Summary and conclusions

Biomass can play a role in mitigating greenhouse gas emissions by substituting conventional materials and supplying biomass based fuels. However, currently only a modest amount of biomass is used for these applications in industrialised countries. Main reason for the low share of biomass applications in Europe (about 6 EJ in the EU-15) is their often-high production costs, among others due to the relatively low availability of agricultural land. Therefore, in the short to medium term more efficient and cost effective routes for the introduction of biomass are needed. One of these routes may be the further development of multi-functional biomass systems and the shift of biomass production to more favourable areas, for example, Central Eastern Europe. Multi-functional biomass systems use the concepts of 'multi-product use' and 'cascading'. Multi-product use is defined as using biomass for different applications, while cascading is the subsequent use of biomass for a number of applications, i.e. materials, recycling of materials and energy recovery. Important parameters for the efficiency of multi-functional biomass systems are savings of non-renewable energy consumption, GHG (greenhouse gas) emission reduction, (agricultural) land use and total costs of the system. However, only very few studies have explicitly addressed multi-functional biomass systems analysing these parameters quantitatively. Therefore, the central research question of this thesis is: *What is the potential of multi-functional biomass systems to improve the costs and the land use efficiency of saving non-renewable energy consumption and reducing GHG emissions in quantitative terms?* Two main aspects play an important role in answering this central question. First, methodologies to account for costs, land use, GHG emissions and non-renewable energy consumptions need to be adapted for the evaluation of multi-functional biomass systems. Particularly, issues of allocation of environmental impacts and costs or system expansion, accounting for the time dimension and the integration of market price changes due to the large-scale introduction of biomass systems deserve special attention. Second, the potential benefits depend on the kind of biomass system regarded and the mechanism of this dependence have to be studied in order to identify promising multi-functional biomass systems.

In this thesis, the performance of multi-functional biomass systems with regard to GHG emissions, non-renewable energy consumption, agricultural land use and costs is quantified. This analysis is carried out by several case studies of multi-functional biomass systems that appeared to be promising from a first review. The case studies are situated in Europe and concentrate on Poland. In such a way the potential of biomass production in Central Eastern Europe can be investigated, because these states have (at present) large areas of agricultural land, potentially high to medium crop yields and comparably low costs of land and labour.

Chapter 2 investigates the concept of multi-product crops. Multi-product crops, i.e. using a crop partially for energy and partially for material purposes, can possibly create additional incomes as well as additional GHG emission reductions. In this chapter, the benefits of multi-product crop systems in comparison to energy crop systems are investigated systems, focussed on the primary biomass fuel costs and GHG emission reductions per area of biomass production. For this analysis a case study approach is followed and the sensitivity of the results is investigated by means of a Monte-Carlo analysis. The multi-product crops studied are wheat, hemp and poplar in the Netherlands and Poland. GHG emission reductions of these multi-product systems are found to be between 0.2 and 2.4 Mg CO_{2eq} per hectare per year in Poland and between 0.9 and 7.8 Mg CO_{2eq} per hectare per year in the Netherlands, while primary biomass fuel costs range from –4.1 to –1.7 €/GJ in the Netherlands and from 0.1 to 9.8 €/GJ in Poland. Results show that the economic attractiveness of multi-product crops depends strongly on material market prices, crop production costs and crop yields. Net annual GHG emission reductions per hectare are influenced strongly by the specific GHG emission reduction of material use, reference energy systems and GHG emissions of crop production. Multi-product use of crops can significantly decrease primary biomass fuel costs. However, this does not apply in general, but depends on kind of crops and material uses. For the examples analysed here, net annual GHG emission reductions per hectare are not lowered by multi-product use. Consequently, multi-product use of crops is not a priori an option to increase the performance of bioenergy systems.

Chapter 3 has a twofold aim: (1) to select and develop a coherent methodological framework for the comparison of different biomass cascading chains in terms of costs, land demand and CO_2 emission reductions and (2) to identify key parameters and issues that influence the efficiency of biomass cascading chains using the methodology developed. For the second purpose, the approach is applied to a case study. A number of cascading chains of short rotation poplar wood are compared to each other on basis of literature data. Results for these chains vary strongly, namely, from net benefits of CO_2 mitigation of 200

€/Mg CO_2 to net costs of CO_2 mitigation of 2200 €/Mg CO_2, and from net CO_2 emission reductions per hectare of biomass production of 28 Mg CO_2 per hectare per year to net CO_2 emissions of 8 Mg CO_2 per hectare per year. Using a present-value approach to determine CO_2 emissions and costs affects the performance of long-term cascading chains significantly, i.e. cost and CO_2 emission reduction are decreased. Throughout, cascading has the potential to improve both CO_2 emission reduction per hectare and CO_2 mitigation costs of biomass usage. However, this strongly depends on the biomass applications combined in the cascading chain. Parameters that significantly influence the results are market prices and gross energy requirements of substituted materials and energy carriers, and the efficiency of biomass production. The method presented in this study is suitable to quantify land use, CO_2 emission reduction and economic performance of biomass cascading systems, and highlights the possible impact of time on the attractiveness of specific cascading chains.

Chapter 4 compares savings of non- renewable energy consumption and greenhouse gas (GHG) emission reductions of bio-based polymers with those of bioenergy on a per unit of agricultural land-use basis. In view of policy goals to increase the energy supply from biomass and current efforts to produce bio-based polymers in bulk, the amount of available land for the production of non-food crops could become a limitation. Hence, given the prominence of energy and greenhouse issues in current environmental policy, it is desirable to include land demand in the comparison of different biomass options. Over the past few years, numerous life-cycle assessment (LCA) studies have been prepared for different types of bio-based polymers, but only a few of these studies address the aspect of land use. Therefore, this chapter extends existing LCA studies by taking into account land requirements in the analysis of energy savings and GHG emission reductions. The results show that referring energy savings and GHG emission reduction of bio-based polymers to a unit of agricultural land, instead of to a unit of polymer produced, leads to a different ranking of options. If land use is chosen as the basis of comparison, natural fibre composites and thermoplastic starch score better than bioenergy production from energy crops, whereas poly(lactides) score comparably well and poly (hydroxyalkaonates) score worse. If the use of agricultural residues for energy purposes is included, the environmental performance of bio-based polymers improves significantly. Moreover, it is very likely that higher production efficiencies will be achieved for bio-based polymers in the medium term. Bio-based polymers thus offer interesting opportunities to reduce the utilisation of non-renewable energy and to contribute to GHG emission mitigation in view of potentially scarce land resources.

Chapter 5 analyses the potential quantitative benefits of multi-functional bio-refinery systems with regard to GHG emission reductions, savings of non-renewable energy consumption and costs in relation to production scale and market volumes. For this analysis a case study of bio-refinery systems for poly lactic acid (PLA) production is carried out. The systems include multi-functional use of biomass resources, i.e. use of agricultural residues for energy production, use of by-products, recycling, and waste-to-energy recovery. We evaluate the performance of these systems per kilogram of bio-based polymer produced and per hectare of biomass production. The evaluation is done using data of Poland assuming that biomass and PLA production is embedded in a European energy and material market. First, the performance of different bio-refinery systems is investigated by means of a bottom-up chain analysis. Second, an analysis is applied that derives market prices of products and land by means of the own-price elasticities. Thus, costs of the bio-refinery systems are determined depending on the demand of land and materials. It is found that all PLA bio-refinery systems considered lead to net savings of non-renewable energy consumption of 70 to 220 GJ per hectare per year and to net GHG emission reductions of 3 to 17 Mg CO_{2eq} per hectare per year. Most PLA bio-refinery systems considered in this study lead to net costs of the overall system of up to 4600 € per hectare per year. On the contrary, PLA production from short rotation wood leads to net benefits of about 1100 € per hectare per year if a high amount of a high-value product, i.e. synthetic fibres, is produced. Multi-functionality is necessary to ensure the viability of PLA bio-refinery systems from biomass with regard to energy savings and GHG emission reduction. However, with regard to costs, the multi-functional use of biomass does not contribute much to overall incomes. Own-price elasticity of the demand for materials influences the overall costs of the bio-refinery system strongly. The own-price elasticity of land demand could become important if biomass systems are introduced on a large scale.

Chapter 6 evaluates the possible influences of the large-scale introduction of biomass material and energy systems and their market volumes on land, material and energy market prices and their feedback to GHG emission mitigation costs. GHG emission mitigation supply curves for large-scale biomass use are compiled using a methodology that combines a bottom-up analysis of biomass applications, biomass cost supply curves and market prices of land, bio-materials and bioenergy carriers. These market prices depend on the scale of biomass use and the market volume of materials and energy carriers and are estimated using own-price elasticities of demand. The methodology is demonstrated for a case study of Poland in the year 2015. The case study applies different scenarios on economic development and trade in Europe that impact biomass supply and markets of land, materials and energy carriers. For the key technologies considered, i.e. medium density fibreboard, poly lactic acid, electricity and methanol production, and for the scenarios investigated in this chapter, GHG emission mitigation costs increase strongly with the scale of biomass production. It is found that the influence of a large-scale introduction on the development of biomass supply costs and market prices of land, materials and energy carriers, reduces the GHG emission reduction potential at costs below 50 €/Mg CO_{2eq} with about 13—70% depending on the different scenarios. Bio-material production accounts for only a small part of the total GHG emission mitigation potential at low costs. This is due to relatively small material markets, that lead to a strong decrease of market prices of bio-materials at large scale of production. GHG emission mitigation costs depend strongly on biomass supply curves, own-price elasticity of land and market volumes of bioenergy carriers. Our analysis shows that these effects should be taken into account for the development of strategies to implement the use of biomass. However, literature estimates of own-price elasticities are highly uncertain and market volumes of biomass applications depend on the competitiveness of the applications. To counteract these uncertainties, a combination of a bottom-up analysis with an analysis of market effects is recommended.

Summarising, we have analysed various multi-functional biomass systems and their potential benefits with regard to GHG emission reduction, energy savings, land use and costs. Results for the different systems vary considerable from plain benefits to no distinct advantage of multi-functional biomass use. The benefits of multi-functional biomass systems are influenced by many factors. These factors depend on the one hand on the type and structure of the biomass systems such as type of material or energy carrier produced or efficiency and costs of production. On the other hand, these factors depend on external circumstances, like market volumes and prices of materials or the CO_2 intensity of reference systems.

Most multi-functional biomass systems regarded in this thesis, however, increase the potential benefits of biomass use in terms of costs, GHG emission reductions and agricultural land use. In comparison to single bioenergy systems, the multi-product systems investigated in chapter 2, decrease primary biomass fuel costs by about 5 to more than 50 €/GJ_{LHV} in cases of very high-value material applications. (For comparison, primary biomass fuel costs of bioenergy systems are about 2—15 €/GJ_{LHV}, while coal prices are about 2 €/GJ_{LHV}.) With regard to GHG emission reductions, these multi-product systems lower the reductions with about 3—10 Mg CO_{2eq} per hectare per year of biomass production. The systems of cascading of short rotation wood that are analysed in chapter 3 show a very broad range of results. Due to cascading, the GHG emissions avoided alter by about –13 to 23 Mg CO_2 per hectare per year and modify GHG mitigation costs by about –300 to 2000 €/Mg CO_2 compared to single energy use. For comparison, the use of short rotation wood for bio-electricity production results in avoided emissions of about 5 Mg CO_2 per hectare per year at costs of about 100 €/Mg CO_2. The use of agricultural residues for energy production that is investigated in Chapter 4 increases the benefits of bio-based polymers production, i.e. GHG emission reductions increase by up to 15 Mg CO_{2eq} per hectare per year. Finally, multi-functional biomass use in the PLA bio-refinery systems analysed in Chapter 5 leads to additional benefits of about 4-12 Mg CO_{2eq} per hectare per year and 0-200 €/Mg biomass input.

In addition, it can be concluded that within the structure of biomass systems, the main material application has the largest influence on the overall performance of multi-functional biomass systems. Also, the utilisation of agricultural residues for energy production can significantly improve the performance of biomass systems. Of course, the evaluation of multi-functional biomass systems depends strongly on the alternative reference systems. The type of materials and energy carriers that are substituted and the waste management system have proven to be crucial for costs as well as for GHG emission reductions obtained for biomass systems.

In the case of bio-materials that have a relatively long lifetime, time dimensions of carbon storage in these materials can play an important role. For example, if time is considered by using a present value approach, net GHG emission reductions of cascading systems decrease. Also, market prices of land, materials and energy carriers influence the economic performance of multi-functional biomass systems strongly. Research in Chapter 6 indicates that with a growing use of biomass for materials and energy, GHG emission mitigation costs of these options may increase. While many multi-functional biomass systems already have quite high GHG emission mitigation costs, the economic potential of these systems to mitigate GHG emissions might even be further limited by these market effects. This is especially the case for bio-materials that have comparably small markets. Moreover, it should be noted that market interactions can influence the type of reference materials and energy carriers, e.g. the type of fossil fuel, that are substituted.

Also, methodological lessons can be learned from the analyses in this thesis. It can be concluded that the inclusion of agricultural land use in the comparison of biomass systems may provide valuable insights in their ranking. Because often bio-based materials, for which land is used for their production, are substituted in the reference system, it is necessary to account for this land use in the reference system as well. The approach used in this thesis, i.e. the assumption of alternative production of bioenergy on this land, is suitable for the comparison of biomass systems. However, an agreement on a standard methodology how to deal with this issue in scientific research would be desirable. Also, a standard methodology needs to be developed for the inclusion of the time dimension in GHG emission balances, because bio-material systems may store carbon for a relatively long time. Our analysis using a present-value approach shows the potentially large influence of the time dimension on the results. Finally, the scale of biomass production and use influences the costs of the system as well as GHG emission balances due to changes of prices and of substituted reference applications. The bottom-up analysis combined with a simple analysis of land, material and energy demands presented in this thesis shows important trends for the dependency of biomass systems on the scale of biomass use.

In conclusion, to use biomass efficiently in terms of GHG emission reduction, (agricultural) land use and total costs of the system, multi-functional biomass systems can be an attractive option if carefully designed, depending on reference systems and land, material and energy markets. The best multi-functional biomass systems analysed in this thesis increase the GHG emission reduction per unit of agricultural land used by a factor 5 compared to single biomass uses and decrease the total systems costs by about the same factor. However, for the performance of biomass systems at a large scale of biomass use, the interactions of biomass use with land, material and energy markets need to be better understood. Therefore, further research on optimal biomass systems for GHG emission mitigation should combine bottom-up information of biomass system with knowledge on market mechanisms from top-down analyses.