWh^{-1}

T_{FL} .... Annual full load hours, h a^{-1}

14.3.1 Part I

c_I...................... Total investment costs, € MW^{-1} (including investment costs of peak load boiler, if required)

$c_{O\&M}$................ Operation and maintenance costs, € MW^{-1} a^{-1}

p_F .... Fuel/feedstock price, € MWh^{-1}

$p_{F,peak}$ .... Price of fuel for peak load boiler, € MWh^{-1}

$p_{BP,j}$ .... Price of by-product j (e.g. DDGS, glycerin, electricity), € MWh^{-1} or € t^{-1}

p_{heat} .... Heat revenue, € MWh^{-1} (20 €/MWh_{heat} in mode 1, 20.94 – 66.21 €/MWh_{heat} in mode 2, depending on plant size)

$q_{BP,j}$ .... Output of by-product j (per MWh of fuel produced), MWh MWh^{-1} or t MWh^{-1}

$\eta_{heat/el/biofuel}$ .... Conversion efficiency (heat / electricity generation / biofuel production), %

$\eta_{heat,peak}$ .... Thermal efficiency of peak load boiler

T_{heat} .... Annual heat full load hours of CHP plant, h a^{-1}

$T_{heat,peak}$ .... Annual heat full load hours of peak load boiler (CHP plant), h a^{-1}

u_{peak}.................. Peak load usage factor of heating plant, %

Short run marginal cost of heat generation:

$$SRMC_{heat} = \frac{p_F}{\eta_{heat}} + \frac{c_{O\&M}}{T_{FL}} \qquad (14\text{-}2)$$

[82] For the calculation of energy generation costs the lifetime of technologies are used (Part I), whereas for investment decisions in the model *SimBioSys* usually depreciation periods of 10 years are assumed.

Short run marginal cost of heating plants with peak load boiler (peak load usage factor u_{peak} = 10% in the default case, i.e. 10% of the total supplied heat is assumed to be generated with the peak load boiler):

$$SRMC_{heat} = \frac{(1-u_{peak})\cdot p_F}{\eta_{heat}} + \frac{u_{peak}\cdot p_{F,peak}}{\eta_{heat,peak}} + \frac{c_{O\&M}}{T_{FL}} \quad (14\text{-}3)$$

Short run marginal cost of biofuel production:

$$SRMC_{biofuel} = \frac{p_F}{\eta_{biofuel}} + \frac{c_{O\&M}}{T_{FL}} - \sum_{j=1}^{m} p_{BP,j}\cdot q_{BP,j} \quad (14\text{-}4)$$

Short run marginal cost of power generation (mode 1):

$$SRMC_{el} = \frac{p_F}{\eta_{el}} + \frac{c_{O\&M}}{T_{FL}} - p_H \cdot \frac{\eta_{heat}}{\eta_{el}} \quad (14\text{-}5)$$

Short run marginal cost of power generation in mode 2 (annual heat full load hours T_{heat} = 3000 and peak load full load hours $T_{heat,peak}$ = 300 in the default case):

$$SRMC_{el} = \frac{p_F}{\eta_{el}} + \frac{c_{O\&M}}{T_{FL}} - p_H \cdot \frac{\eta_{heat}}{\eta_{el}} \cdot \frac{T_{heat}}{T_{FL}} + \frac{p_{F,peak}}{\eta_{heat,peak}} \cdot \frac{T_{heat,peak}}{T_{FL}} \quad (14\text{-}6)$$

Long run marginal cost (total energy generation cost):

$$LRMC = SRMC + \frac{c_I\cdot\alpha}{T_{FL}} \quad (14\text{-}7)$$

14.3.2 Part III

Parameters, according units and subscripts used in Part III are summarized below. The parameters are partly denoted with subscripts to increase clarity. (In the text they appear both with and without subscripts, depending on the necessity and context.)

Parameters

a_j .... profitability indicator of technology j (used in cost-based deployment algorithm)

c .... cost of biomass provision, €/MWh^{-1}

c^{be} .... (marginal) energy generation cost of bioenergy technology, €/MWh^{-1}

c^{ref} .... reference price/costs, €/MWh^{-1}

c^{fix} .... fixed costs (used in simplified formula for energy generation costs), also written as vector $\overrightarrow{c^{fix}} = [c_j^{fix}]_{j=1,\dots,n}$, €/MWh^{-1}

δ_k .... parameter used in the definition of diffusion curves (referring to output cluster k)

ε .... supply elasticity used in definition of supply curves

p .... biomass price (marginal cost), also written as vector $\vec{p} = [p_i]_{i=1,\dots,m}$, €/MWh^{-1}

$p*$ .... biomass equilibrium price, €/MWh^{-1}

$p^{min/max}$ .... minimum/maximum biomass price, €/MWh^{-1}

p^{cert} .... price of certificate (related to a quota), €/MWh^{-1}

$P_{(t)}$ .... total installed plant capacity of certain technology (in the year / simulation period t), referring to main output, MW

P_t^{add} .... additional plant capacity (being installed in year/simulation period t), referring to main output, MW

PS .... producer surplus, €

q .... biomass quantity, also written as vector $\vec{q} = [q_i]_{i=1,\dots,m}$, GWh

$q_{(B/E)}$ .... quantity of biomass (used at the beginning (B) / end (E) of a simulation period), GWh

$q*$ .... biomass quantity at equilibrium price, GWh

$\eta_{(ji)}$ .... efficiency (of technology j in converting fuel i to energy commodity), also written as matrix $H = [\eta_{ji}]_{n\times m}$, %

$\rho_{(ji)}$ .... reciprocal values of efficiencies, also written as matrix $R = [\rho_{ji}]_{n\times m}$

$y_{(j)}$ .... quantity of energy output / commodity (heat, electricity, fuel) produced by technology j; also written as vector $\vec{y} = [y_j]_{j=1,\dots,n}$, GWh

$y_k^{\max}$ .... maximum energy generation of output cluster k (corresponds to demand-side potential), GWh

y_k^{add} .... maximum additional energy generation of output cluster k, GWh

$\Delta y_k^{\max}$ .... parameter used in the definition of diffusion curves (referring to output cluster k)

y^{demand} .... demanded energy quantity, determined by an obligatory quota, GWh

Subscripts

i .... biomass fuel type

j .... technology type

k .... technology cluster / output cluster

t .... year / simulation period

B/E .... referring to the beginning/end of a simulation period

14.4 References

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14.5 List of figures

14.6 List of tables