CHAPTER 1:

Introduction

1 Biomass and greenhouse gas mitigation

In order to achieve sustainable development, many socio-economic and environmental issues of energy and material demand and supply still need to be solved (Goldemberg et al., 2000). Human-induced climate change is one of the most serious environmental concerns. Its negative long-term effects on human society and ecosystems are potentially large (IPCC, 2001c). Climate change can be the result of an increase of the greenhouse effect due to anthropogenic greenhouse gas (GHG) emissions (IPCC, 2001a). To limit the rate and level of climate change, a number of countries have formulated governmental policies to reduce these emissions. In the Kyoto Protocol of the Conference of Parties to the United Nations Framework Convention on Climate Change, quantitative objectives of greenhouse gas emissions reduction are specified. In this context, the European Union committed itself to an 8% reduction of 1990 greenhouse gas emissions in the period 2008 to 2012 (UNFCC, 1997)[1].

Mitigation of greenhouse gas emissions can be achieved by various options, i.e. increase of energy efficiency, increase of material efficiency, low carbon energy supplies, CO_2 capture and storage and enhanced carbon sequestration. Biomass can play a role in the mitigation process as well as in addressing other environmental, social and economic aspects of sustainable development[2] (Turkenburg et al., 2000). Biomass can be a substitute for conventional materials and can supply solid, liquid and gaseous fuels. Thus, biomass can lower the net CO_2 emissions of energy and material supplies (Johansson, 2000; IPCC, 2001b). In addition, biomass plantations can achieve net sequestration of carbon in plants and soils depending on the former use of the land.

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[1] Greenhouse gas emissions in 1990 in the European Union were $4.2*10^9$ Mg CO_2 equivalent (UNFCC, 1997).

[2] For example, the production of biomass may improve access to modern energy carriers, create employment in rural areas, contribute to a more sustainable agriculture, reduce dependency on imported fuels and exploit new material markets.

Many uses of biomass for materials and energy are possible. Main uses for material are chemical products, pulp and paper and construction materials. Main uses for energy are the production of heat, electricity and transportation fuels. Figure 1.1 gives an overview of principal uses of biomass crops for energy and material purposes.

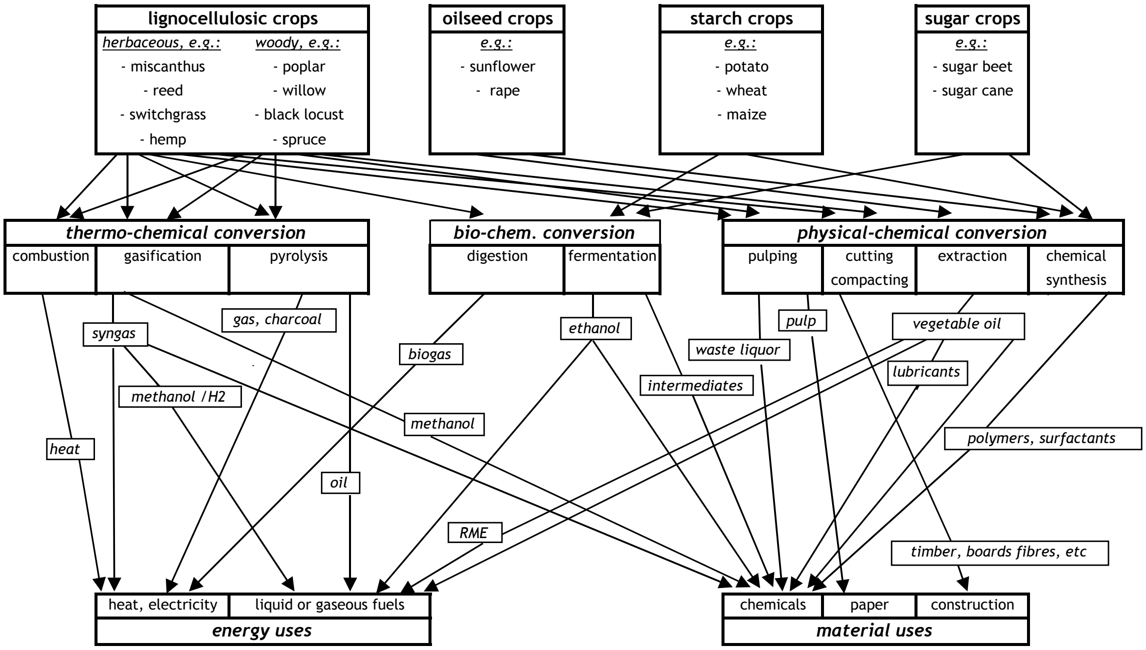

Figure 1.1: Principal uses of biomass for energy and material

In the scientific literature, the total global potential of biomass energy and material supplies is estimated to range between 80 to 1250 EJ/year in the long term (Hoogwijk et al., 2003), while the global primary energy consumption in the year 2001 was about 420 EJ/yr. (IEA, 2003a; IEA, 2003b). However, most studies expect a contribution of 50-200 EJ from biomass energy in 2050 with the largest part from dedicated energy crops and limited contributions from biomass residues (Berndes et al., 2003). Assuming that the global biomass potential of 50-200 EJ substitutes present primary energy supplies, GHG emission reductions of about $3*10^9$ to $12*10^9$ Mg CO_2/year could result (IEA, 2002c). For bio-materials the potential GHG emission reduction that can be achieved is more difficult to estimate, because various materials can be substituted. For example, Gielen et al. (2000) estimate that the technical potential of GHG emission reduction by bio-material use could be about $0.5*10^9$ Mg CO_{2eq}/year in Western Europe in 2030.

The potential amount of agricultural and forestry residues—available at low costs without an additional demand for land—is limited and estimated to be 30-90 EJ globally (Hoogwijk et al., 2004a). Therefore, dedicated energy and industrial crops also have to be used if biomass is to contribute substantially to the mitigation of greenhouse gas emissions. Currently, most alternatives for energy and material production from fossil fuels or the use of mineral resources are cheaper than energy or materials from dedicated crops, partly because agricultural land resource may be scarce and/or expensive. In scientific literature production costs of woody biomass range from 0.5 to 17.7 US$/GJ worldwide. In Europe this figure ranges from 2.5 to 16.4 US$/GJ (Hoogwijk et al., 2004b), while coal prices in Europe are at present about 2 US$/GJ (IEA, 2003c). (The potential of woody biomass production in Europe is estimated at 17-25 EJ (Johansson and Turkenburg, 2004).)

With regard to costs, the mitigation of GHG emissions by means of biomass use has to compete with other mitigation options. According to the IPCC, costs of selected GHG emissions reduction options are at present in a range of –110 to +60 US$/Mg CO_{2eq}[3], with GHG emission reduction costs of biomass substituting coal and gas ranging from –10 to +50 US$/Mg CO_{2eq} (IPCC, 2001b). However, most biomass uses from dedicated energy crops may at present be more expensive. For example, related to modern bio-fuels, Hamelinck (2004) estimates these costs to be in the range of 20 to 170 US$/Mg CO_2. Gielen et al. (2000) argue that most biomass material and energy uses will result in GHG emission reduction costs of above 50 US$/Mg CO_{2eq}. Consequently, to implement biomass for GHG emission mitigation on a large scale, GHG emission mitigation costs of many biomass material and energy options need to be reduced.

The availability of land for the production of biomass energy and materials is limited due to the competition with food production and the use of land for other purposes and functions (Hoogwijk et al., 2003). Consequently, several authors have indicated that an increasing demand for biomass for energy and material use will increase the market prices of agricultural land and subsequently the market prices of food, bioenergy and bio-materials; see e.g. Green (2000), Hoogwijk et al. (2004b) and Azar and Berndes (1999). This relation between demands, market prices and the amount of biomass supplied for food, materials and energy has been studied by e.g. De La Torre Ugarte et al. (2003), Gielen et al. (2000), Gielen et al. (2003) and Yamamoto et al. (2001)[4] and should be taken into account when analysing costs of biomass utilisation strategies.

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[3] These GHG emission reduction options are divided in the following categories: Buildings and appliances (-110 to 10 US$/Mg CO2eq), transport, i.e. automobile efficiency improvements (-60 to 60 US$/Mg CO2eq), manufacturing (-70 to 60 US$/Mg CO2eq), agriculture (-20 to 60 US$/Mg CO2eq), wastes (-10 to 10 US$/Mg CO2eq) and energy supply (-10 to 60 US$/Mg CO2eq).

[4] De La Torre Ugarte et al. (2003) investigated the available land for energy crops in the U.S. depending on their market price using an agricultural policy model that includes demands and supplies in the agricultural sector. Gielen et al.

Currently, a modest amount of biomass is used for material and (non-traditional) energy supply in industrialised countries and most biomass used for energy are residues. In the European Union (EU-15) only about 2.5% of gross inland energy consumption or 1.5 EJ were derived from biomass in the year 2000 (Johansson and Turkenburg, 2004). On the material side biomass is used mainly for traditional application as pulp & paper, sawn wood and particleboard. In total wood products and pulp and paper accounted for about 25% of bulk material[5] production in the European Union in 1999, which is about 4 EJ. In contrast, advanced bio-materials are at present used to a much lesser degree. For example, bio-based plastics had a market share of below 0.1% (below about 3 PJ) in the European Union in 1998 (ECCP, 2001).

In conclusion, the availability of agricultural and forestry residues is limited, while the technical potentials for biomass production are quite high (Hoogwijk et al., 2004a). Focusing on Europe, one of the main reasons for the low share of biomass applications from dedicated crops are the often-high production costs due a.o. the relative low availability of agricultural land. Therefore, more competitive routes for the introduction of biomass are needed in the short to medium term.

2 Multi-functional biomass systems

Multi-functional biomass systems may contribute substantially to a more efficient use of biomass resources and agricultural land, resulting in low mitigation costs of greenhouse gas emissions. Therefore, in this thesis two concepts of multi-functional biomass systems—multi-product use and cascading—are investigated. In this section, the basic principle of multi-functional biomass systems, namely the multiple-use of resources, is discussed and the concepts of multi-product use and cascading are defined. Also, an overview of possible multi-functional biomass systems is given.

(2000) modelled the future use of biomass for energy and materials in Western Europe depending on the market price of GHG emissions. The authors use a linear optimisation model, which calculates optimal technological choices (e.g. kind of biomass production) given an exogenous demand of products. Yamamoto et al. (2001) estimated the global potential supply of bioenergy depending on the demand for material and food using a land use model that simulates competitions between the various uses. Finally, Gielen et al. (2003) analysed different biomass policies for CO2 emission reduction considering global demands for materials, energy and food modelling the competing land uses maximising consumer/producer surplus in an ideal market.

[5] Round wood, plastics, crude steel, aluminium, glass, paper & board, cement and bricks & tiles (Phylipsen et al., 2002; UN/ECE and FAO, 2001).

2.1 Multiple use of resources

Within the concept of multiple land use, land generates more than one type of product or service like the production of food, fodder, energy and materials, the protection of the soil, wastewater treatment, recreation, or nature protection; see e.g. (Börjesson, 1999; Londo, 2002; Lewandowski et al., 2003) In this thesis, however, we concentrate on multiple use of biomass resources. Hence, we exclude multiple land use from the analysis.

The multiple use of biomass resources can be achieved in several ways. First, different parts of a crop may each be used for a specific purpose. Second, processing of biomass may lead to various product and by-products. Finally, biomass may be used to produce materials and energy in succession, i.e. the recycling and cascading approach.

In scientific literature, the potential of using each part of a biomass resource for a specific purpose, thus increasing efficiency of biomass utilisation mainly with regard to costs, has often been discussed; see e.g. (DTO, 1997; Benjamin and Weenen, 2000).

Producing several products and by-products from biomass is also an often-examined concept. Wright and Cushman (1997) stress the importance of increasing the use of by-products, and Williams et al. (1995) and Turkenburg et al. (2000) discuss the co-production of fuels, heat and electricity. Another concept of multiple biomass resource use is the bio-refinery; see e.g. (Scott et al., 1997; Benjamin and Weenen, 2000; Elliot, 2004; Paster et al., 2003; Realff, 2003). A bio-refinery is an analogy to a petrochemical refinery where crude oil is completely reverted into many different value-added products maximising the economic benefits. In a bio-refinery, the biomass resource is converted into bio-materials and/ or energy carriers. Often a main product of bio-refinery is a bulk chemical.

Increasing the efficiency of biomass utilisation by recycling of bio-materials and waste-to-energy conversion is discussed by several studies; see e.g. (Goverse et al., 2000; Fraanje, 1997; Boogardt, 2000). However, in these studies the cascading of wood products is investigated mostly in a qualitative way.

Hence, in scientific literature, the multiple use of biomass resources is seen as an important possibility to increase the efficient use of biomass for materials and energy, and reduces the costs of biomass options to mitigate GHG emissions. Nevertheless, only very few studies have investigated the potential of multi-functional biomass systems in a quantitative way.

2.2 Multi-product use and cascading

The principles of multiple biomass resource use can be summarised under the terms *'multi-product use'* and *'cascading'*. *Multi-product use* is defined as using biomass for different applications. *Cascading* is the subsequent use of biomass for a number of applications. In other words, biomass is used first for a material application; next, it may be recycled for several further material applications; and finally, energy is recovered from the bio-material waste.

In this thesis, multi-functional biomass systems are systems that combine in principle bio-material use(s) and bioenergy use(s). Figure 1.2 gives an overview of such a multi-functional biomass system.

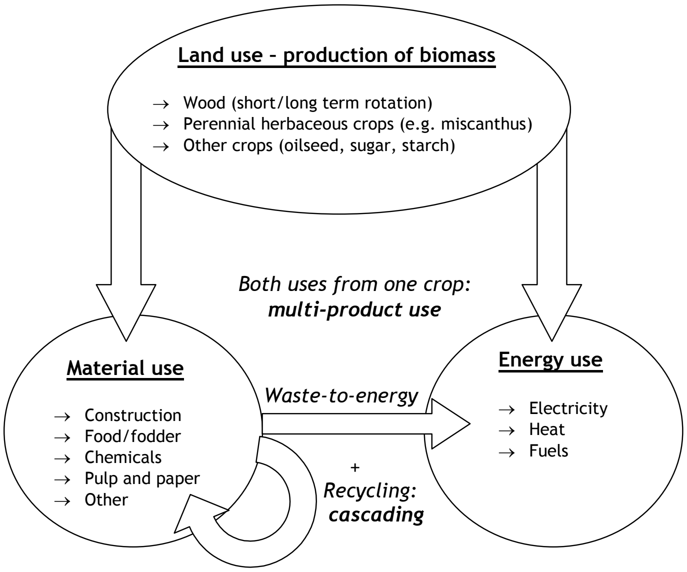

Figure 1.2: Schematic overview of multi-functional biomass systems

2.3 Multi-functional biomass systems

As many different biomass crops, bio-material applications and bioenergy conversion steps exist, obviously, a very large number of multi-functional biomass systems are possible. The main application of the biomass resource characterises the feasibility of a multi-functional biomass system. In the case of material production, the application determines the selection of crops, the availability of agricultural residues, the supply of by-products, potential recycling steps and waste-to-energy conversions.

The bio-material application in a multi-functional biomass system should at least offer a good possibility for multi-product use or cascading. In the case of multi-product use, this

Table 1.1: Selected biomass material applications and their suitability for multi-functional biomass systems

Application	Biomass resource	Main substitution	By-products and residues	Cascading	Market price[a]	Market volume[b]	Spec. CO_2 emission reduction	Profi-tabi-lity	Add. market volume	Remarks
Pulp and paper										
Pulp and paper	Ligno-cellulose fibres	Pulp from forestry	Lignin, bark, twigs	Waste paper	430-440 $\text{US\$}_{2002}$/Mg	34*10^6 Mg$_{2002}$ (0.1 EJ)	--/-	+	-/0	Well established, low additional potential
Chemicals										
Ethylene	Sugar, ligno-cellulose	Petrochem. ethylene	Agric. residues, fodder, lignin	Inter-mediate	550-620 $\text{US\$}_{2001}$/Mg	20*10^6 Mg$_{2002}$ (1.0 EJ)	+/++	-/+	++	Better if ligno-cellulose route developed
Bio-based polymers	Sugar/starch ligno-cellulose	Petrochem. polymers	Agric. residues, fodder, lignin	Polymer recycling	770-1540 $\text{US\$}_{2002}$/Mg	34*10^6 Mg$_{2002}$ (1.3 EJ)	0/+	-/+	0/++	Better if lingo-cellulose route developed
Fibre reinforced composites	Ligno-cellulose fibre	Glass fibre composites	Agric. residues	None	3180-6360 $\text{US\$}_{2001}$/Mg	2*10^6 Mg$_{2002}$ (≈ 0 EJ)	-/0	+/++	-/0	Possible profitable, but only small market volume
Lactic, levulinic, succinic acid	Sugar/starch	Various petrochemicals	Agric. residues, food	Inter-mediate	See ethylene	See ethylene	-/+	-/+	0/+	Shift of chemical products necessary
Solvents	Vegetable oil	Petrochem. solvents	Agric. residues, fodder	Re-use	300-2000 $\text{US\$}_{2001}$/Mg	4*10^6 Mg$_{1999}$ (0.2 EJ)	-/++	0	-/0	Small market
Lubricants	Vegetable oil	Petrochem. lubricants	Agric. residues, fodder	Re-use	≈3000 $\text{US\$}_{1998}$/Mg	5*10^6 Mg$_{1999}$ (0.2 EJ)	+/++	0	-/0	Small market
Construction materials										
Sawn timber	Wood	Construction material	Small wood pieces	Wood products	190-210 $\text{US\$}_{2002}$/m^3	80*10^6 m$^3{}_{2002}$ (0.8 EJ)	+/++	0/+	0/+	High requirements wood properties
Engineered wood prod.	Wood	Construction material	Small wood pieces	Sawn wood	≈420 €$_{2003}$/m^3	1*10^6 Mg$_{2002}$ (0.0 EJ)	+/++	0/+	0/+	High requirements wood properties
Insulation	Ligno-cellulose fibres	Mineral insulation	Agricultural residues	Re-use fibres	40-50 ECU$_{1995}$/Mg	52*10^6 Mg$_{1992}$ (0 EJ)	+/++	0	0/+	Recycling feasibility largely unknown
Fibre, particle board	Ligno-cellulose fibres	Board materials	Bark, twigs, agric. residues	Re-use fibres, part.	190-320 $\text{US\$}_{2002}$/m^3	40*10^6 m$^3{}_{2002}$ (0.4 EJ)	0	0/+	0	Good cascading possibilities

--: not suited, -: poorly suited, 0: medium suited, +: well suited, ++: very well suited

[a] Values in this column are current market prices of wood products and non-biomass reference materials: pulp (FAO, 2004); ethylene (Anonymous, 2001) ; bulk plastics (Leaversuch, 2002), bulk fibre reinforced composites (DiGITIP, 2002); range solvents (Klass, 1998); synthetic lubricants (Technical Insights, 1999); sawn timber (FAO, 2004); engineered wood products (Finnforest, 2003); insulation material (EU, 1997); particle and fibreboard (FAO, 2004).

[b] Market volumes are in the case of wood products the currently produced amounts and in other cases the amounts of fossil or mineral alternative products in Western Europe. Thus, no estimation of future bio-based market potentials has been made, here. The potential in EJ is based on the heating value of the products. Market volumes: pulp (FAO, 2004); ethylene (CEFIC, 2003); plastics (APME, 2003); fibre reinforced composites (DiGITIP, 2002) – heating value of only glass fibres, partly also carbon fibres are used; solvents (ECCP, 2001); lubricants (ECCP, 2001); sawn timber (FAO, 2004) – for comparison density of wood and wood products is roughly 0.5 Mg/m^3 ; engineered wood products (UN/ECE and FAO, 2001); insulation material, i.e. mineral wool (EC, 2002); prices particle board and fibreboard (FAO, 2004).

means that residues or by-products from material production may be used and in the case of cascading, that the material may be recycled. Table 1.1 shows principle bio-material applications that fulfil this criterion.

Moreover, as discussed above, the bio-material should contribute to an efficient reduction of GHG emissions in terms of costs and land use. Three related parameters are used and evaluated qualitatively in Table 1.1. First, the *specific* CO_2 *emission reduction* describes the reduction of CO_2 emissions per unit of bio-material. This parameter depends mainly on the fossil fuel use during bio-material production and the production of the reference material. Second, the *profitability*, which is derived from, the difference between the market prices of bio-materials and their respective production costs. Third, the *additional market volume* describes the total technical potential minus current bio-material production. This parameter is an indicator for the total potential GHG emission reductions that can be achieved.

Main sectors of bio-material uses are *pulp and paper*, *chemicals* and *construction*. The *pulp and paper* industry currently uses a large part of woody biomass. The additional potential for pulp and paper production, to substitute the use of other materials—e.g. plastics—and, thus, to reduce GHG emissions is probably low. Contrary, the *chemical* industry is an interesting sector offering new opportunities for biomass utilisation (DTO, 1997). Especially bulk chemicals from biomass have a large potential to substitute fossil fuel feedstock in the chemical industry. Finally, bio-materials for *construction* have already a large market share. In this case, particularly a large cascading potential exists, based on a variety of recycling options.

Obviously, *biomass resources* should have a suitable quality for the application selected. Furthermore, biomass crops in a multi-functional biomass system should either have a high total biomass yield for bulk material and energy applications or have a high yield of a specific plant component required for a high-value added material application, e.g. fibres, sugar or starch. Finally, *bioenergy* conversion technologies in a multi-functional biomass system should be able to convert efficiently the available agricultural residues, processing residues and bio-material wastes.

Summarising, multiple biomass resource use may be a promising concept to decrease the costs and land use of GHG emission mitigation by biomass material and energy uses. In this thesis, we will focus on multi-functional biomass systems with multi-product use and cascading. Material application that seem promising for these systems are bulk chemical and construction materials.

3 Efficiency of biomass systems

Concluding that an efficient reduction of GHG emissions at low costs and with minimal land use is an important criterion for the evaluation of (multi-functional) biomass systems, leads to the question of how to quantify this efficiency. Important parameters are savings of non-renewable energy consumption (GJ), GHG emission reduction (Mg CO_{2eq}), (agricultural) land use (ha) and costs (€). From, these parameters the efficiency of GHG emission reduction, i.e. costs (€/Mg CO_{2eq}) and land use (ha/Mg CO_{2eq}) can be derived.[6]

3.1 Savings of non-renewable energy consumption

Investigating energy balances of different biomass systems is a common way to compare especially bioenergy systems. Furthermore, energy balances can be an important indicator of GHG emission balances as most GHG emissions in biomass systems are related to fossil energy uses and savings. In order to set up an energy balance, generally energy inputs and outputs of a biomass system have to be accounted for. These inputs are direct energy uses, e.g. diesel use for tractor in biomass production, or indirect energy uses, e.g. energy uses for the production of a biomass combustion plant. In scientific literature, the energy inputs are compared often to the energy content of the bioenergy carrier resulting in net energy outputs or net energy ratios; see e.g. the overview of bioenergy balances of bio-ethanol in Shapouri et al. (2002) or the comparison of energy crops in Venturi and Venturi (2003).

Taken into account that a material or energy carrier produced from biomass replaces a reference product with the same function, energy balances can also be used to investigate primary or non-renewable energy savings. This approach has been applied to compare energy balances of bio-based materials with each other (see e.g. Patel et al., 2003) and to compare bio-materials to bioenergy production (see e.g. Kaenzig et al., 2004). Because evaluating biomass systems by savings of non-renewable energy consumption allows comparing different types of products and systems, this parameter is used for the analysis of multi-functional biomass systems in this thesis.

3.2 GHG emission reductions

Most important greenhouse gases in the context of biomass systems are carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Bioenergy and -material have a 'short car-

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[6] Note, that many other criteria may play a role in the assessment of biomass systems, e.g. eutrophication, health impacts, contribution to rural development, employment or public perception. Given the central research question of this thesis, however, these aspects are not considered here.

bon cycle', i.e. carbon is removed from the atmosphere during biomass growth and then released during biomass use. Thus, in comparison to the 'long' carbon cycle of fossil energy carriers CO_2 emissions are reduced when fossil fuel use is replaced by the use of biomass resources. Nitrous oxide is emitted in biomass production systems during N-fertilisation. N_2O may be an important fraction of the total GHG emissions of biomass production systems depending on the agricultural management scheme; see e.g. IPCC (2001b) and Heller et al. (2003). Finally, methane may be emitted if (part of) the biomass is decomposed anaerobically, e.g. stumps left during forest harvesting or land filled bio-materials. However, in most agricultural biomass system—apart from rice cultivation—methane emissions play a minor role (IPCC, 2001b). All GHG emissions can be expressed by their global warming potential (IPCC, 2001a). In this thesis, we use the expression CO_2 equivalents when evaluating GHG emissions based on the global warming potential of each greenhouse gas during 100 years. (Consequently, 1 kg CH_4 is equivalent to 23 kg CO_2 and 1kg N_2O is equivalent to 296 kg CO_2 (IPCC, 2001a).)

Accounting of GHG emission balances follows the same principle as accounting for energy balances, i.e. determining all direct and indirect GHG emissions of biomass systems. GHG emission reductions are also calculated by comparing the emissions of the biomass system to the emissions of a reference system that produced comparable materials and/or energy carrier; see e.g. Börjesson and Gustavsson (2000). An important methodological aspect in this context is the choice of the reference system as very different materials and energy carriers may be substituted by biomass utilisation (Vikman et al., 2004; Schlamadinger et al., 1997). Waste treatment plays an important role, too, because the type of waste treatment influences the release of carbon embodied in materials; see e.g. Finnveden and Ekvall (1998) and Patel et al. (2003). For example, incineration releases all embodied carbon but might recover energy and, thus, reduce GHG emissions from fossil energy, while land filling may store part of this carbon.[7] Consequently in this thesis, special attention is paid to the choice of the reference system and waste treatment of bio-materials and reference materials are included in the GHG emission balances.

Time aspects may also play an important role in GHG emission reduction accounting. Mitigation of carbon dioxide emissions can be achieved by the reduction of carbon emissions from fossil resources or the storage of carbon outside the atmosphere, e.g. in forests or bio-materials. However, if carbon is stored in forest or bio-material, carbon dioxide

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[7] Gardner et al. (2002) show that large part of wood remains intact in a 20 to 30 year old Australian landfills. However, IPCC (2001b) argues that even though some of the carbon might be sequestered infinitely, land filling is a disadvantageous waste treatment technology for organic wastes compared with composting and digestion.

emissions are not avoided for an indefinite period. Methods to account for such carbon storage are widely discussed, especially for carbon sequestration in forests; see e.g. OECD and IEA (2001), Kirschbaum (2003) and Richards and Stokes (2004).

For bioenergy production, Schlamadinger et al. (1997) developed a methodology to account for changes in carbon stocks in the whole system. This methodology includes the definition of a reference system including for example land use and energy production. Moreover, it is argued that rather the dynamic change of carbon stocks in the different carbon pools—e.g. fossil fuels, standing forest—should be measured over a longer time period than CO_2 emission reduction at a certain moment in time. However, studies that compare the temporarily storage of carbon in bio-material systems with the substitution of fossil energy carriers and aggregate the results as total GHG emission reduction are rare. Methodological work in this field is still going on; see e.g. IEA (2004a). In this thesis, we attempt to describe carbon stock changes in biomass material and energy systems in terms GHG emission reductions.

3.3 Agricultural land use

Land use in different biomass systems per unit of non-renewable energy savings, GHG emission reduction or costs can vary considerable. This is due to different yields of crops, materials and energy carriers and to different values of biomass products in terms of energy savings, GHG emission reductions and costs. In early studies of biomass system land use played a minor role. However, the comparison on an agricultural area basis becomes more and more an important issue; see e.g. IPCC (1995), van den Broek et al. (2001), Keith (2001) and Kaenzig et al. (2004). Also, Dinkel et al. (1996), who carry out an analysis of bio-based polymer production, conclude from their result that a comparison of bio-materials and bioenergy on an agricultural land use basis would be desirable.

The impact of land use can also be described by other criteria, e.g. influence on soil quality, erosion prevention or bio-diversity; see e.g. Baitz et al. (2000) and Lindeijer (2000). The implementation of biomass systems on a large-scale in order to reduce a significant amount of GHG emissions, however, is mainly limited by the costs and scarcity of agri cultural land. Therefore, in this thesis we concentrate on the amount of land that is used for bio-material and energy production and the reduction of GHG emissions as important parameters.

3.4 Costs of biomass systems

Finally, costs of biomass systems are an often-studied criterion; see e.g. JRC (2003), Hamelinck (2004) and Hallam et al. (2003). Like GHG emission and energy balances, net costs can be calculated over the whole biomass systems accounting for all costs and revenues. Cost calculations from an industrial perspective, using typically high discount rates and short lifetimes, lead to higher cost estimates than calculations from a societal perspective, using typically lower discount rates and longer lifetimes. Moreover, analyses from a societal perspective often consider the whole biomass systems, while in an industrial perspective often single processing steps, e.g. bio-electricity production or bio-material production, are regarded. This may also lead to different cost estimates.

Moreover, costs can be calculated using either a bottom-up or top-down approach. In the bottom-up or 'engineering' approach, costs of every part of the biomass system, e.g. agricultural land rent, transport costs or equipment for biomass combustion, are estimated and added up. In contrast, the top-down approach uses aggregated data from economic sectors and estimates the induced changes in the economy by the introduction of a biomass system. Therefore, in a top-down approach, cost estimates on a technology level are much less detailed. On the other hand, interactions between sectors—resulting for example in market prices changes—can be investigated much better.

Consequently, results of bottom-up and top-down studies are principally different but can supplement each other. Richards and Stokes (2004) compare the results of these different approaches in several studies for carbon sequestration. For bio-material and bioenergy systems it is found that the change of market prices of agricultural land and biomass products can play an important role, if these systems are introduced on a large scale. For example, Azar and Berndes (1999) show that food and land prices increase due to higher bioenergy prices and Otto and Gallagher (2004) studied price effects in the feed market due to an increased production of ethanol. However, bottom-up cost estimates of bioenergy and material systems typically do not include such market price changes.

As governments initiate GHG emission reduction policies, cost estimates from a societal point of view using a bottom-up approach, seem an appropriate approach to determine specific benefits of different multi-functional biomass systems. To evaluate costs and effects of large-scale implementation of multi-functional biomass systems, however, market price changes caused by this implementation need to be investigated, too.

3.5 Efficiency of multi-functional biomass systems

Summarising, in the literature, many different biomass systems have been compared in view of their energy savings, GHG emission reduction, costs and to a lesser degree land use efficiencies. Methods for this comparison are available or in the case of GHG emission reductions still in development.

However, only very few studies have explicitly addressed multi-functional biomass systems, i.e. multi-product use and cascading, in a quantitative way. In the context of multi-product use, studies of bio-material production often take into account the use of processing residues for energy (see e.g. Hekkert and Worrell, 1998) but usually do not include the utilisation of agricultural residues. Furthermore, few studies investigate the benefits of producing several products from a biomass resource quantitatively. As an exception Wyman (2003) investigated potential economic synergies of bio-refineries.

In view of cascading, several studies have compared recycling and reuse of a material to virgin production or other waste treatment strategies; see e.g. Finnveden and Ekvall (1998). However, cascading chains of biomass including several successive applications have not been compared quantitatively.

Summing up, the potential benefits of multi-functional biomass systems still need to be proven in quantitative analyses. For this purpose, adaptation or further development of methodologies are sometimes needed. Particularly, problems of allocation or system expansion to account for different products and land uses in multi-functional biomass systems have to be solved; see e.g. Overend (2004) and Edwards (2004). Moreover, the issue of accounting for the time dimension in especially long-life cascading applications needs to be solved. Finally, the integration of market price changes of bio-materials, bioenergy and land due to the large-scale introduction of biomass systems in bottom-up costs analysis deserves special attention.

4 **Objective and scope of this thesis**

Summarising the possibilities of multi-functional biomass use to contribute to a necessary reduction of costs and an efficient use of land of bioenergy system need to be better understood in a quantitative way. 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 such multi-functional biomass systems. Second, the potential benefits depend on the kind of biomass system regarded, i.e. the materials and energy carriers produced, the scale of the system and the multi-functional resource uses applied. The mechanism of this dependence have to be studied in order to identify promising multi-functional biomass systems.

Therefore, in the following chapters the performance of multi-functional biomass systems is quantified. In this thesis, we investigate biomass system costs from a societal perspective using e.g. low discount rates. A main focus will be on the review of methodologies for accounting GHG emissions, non-renewable energy consumption, agricultural land use and costs as well as the adaptation of these methodologies to special aspects of multi-functional biomass use. The analysis of the potential benefits of multi-functional biomass systems is carried out by several case studies of biomass systems including various waste treatment technologies for the short term —present until 2010[8]—that appeared promising after a first review.

Because at present the shift of biomass production to more favourable areas seems to be an alternative for more efficient biomass systems,[9] these case studies are situated in Europe and concentrate on Poland in order to investigate the potential of biomass production in the new EU-member states of Central Eastern Europe.[10]

In *Chapter 2* of this thesis, the concept of multi-product use and its potential impacts on fuel costs of bioenergy and GHG emission reduction per area of agricultural land use are investigated. Especially, the relation between the economic value and the specific GHG emission reduction of a possible material application and the potential benefits of multi-product use is analysed. As for different parts of a crop more or less valuable material ap-

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[8] Because of short timeframe, increase of agricultural productivity is not considered in this thesis.

[9] In the longer term, also an increase of productivity of biomass production is expected.

[10] Within Europe the new accession states of the European Union in Central Eastern Europe seem to be a good option, because these states have at present large areas of available agricultural land, potentially high to medium crop yields and comparably low costs of land and labour; see e.g. van Dam et al. (2004).

plications are possible, the benefits of multi-product use vary with the percentage of crop used for material applications, which is investigated in this chapter.

For this analysis, a case study of hemp, poplar and wheat is carried out. Material uses regarded for multi-product use are the use of wheat grains for food, wheat straw for animal litter, hemp bark fibres for reinforced composites, hemp core fibres for animal litter, hemp seeds for food and cosmetics and poplar wood chips for pulp. For energy uses parts of the crops are used as solid fuel for electricity production. This case study compares potential benefits in a Western European and a Central Eastern European Country, i.e. the Netherlands and Poland.

Chapter 3 examines the concept of cascading more closely. In this chapter, the main focus is on the development of methodology for accounting CO_2 emissions and costs of cascading, as methodological aspects play a large role if several materials and energy carriers are produced subsequently from a given biomass resource. In this context, the boundaries of the biomass cascading system and the respective reference system, the inclusion of land use, the time dimension and the definition of reference applications are important issues that are discussed in detail.

Moreover in this chapter, key parameters and issues that influence the efficiency of biomass cascading chains are identified like it is done in Chapter 2 for multi-product use. Parameters to investigate the performance of cascading chains are their CO_2 emission reduction, their total costs per area of agricultural land use and their CO_2 mitigation costs. Special attention is paid to the influence of time and discount rates, to the combination of different material and energy applications in cascading chains and to the historical variations of markets prices on the performance parameters. This is done by a case study of cascading chains of short rotation (SR) poplar. Different material and energy applications of SR poplar are regarded within these cascading chains, i.e. particle lumber, MDF board, transportation pallets, pulp, ethylene, viscose, methanol and electricity. Geographical scope of this case study is Poland.

Chapter 4 deepens the investigation of the importance of land use efficiency as criteria to evaluate non-renewable energy consumption and GHG emission reduction of biomass uses and to compare the benefits of bio-materials and bioenergy. Here, the difference between a mass-based evaluation of bio-materials and an area-based evaluation is analysed. Moreover, the possible improvement of savings of non-renewable energy consumption and GHG emission reduction of bio-material by the use of agricultural residues is investigated. The influence of allocation methods on the results is particularly studied.

Subject of this investigation are different bio-based polymers including natural fibre composites. These polymers are compared to each other, using different evaluation criteria and to some options of bioenergy production. This analysis is based on an extension of existing Life Cycle Assessment (LCA) studies.

Following *Chapter 5* studies a more complex multi-functional biomass system, combining multi-product use and cascading. The influence of key factors in the set-up of biomass systems—including the kind and amount of multi-functional biomass resource use—on the savings of non-renewable energy consumption, the reduction of GHG emissions and costs of the biomass system are studied. In Chapter 2 and 3, it turned out that market prices of materials are crucially important for the economic success of multi-functional biomass use, but that these market prices can be quite variable and may depend on the market size. Therefore, in this chapter a market analysis is added to the chain analysis that takes into account increasing land prices and decreasing prices of material products and by-products if biomass systems are introduced on a large scale. This market analysis is combined with economies of scale to determine impact of production volume on the costs of multi-functional biomass systems.

In this study, the case of a poly lactic acid (PLA) bio-refinery system in Poland is analysed. PLA is a commercially produced bio-based polymer that appeared promising from the assessment of bio-based polymers in Chapter 3. The bio-refinery system includes the production of biomass, i.e. wheat or short rotation wood, the use of residues for bioenergy, the use of material by-products, the substitution of petrochemical polymers by PLA products, back-to monomer recycling of parts of the PLA produced and waste treatment of the remaining PLA.

Finally, in *Chapter 6* the introduction of multi-functional biomass systems on a large scale is studied. Main focus of the analysis is the effect of increasing scale of biomass use on the mitigation costs of GHG emissions. Increasing agricultural land prices, decreasing bio-material and bioenergy prices due to a larger demand or supply of these commodities are taken into account as well as increasing biomass supply costs.

For this market analysis of GHG mitigation costs, four biomass systems from the previous chapters are compared to each other, i.e. the production of MDF board, PLA, methanol and electricity. The case study is again situated in Poland.

This thesis finishes with a summary, the conclusions of the previous chapters and a reflection on the results of the overall thesis related to the central research question.