The role of biomass in climate change mitigation

Assessing the long-term dynamics of bioenergy and biochemicals

in the land and energy systems

Vassilis Daioglou

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Vassilis Daioglou, May 2016

The research reported in this thesis was carried out at the 'Energy and Resources group' of the 'Copernicus Institute, Faculty of Geosciences, Utrecht University', and the 'Climate Air and Energy' department of the 'Netherlands Environmental assessment Agency' (PBL). The work was done in the context of the research program 'Knowledge Infrastructure for Sustainable Biomass' which was funded by the Dutch Ministries of 'Economic Affairs' and 'Infrastructure and the Environment'. Chapter 6 was conducted as part of the IIASA-YSSP program and was partially funded by the 'Netherlands Organisation for Scientific Research' (NWO).

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Assessing the long-term dynamics of bioenergy and biochemicals in the land and energy systems

De rol van biomassa in klimaatbeleid

Beoordeling van lange-termijn gevolgen voor landgebruik en het energiesysteem door gebruik van bioenergie en -materialen

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op vrijdag 13 mei 2016 des middags te 2.30 uur

door

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Copromotor:	Dr. B. Wicke

What questions must one ask in order to understand the world?

(paraphrasing) T.S. Kuhn

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Abbreviations and Units

AFOLU	Agriculture, Forestry and Other Land Use
ABG	Above Ground Biomass
AR	Assessment Report (IPCC)
BECCS	Bioenergy with Carbon Capture and Storage
BGB	Below Ground Biomass
BMCEC	Bioenergy Marginal Cumulative Emission Change
BP	Bioenergy Production
BtF	Back-to-Feedstock
BTX	Benzene, Toluene & Xylene
CC	Carbon Content
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium
EF	Emission Factor
EU	European Union
FAO	UN Food and Agriculture Organisation
FSU	Former Soviet Union
FT	Fischer-Tropsch
GCAM	Global Change Assessment Model
GDP	Gross Domestic Product
GEA	Global Energy Assessment
GHG	Greenhouse gas
GLOBIOM	Global Biosphere Management Model
HHV	Higher Heating Value
HVC	Higher Value Chemicals
IAM	Integrated Assessment Model
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
iLUC	Indirect Land-Use Change
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LPJmL	Lund Potsdam Jena model with Managed Lands
LUC	Land-Use Change
MAGNET	Modular Applied General Equilibrium Tool
MCEC	Marginal Cumulative Emissions Change
MR	Mechanical Recycling
MS	Market Share
NEDE	Non-Energy Demand and Emissions model
NV	Natural Vegetation
ODU	Oxidised During Use
OECD	Organisation for Economic co-operation and Development
O&M	Operation and Maintenance costs
PBL	the Netherlands Environmental Assessment Agency *(Planbureau voor de Leefomgeving)*
PBP	Payback Period
PCW	Post-Consumer Waste
PE	Partial Equilibrium
PED	Price Elasticity of Demand
PFT	Plant Functional Type
Prim	Primary energy carriers
RED	Renewable Energy Directive (EU)
RCP	Representative Concentration Pathway
RPR	Residue to Product Ratio
RSR	Residue to Surface-area Ratio
Sec	Secondary energy carriers
SOC	Soil Organic Carbon
SRREN	Special Report on Renewable Energy Sources (IPCC)
SSP	Shared Socio-economic Pathway
TCEC	Total Cumulative Emission Change
TFC	Total Final Consumption
TIMER	The IMAGE Energy Regional model
TPES	Total Primary Energy Supply
WEO	World Energy Outlook (IEA)

All measurements are reported in the International System of Units (SI) and their accepted derivatives. Monetary quantities are reported in 2005 United States dollars ($2005).

1

Introduction

1.1. Assessing biomass in the context of climate change mitigation

Observed climate change since pre-industrial times can almost certainly be attributed to the increase in the concentration of anthropogenic greenhouse gasses (GHG). This increase mostly results from GHG emissions caused by the combustion of fossil fuels for energy purposes (see Box 1.1) (IPCC, 2014). Mitigating these emissions will require fundamental changes to energy supply and demand, such as enhancing energy efficiency and substituting fossil fuels by alternative sources of energy (Bruckner et al., 2014; UNEP, 2014). Such sources include solar, wind or hydro power. These options, however, can only provide electricity and suffer from intermittency issues. Biomass is another alternative energy source that can be based on a number of primary feedstocks (various crops, residues, waste streams and algae) and can provide multiple services such as heat and power, liquid fuels for transport and act as a feedstock for non-energy uses such as chemicals (Chum et al., 2011). A further advantage is that biomass derived energy carriers (bioenergy) can be easily integrated in existing energy infrastructure.

The possible role of biomass and bioenergy in climate change mitigation is controversial. First of all, there is a large disagreement on the primary potential of biomass. Chum *et al.* (2011) summarised existing literature and reported a range for global technical potential in 2050 of 50-500 EJ_{Prim}/yr (current total primary energy use is around 570 EJ_{Prim}/yr). The Global Energy Assessment (2012) gauged the possible 2050 supply at around 160-270 EJ_{Prim}/yr. More recently, the IPCC considered the 2050 technical potential with high-to-medium agreement to range from <100 EJ_{Prim}/yr to 200 EJ_{Prim}/yr (Smith et al., 2014).

Secondly, the effectiveness of biomass in reducing GHG emissions by replacing fossil fuels partly depends on the emissions from the production and conversion of biomass. Production of purpose grown agricultural feedstocks leads to changes of existing land use (LUC) which may result in losses of above- and below-ground carbon stocks (Fargione et al., 2008). Furthermore, indirect land-use change (iLUC) may occur when LUC due to biomass production leads to shifts in land management activities outside the region of primary production (Searchinger et al., 2008). Uncertainties in land use dynamics lead to emission factors in literature ranging from negative (e.g. when production is done on degraded lands) to values above those of fossil fuels (> 100 $kgCO_2$-eq/GJ_{Prim}) (Searchinger et al., 2008; Laborde, 2011; Chum et al., 2011; Plevin et al., 2015). Besides direct and indirect LUC, life cycle GHG emissions also arise from biomass production operations (fertiliser production and application, fossil fuel use for farm machinery and transport) and energy use during conversion to the final energy carrier or material. These emissions (and how they may change in the future) depend on the feedstock, supply chain configuration, transport distance, pre-treatment and conversion technology used (Hoefnagels et al., 2010; Gerssen-Gondelach et al., 2014). Again, estimates of lifecycle emissions (without LUC) show a large range between negative (e.g. when by-products can lead to further reductions) and >100 $kgCO_2$-eq/GJ_{Sec} for different biomass based energy carriers (Chum et al., 2011).

Finally, the overall emission reduction potential of different biomass, bioenergy and biochemical chains depends on changes in the energy system. The avoided GHG emissions from different uses of biomass can range widely (<0 to >200 $kgCO_2$-eq/GJ_{Sec}), with power production offering the best results (Gerssen-Gondelach et al., 2014). Furthermore, the possibility of combining bioenergy with carbon capture and storage (BECCS) can potentially lead to significant negative GHG emissions (Azar et al., 2010; Fuss et al., 2014).

The large spread in estimates on future biomass potentials and GHG effects are a testament to the uncertainties involved as they depend on a number of technical, social, behavioural, political and economic factors (Dornburg et al., 2010). Batidzirai *et al.* (2012) stressed that bioenergy assessments should explicitly discuss the effects of demographic dynamics, competition between biomass resources and applications, and account for potential improvements in management of agriculture and forestry production systems. Facilitating such assessments requires integrated analytical frameworks with high spatial resolution which account for key factors and feedbacks.

Box 1.1. Climate change and greenhouse gas emissions

The 5th Assessment Report of the Intergovernmental Panel on Climate Change reiterated that the observed warming of the climate system since the mid-20th century is extremely likely to have been caused by the increasing concentration of GHGs. Over the period 1970 to 2010, GHG emissions increased from 27 to 49 GtCO2-eq/yr (IPCC, 2014). Over two thirds of this increase was due to energy supply and demand, which, accounted for 76% of total GHG emissions in 2010 (Figure 1.1). The remaining 24% originated from agriculture, forestry and other land use (AFOLU). Energy based emissions are driven by the use of fossil fuels which in 2013 accounted for over 80% of total primary energy supply (IEA, 2015).
In the future it is expected that, without additional efforts to constrain emissions, GHG concentrations will continue to increase. This is projected to lead to a global average temperature change of over 3°C above pre-industrial levels by the end of the 21st century, increasing the likelihood of severe, pervasive and irreversible impacts on people and ecosystems. The so-called Paris Agreement adopted at the 2015 United National Climate Change Conference (COP 21) aims to limit "global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C", though it does not spell out specific strategies towards meeting this goal.

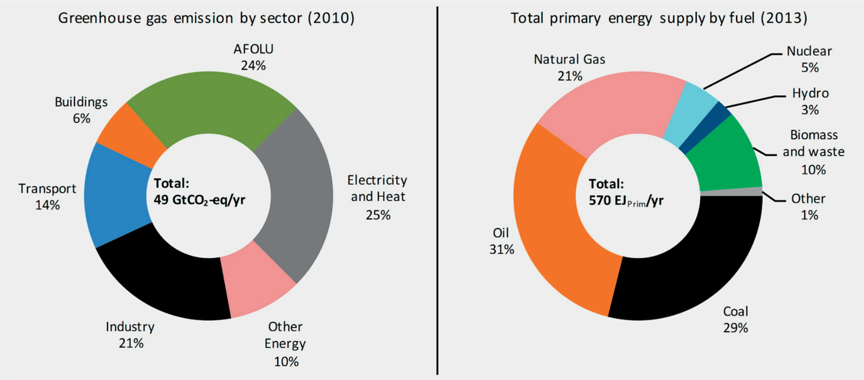

Figure 1.1. Total GHG emissions by sector in 2010 (left) and primary energy supply by fuel in 2013 (right). Adapted from the IPCC 5th Assessment Report (2014) and the IEA 2015 key world energy statistics (2015) respectively. *Other* fuels include non biomass renewables, while *Biomass and waste* includes modern and traditional uses of biomass.

1.2. State of the art

1.2.1. Tools and methods

Several methods can be used to assess the potential role of biomass in climate change mitigation. These can be broadly categorised as (i) bottom-up analyses, (ii) economic land-use models, and (iii) integrated assessment models (Wicke et al., 2014). These tools vary across level of detail, time frame, geographic scope and system boundaries.

Bottom-up analyses

Bottom-up analyses contain detailed descriptions of technologies, processes, agents or resources. Remote sensing and biophysical models have been used to determine the total potential of biomass and investigate how nutrient and water availability may increase productivity (Pan et al., 2014; Niedertscheider et al., 2016). Concerning the assessment of biomass and bioenergy, tools include process-based technical and biophysical models, land use allocation models, cost-benefit analyses, multi-criteria assessments, technological development studies and life cycle assessment (LCA) studies (de Wit et al., 2010; Scott et al., 2012; van der Hilst et al., 2012; Wang et al., 2012; Wiloso et al., 2012; Shen et al., 2012a; J. L. Thompson & Tyner, 2014; de Wit et al., 2014; Gerssen-Gondelach et al., 2014). These studies have highlighted, amongst other things, the potentially beneficial (from a climate perspective) use of biomass for the production of fuel, electricity and chemicals. Furthermore, they offer detailed insights on the techno-economic environmental and social characteristics and impacts of bio-based systems. However, these methodologies are limited by spatial and temporal boundaries, offering limited understanding for the global and long-term scope of climate mitigation strategies. Bottom-up methods are also static in that they do not take into account market effects as well as structural changes outside their system boundaries (Creutzig et al., 2012).

Economic land-use models

Various economic models look at the medium/long-term market effects of biomass and bioenergy. Partial equilibrium (PE) models use simplified representations of processes and flows, and are usually focused on specific economic sectors. PE models have been used to assess the effect of biomass and bioenergy in food, land and energy markets. Applications have focused on supply and demand possibilities and first order effects on the respective systems (De La Torre Ugarte & Ray, 2000; Havlik et al., 2011; Schmidt et al., 2011; Rosegrant et al., 2012; Beach et al., 2012; Taibi et al., 2012). Computable general equilibrium (CGE) models tend to have little or no biophysical representation, focusing on balancing markets across the entire economy. Typically they have been used to assess market implications of biomass and bioenergy policies concerning, among other aspects, land-use changes and GHG emissions (Rajagopal et al., 2011; W. Thompson et al., 2011; Taheipour & Tyner, 2012; Laborde & Valin, 2012; van Meijl et al., 2012). Sociometabolic models aim to integrate physical stocks and flows in ecosystems and economies (materials, energy or carbon) in order to analyse aspects such as biomass availability and land competition (Haberl, 2015). The above methods display medium/long-term dynamics and structural shifts across different geographic scales in production and consumption methods. Consequently, they can better evaluate the mitigation potential of biomass, bioenergy and biochemicals across a number of economic sectors than bottom-up analyses. However, they do not fully account for the interaction between economic and natural systems, such as the effects on nutrients, water, land-based carbon stocks, climate, etc.

Integrated assessment models

Integrated assessment models (IAMs) have been developed as a tool to investigate the interactions between human and natural systems in order to assess the impacts of different policy settings. Through the use of simplified and stylised numerical approaches, they represent the most relevant systems including land, energy, economy and climate (Clarke et al., 2014). IAMs tend to have a spatially explicit representation of land and biophysical processes while human-economic systems are more aggregate with different economic sectors across a number of regions. While IAMs try to represent the complex interactions between and within these systems, their formulation has to be simple enough in order to maintain transparency. Thus, while IAMs have a greater scope and better representation of relevant large scale dynamics for the impacts of biomass and bioenergy than bottom-up or equilibrium models, they tend to make assessments on a more aggregate level (Stehfest et al., 2014; Clarke et al., 2014). As this thesis focuses on the representation of biomass and bioenergy in IAMs, the next section highlights some of the main outcomes of these models and the main knowledge gaps.

1.2.2. IAM projections and knowledge gaps

The long-term projections of bioenergy production and use as generated by IAMs depend on the assumed developments in technological and socio-economic factors. Broadly, these include demographic and economic development, technological change, resource availability, behavioural change, etc. Specifically for bioenergy, important factors also include agricultural production, land availability, crop yields, availability and cost of advanced conversion technologies, and policy settings which affect choices of producers and consumers. The large uncertainty in these factors may lead to highly divergent futures. In order to develop a consistent set of assumptions for a wide range of different factors, *storyline-based scenarios* are often used[1]. Scenarios are plausible and consistent descriptions of how uncertain drivers may unfold (Nakicenovic et al., 2000). Models can be used to quantify these scenarios which are crucial to understanding future biomass supply and demand and the associated GHG impacts (van Vuuren, Kriegler et al., 2014). The different scenario studies can be grouped as follows:

Supply potential

IAMs have been used to investigate how different scenarios affect the supply of biomass. They aim to account for changes in demand for food, feed and fibre and different environmental constraints driven by varying scenario storylines. Hoogwijk *et al.* (2005; 2009) used the IMAGE model in order to project the supply-curves of biomass according to the SRES scenarios (Nakicenovic et al., 2000). The results project the ultimate primary potential ranging between 130-410EJ_{Prim}/yr, with up to 270EJ_{Prim}/yr available at less than 2$\$_{2005}$/$GJ_{Prim}$. Beringer *et al.* (2011) used the LPJmL model to estimate the potential for the SRES scenarios with extra agricultural constraints, concluding that 52-174 EJ_{Prim}/yr may be available by 2050. Haberl *et al.* (2011) also use the LPJmL model to investigate the potential of energy crops and agricultural residues while taking into account changes in temperature, precipitation and elevated CO_2 levels. The study found the potential in 2050 to be 105 EJ_{Prim}/yr, increasing to over 150 EJ_{Prim}/yr when climate change is included. Hayashi *et al.* (2015) investigated the energy crop potential across different socio-economic and climate scenarios, concluding that by 2050 the potential reaches 220-270 EJ_{Prim}/yr due to increases in available land with climate having little impact.

Although the above studies have investigated the potential future supply of biomass and how this varies across scenarios, the representation of the different sources, especially residues, is still very uncertain. Residues are generally considered to have low cost and GHG effects, yet its potential is based on poorly defined assumptions of residue productivity and availability without explicitly accounting for ecological constraints, alternative uses and impacts of changes in agricultural and forestry systems (Berndes et al., 2003; Searle & Malins, 2014). Consequently, there is limited understanding on the drivers, constraints and sensitivities of this resource.

Demand and use in the energy system

IAMs have also investigated the importance of different biomass conversion routes in the energy system. These studies include projections of its potential use in the

[1] Scenarios which assume no action on climate change are called baseline scenarios, while those which implement policies in order to meet a climate goal are called mitigation scenarios.

transport and electricity sectors, highlighting the competitiveness of liquid fuels (Reilly & Paltsev, 2007). Scenarios aiming at meeting stringent CO_2 targets stressed the importance of BECCS (Luckow et al., 2010; Klein et al., 2011). Overall, IAMs project that biomass use increases in the future, with projections estimating overall use in 2100 reaching 50-250 EJ_{Prim}/yr and 100-350 EJ_{Prim}/yr by 2100 in baseline and climate mitigation scenarios, respectively (Rose et al., 2014; Clarke et al., 2014).

Despite the existing studies, there is limited understanding on the drivers of biomass and bioenergy demand as well as the trade-offs in the energy system. This in particular concerns information on the critical aspects which determine the demand and the mitigation potential. Different uses and how they interact with each other, temporal aspects of the distribution and availability of energy services, as well as the cost and performance of competing technologies have not been assessed consistently (Batidzirai et al., 2012). These should be accounted for in order to investigate the potential to displace fossil fuels in different energy and non-energy end-uses in a dynamic and consistent manner while accounting for uncertainties in how the energy system may evolve. Furthermore, the representation of novel uses of biomass, especially biochemicals, in IAMs is usually aggregate or opaque and offers little insight on this potential use. These shortcomings would benefit from an integrated analysis using appropriate dynamic energy models.

Climate mitigation potential

Biomass and bioenergy use affect the carbon balances of both the land and energy systems, leading to large ranges in the potential emission mitigation. Studies accounting for increased bioenergy demand have highlighted that this may lead to significant increases of LUC emissions unless forest protection measures are put in place (Gillingham et al., 2008; Popp et al., 2012; Kraxner et al., 2013; Calvin et al., 2014). Humpenöder *et al.* (2014) specifically investigated the trade-off between afforestation and biomass production, pointing out that both these measures can be applied in parallel with afforestation early on and BECCs application in the second half of the 21st century.

Assessing the climate mitigation potential of biomass is complex due to the multiple supply and end-use possibilities, as well as the fact that it interferes with both the land- and energy-use systems. It is important to investigate the sensitivities of the supply options, responses of end-use sectors and the associated carbon balances. These include assessing how different land-use scenarios affect biomass productivity and carbon stocks, as well as the trade-off between land-based mitigation and bioenergy production. Furthermore, given the dynamics of the energy system mentioned above, studies often ignore the possibility of lock-in with sub-optimal technology settings (Sathaye et al., 2011; Fischedick et al., 2011). The long-term mitigation potential of each option should be better investigated in the context of multiple energy choices interacting in a dynamic matter, and socio-economic aspects driving technological change and the demand for energy services.

The role of biomass in integrated scenarios

IAMs can investigate strategies for climate mitigation while accounting for changes in the human and natural systems. They have been used in order to investigate how biomass and bioenergy may contribute to mitigation efforts and highlight the required transformational changes and possible feedbacks on the land and energy systems (van Vuuren et al., 2007; Wise et al., 2009; Clarke et al., 2014; Kriegler et al., 2014). Multi-model comparisons have highlighted that land and bioenergy may contribute to 5-29% of the total required stabilisation, with biomass production accounting for 24-36% of total crop land (Rose et al., 2012; Popp et al., 2014). Concerning biomass production, multi-model comparisons show baseline deployment rates of primary biomass ranging from 10-90 EJ_{Prim}/yr in 2050 and 45-250 EJ_{Prim}/yr in 2100. In mitigation scenarios these ranges increase to 110-230 EJ_{Prim}/yr and 80-350 EJ_{Prim}/yr respectively (van Vuuren et al., 2010a; Calvin et al., 2013; Rose et al., 2014). There is also agreement that in mitigation scenarios BECCS technologies become increasingly important as high carbon taxes and the possibility for negative CO_2 emissions makes this technology a cost-effective mitigation measure. Sensitivity scenarios have highlighted that the availability of biomass and its combination with CCS are crucial in order to make strict climate targets achievable (Luderer et al., 2014; Kriegler et al., 2014).

While these comparisons have highlighted the potential importance of biomass in mitigation scenarios, there is large variance across the models concerning the sources, the final uses and overall biomass strategies for climate mitigation. Furthermore, these studies tend to be based on single baseline scenarios, and focus on the results of mitigation and sensitivity projections. The Special Report on Renewable Energy Sources (SRREN) highlighted that there is no agreement on how its future role may depend on, and vary across, technological and socio-economic uncertainties (Chum et al., 2011). The uncertainty, risks and opportunities of this resource as a mitigation measure can be assessed by investigating the biomass strategies and changes in emission profiles across different scenarios. Models should be used in order to explore the possibilities of biomass supply and demand and highlight the management and socio-economic conditions which would minimise negative side-effects (LUC emissions, food vs. fuel, displacement of livelihoods, etc.) and exploit potential synergies. This requires an integrated analytical framework which includes spatial details of biomass availability and carbon dynamics as well as a dynamic representation of competing biomass resources and applications (Batidzirai et al., 2012; Creutzig et al., 2015). Yet, it is also important to account for uncertainties due to model structure and the representation of the land and energy systems which, as highlighted above, lead to varying deployment rates and mitigation strategies (Clarke et al., 2014).

1.3. Aim

This thesis aims to investigate the role of biomass as a climate change mitigation option by using an integrated assessment model, the *Integrated Model to Assess the Global Environment* (IMAGE). Specific modules of the IAM are improved so as to better represent the supply and demand of biomass. Subsequently the IAM is used to develop new scenarios and investigate key uncertainties in an integrated manner. In developing and using the IAM, this thesis addresses the following research questions:

1. What is the potential future supply of modern biomass from residues and energy crops when accounting for the drivers and constraints in a spatially explicit manner?
2. What is the demand for biomass for different energy and chemical purposes in a dynamic energy system model?
3. What is the overall greenhouse gas impact of biomass deployment for bioenergy and biochemicals, taking the potential dynamics of future land use and the energy system into account?
4. What is the future role of biomass, bioenergy and biochemicals in various climate change mitigation scenarios when accounting for the land and energy systems in an integrated manner?

In answering these questions, we use different scenarios describing plausible developments in the land and energy systems which affect the supply and use of biomass for energy and chemical purposes. These scenarios cover the effect of different land-use projections on biomass productivity and carbon stocks as well as technological developments and overall demand in the energy system. This allows us to highlight synergies and pitfalls for the effective supply and demand of biomass.

The questions are addressed by adapting and using the land use and energy system aspects of the IMAGE model. An overview of this modelling framework is given in section 1.4. This work uses the methods developed by Hoogwijk *et al.* (2003; 2009) and van Vuuren *et al.* (2007) as a foundation of biomass supply and energy system description, respectively. Besides using various aspects of the framework, improvements and additions are also made concerning agricultural and forestry residues, biochemical processes and overall techno-economic parameterisation (as described in the following chapters). For question 4, IMAGE projections are also compared to those of a second IAM, the MESSAGE-GLOBIOM model framework developed by the *International Institute for Applied Systems Analysis* (IIASA) (Riahi et al., 2012; Havlik, 2015).

1.4. The IMAGE model

IMAGE is an integrated modelling framework used to investigate the interactions between the human and natural systems in order to assess global change and the effect of different policies. A detailed description of the model and all its components can be found in Stehfest *et al.* (2014) and at www.pbl.nl/IMAGE. The model has been progressively developed since the 1980s with a number of releases, the latest of which is version 3.0. The model is primarily developed and operated by the Netherlands Environmental Assessment Agency (*Planbureau voor de Leefomgeving,* PBL) in close collaboration with institutes and universities in the Netherlands and elsewhere. As shown in Figure 1.2, the IMAGE framework is structured so as to comprise of two main systems. The *human* system describes the long-term development of human activities concerning land and energy use and the *earth* system accounts for changes in the natural environment. The two systems are linked by the impacts each has on the other. Socio-economic processes have a geographic resolution of 26 regions, while the earth system is represented at 5×5 minute (land use and land-use change) or 30×30 minute (plant growth, carbon and water cycles) resolution. The description below does not include the improvements made during the research conducted in this thesis as these are described in the relevant chapters.

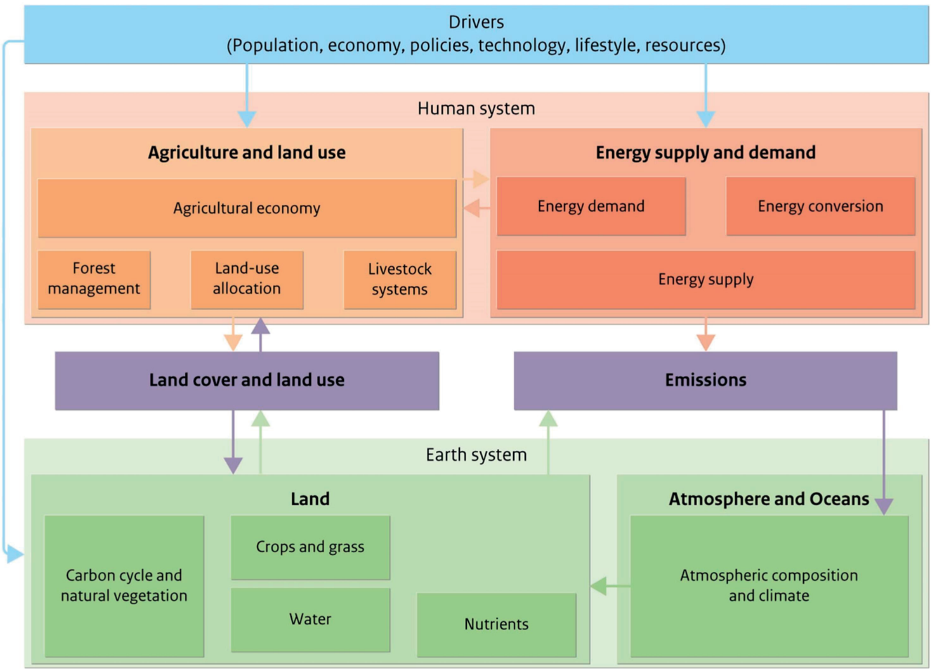

Figure 1.2. Structure of the IMAGE 3.0 framework. Adapted from Stehfest *et al.* (2014).

1.4.1. Biomass and bioenergy in IMAGE

Concerning biomass and bioenergy, the IMAGE framework has three relevant subsystems: (i) an agricultural economic equilibrium model, (ii) a biophysical crop growth and land-allocation model, and (iii) a system dynamic energy model.

Agricultural economy

The agricultural economy is represented using the *Modular Applied General Equilibrium Tool* (MAGNET), an agro-economic computable general equilibrium model (Hertel, 1997; Woltjer et al., 2011; Woltjer et al., 2014). The model is driven by exogenous demographic and economic projections which lead to changes in volume and structure of demand for agricultural and livestock commodities. The model determines changes in regional agricultural production and trade, production intensity, prices and technological progress[2]. MAGNET uses information from IMAGE concerning land availability, suitability and changes in yields due to climate change or expansion into less productive lands. It is important to note that –when used with IMAGE– MAGNET does not include energy crops, which are modelled separately (described below).

Land allocation and bioenergy potential

The land cover model and terrestrial biosphere model of IMAGE are used to determine spatially explicit crop yields, carbon fluxes and nutrient dynamics. The terrestrial biosphere in IMAGE is represented by the Lund-Potsdam-Jena model with Managed Lands (LPJmL) (Gerten et al., 2004; Bondeau et al., 2007). The agricultural and livestock demand from the MAGNET is used to project spatially explicit land-use change and consequent impacts on carbon, nutrient and water cycles. Once agricultural and pasture lands have been allocated and urban, bio-reserves (forests) and unsuitable lands have been excluded, the remaining land can in principle be used for biomass growth. Thus, the model takes an explicitly *food-first* approach. Maps of crop productivity together with regional labour and capital costs are used to construct supply curves for primary biomass as described in Hoogwijk *et al.* (2009). Potential bioenergy crops include sugarcane, maize, and short rotation grassy (miscanthus) and woody (eucalyptus and willow) crops.

Energy System

The energy system is represented via *The IMAGE Energy Regional* (TIMER) model, a dynamic recursive simulation of energy supply and demand. Energy demand functions are disaggregated for specific economic sectors (industry, transport, residential, services and other) and are driven by increases in welfare. Primary energy carriers include coal, oil, natural gas, modern and traditional biomass, nuclear, solar, wind

2 This includes changes in crop yields due to economic pressures, i.e. intensification.

and hydro-power. These can be converted -where appropriate- to secondary and final energy carriers such as solid, liquid and gaseous fuels as well as electricity, heat and hydrogen. Primary biomass can be converted to pellets for direct use as a heating fuel and a portfolio of 1st and 2nd generation liquid fuels (ethanol, methanol and diesel). Furthermore, biomass can be converted to electricity or hydrogen, potentially combined with BECCS technologies.

Final energy carriers compete for a market share of final energy demand based on their relative costs. For non-renewable energy sources, fuel costs are calculated based on cumulative production and exogenous supply curves, while for renewables costs depend on production levels. On the demand side, efficiency improvements are based on assumed technological trends (autonomous) as well as changes in fuel prices (price-induced). The model includes dynamics such as learning-by-doing, capital stock inertia (based on capital lifetimes) and bilateral trade of homogenous energy carriers. Being a dynamic recursive simulation model, results are not optimised intertemporally.

1.5. Thesis outline

In order to develop and apply the methods required to answer the research questions posed above, this thesis is divided into three sections: *biomass supply* (Chapters 2&3), *biomass demand* (Chapters 4&5) and *integrated scenarios* (Chapters 6&7). Table 1.1 below shows the overview of the chapters and the research questions addressed in them. Each chapter addresses one or more of the research questions by developing and investigating modelling methods and performing (integrated) scenario analyses.

Chapter 2 describes the method developed in order to determine the long term supply and cost of residues from agricultural and forestry operations. IMAGE projections of the production and intensity of these sectors are used to calculate the spatially explicit supply of residues. Ecological and competing uses of residues such as livestock feed and traditional fuel use (also determined in IMAGE) are subtracted in order to determine the volume available for modern biomass applications. Subsequently, spatially-specific costs are calculated by accounting for intensity of production, capital, labour and transport costs. Finally, cost-supply curves for this resource are constructed. The study also looks into the impact of uncertainty, including the effects of different socio-economic scenarios and the sensitivity to key parameters.

Chapter 3 introduces the concept of emission-supply curves. This is a novel method highlighting the LUC emissions as a function of supply (and underlying land availability). For this, IMAGE projections of land-based carbon stocks and biomass yields are used to calculate spatially specific emission factors and GHG payback periods. Emission supply curves for different 1st and 2nd generation biofuels are presented, paying special attention to the suitability of different biomes and the sensitivity to key assumptions.

Chapter 4 presents the inclusion of non-energy uses of energy carriers (feedstocks for chemicals) in the TIMER model. The sector is disaggregated into four key non-energy products: higher value chemicals, ammonia, methanol and heavy refinery products; and includes key conversion and recycling technologies. The data and model techniques used are described and projections of the primary energy carrier demand and emissions of this sector are presented. The model is used in order to investigate the long-term potential of biochemicals, the effect of climate policy, and mitigation potential of cascading chemicals through recycling and/or incineration with power production.

Chapter 5 uses the TIMER model (including the non-energy sector described in Chapter 4) in order to investigate the long-term use and emission implications of biomass in the energy system (including non-energy). The study looks into the mitigation potential of biomass in different end-use sectors. Attention is paid to the emission reduction per unit biomass use for each sector, the role of competing uses and the effect of increasingly stringent climate policy. Furthermore, the results are tested across uncertainties in biomass availability and technological development.

Chapter 6 compares the structures and results of two IAM frameworks: IMAGE and MESSAGE-GLOBIOM. Their representation of the land and energy systems are described, focusing on how each determines the supply and demand of biomass and bioenergy. Consistent baseline and mitigation scenarios are projected and a sensitivity scenario investigating the trade-off between biomass production and land-based mitigation is applied. Differences in the adopted bioenergy strategies are explained by contrasting the structures and bioenergy routes of each model. The chapter highlights the importance of different dynamics and the inherently limited scope of individual model perspectives.

Chapter 7 uses the improved IMAGE model (including the additions of Chapters 2&4) in order to investigate the role of biomass for climate change mitigation in an integrated manner. This is done by projecting three baselines with differing socio-economic storylines, and their respective climate mitigation pathways. The scenarios show the ranges, drivers, constraints and sensitivities of biomass and bioenergy pathways and how these vary across different potential futures. Finally, this chapter integrates the individual results from the preceding chapters in order to answer the research questions, give policy recommendations and propose further research avenue

Table 1.1. Overview of thesis chapters and their relation to the research questions.

	Chapter	Research Question			
		1	2	3	4
Supply	2. Projections of the availability and cost of residues from agriculture and forestry	×			
	3. Greenhouse gas emission-curves for advanced biofuel supply chains	×		×	
Demand	4. Energy demand and emissions of the non-energy sector		×	×	
	5. Competing uses of biomass for energy and chemicals: Implications for the long-term global CO_2 mitigation potential		×	×	
Integrated	6. The role of biomass and bioenergy in the mitigation strategies of two different integrated assessment modelling frameworks	×	×	×	
	7. Integrated assessment of biomass supply and demand in climate change mitigation scenarios	×	×	×	×

2

Projections of the availability and cost of residues from agriculture and forestry

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Abstract

By-products of agricultural and forestry processes, known as residues, may act as a primary source of renewable energy. Studies assessing the availability of this resource so far offer few insights on the drivers and constraints of the available potential, the associated costs and how the availability may vary across scenarios. This study projects long-term global supply curves of the available potential by using consistent scenarios of agriculture and forestry production, livestock production and fuel use from a spatially explicit integrated assessment model. Particular attention is paid to the drivers and constraints. In the projections residue production is related to agricultural and forestry production and intensification, and the limiting effect of ecological and alternative uses of residues are accounted for. Depending on the scenario, theoretical potential is projected to increase from approximately 120 EJ_{Prim}/yr today to 140-170 EJ_{Prim}/yr by 2100, coming mostly from agricultural production. In order to maintain ecological functions approximately 40% is required to remain on the field, and a further 20-30% is diverted towards alternative uses. Of the remaining potential (approximately 50 EJ_{Prim}/yr in 2100), more than 90%, is available at less than 10 $\$_{2005}/GJ_{Prim}$. Crop yield improvements increase residue productivity, albeit at a lower rate. The consequent decrease in agricultural land results in a lower requirement of residues for erosion control. The theoretical potential is most sensitive to baseline projections of agriculture and forestry demand; however this does not necessarily affect the available potential which is relatively constant across scenarios. The most important limiting factors are the alternative uses. Asia and North America account for two thirds of the available potential due to the production of crops with high residue yields and socio-economic conditions which limit alternative uses.

2.1. Introduction

Residues from agricultural and forestry operations are regarded as a possible primary source of biomass for energy and material uses. Their use is attractive as they are not related to direct or indirect land-use change issues and they are estimated to have a low cost since they are by-products of existing operations. Many integrated assessment models (IAMs) show that residues may play an important role as a primary energy source, especially in scenarios with strict climate mitigation (Rose et al., 2014). However, the availability and associated costs of residues are poorly represented in IAMs: often using a generic supply curve with little biophysical and socio-economic backing (Berndes et al., 2003; van Vuuren et al., 2010a). Furthermore, there is little understanding on how the availability of this resource is related to the intensity of agriculture and forestry operations and how it may be limited by current alternative uses such as feed for livestock and fuel use in poor households (Chum et al., 2011).

A number of studies have estimated the potential of residues in 2050, with a range of 15-280 EJ_{Prim}/yr globally (Berndes et al., 2003; Hoogwijk et al., 2005; Hamelinck & Hoogwijk, 2007; Dornburg et al., 2010; Chum et al., 2011). This large range is itself an indication of the poor understanding of the drivers for availability, the inconsistent methodologies that are used and the lack of a comprehensive evaluation of residue generation and alternative uses (Searle & Malins, 2014). Estimates of bioenergy production from residues need to account for ecological constraints and alternative uses of the total potential (IEA, 2010a). Studies agree that agriculture and forestry production form the most important source of residues, and consequently most studies in the literature estimate the potential by multiplying total crop/forest production by *residue production* and *recoverability* factors. These studies lack a physical representation of residue productivity, ecological functions and alternative uses, as well the impacts of changes in the intensity of agricultural and forestry systems (Berndes et al., 2003). Integrating detailed information on agriculture and forestry residue productivity with biophysical and economic models would allow for a better understanding of the availability of this resource under different scenarios (Wicke et al., 2014).

This chapter seeks to address these issues by assessing the availability of residues for advanced energy and material uses by investigating the mass flows while accounting for ecological and alternative uses. We develop and apply a methodology which projects residue availability within the integrated assessment model IMAGE (Stehfest et al., 2014). We project the global potential of residues to 2100 by accounting for changes in the demand of agricultural and forestry products as well as their intensity of production. Subsequently, we determine the volume of residues required for ecological functions and the demand of residues for alternative uses. Finally, we determine supply curves for the available potential by including location specific collection and transport costs. Since a single integrated assessment model is used, the projections are internally consistent and the effect of changes in the agricultural, forestry, livestock and energy systems can be assessed.

In this chapter, we describe the methodology used to determine the available potential of residues and the supply curves. Furthermore, we outline the different scenarios used to assess projections of residue availability. Following, we present the results of the reference and sensitivity scenarios, highlighting the main drivers and constraints. Finally we offer a discussion on the methodology, a comparison of our results with existing literature, and the conclusions of this study.

2.2. Materials and methods

In the context of bioenergy, residues are typically defined as by-products associated with food/fodder and forest sector production and processing (Chum et al., 2011). Consequently, residue generation is driven by the demand and production methods of the agriculture and forestry sectors. Part of these residues are already used for other purposes, such as maintenance of ecological functions, livestock feed, and fuels for poor households (IEA, 2010a). An analysis of the bioenergy potential from residues therefore would need to estimate future availability on the basis of these drivers and constraints. Here, we do so by using spatially explicit projections of the production and intensity of the agriculture and forestry sectors, while accounting for ecological constraints and the use of residues for feed and traditional fuels. Maps of agriculture and forestry production as well as residue demand for other uses are derived from the IMAGE model, providing a consistent description of different forms of land use, land-use intensity and demand for feed and fuel.

Three levels of residue potentials are evaluated: the *theoretical, ecological* and *available* potential. These potentials and the different residue sources are defined in Table 2.1. The calculation process employed in this study is outlined in Figure 2.1. In order to maintain consistency for different residue uses, in the calculations all quantities are measured in tons (wet-basis). Since the focus of this chapter is residue availability for bioenergy, all results in this chapter are presented in energy terms by using relevant moisture contents and Higher Heating Values (HHV) (Table 2.2).

Table 2.1. Definitions of residues and potentials included in this study.

	Theoretical potential	**Ecological potential**	**Available potential**
	Maximum available residues from crop harvest and round wood logging operations. Acts as a theoretical upper limit.	Theoretical potential minus residue requirements to avoid severe ecological degradation.	Ecological potential minus livestock and traditional fuel use. This potential is considered available for modern bioenergy.
Agriculture (Harvest Residues)	Aboveground straw and stalks for: Temperate cereals, rice, maize, tropical cereals, pulses, roots & tubers, oil crops, vegetables, fruit crops, fibre crops and sugarcane.	Theoretical potential minus residue requirements to avoid environmental degradation (250t/km^2).	Ecological potential minus feed for livestock and (part of) traditional fuel use. Animal bedding not included as this is usually returned to field and thus can be considered part of the fraction remaining for ecological reasons.
Forestry (Logging residues)	Unmerchantable stems and branches from final harvest and non-merchantable trees from thinning and pruning operations. Forest management types include clear-cut, selective-cut and wood plantations. Note: leaves, roots and stumps not included in theoretical potential.	Theoretical potential minus residue requirements to avoid soil erosion (1000t/km^2).	Ecological potential minus (part of) traditional fuel use.
Process residues	*Agricultural*: Husks, shells and cobs for rice, maize and oil crops. *Forestry*: Sawmill and plywood production residues, and timber and paper scrap.		Theoretical potential minus (part of) traditional fuel use.

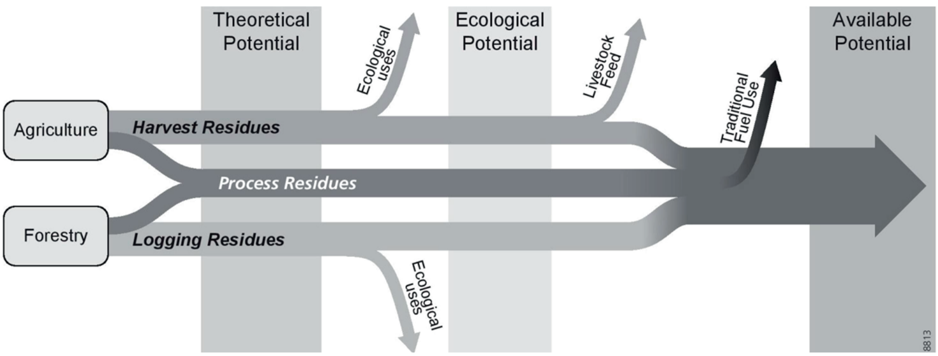

Figure 2.1. Flowchart indicating methodology used to determine the residue availability. Outflows leading to different potentials are shown, and data inputs are indicated in ovals. Note: Figure for illustration purposes only, flow sizes may be of different magnitudes.

2.2.1. Theoretical potential

The theoretical potential comprises of the absolute maximum volume of residues produced given projections in agricultural and forestry productivity. It acts as an upper limit of the availability and does not take into account environmental or economic constraints, recoverability and possible current uses. Below, the calculation method for agriculture and forestry harvest and process residues is presented.

Agricultural residues

The production of agricultural residues depends on the volume of agricultural production, the crops being produced and the yield of these crops (Kim & Dale, 2004; Chum et al., 2011). In this study agricultural residues are defined as above ground straw or stalks. The yield affects residue potential through the residue to product ratio (RPR), defined as the ratio of above ground crop production to the total grain production (Lal, 2005). Data from a number of studies indicate the RPR varies across different crop types and tends to decrease with increasing yields (see references in Scarlat *et al.* (2010)). This is because gains in crop yields improve the production of the harvestable component rather than the residue component.

The IMAGE model includes crop production (and yields) for the following groups: temperate cereals, rice, maize, tropical cereals, sugarcane, pulses, roots & tubers, and oil crops. The relationship between crop yield and RPR used in this study is shown in Table 2.2. For pulses, roots & tubers, and oil crops no meaningful relationship could be determined from the literature and thus the arithmetic mean of the available data was used. The IMAGE model also includes a land use category *other crops* covering all crops not mentioned above. We have divided the land use of *other crops* amongst sugarcane, vegetables, fruit and fibre crops based on FAO data (2014), with the shares of each of these crops kept constant in future projections. Since yields of each of these crops are not provided from IMAGE, a residue to surface area ratio (RSR), determined from literature, was used (Gemtos & Tsiricoglou, 1999; Di Blasi et al., 1999; Lal, 2005; Garcia-Galindo & Royo, 2009). This crop-specific factor determines the tons of residue production per km^2 of crop production.

Table 2.2. Agricultural crops included in assessment, proposed correlations between RPR and yield, and assumed higher heating value (HHV).

Crop	**RPR ($t_{residue,wet}/t_{product}$)[3]**	**Moisture Content (%)**	**HHV (GJ_{Prim}/t_{wet})**
Temperate Cereals[4]	-0.281 × *Ln*(Yield) + 2.7423	12	16
Rice	-0.925 × *Ln*(Yield) + 7.371	13	13
Maize	-0.138× *Ln*(Yield) + 1.8681	12	16
Tropical Cereals	-0.266× *Ln*(Yield) + 3.108	11	15
Sugarcane	-0.18×*Ln*(Yield) + 1.4289	10	16
Pulses	1.24	15	15
Roots & Tubers	0.46	73	4
Oil Crops	1.53	8	16
Other Crops	**RSR ($t_{residue,wet}/km^2$)**	**Moisture Content (%)**	**HHV (GJ_{Prim}/t_{dry})**
Vegetables	2734	80	3
Fruit	342	40	11
Fibre	559	17	15

References: (Di Blasi et al., 1999; Gemtos & Tsiricoglou, 1999; Kim & Dale, 2004; Lal, 2005; Garcia-Galindo & Royo, 2009; Scarlat et al., 2010; CGPL, 2010; ECN, 2012; Jiang et al., 2012; Xu et al., 2013)

The theoretical potential is calculated per crop type and grid cell using IMAGE maps of crop area and yields and the equations shown in Table 2.2. The theoretical potential of agricultural residues (*AgrTheo),* in tons, is calculated using equation (2.1).

$$AgrTheo_{c,i} = RPR_{c,i} \times CropArea_{c,i} \times CropYield_{c,i} \tag{2.1}$$

Where *CropArea* and *CropYield* are the cultivation area (km^2) and yield (t/km^2), respectively, as projected by the IMAGE model. The subscripts *c* and *i* stand for crop and grid-cell, respectively.

For process residues, it is assumed that they accrue during the processing of the main product. Thus, their potential is determined by multiplying the production of each crop by a residue generation factor. These are set as 0.2 for rice husks, 0.3 for maize cobs and husks, and 0.1 for oil crops (Koopmans & Koppejan, 1997; Yamamoto et al., 2001; Smeets et al., 2007a; CGPL, 2010).

Forestry residues

The theoretical residue potential of forestry is very site specific and depends on a number of aspects such as biome, tree species and their diversity, management type

3 Crop yields are measured in wet tons per km^2.

4 Scarlat *et al.* (2010) assessed wheat, rye, oats and barley separately. In this study the aggregate of these crop categories are used for *Temperate Cereals* by taking the average RPR of these crops at different yield levels.

(clear cut, selective cut, reduced impact logging, plantation), silvicultural practices (thinning, pruning) and end product (timber, pulp & paper). Also, the residue sources themselves are diverse (twigs, branches, stumps, roots or low quality stems) (Buck 2013; van Dijk 2014). This means that forestry residue potential cannot be aggregated easily. Most literature sources simply assume a percentage of the total tree volume is residue. This is usually set to 30-60% (Koopmans & Koppejan, 1997; Smeets & Faaij, 2007b; USDE, 2011). A study by Lauri *et al.* (2014) estimates that in tropical zones 20-50% of growing stock are of species relevant for roundwood production and harvest residues make up 20% of merchantable trees.

In IMAGE, harvesting can be conducted under three possible management types: Clear-cut, selective cut and wood plantations, as defined in Arets *et al.* (2010). While a specific forest does not produce merchantable wood annually (due to growth cycles), in IMAGE the production is averaged over the growth cycle and is thus considered annual. In this study, projections of this annual wood production are used together with harvest residue generation factors, per biome and management type, derived from literature in order to determine the theoretical potential. These residue generation factors are shown in Table 2.3 and include all forestry operations (i.e. thinning, intermediate cut, final cut) and represent the ratio of residues to merchantable wood production over the entire growing cycle.

Table 2.3 Residue fraction per unit merchantable wood removed (%) for each forest and management type.

<table>
<tr><th rowspan="3">Forest Biome (IMAGE)</th><th colspan="3">Management Type</th></tr>
<tr><th>Clear Cut</th><th>Selective Cut</th><th>Wood Plantation</th></tr>
<tr><th colspan="3">Residue production per wood production (%)</th></tr>
<tr><td>Boreal
Wooded Tundra</td><td>69</td><td rowspan="2">NA[5]</td><td>78</td></tr>
<tr><td>Cool Conifer
Temperate Mixed
Temperate Deciduous</td><td>53</td><td>63</td></tr>
<tr><td>Savannah
Warm mixed
Tropical Woodland
Tropical Forest</td><td>39</td><td>18</td><td>52</td></tr>
</table>

References: (Nilsson et al., 2002; Buck, 2013)

These ratios have been determined by investigating average species diversity, crown/stem ratios, wood removal rates, rotation lengths and silvicultural practices (Buck, 2013; van Dijk, 2014). A representative tree species is selected for each biome, with a unique crown/stem ratio. Wood removal rates, rotation lengths, stocking density

[5] Selective cut is not practiced in these biomes.

and other practices vary per management type. Thus we determine, over the entire growing cycle, residue production from thinning, intermediate and final harvest. Consequently the ratio of residue to merchantable wood over the entire growing cycle is determined. Roots and stumps are not included since their removal leads to significant disruption to the forest area. Approximately half of the residues come from thinning, and the other half from the final harvest, with thinning being more important in plantations.

For forests under clear cut management, it is assumed that a whole natural forest area is completely felled and harvested. In selective cut only trees with the highest economic value are felled. This management type is mainly practiced in tropical forests where only few commercial trees are available due to the heterogeneous nature of these forests (Arets et al., 2010). Since only relevant trees are felled, this management type has the lowest residue productivity. Wood plantations contain selected tree species which may be endemic or exotic. These forests are intensely managed, may be irrigated and apply pest control and fertiliser use in order to maximise production. Wood plantations tend to have higher residue generation potentials due to very short rotation periods, removal of unmerchantable stands, high stocking density and intense silvicultural management such as pruning and pre-commercial thinning (Hakkila, 2004; van Dijk, 2014). Overall boreal forests have higher residue generation rates than other forest types due to higher crown-to-stem ratios (Standish et al., 1985). The theoretical potential of forestry residues (*ForTheo*), in tons, is calculated using equation (2.2).

$$ForTheo_{B,i} = \frac{ForTheoFrac_{B,i}}{100} \times WoodProd_{B,i} \tag{2.2}$$

Where *ForTheoFrac* is the ratio of forest residues to merchantable wood production, as listed in Table 2.3, and *WoodProd* is the total merchantable wood production which is provided from IMAGE. The subscripts *B* and *i* stand for forest biome and grid cell respectively.

Concerning process residues from wood production (sawdust, trimmings, shavings etc.), the production of merchantable wood is multiplied by a process residue generation factor (constant across biomes and management types). This is set at 0.3 (Koopmans & Koppejan, 1997; Yamamoto et al., 2001; Smeets & Faaij, 2007b; CGPL, 2010; Lauri et al., 2014).

2.2.2. Ecological potential

Residues perform a number of ecological functions such as protection from soil erosion, maintaining soil organic carbon (SOC), improving water infiltration, reducing soil moisture evaporation rates, and preservation of biodiversity (Richardson et al., 2002; Andrews, 2006; Blanco-Canqui & Lal, 2007; Lattimore et al., 2009; Lamers et al., 2013a). The volume of residues required in order to provide these ecological functions depends on a number of factors including local topography, soil types, climate conditions, crop rotation and tillage. Assessing the ecological potential at this level of detail is not possible and thus we apply a global constraint which would ensure an adequate level of environmental protection. Concerning SOC, studies agree that it is much more sensitive to the tillage employed, and with appropriate tillage techniques residue removal rates can increase significantly without affecting SOC content (Reicosky et al., 2002; Johnson et al., 2006). In this study it is assumed that ecological services are maintained if soil erosion can be controlled by limiting the amount of residue extraction (Papendick & Moldenhauer, 1995; P. Gallagher et al., 2003; Lemke et al., 2010; Glithero et al., 2013; Liska et al., 2014). We only extract surface residues as below ground residues are assumed unavailable throughout this study. Below we show the calculation for the limitations to residue extraction for both agricultural and forestry residues.

Agricultural residues

Gallagher *et al.* (2003) determine the volume of residues required in order to avoid wind and water erosion for a number of different land classes. Their results show that, in the most pessimistic cases, erosion constraints are met if up to 250 tons of residues remain per km^2 of cultivated land. This is also the constraint used in this study. The formulation used to determine the agricultural ecological potential, in tons, is shown in equation (2.3).

$$AgrEco_{c,i} = max\left[AgrTheo_{c,i} - \left(250 \times CropArea_{c,i}\right), 0\right] \qquad \textbf{(2.3)}$$

Forestry residues

Literature states that additional to leaves and small branches, a minimum of 1000t/km^2 of forestry residues from final harvest should remain on site in order to maintain soil properties (Graham et al., 1994). As stated above, in this study we include residues from various stages of forest growth as well as the final harvest and these are spread over the entire growing cycle. Following the method used to determine the theoretical potential we reduce the residues, only from the final harvest, by 1000t/km^2, and determine the ratio of the ecological to the theoretical potential ($ForEcoFrac_{B,i}$). This ranges between 60-90% depending on the biome. Note that (non-foliage) residues produced during intermediate operations (≈50% of theoretical potential) are assumed useable, and thus $ForEcoFrac_{B,i}$ depends on residue production during final harvest only. The ecological potential is calculated according to equation (2.4).

$$ForEco_{B,i} = ForTheo_{B,i} \times ForEcoFrac_{B,i} \quad \textbf{(2.4)}$$

2.2.3. Available potential

Residue availability can be limited by other uses which are dependent on local physical and economic circumstances. The most important current uses of agricultural and forestry residues are as a source of feed for livestock, and fuel in poor households (Koopmans & Koppejan, 1997; IEA, 2010a; USDE, 2011). IMAGE provides projections of demand of residues for both livestock feed (based on projected developments in livestock demand and production) and traditional fuel use in households (based on changes in affluence). These projections are done on a regional level according to the 26 IMAGE regions (Stehfest et al., 2014). For the available potential (*AvailablePot*), it is assumed that residue demand for livestock feed is met solely from agricultural residues. Concerning traditional fuels, it is assumed that 50% of traditional fuels are residues, the rest coming from coal, household waste, charcoal, fuelwood, dung and others (WHO, 2011). Residue based traditional fuels are supplied from an aggregate of harvest, logging and process residues (*AgrProc* and *ForProc* for agricultural and forestry process residues respectively). Available potential is determined on a regional basis, *R*.

$$\begin{aligned} AvailablePot_R = {} & [(AgrEco_R - FeedDem_R) \\ & + ForEco_R + AgrProc_R + ForProc_R] - TradFuelDem_R \end{aligned} \quad \textbf{(2.5)}$$

2.2.4. Costs

Supply curves of the *available potential* are generated based on the main cost components determined from literature. Data sources are often region or even site-specific, and thus in this global study the data has to be made more generic. Costs are scaled across regions based on the relative labour costs as projected by the scenarios.

Agricultural residues

Detailed cost estimates for agricultural residues across different world regions and crops are scarce. In this study estimates are based on studies and surveys focussing on US agricultural residue collection due to their comprehensive nature and the ability to compare costs amongst them (P. Gallagher et al., 2003; Edwards and Johanns, 2014; J. L. Thompson and Tyner, 2014).

1. **Harvest Costs:** These costs are assumed to be constant on a per-area basis as they are related to trips across the field, such as chop and bale. Consequently, areas or

crops that produce residues more intensely will have lower harvest costs. After Gallagher *et al.* (2003) these are set at 4800 $\$_{2005}$/km^2.

2. **Operations:** These include on-farm hauling (0.1 $\$_{2005}/GJ_{Prim}$) which is the same for all crops, as well as costs of replacing nutrients (via the application of fertiliser) due to the removal of residues. Fertiliser costs vary across crops (0.3-0.5 $\$_{2005}/GJ_{Prim}$). All the values are taken from Gallagher *et al.* (2003).
3. **Storage and drying:** These costs were estimated at 1.2 $\$_{2005}/GJ_{Prim}$ and assumed constant across all crops (J. L. Thompson and Tyner, 2014).
4. **Transport:** The cost of transporting bales to a processing facility are set at 0.012 $\$_{2005}/GJ_{Prim}$/km (Edwards and Johanns 2014). Transport distance is inversely related to population density and assumed to increase exponentially as population density approaches 0. With this function, globally transport costs range from 0.2 $\$_{2005}/GJ_{Prim}$ to 5 $\$_{2005}/GJ_{Prim}$.

For process residues, a single price is given for all types of crops and processes. These residues are generated in grain processing facilities and thus their cost could be considered zero or even negative. However, we attach a price to them in order to cover collection and handling costs and since once a demand is created negative costs will not persist (Junginger et al., 2001; USDE, 2011). The price of agriculture process residues is set at 2 $\$_{2005}/GJ_{Prim}$ (Gregg and Smith 2010; USDE 2011).

Forestry residues

Details on forest residue collection methods and cost estimates are sparse and tend to focus on European boreal forests. Two comprehensive studies have been used in order to get cost estimates. Junginger *et al.* (2005) has identified cost reduction trends in forest residue collection in Sweden by assessing different components of the cost structure. Eriksson *et al.* (2010) assess six different residue collection systems, for Sweden and Finland, by comparing the cost components. Based on these studies, the following cost structures have been estimated.

1. **Forwarding:** Costs of forwarding of residues or bundles from the forest area to a roadside range from 0.3-0.9 $\$_{2005}/GJ_{Prim}$. This study assumes forwarding costs at 0.6 $\$_{2005}/GJ_{Prim}$.
2. **Chipping/Compressing:** The literature gives costs of roadside chipping or in forest-bundling and compressing ranging from 1-1.9 $\$_{2005}/GJ_{Prim}$. The higher values are from the 1980s as the chipping process has shown significant cost reduction. This study assumes chipping/compressing costs to be 1.2 $\$_{2005}/GJ_{Prim}$.
3. **Transport:** Same method is used as with agricultural residues.
4. **Additional Costs:** These include stumpage fees, overhead costs, covering of piles, operation and maintenance, etc. Junginger *et al.* (2005) estimated it as 15% of

total cost, while Eriksson *et al.* (2010) gave absolute costs for each collection method. In all cases these costs varied between 0.1 and 1.4 $\$_{2005}/GJ_{Prim}$. This study assumes additional costs to be 0.5 $\$_{2005}/GJ_{Prim}$.

2.2.5. Scenarios

In order to investigate the dynamics of residue availability we project the potentials and costs for three scenarios: *Medium, Optimistic* and *Pessimistic*. The scenarios are based on the *Shared Socio-economic Pathways* (SSPs) – a set of scenarios developed to support climate and global environmental research. The SSPs describe plausible alternative trends in the evolution of society and ecosystems over a century timescale (van Vuuren et al., 2014). The purpose of the SSP scenarios is to explore how diverging socio-economic conditions (such as demographic, political, social, cultural, institutional, lifestyle, economic and technological aspects) affect the energy and the land use system, and greenhouse gas emissions, and what challenges result for mitigation and/or adaptation to climate change (O'Neill et al., 2014). Population and GDP

Table 2.4 Qualitative description of baseline and sensitivity scenarios.

Reference scenarios	
Optimistic	The *Optimistic* scenario is based on SSP1 and illustrates a world with reduced mitigation and adaptation challenges to climate change. The global population stabilises by 2050 and slowly decreases thereafter. Per capita income, consumption and access to modern energy increase significantly. The agricultural system is characterised by optimistic improvements in crop yields, increased use of irrigation and intensification of livestock systems.
Medium	The *Medium* projection is based on SSP2, a continuation of current trends, and assumes intermediate challenges to climate adaptation and mitigation. Population increases and stabilises by 2090, leading to increased demand of agricultural, livestock and forestry products compared to the *Optimistic* case. Developments in the agricultural systems also follow business-as usual projections, as described by the FAO (Alexandratos and Bruinsma, 2012).
Pessimistic	The *Pessimistic* scenario is based on SSP3 and depicts a world dominated by regional competition. This includes a strong increase of population throughout the projection period, leading to increased demand in agriculture, livestock and feed products. Yet per-capita income and consumption is lower than in the other scenarios and residues play a more important role as a traditional fuel. It represents a "regionalised" world with low technology transfer, low improvements in yields and limited intensification in livestock systems.
Sensitivity Scenarios	
Medium - Extensive	Population and GDP of *Medium* with agricultural intensity parameters of *Pessimistic* (i.e. less intensification compared to reference *Medium*).
Medium - Intensive	Population and GDP of *Medium* with agricultural intensity parameters of *Optimistic* (i.e. more intensification compared to reference *Medium*).

projections are taken from the SSP database (IIASA, 2015). These pathways have been implemented in the IMAGE model framework resulting in a quantitative description of the global energy, land and environmental systems (see description in the Appendix). The *Medium* scenario represents a business-as-usual development of socio-economic indicators. The *Optimistic* scenario represents a world with relatively low mitigation and adaptation challenges to climate change, and the *Pessimistic* scenario a world where these challenges are high (Table 2.4). The diverging developments in each scenario lead to different agricultural and forestry product demands as well as intensities of production. Furthermore, socio-economic differences between the scenarios lead to varying livestock feed and household energy use; which affect the competing uses of residues. One of the major uncertainties in scenarios on global agriculture and land use is the intensity of agricultural production. It is well-known that in many regions large potentials exist for increasing the efficiency of livestock systems (e.g. via increased stocking rates, improved feed composition, better grassland management and improved breeds), and increasing crop yields (e.g. via increasing fertiliser input, managing pests and diseases, and improving plant breeds). Changes in these intensity parameters will have strong implication for land use. In order to investigate the effect of agricultural intensity (i.e. isolate for changes in population and income), we also run sensitivity scenarios on the *Medium* scenario. A qualitative description of the reference and sensitivity scenarios is shown in Table 2.4.

2.3. Results

It is important to highlight how the main driving forces of the results evolve over the projection period for each scenario. These are shown, indexed to 2010, in Table 2.5. The demand of agricultural and forestry products (which are primarily driven by population growth) are lowest for the *Optimistic* and highest for *Pessimistic* cases. Conversely, the productivity (i.e. crop yields) is highest for the *Optimistic* and lowest for *Pessimistic* case. Consequently, the *Optimistic* case has the lowest total land use and *Pessimistic* the highest. The residue productivity (measured in GJ_{Prim}/km^2) depends on which crops are produced, crop yields, cropping intensities and the forest management types. Overall, an increase in the productivity for the theoretical potential over time is witnessed, driven by increases in crop yields. The lower rate of increase for residue productivity with respect to crop yields is due to decreases in residue to product ratios. The productivity for the available potential, which drive the final costs, are determined after ecological and alternative uses are accounted for. They increase at a greater rate than the theoretical potential productivity for two reasons, (i) as residue yields increase, all gains are included in the ecological potential once the constraints are met, and (ii) alternative uses decrease for all scenarios over time. The medium scenario has the highest productivities due to a combination of high yields, and demand for agricultural and forestry products.

Table 2.5. Relative changes of key indicators for all reference scenarios (2010=100). IMAGE provides projections of the volume demand and production intensity of the agricultural and forestry sectors. Aggregate residue productivity (GJPrim/km^2) for the theoretical and available potentials determined from present methodology.

	Reference Scenario	2010	2030	2050	2080	2100
				Inputs from IMAGE		
Demand for agricultural and forestry products	Optimistic	100	129	150	156	160
	Medium	100	134	155	166	174
	Pessimistic	100	145	169	186	199
Intensity of production (agriculture and forestry)	Optimistic	100	144	179	204	222
	Medium	100	143	169	192	219
	Pessimistic	100	142	161	178	196
				Results		
Residue productivity for the theoretical potential	Optimistic	100	110	116	116	117
	Medium	100	112	119	120	120
	Pessimistic	100	107	110	112	113
Residue productivity for the available potential	Optimistic	100	115	127	128	130
	Medium	100	120	133	137	139
	Pessimistic	100	116	121	125	128

2.3.1. Reference scenarios

Figure 2.2 shows the projections of the different potentials for the reference scenarios. The theoretical potential increases over the projection period due to increases in the demand of agricultural and forestry products, with the *Pessimistic* case having the largest increase. The results imply that approximately 50% of agricultural residues and 30% of forestry residues have to remain on the field for ecological services. Next, the available potential is about 50-66% of the ecological potential (thus 30-40% of the theoretical). Figure 2.3 shows the different flows of residues from theoretical to available potential, for all the reference scenarios.

The ecological uses depend on the land area being used, and thus increase across the scenarios. This leads to a closing of the gap between scenarios for the ecological potential compared to the theoretical. Interestingly, the available potential follows a different trend than the theoretical/ecological potentials across the scenarios. Alternative uses differ significantly due to changes in livestock feed demand and the use of traditional fuels in poor households. Due to its lower economic development and dependence of livestock feed on residues, the *Pessimistic* case has the largest competing uses. In other words, even though the *Pessimistic* case has the highest theoretical and ecological potential in 2100 the alternative uses lead to an available

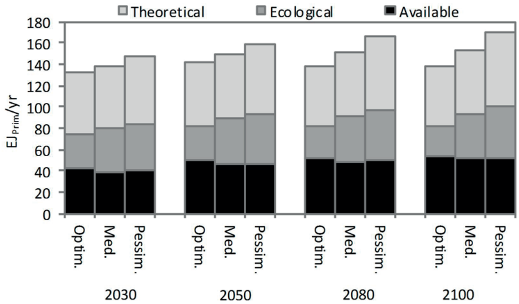

Figure 2.2. Projections of theoretical, ecological and available potential. Agricultural, forestry and process residues for all reference scenarios.

potential lower than the *Optimistic* and *Medium* cases. It is worth noting that traditional biomass in 2008 was estimated to be approximately 40 EJ/yr globally, thus all the scenarios assume significant progress towards energy access (Chum et al., 2011).

By 2100 Asia accounts for most of the available potential, increasing from approximately 30% today to over 40% in 2100. This dominance is largely due to intensive production of rice in the south and oilcrops (soybean and palm oil) in the southeast. Asia has large agricultural areas and the residue productivty is the highest of the world by 2050. North America accounts for 35% of the available potential today, driven my maize production, but this decreases to 26% by 2100. By 2100 Eastern Europe and Russia account for about 10% (from temperate cereals and forestry), while Europe, Africa, the Middle East, Oceania and Latin America account for <10% each. Residue production in these regions is relatively low due to the production of crops with low RPR/RSR (Europe and Oceania), very low crop yields (Africa and Middle East), or high diversion of residues due to livestock feed and traditional fuel uses (Latin America, Africa and Middle East). Detailed numerical results for all scenarios and regions are available in Table 2.7 in the Appendix.

Figure 2.4 shows global maps of the (a) theoretical and (b) ecological potentials, as well as the supply costs (c). Figure 2.5 shows the supply curve of available residues (costs per grid cell sorted in ascending order). In both 2050 and 2100 and for all reference scenarios, over 90% of the potential is available at costs lower than 10 $\$_{2005}$/GJ$_{Prim}$. Over 60% is available at 5 $\$_{2005}$/GJ$_{Prim}$. About 25 EJ$_{Prim}$/yr are available at less than 3\$/GJ$_{Prim}$. The cheapest available residues are supplied from Asia which enjoys high residue productivity leading to low harvest and transport costs. The large potential at 2 $\$_{2005}$/GJ$_{Prim}$ are the available process residues. Regional supply curves are available in Table 2.9 in the Appendix.

On aggregate, the most important cost components for agricultural residues are transport costs (approximately 40% of total cost) followed by harvest costs (20-30%). For forestry, transport costs are the most important, accounting for 50-60% of the

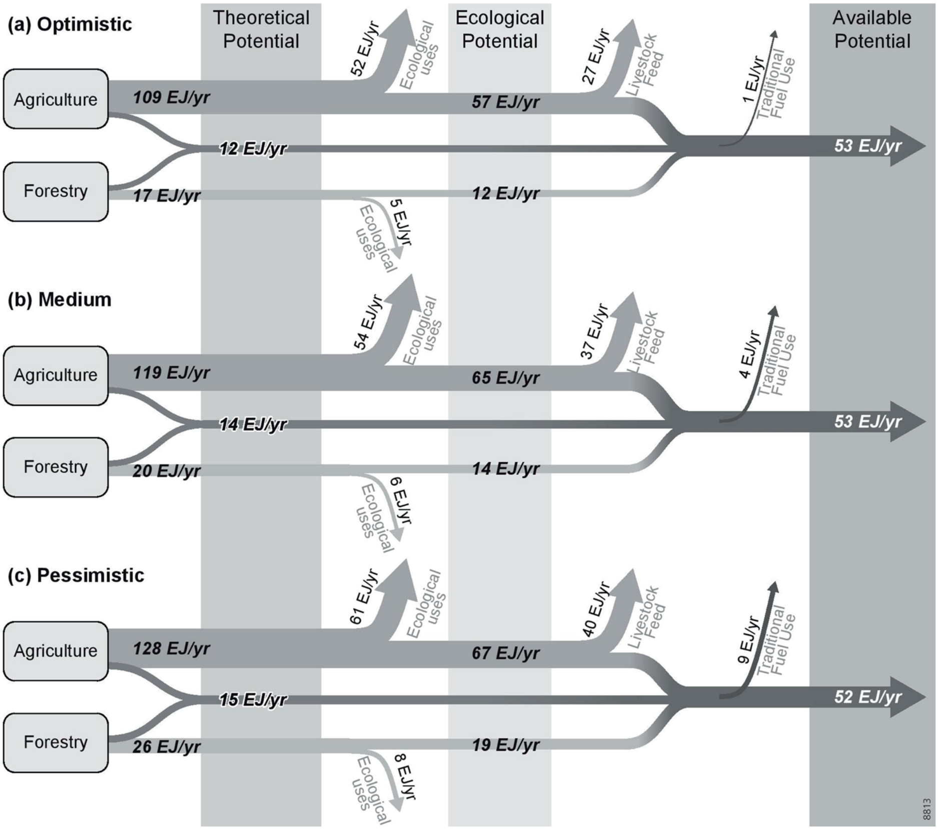

Figure 2.3. Flows and potentials of residues for the (a) *Optimistic*, (b) *Medium* and (c) *Pessimistic* reference scenarios in 2100. Definitions of flows same as in Figure 2.1. Results for 2050 shown in Table 2.8 in the Appendix.

total cost, followed by chipping and forwarding costs. Overall, Figure 2.5 shows that the projected supply curves do not vary much across the scenarios, largely since the available potential is very similar. Supply costs increase with increasing transport distance and decreasing residue productivity. Overall the *optimistic* (and to a lesser extent the medium) scenario has the flattest supply curve due to its high residue productivity and smaller transport distances. Costs decrease between 2050 and 2100 due to improvement in residue productivity for the available potential in all scenarios.

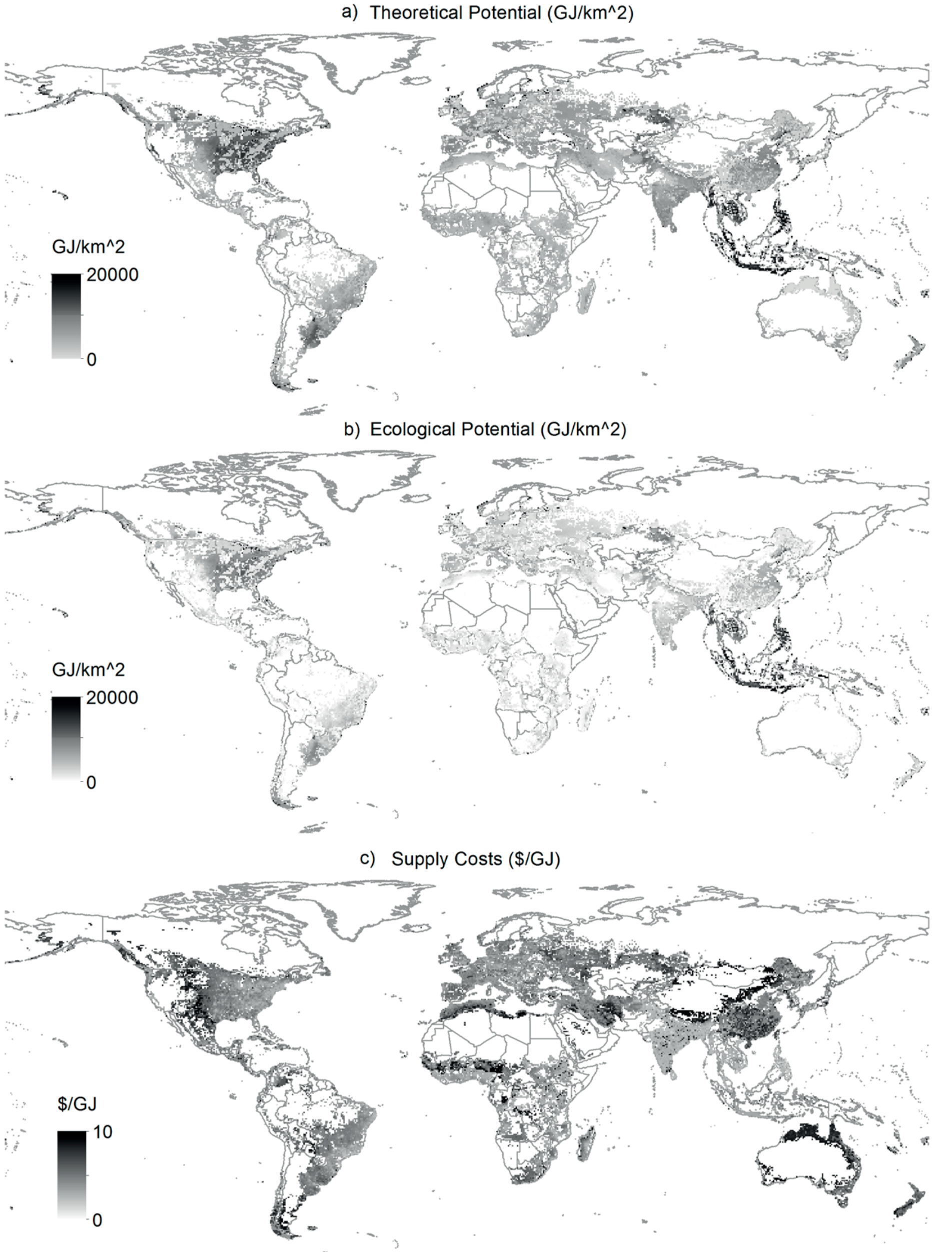

Figure 2.4. Maps of (a) Theoretical Potential, (b) Ecological Potential and (c) Supply costs in 2100 for the *Medium* scenario.

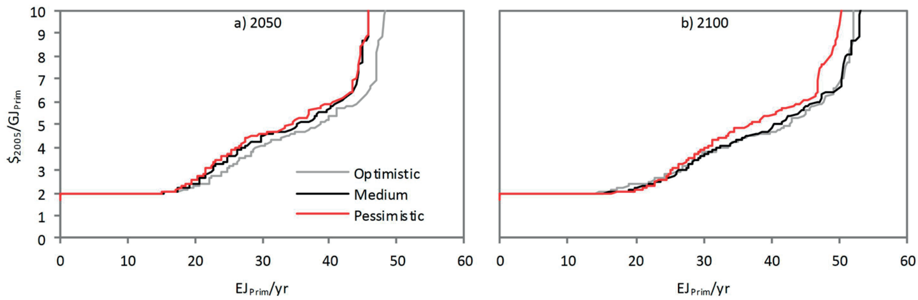

Figure 2.5. Global supply curves for available residues in (a) 2050 and (b) 2100 for all reference scenarios. Only displaying available potential at <10 $\$_{2005}/GJ_{Prim}$.

2.3.2. Sensitivity scenarios

In the results so far, the variation across scenarios imply that several changes are made at the same time. The sensitivity scenarios assume the demand of agricultural and forestry products of the *Medium* scenario while adopting production intensities and competing uses of the *Optimistic* (intensive) and *Pessimistic* (extensive) cases. Figure 2.6 shows how the potentials change under these conditions. For the intensive case, as crop yields increase, RPR decreases and thus the overall increase in theoretical potential is minor. The converse is true for the extensive case where even though RPR may be higher (since overall yields are lower), the theoretical potential is slightly lower. Ecological use is proportional to land use. Thus the intensive case, which has an overall lower land use, has a slightly higher ecological potential. By far the most important difference between the scenarios, as with the baselines, is the competing uses. The extensive scenario which also has inefficient livestock and household energy use parameters has a significantly reduced available potential due to the diversion of residues for alternative uses.

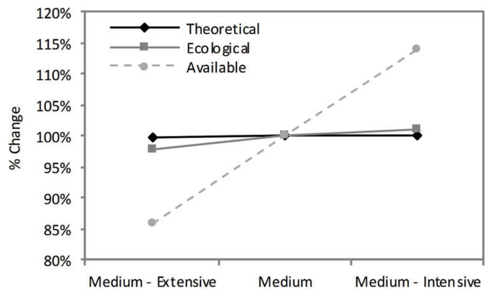

Figure 2.6. Changes in the theoretical, ecological and available potentials for the sensitivity scenarios in 2100.

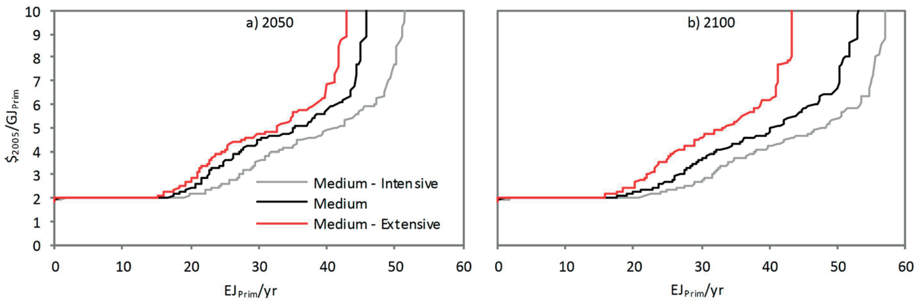

Figure 2.7. Global supply curves for available residues in (a) 2050 and (b) 2100 for the *Medium* and sensitivity scenarios. Only displaying available potential at <10 $\$_{2005}/GJ_{Prim}$.

Differences in the agriculture and forestry intensity parameters and competing uses significantly affect the supply curves, as shown in Figure 2.7. Increasing differences in the competing uses lead to the widening divergence of supply curves throughout the projection period. For the extensive case, the costs increase rapidly due increases in transport and harvest costs as the marginal supply is increasingly spread out over larger areas.

2.4. Discussion

Residue generation rates and supply costs for different crops and forest types vary widely. Since this study focusses on long-term global potential, assumptions consistent with the IMAGE model approach have been made. While we link agricultural residue generation to crop yields for a number of major crop groups, in reality this factor may vary amongst different crops in each group, and local conditions (topography, soil type, climate, etc.). Forest residue production in this study has been varied across forest biomes and management types due to different characteristics of tree species and management processes. Scarce data availability as well as high spatial variability means that residue productivity factors cannot be easily determined across these dimensions. Despite these limitations, this study still successfully highlights trends of residue availability and costs under different scenarios and provides insights on the key elements which limit the available potential.

Maintenance of soil organic carbon (SOC) is widely cited as an important ecological service provided by residues, however the feedbacks and mechanisms involved are unclear (Mann et al., 2002; Lal, 2005). Loss of SOC is hard to evaluate due to high spatial variability of carbon stocks and inability to detect small changes in annual levels. A number of studies which include field trials highlight that SOC levels are dependent on erosion and management as opposed to just residue cover (Reicosky et al., 2002; Lemke et al., 2010; USDE, 2011; Glithero et al., 2013; Liska et al., 2014).

This led to the assumption adopted in this study that erosion control is the limiting factor, and the assumptions concerning the requirement of residues in order to avoid dangerous erosion used in this study are conservative (Papendick & Moldenhauer, 1995; P. Gallagher et al., 2003). Interestingly, the study of Johnson *et al.* (2006) shows that at residue retention rates lower than those used in this study (250t/km^2), SOC levels may in fact increase under a number of management conditions. An improved approach could adopt the revised universal soil loss equation (RULSE) and the wind erosion equation (WEQ), which take into account soil characteristics and factors for topography and cropping management (Skidmore, 1988; USDA, 1997). Applying these methods which account for the importance of local conditions requires considerable data, especially for a global long-term study, and thus a generalised approach had to be adopted.

Literature points to a number of management improvements, such as no-till, cropping-rotation and improved forest management, which can limit erosion, SOC loss and costs. (Junginger et al., 2005; USDE, 2011; Batidzirai et al., 2016). This study was limited to specific agricultural and forestry practices based on IMAGE, however it is important to note that the above measures can contribute to increasing the ecological potential of residues. Further understanding is required on how management and residue removal affect SOC and nutrient levels as well as feedbacks on crop yields. This would allow for an improved assessment of residue availability and their environmental and climate feedbacks.

In this study, competing uses of residues for livestock feed and traditional fuel use are considered out of bounds for modern bioenergy. Furthermore it is assumed that residues are a by-product and not a function in producers' decision making. Presumably, if farmers are offered a price for residues, there may be feedbacks on the factors affecting residue availability. Potential feedbacks include changes towards livestock practices which require fewer residues (Kretschmer et al., 2012). However, it is still unclear how producers and supply chains may be affected by increased commodification of residues. Further research is needed to investigate the effect of these feedbacks on the available potential and how sensitive farmers and households may be affected.

Figure 2.8 shows how our results (*Medium* case) compare with other studies that explicitly report the global potential for agricultural and/or forestry residues. Most studies follow a standard methodology: a residue fraction is assigned to the production of agricultural and forestry products. Next, they use an *availability* or *recoverability* fraction which accounts for – usually poorly defined – ecological, technical and economic uses. Yamamoto *et al.* (2001) use a global land and energy use model (GLUE) to determine biomass potentials. The results differ with ours because of different population projections (Yamamoto reaching 11.5 billion compared to 9 billion here) and additional residue sources (black liquor, paper scrap, animal dung, kitchen

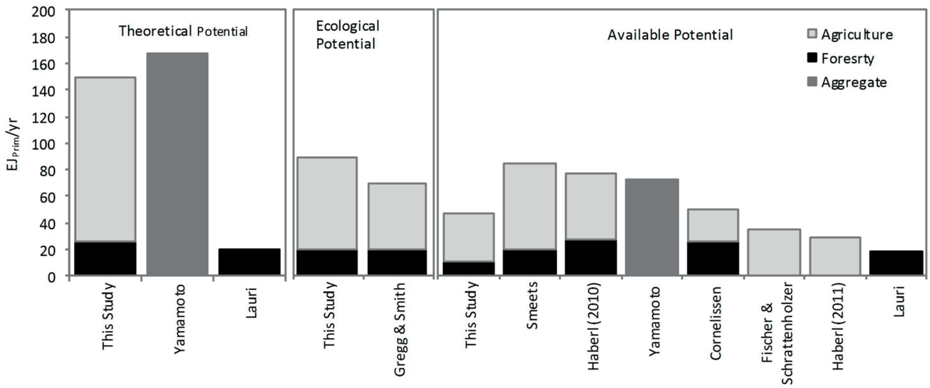

Figure 2.8. Comparison of this study (*Medium* scenario) with the results of other global studies for 2050. Where appropriate, theoretical, ecological and available potential shown. References: (Yamamoto et al., 2001; Fischer & Schrattenholzer, 2001; Lal, 2005; Smeets et al., 2007a; Gregg & Smith, 2010; Haberl et al., 2010; Haberl et al., 2011; Cornelissen et al., 2012; Lauri et al., 2014).

refuse and human faeces). The population projection of Yamamoto is similar to our *Pessimistic* scenario, which also results in a similar theoretical potential, however our available potential is significantly lower. Lauri *et al.* (2014) use an economic equilibrium model focusing on the availability of woody bioenergy from harvest losses (50% availability). Fischer and Schrattenholzer (2001) use a global land-use model to project regional crop production. Residue productivity depends on the yields of five crop categories and an arbitrary availability fraction. The studies of Smeets *et al.* (2007a), Haberl *et al.* (2010) and Cornelissen *et al.* (2012) attach residue generation and availability rates (harvest, process and waste streams) to forecasts for agriculture and forestry production. Differences with this study include the inclusion of potential waste streams as well as varying requirements for livestock feed. As mentioned, the above studies limit the residue potential by assigning an availability/recoverability factor of approximately 50%, partly representing technical limits to agricultural residue collection. Due to the long-term and exploratory nature of this study, such technical limits are not considered. However, it is worth noting that the ecological potential never surpasses 60% of the theoretical potential thus such technical limits are satisfied nonetheless.

For forestry, to the best of our knowledge there is no clear consensus on the minimum amount of organic material required to remain on site to maintain ecosystem services. Most estimates (15-50% or approx. 1000 t/km^2) are based on expert opinions and highlight the importance of local conditions (Graham et al., 1994; Herrick et al., 2009; Evans et al., 2013; Thiffault et al., 2015). The results of this study imply a 70% ecological potential on aggregate, which is assumed recoverable. Recent literature for Canada has shown that residue recoverability rates range from 4% to 89% with a mean of 52% (Thiffault et al., 2015). Nordic countries enjoy higher recovery rates with trials indicating 72% of residues as recoverable (Routa et al., 2013). Recovery rates depend on logging operations as well as the size, spacing and uniformity of tree species. It is important to point out that most studies only account for harvest residues, while this study also includes residue generation throughout the growth cycle (i.e. thinning and pruning). Thus, our *final harvest* ecological potentials (and recoverability rates) are significantly smaller than the 70% value of the total recoverable potential.

The methodology presented here is similar to the study of Gregg and Smith (2010) who determine the use of residues from (agriculture and forestry) using the MiniCam model. They use projections of crop yields and volume production together with constant crop specific “residue ratio” and “residue retention” parameters. According to their study, an increase in yields has twofold impact on residue supply: Increased residue production and increased ecological potential since more residues can be removed without an increase in erosion rates. Our study agrees with this and further highlights that decreases in RPR as crop yields increase mean that the rate of residue production increase is lower than that of crop yields. Gregg and Smith (2010) assume that residue supply curves follow a logistic function and 100% of residues are available at 6$\$_{2005}$/$GJ_{Prim}$. In our study, where cost components are determined based on biophysical conditions, approximately 80% are available at 6$\$_{2005}$/$GJ_{Prim}$.

In contrast to the above studies, this chapter develops and applies a methodology which projects theoretical, ecological and available residue potentials by assessing specific mass flows. The method is used to make projections for a number of scenarios in a consistent manner within a biophysical integrated assessment model. The key insights and results can be summarised as follows:

The method offers a step forward in assessing the availability of residues for modern energy purposes. Residue generation and supply costs depend on both volume and intensity of production while the unavailable portion of residues is assessed explicitly. This method accounts for these in a spatially explicit manner within an integrated assessment model and thus consistently deals with interrelated agriculture, forestry, livestock and energy systems. Thus the availability of residues can be assessed consistently across scenarios. This is an improvement on existing global assessments which lack spatial variation, do not explicitly account for how changes in agricultural and forestry intensity as well as broader developments may affect the availability, and do not account for spatially specific determinants of costs.

The current theoretical potential is estimated to be 116 EJ_{Prim}/yr, and is projected to increase to 140-170 EJ_{Prim}/yr by 2100, depending on the scenario. Available potential increases from 33 EJ_{Prim}/yr to over 50 EJ_{Prim}/yr and does not vary much between reference scenarios. The increase is driven by growth in the demand of agricultural products, with forestry playing a smaller role. The reference scenarios show that increases in crop yields also lead to increases residue productivity, albeit at a lower rate. The theoretical potential is reduced to 80-100 EJ_{Prim}/yr after erosion control is accounted for. Competing uses for livestock feed and, to a lesser extent, fuel use in poor households further reduces the available potential to approximately 50 EJ_{Prim}/yr for all scenarios. North America and Asia account for more than 65% of the available potential primarily due to maize production in the former, rice and oil crop production in the latter and favourable conditions concerning competing uses.

Approximately 70% of the available potential is available at a cost below 5 $\$_{2005}$/ GJ_{Prim}. This increases to more than 90% at 10 $\$_{2005}/GJ_{Prim}$. Over 20% of the potential are process residues which are assumed available at a low cost (2 $\$_{2005}/GJ_{Prim}$). For non-process residues, costs are primarily affected by collection costs (driven by residue productivity and labour costs) and transport distance. Consequently, increases in residue productivity may reduce supply costs. As shown in the sensitivity scenario, all else being equal, extensive production has the highest costs due to low residue productivity and increased transport costs.

There are differences between intensive and extensive production systems, however, the availability of this resource is most sensitive to developments of livestock feed and fuel use in poor households. Intensification leads to increased residue productivity, although at a lower rate due to changes in RPRs. For extensive production, additional to having a lower theoretical potential, the residues are spread over a larger area resulting in increases in collection and transport costs and a higher diversion of the theoretical potential in order to avoid erosion. Given the trade-offs between production methods and ecological constraints, the effect on crop production of different management types which may allow further residue removal (i.e. no-till) and the feedbacks of residue removal should be further investigated. By far the most important determinants of residue availability are the alternative uses of this resource as feed for livestock or fuel for poor households. Further research should focus on how commodification of this resource may increase the portion of available residues and how this may affect groups who depend on residues for certain services.

Acknowledgments

We would like the thank Jonathan Doelman, Jelle van Minnen and Liesbeth de Waal from the IMAGE team for their support and Misha Valk, Lucy Buck and Rosemarye van Dijk for their valuable M.Sc. research on which this study is based.

2.5. Appendix

In implementing the scenarios, the development of the global agricultural system is calculated with the agro-economic model MAGNET (Woltjer et al., 2014), coupled to IMAGE. In both models, agricultural management intensity is described in aggregated parameters, the so-called management factor for crops (relating actual to potential yields), and as feed and production efficiency parameters for livestock (see Stehfest *et al.* (2014) for more detail). Trends in crop yields and the intensity of livestock systems is based on a relation between intensification in FAO projections (Alexandratos & Bruinsma, 2012) and GDP trends, with the *Medium* scenario following FAO projections.

Table 2.6 Relative changes of key indicators for all reference scenarios (2010=100). IMAGE provides projections of the volume demand and production intensity of the agricultural and forestry sectors. Aggregate residue productivity (GJ_{Prim}/km^2) for the theoretical and available potentials determined from present methodology.

	Reference Scenario	**2010**	**2030**	**2050**	**2080**	**2100**
				Inputs from IMAGE		
Demand for agricultural and forestry products	*Optimistic*	100	129	150	156	160
	Medium	100	134	155	166	174
	Pessimistic	100	145	169	186	199
Intensity of production (agriculture and forestry)	*Optimistic*	100	144	179	204	222
	Medium	100	143	169	192	219
	Pessimistic	100	142	161	178	196
				Results		
Residue productivity for the theoretical potential	*Optimistic*	100	110	116	116	117
	Medium	100	112	119	120	120
	Pessimistic	100	107	110	112	113
Residue productivity for the available potential	*Optimistic*	100	115	127	128	130
	Medium	100	120	133	137	139
	Pessimistic	100	116	121	125	128

Table 2.7 Theoretical, ecological and available potential of residues (EJ_{Prim}/yr). All reference scenarios, per world region for 2050 and 2100. Process residues included.

Year	Scenario	Potential	North America	Central and South America	Europe and Turkey	Eastern Europe and Russia	Africa and Middle East	Asia	Oceania	World Total
2050	Optimistic	Theoretical	23	15	12	12	22	56	2	142
		Ecological	16	8	7	7	8	36	1	83
		Available	13	3	4	6	4	20	0	49
	Medium	Theoretical	25	16	14	13	21	58	2	150
		Ecological	17	9	8	8	7	38	1	89
		Available	14	2	4	6	2	17	0	47
	Pessimistic	Theoretical	27	17	15	15	23	61	3	160
		Ecological	18	9	9	10	7	39	1	93
		Available	14	2	5	8	1	15	1	47
2100	Optimistic	Theoretical	21	16	11	9	26	53	2	138
		Ecological	15	9	7	6	10	34	1	81
		Available	13	3	4	5	6	22	1	53
	Medium	Theoretical	24	18	14	11	25	58	2	153
		Ecological	17	11	9	7	10	39	1	93
		Available	14	3	5	6	3	22	1	53
	Pessimistic	Theoretical	26	18	15	14	28	66	3	170
		Ecological	18	10	9	8	9	44	1	101
		Available	15	2	5	7	2	19	1	52

Table 2.8. Global residue potentials (EJ_{Prim}/yr) for all reference scenarios for 2050 and 2100. Terminology is the same as Figure 2.1. Table may contain rounding errors.

	Optimistic		Medium		Pessimistic	
	2050	2100	2050	2100	2050	2100
A. Agricultural Theoretical Potential	111	109	114	119	117	128
B. Forestry Theoretical Potential	18	17	22	20	28	26
Ecological Uses						
Agriculture	54	52	54	54	58	61
Forestry	5	5	6	6	8	8
C. Agricultural Ecological Potential	57	57	60	65	59	67
D. Forestry Ecological Potential	13	12	15	14	20	19
E. Process Residues	13	12	14	14	14	15
Alternative Uses						
Livestock Feed (only agricultural)	29	27	33	37	35	40
Traditional fuel	5	1	9	4	12	9
F. Total Available Potential	49	53	47	53	47	52

Table 2.9. Cumulative available residues (EJ_{Prim}/yr) for increasing supply cost. Per region for all reference scenarios for 2050 and 2100.

Year	Cost ($\$_{2005}$/ GJ_{Prim})	Region: North America	Central and South America	Europe and Turkey	Eastern Europe and Russia	Africa and Middle East	Asia	Oceania
		Optimistic Scenario						
2050	4	3.1	1.5	2.0	1.0	2.1	16.8	0.1
	8	11.5	2.0	3.1	5.0	3.0	18.4	0.3
	12	11.5	2.3	3.6	5.0	3.0	19.5	0.3
	16	11.5	2.3	4.0	5.0	3.0	20.1	0.3
	20	11.5	2.3	4.0	5.4	3.0	20.1	0.3
2100	4	5.2	1.7	1.5	0.8	1.4	15.7	0.1
	8	12.3	2.7	2.3	4.2	5.2	19.5	0.4
	12	12.3	3.4	2.3	4.2	5.2	19.5	0.4
	16	12.3	3.4	2.3	4.5	5.8	20.5	0.4
	20	12.6	3.4	2.3	4.5	5.8	20.5	0.4
		Medium Scenario						
2050	4	3.4	1.6	2.2	1.7	1.6	14.6	0.2
	8	12.3	1.6	4.1	6.1	2.0	17.0	0.4
	12	12.3	2.0	4.1	6.1	2.0	17.0	0.4
	16	12.3	2.0	4.1	6.1	2.0	17.0	0.4
	20	12.3	2.0	4.1	6.1	2.0	17.0	0.4
2100	4	4.7	1.9	1.7	1.3	1.5	16.7	0.2
	8	12.6	2.3	4.6	5.0	2.2	19.0	0.5
	12	12.6	2.3	4.6	5.0	2.2	20.0	0.5
	16	12.6	3.2	4.6	5.0	2.7	20.7	0.5
	20	12.6	3.7	4.6	5.2	2.7	20.7	0.5
		Pessimistic Scenario						
2050	4	3.4	1.6	2.7	2.2	1.2	13.9	0.2
	8	12.8	1.9	3.8	6.6	1.2	14.1	0.8
	12	13.3	1.9	3.8	6.6	1.2	15.8	0.8
	16	13.3	1.9	3.8	6.6	1.2	15.8	0.8
	20	13.3	1.9	4.3	6.6	1.2	15.8	0.8
2100	4	3.4	1.8	2.8	3.0	1.6	16.9	0.2
	8	14.1	2.2	3.0	6.5	1.7	18.0	0.8
	12	14.5	2.2	3.0	6.5	1.7	18.0	0.8
	16	14.5	2.3	3.0	6.5	1.7	18.0	0.8
	20	14.9	2.7	3.0	6.5	1.7	18.0	0.8

3

Greenhouse gas emission-curves for advanced biofuel supply chains

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Abstract

Most climate change mitigation scenarios rely on a large-scale contribution of biomass, including (advanced) biofuels. However, biofuel production could be associated with substantial land-use change emissions, influencing the effectiveness of biofuel-based strategies for meeting emission mitigation goals. Previous studies show a wide range of land-use emissions, often neglecting the influence of spatial heterogeneity. Here we introduce a spatially-explicit method to assess advanced biofuel supply and associated emission factors and payback periods, and present the results as so-called emission-supply curves. We show that the potential of biofuels from dedicated crops for a greenhouse gas payback period of less than 20 years is 11-31 EJ_{Sec}/yr for different crops and conversion routes, increasing to 18-76 EJ_{Sec}/yr in land-use scenarios with lower agricultural land demand. The method presented here allows for coherent greenhouse gas accounting with respect to biomass use in an integrated assessment context.

3.1. Introduction

Meeting the greenhouse gas emission (GHG) reduction targets currently discussed for international climate policy will require a complete de-carbonisation of the energy system (Collins et al., 2013; Clarke et al., 2014). Mitigation scenarios are often used to explore how this can be achieved. Bioenergy plays a key role in many of these scenarios, used mostly as a fuel in the transport sector or as feedstock for power production (possibly in combination with carbon-capture-and-storage) (Wise et al., 2009; IEA, 2014; Kriegler et al., 2014; Rose et al., 2014). Policymakers have, in fact, already put policies in place to promote the use of bioenergy through blending targets and support schemes for fuels (Sorda et al., 2010). However, questions have been raised about the possible impacts of large-scale bioenergy production on food production and protection of biodiversity, while the effectiveness in reducing GHGs has also been challenged (Kartha et al., 2006; Royal Society, 2008; E. Gallagher, 2008; Searchinger et al., 2008). Emissions from bioenergy production (with the exception of residues) are partly associated with land-use change, which lead to changes of both above and below ground carbon stocks (Leemans et al., 1996). These emissions include both *instantaneous* emissions during land conversion, but also *gradual* emissions (or sequestration) as a result of long-term changes in carbon stocks (Haberl et al., 2012). In addition, there are further emissions associated with fertiliser and non-renewable energy use in the production of the bioenergy.

The emissions associated with bioenergy production can be expressed in terms of the ratio of total GHG emissions to bioenergy production, called the *emission factor* (EF). The GHG *payback period* (PBP_{GHG}) metric is also commonly used (Gibbs et al., 2008; Fargione et al., 2008; Lamers & Junginger, 2013b; Elshout et al., 2015) and is defined as the number of years bioenergy has to be used before GHG savings from displacing fossil fuels outweigh the emissions from biofuel production (incl. LUC). Studies have looked into LUC emissions of bioenergy supply by, for example, investigating specific supply chains or using equilibrium models in order to project LUC emissions (Laborde, 2011; Wicke et al., 2012; Lamers & Junginger, 2013b; Plevin et al., 2015). These studies have led to a large range of possible outcomes with reported biofuel PBP_{GHG} ranging from 1 to >1000yrs and EFs ranging from negative to >100kgCO_2-eq/GJ_{Sec} (Chum et al., 2011). These discrepancies are caused by the large uncertainty and variation of key parameters such as crop yields, carbon stocks and assumed land-use changes. Some studies have highlighted this variation by using spatially explicit crop yields and land-based carbon stocks in order to estimate GHG effects of different biofuels (Gibbs et al., 2008; Elshout et al., 2015; Albanito et al., 2016). However, the potential supply of advanced biofuels and associated GHG emissions, as well as understanding what land-use changes would provide the best possibilities for advanced (2nd generation) biofuels as a climate mitigation strategy are still important knowledge gaps.

Here we develop and apply a consistent and spatially explicit method for determining EF and PBP_{GHG} for bioenergy. Since in the short run biofuels often form a major component of bioenergy use in climate mitigation scenarios, we concentrate our calculations on three production chains for advanced biofuels, namely, lignocellulosic (grass or wood based) methanol and sugarcane ethanol. Following, we highlight the potential supply of these advanced biofuels at different EF and PBP_{GHG} levels, hereafter called *emission-supply* curves. We include both these indicators as each highlights different aspects of the mitigation potential: The EF offers a direct comparison with other energy carriers while PBP_{GHG} provides insight into the temporal dimension of emission savings with respect to fossil fuels. The results are presented using a novel method of biofuel supply curves as a function of increasing EF or PBP_{GHG}. These curves show how associated GHG emissions change as biofuels are increasingly produced on (from a GHG perspective) unfavourable lands. This allows us to go beyond existing research by providing insight into both the spatial aspect of GHG characteristics and the potential supply of advanced biofuels for given emission constraints. We also highlight which land-use changes offer the most favourable results. Furthermore, we investigate how uncertainties on future crop yields, technological development, demand for agricultural land and climate change may affect the results.

We use the IMAGE modelling framework (Stehfest et al., 2014), which makes use of the fully coupled vegetation, crop and hydrological model LPJmL. This framework projects the biofuel potentials and long-term carbon fluxes of land-use change while also accounting for other dynamic factors such as the land-use scenario and the impact of climate change and CO_2-fertilisation. The main results assume a median land-use scenario in combination with a 2.6 W/m^2 radiative forcing climate scenario (van Vuuren et al., 2014; van Vuuren et al., 2016). In our results, we assume that lands used for agricultural production according to the land-use scenario are unavailable for biofuel production. This assumption is based on the fact that using food production areas would often lead to indirect land-use emissions in the grid cells we already directly evaluate. The disadvantage is that we do not account for possible yield increases in food production induced by bioenergy production. The spatially explicit (0.5°×0.5° cell resolution) EF and PBP_{GHG} values are determined and account for emissions covering the complete supply chain, including instantaneous and gradual changes in carbon stocks due to LUC, nitrogen from fertiliser application, and non-renewable energy use in biofuel production.

3.2. Tracking carbon fluxes

Many studies and established methods for assessing biofuel GHG emissions significantly simplify the emissions from LUC (IPCC, 2006; Hoefnagels et al., 2010; Cherubini, 2010). They tend to ignore or simplify the carbon fluxes due to re-balancing of soil carbon stocks as well as *baseline* changes that would have happened if the natural vegetation had remained, such as forest growth or decay (Haberl et al., 2012; Wise et al., 2015). In this study, the biophysical process model (IMAGE-LPJmL) is used to project the development of above and below-ground carbon stocks for two cases till 2100: (i) a counterfactual assuming the presence of natural vegetation (NV), and (ii) presence of energy crops for biofuel production (BP).

All emissions are calculated as the difference in the carbon stocks between NV and BP. Instantaneous emissions due to land clearing take place in 2015, while in all following years (2016-2100) differences in carbon stocks between the two cases form the gradual increase (or decrease) of cumulative emissions. Spatially-explicit EFs are calculated by determining the ratio of cumulative biofuel production to cumulative emissions over the projected period (2015-2100). Consequently, if cumulative production of biofuel increases faster than the cumulative emissions, the EF will decrease over time. Thus, the selection of the time horizon is very important. In the IPCC GHG accounting guidelines, for instance, a 20 year time horizon is used (IPCC, 2006). As explained above, our calculations for the emission factors are based on a 85 year time horizon (called EF_{85}) in order to better capture the long-term effects of bioenergy production and land-based carbon stocks. The PBP_{GHG} is derived by tracking the projections of EFs until they fall (and remain) below that of gasoline, i.e. the time required to achieve $EF_{Biofuel} < EF_{Gasoline}$ is the PBP_{GHG}, as beyond that point the cumulative emissions from biofuel production are less than the emission savings from gasoline replacement.

3.3. Spatial variation

The maps of the instantaneous and gradual components of the EF_{85} are shown in Figure 3.1. The emissions from non-energy use in biomass production and biofuel conversion are not explicitly shown (but are included in the Total) and vary between 0-20 $kgCO_2/GJ_{Sec}$ depending on the production chain. The large spread in EF_{85} is due to spatial variations in initial and projected carbon stocks and the differences in biofuel productivity. In most cases the gradual emissions are a significant fraction of the EF_{85}, highlighting the importance of accounting for emissions from changes in carbon stocks in both NV and BP cases. Gradual emissions are most important in boreal forests and grasslands where they contribute up to 50% of final EF_{85}.

The mean EF_{85} and 10^{th}-90^{th} percentile range are 76 (37-138), 67 (42-94) and 61 (35-85) $kgCO_2\text{-eq}/GJ_{Sec}$ for grass methanol, wood methanol and sugarcane ethanol, respectively. For comparison, the emission factor of gasoline is 87 kg $CO_2\text{-eq}/GJ_{Sec}$. Focusing on specific biomes, the lowest mean EF_{85} is observed on grasslands at 48 (22-74), 57 (20-87) and 38 (26-50) $kgCO_2\text{-eq}/GJ_{Sec}$ for grass methanol, wood methanol and sugarcane respectively. Furthermore, due to their high productivity, emission factors below 60 (29-92) $kgCO_2\text{-eq}/GJ_{Sec}$ can also be achieved on agricultural lands projected to be abandoned in this land scenario.

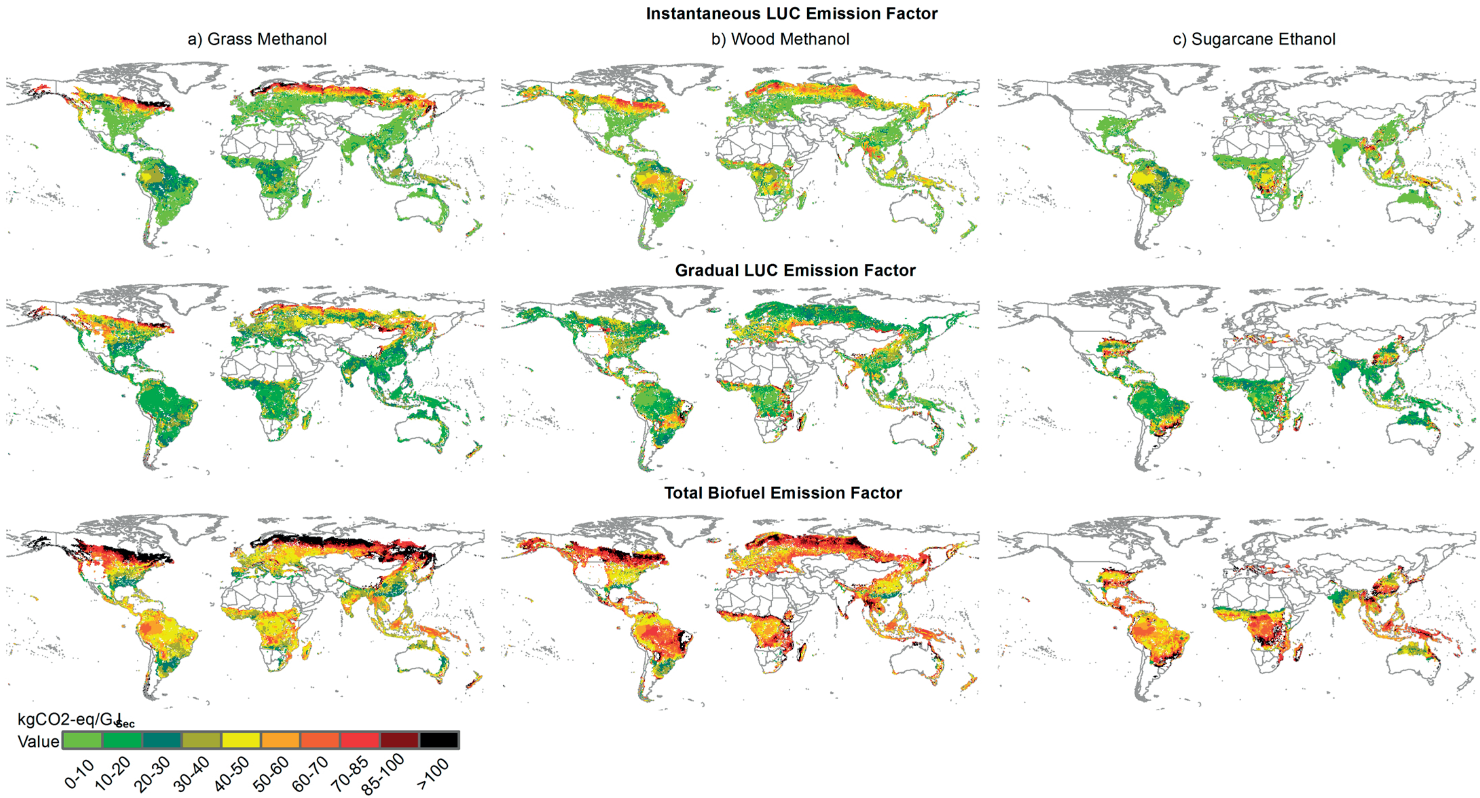

Figure 3.1. Maps of EF_{85} and its components. (a) grass methanol, (b) wood methanol, (c) sugarcane ethanol. Top: Instantaneous emissions due to land clearing. Middle: Gradual emissions (2016-2100). Bottom: Total EF_{85}. Note: Conversion emissions (≈0-20 $kgCO_2$-eq/GJ_{Sec}) are not shown and but included in the Total EF_{85}. These maps include current and projected agricultural lands which are excluded in all other figures and quoted results.

3.4. Biofuel supply and corresponding emissions

The very high ranges of EF_{85} indicate that it is not useful to calculate mean EFs for biofuels, even when stated for specific biomes. Thus it makes little sense to apply average emission factors when assessing the climate effects of biofuel production. Furthermore, while the spatial results highlight the high variance of EF_{85} of biofuels, they do not provide information on the biofuel potential at any given emission rate. Knowledge of EFs alone are not sufficient to assess the possible role different biofuels may play in climate mitigation. Expressing biofuel potentials in terms of their emission supply curves can help with better understanding this. In Figure 3.2, such biofuel emission supply curves are presented showing the potential of each biofuel with increasing EF_{85} and PBP_{GHG}. These curves are related to each other since the PBP_{GHG} curve shows the biofuel potential at which EF_{85} has fallen below that of gasoline (87 $kgCO_2/GJ_{Sec}$), and the time required for that to happen. The curves have been disag-

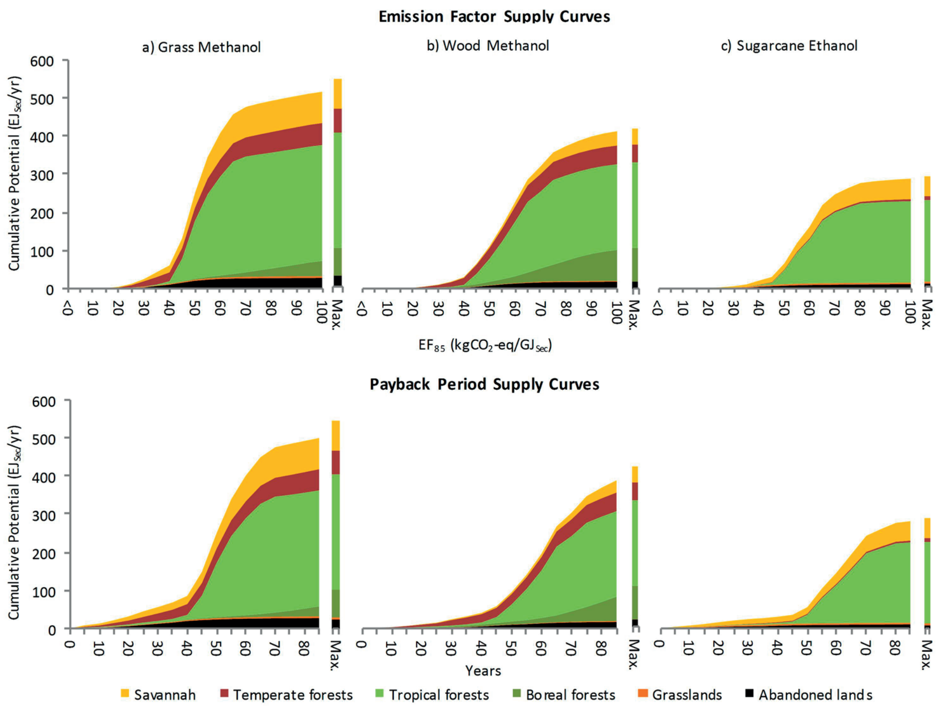

Figure 3.2. Supply curves of (a) Grass methanol, (b) Wood methanol and (c) Sugarcane ethanol, disaggregated for different initial land cover types. Top: EF_{85} supply curve. Bottom: PBP_{GHG} supply curve (in both cases averaged over the 2016-2100 period). Last column of each panel shows the maximum potential for each biofuel. Curves account for projected changes in crop yield. Note: The supply curves of different chains cannot be added. Numerical results of global supply curves are available in Table 3.2 and Table 3.3 in Appendix II.

gregated across five biomes: natural grasslands, savannah, as well as boreal, tropical and temperate forests as defined in the IMAGE-LPJmL model. Furthermore, lands that are projected to be abandoned in the selected land scenario are also included.

Globally, there is –for all feedstocks– a very large potential (in excess of 300 EJ_{Sec}/yr) for biofuels, with a large contribution from tropical biomes. Approximately 90% of the ultimate potential, however, is only available at an EF_{85} above 40 $kgCO_2$-eq/GJ_{Sec} or a PBP_{GHG} greater than 30 years. The supply curves highlight that even though natural grasslands have the lowest mean EF_{85}, the potential in these lands is less than 4 EJ_{Sec}/yr due to the limited area of this biome and the relatively low yields. When comparing the three supply chains, it can be seen that even though sugarcane ethanol has better EF_{85} on aggregate, it has a lower potential at any given emission level than grass and wood based biofuels. This is because the latter two can be grown in more locations than sugarcane.

Using a PBP_{GHG} criterion of less than 20 years, the potential of grass methanol, wood methanol and sugarcane ethanol are 31, 11 and 16 EJ_{Sec}/yr respectively. These numbers increase significantly to 249, 95 and 55 EJ_{Sec}/yr if the PBP_{GHG} is increased to 50 years. For lignocellulosic crops, approximately half of this potential comes from tropical forests while significant volumes (>10%) come from savannah lands, temperate forests and abandoned agricultural lands. For sugarcane crops, whose growth is limited to tropical regions, the importance of savannah lands increases (>30%). For all feedstocks, at higher EF_{85} and PBP_{GHG}, very large increases in biofuel potential come from tropical forests with smaller increases coming from temperate and boreal forests (except for sugarcane) and savannahs.

3.5. Importance and interpretation of uncertainties

Figure 3.3 shows the impact of various uncertainties on the outcomes of the calculations. The sensitivity of the results on technological assumptions indicates that improvement of crop yields and conversion technologies is a requirement for low GHG biofuels as keeping these factors constant at 2015 levels results in significantly reduced potentials. In our method, the assumed exclusion of agricultural lands relates directly to uncertainties in the future development of agricultural demand. The default projection assumes that approximately 300 MHa are abandoned by 2100, while a more optimistic assumption (see Appendix I) on land availability (resulting from a low global population and changes in dietary choices) shown in Figure 3.3 leads to land availability increasing to 1000 MHa. As abandoned agricultural lands tend to be the most productive, the biofuel potential at low EF_{85}/PBP_{GHG} is boosted in this case. The use of more agriculture area for bioenergy production could also be achieved as a result of increased yields induced by bioenergy demand, something which is

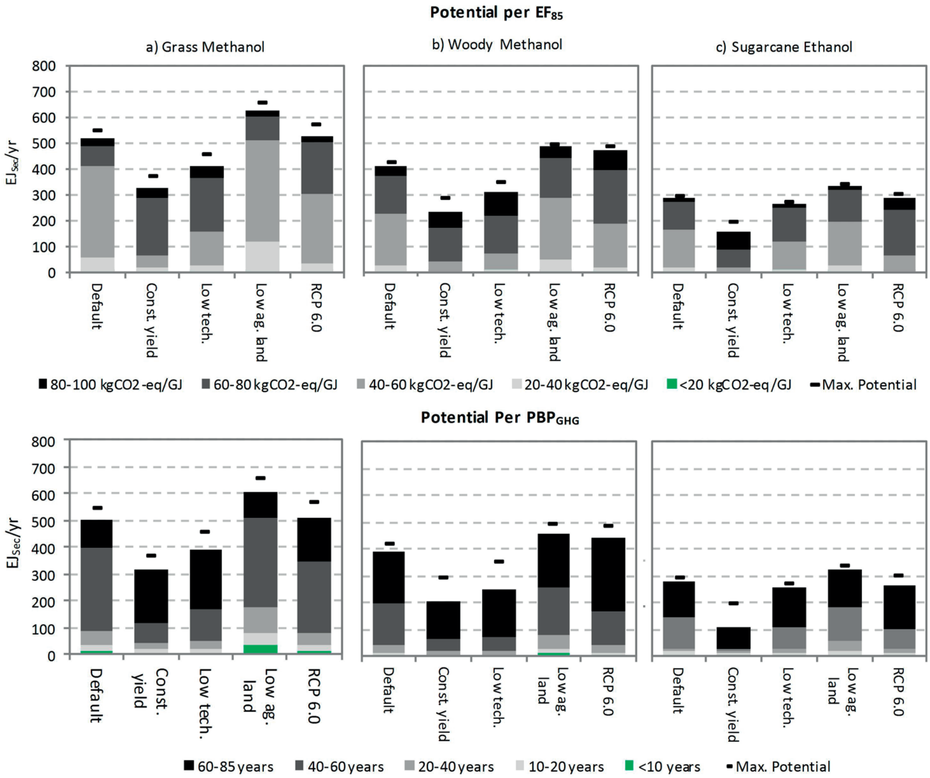

Figure 3.3. Effect of assumptions on potential at different EF_{85} (top) and PBP_{GHG} (bottom) for (a) Grass methanol, (b) Wood methanol and (c) Sugarcane ethanol. Each assumption is tested independently. Const. yield: Yields kept constant at 2015 levels, Low tech.: Use pessimistic projections on biofuel conversion technological development, Low ag. land: Land availability based on a land scenario with increased agricultural abandonment, RCP 6.0: Use climate projections with a radiative forcing in 2100 of 6.0W/m^2. Numerical results and underlying assumptions are available in Appendix I and II.

not specifically investigated here. Assumptions on climate projections also affect the results due to changing crop productivities (in both NV and BP cases). Evaluating the potential for a 6.0 W/m^2 climate projection leads to a slight increase in the overall potential of lignocellulosic crops, driven by increased to CO_2 fertilisation. However, higher carbon stocks in natural vegetation imply that the GHG effect is ambiguous or even adverse in this climate scenario. For sugarcane crops this climate scenario negatively affects the results as yields in tropical regions are projected to suffer.

Other key assumptions influence the interpretation of our results. This study focuses only on biofuels, while other uses of biomass for energy purposes (gasses, heat and electricity) may lead to very different supply curves. While EFs would be broadly similar, the PBP_{GHG} of woody and grass-based biomass could be much lower if converted to electricity while substituting coal generators. Additionally, if biofuel or bio-electricity production is combined with carbon capture and storage, further emission reductions could be achieved (Tavoni & Socolow, 2013). An explicit assumption of our method is that the original natural vegetation cleared prior to biofuel production has its carbon content emitted with no energy production. Determining the energy potential of the original natural vegetation is difficult due to uncertainties in the quality of the original natural vegetation. However, first order estimates (method described in section 3.8.4 in the Appendix) lead to emission factors decreasing by 10-15%.

3.6. Time horizon selection and the relevance for biofuel policies

The selection of a time horizon is a key methodological issue for assessing GHG implications of biofuel production. However, this choice is inherently arbitrary, with the IPCC and EU using 20 years, and the US EPA using 30 years (IPCC, 2006; EC, 2009; EPA, 2010). These time horizons have been justified as they better reflect the lifespan of typical biofuel production facilities and policies, uncertainty of future biofuel production and emissions, and difficulty with valuing future emissions. The results presented above use a longer (85 year) time horizon as this allows for better accounting of the gradual carbon fluxes which form a significant portion of the final emission factor. Our 85 year time-horizon implicitly assumes biofuel production and consumption over that period, in agreement with climate mitigation pathways of integrated assessment models (Kriegler et al., 2014; Rose et al., 2014; Clarke et al., 2014). Furthermore, given that climate change mitigation is a long-term goal, it has been argued that a time horizon of up to 100 years may be appropriate (Fearnside, 2002; ICF, 2009).

Some policies aimed at promoting biofuel use assign specific time horizons, and thus implicitly make judgements on the volume of bioenergy which can be supplied. The European Renewable Energy Directive (RED) 2009/28/EC (EC, 2009) requires that GHG savings of biofuels should be at least 35% until 2016, 50% from 2017 to 2018 and 60% thereafter while annex V of the directive states that biofuel GHG calculations should have a 20 year time horizon. Using the methods developed in this study, we can estimate the biofuel supply –produced only from energy crops, not from residues– in 2020 with a 20 year time horizon (i.e. EF_{20}). When applying the 60% GHG savings target (or a required EF_{20} of 35 kgCO_2-eq/GJ), less than 1 EJ_{Sec}/yr are globally consistent with this target in 2020, increasing marginally by 2050. Using a more optimistic land scenario does not improve this significantly, highlighting that the available locations with such a low EF_{20} are very limited. Instead, if the EF_{85} supply curves were used, the RED conformant biofuel supply would be 8-30 EJ_{Sec}/yr in 2020, increasing to 10-41 EJ_{Sec}/yr in 2050 (Note: This is the supply in those particular years and cannot be derived from Figure 3.2 where biofuel potentials are based on 2016-2100 average).

To put these numbers in context, in 2012 the demand for transport fuels was in the order of 100 EJ_{Sec}/yr and is projected to approach 150 EJ_{Sec}/yr by 2050 (IEA, 2014). Consequently, combining a 60% reduction target and the EF_{20} in the RED severely limits the potential of biofuels produced from energy crops. Furthermore, the results of this study show that GHG effects of biofuels vary hugely across both locations and source of emissions (instantaneous, conversion or gradual). This heterogeneity creates challenges for successful policies as restrictions and guidelines have to be precise in order to be effective.

3.7. Future avenues

By presenting biofuel supply in terms of emission-supply curves, this study aims to provide a clearer understanding of biofuel quantities and their climate implications – making a considerable step forward compared to methods based on mean values. Furthermore, by tracking the long-term changes in carbon stocks due to biofuel production and natural changes, this study highlights both the spatial and temporal aspects of biofuel GHG implications. The concept of emission-supply curves provides a transparent tool to contrast marginal emissions and mitigation potential of biomass use and to explore the impact of different assumptions and uncertainties across models. The use of such curves could help evaluate the trade-off between biofuel supply and afforestation possibilities, which would increase biogenic carbon uptake, and could provide further insights for land-use and climate policy (Humpenöder et al., 2014; Albanito et al., 2016). Finally, it is important to note that besides biofuel production, biomass can reduce emissions from a number of energy and material processes (electricity, heat, and chemicals) and can possibly be combined with carbon capture technologies in order to achieve so-called negative emissions. The method introduced here can be used together with bioenergy mitigation curves of various end uses and conversion technologies in order to better evaluate different biomass use strategies. Overall, these curves can act as a basis for a more constructive discussion of the advantages and disadvantages of different bioenergy uses in terms of their GHG balances.

3.8. Appendix I: Method

3.8.1. Boundary conditions

Greenhouse gas emissions included in this study are CO_2, CH_4 and N_2O from land-use change, biomass production and non-renewable energy use for conversion of biomass to biofuels. The study is conducted on a global scale, however all calculations are done on 30×30 minute raster maps. Consequently, the globe is represented by 66663 grid cells. The calculations are done for grass-methanol, wood-methanol and sugarcane-ethanol separately. Grass crops are assumed to be Miscanthus, and woody crops are Willow and Eucalyptus for temperate and tropical biomes, respectively.

3.8.2. Data from IMAGE

This study uses the IMAGE model to project maps of carbon content (tC/km^2), biomass yields (t/km^2) and Land cover per grid cell (Stehfest et al., 2014). IMAGE uses the Lund-Potsdam-Jena model with Managed Land (LPJmL) for its carbon cycles and biome allocations (Sitch et al., 2003; Gerten et al., 2004; Bondeau et al., 2007).

Land cover

Land cover and land use in IMAGE is described on a spatial grid of 5 or 30 minutes resolution (here 30 min resolution is applied). Historically, spatial distribution of agricultural land use is based on the HYDE database (Klein Goldewijk et al., 2011), and regional trends of land use, yields and production are calibrated to FAO statistics (Alexandratos & Bruinsma, 2012). Future projections of agricultural demand are projected with the agro-economic model MAGNET, coupled to IMAGE (Stehfest et al., 2013), and are spatially allocated based on an empiric suitability algorithm (Stehfest et al., 2014). This study uses land use patterns in 2015, which is derived from the SSP2 scenario as implemented in IMAGE (van Vuuren et al., 2014; IIASA, 2015; van Vuuren et al., 2016), as the full set of statistical data is not yet available for 2015.

Vegetation dynamics and crop yields

LPJmL is a dynamic global vegetation model which simulates vegetation distribution using the concept of multiple plant functional types (PFTs). These are differentiated according to their bioclimatic (temperature requirement), physiological, morphological, and phonological (growing season) attributes, as well competition for resources (light and water). Plant dynamics are computed for each PFT separately, and the composition of PFTs in a grid cell is translated into a number of biome types which for the purposes of this study have been aggregated to: grasslands, boreal forests, temperate forest, tropical forests and savannah. Similar to the concept of PFTs, LPJmL calculates the yields of major crop groups, which are described in more detail for energy crops below (Bondeau et al., 2007).

Biomass yields

Within IMAGE, crop productivity is computed by LPJmL according to a representation of photosynthesis, maintenance and growth respiration (Bondeau et al., 2007). Other yield constraints are added to this potential in order to derive *actual* yields. These include water limited yields and a *management factor* representing management and farmer behaviour such as fertiliser use, improved sowing dates, improved varieties and pest control. Bioenergy PFTs included in this study are woody (willow and eucalyptus for temperate and tropical biomes respectively), grassy (miscanthus) and sugarcane. Yields are calculated on a grid cell level based on the local biophysical and management conditions. IMAGE projections of crop yields on an aggregate global level are shown in Figure 3.4. The yield projections imply annual growth rates of the order of 0.2-0.6%. Observed growth rates for agricultural crops over the period 1961-2010 are 0.7-1.6% (Gerssen-Gondelach et al., 2015).

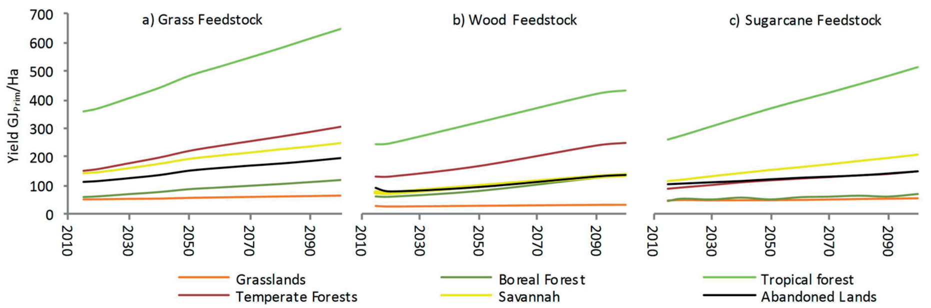

Figure 3.4. IMAGE projections of global crop yields (GJ_{Prim}/Ha) for (a) Grass , (b) Wood, and (c) Sugarcane.

Carbon content

LPJmL provides maps of carbon content per grid cell aggregated according to specific *pools*: Above ground, below ground, soil litter and soil carbon. The model covers carbon-cycle processes and tracks carbon fluxes between the atmosphere and biosphere. These are based on uptake and release from plants (photosynthesis, respiration), transfer of plant carbon to the soil (shedding, turnover, mortality) and mineralisation of soil organic carbon (heterotrophic respiration). Carbon stocks are in line with IPCC estimates while the dynamics of the carbon cycle, which drive the results of this study, have been shown to be well within the range of other dynamic global vegetation models (Friend et al., 2014).

Emissions from fertiliser application

We assign a N_2O emission factor from fertiliser application based on existing literature (Hamelinck & Hoogwijk, 2007; Smeets et al., 2009). This emission factor may vary regionally and is determined using a statistical model that uses spatial data on climate and soil. Typical values are shown in Table 3.1.

Climate

The selection of baseline climate determines climate change impacts on crop yields, vegetation dynamics, and CO_2 fertilisation rates. The climate system responds dynamically to developments in energy and land use, and ideally climate feedbacks at given biomass supply levels would be included. In this study, the default results assume a representative concentration pathway (RCP) of 2.6 W/m^2 (RCP 2.6), with a sensitivity conducted for RCP 6.0 (Collins et al., 2013). These climate projections span likely outcomes of mitigation and baseline scenarios respectively.

Biofuel conversion technologies

Biofuels included are methanol from grassy and woody feedstocks as well as ethanol from sugarcane, since these biofuels have been shown to be the most competitive with gasoline (Gerssen-Gondelach et al., 2014). The data for the conversion processes are shown in Table 3.1. Grass and wood based methanol are both grouped under "Lignocellulosic methanol" processes. All parameters are taken from recent literature reviews (Hamelinck & Hoogwijk, 2007; Macedo et al., 2008; Smeets et al., 2009; Gerssen-Gondelach et al., 2014).

Table 3.1. Technical parameters for the biofuel production routes. Pessimistic values used in scenario analysis shown in brackets.

	Year	Ligocellulosic Methanol	Sugar Ethanol
		%	
Conversion Efficiency[6]	*Present*	60 (48)	45.4[7]
	2050	60 (48)	54.9 (45.4)
	2100	60 (48)	65.3 (45.4)
		GJ_{Elec}/GJ_{Sec}	
Electricity Demand[8]	*Present*	0.07	-
	2050	0.002	-
		$kgCO_2$-eq/GJ_{Prim}	
N_2O Emissions		0.295	0.91[9]
		GJ_{Fossil}/GJ_{Prim}	
Non-renewable energy use in cultivation		0.3	0.1

6 Based on Higher Heating Value. Future improvements largely based on increased capacity.

7 Studies for autonomous distilleries producing only ethanol shows current ethanol yields at 86.3 $l_{ehtanol}/t_{cane,wet}$ and future yields at 91 $l_{ethanol}/t_{cane,wet}$. We convert to energy terms assuming a sugarcane HHV of 4.5 $MJ/_{kgcane,wet}$.

8 Electricity and heat demand is allocated to production of fuel, i.e. no allocation to possible by-products and based on values from Hamelinck *et al.* (2007).

9 Values for South America are 4.4 $kgCO_2$-eq/GJ_{Prim}.

Especially for second generation biofuels the conversion efficiencies and energy requirements are based on modelling results, and grass and wood feedstocks are grouped under "lignocellulosic" processes. Thus the particularities of grass and wood based processes are not captured and uncertainty exists concerning the attainable technical parameters. Similar uncertainties exist concerning the non-renewable energy use during crop cultivation, which is based on LCA studies conducted in Brazil, Nicaragua, Ireland and the Netherlands (Hamelinck & Hoogwijk, 2007). Unfortunately, limited data makes it impossible to properly assess regional variations. These uncertainties are important as the sensitivity analysis shows that the results change significantly depending on these parameters.

Gasoline emission factor

In order to calculate the PBP_{GHG} of biofuels, the EF of gasoline is required. This is based on the $CO_{2,}$ CH_4 and N_2O emission factors of gasoline together with 100 year global warming potentials (IPCC, 2006; Myhre et al., 2013). Upstream emissions are taken from Ecoinvent database (v3), and are set as 17.213 $kgCO_2$-eq/$GJ_{Gasoline}$ (Weidema et al., 2013). The final emission factor is calculated to be 86.756 $kgCO_{2\text{-}eq}/GJ_{Gasoline}$.

3.8.3. Calculations

IMAGE projections are used in order to determine the changes in carbon and nitrogen balances, per grid cell, due to biofuel production. These projections are not intended to be realistic scenarios, but rather stylised model results in order to make the EF and PBP calculations possible. The methodology applied here takes into account future developments of carbon and nitrogen stocks. Thus re-balancing of soil carbon in the *bioenergy production* case (BP) and projections of above and below ground carbon stocks in the *natural vegetation* case (NV) are accounted for. Emissions due to biofuel production are calculated by comparing the carbon and nitrogen balances between two cases:

Natural Vegetation (NV): A counterfactual with no biofuel production. Land cover is either *natural vegetation* or *agricultural land*. This case acts as the benchmark to which biofuel production is compared. As mentioned above, the land use scenario is based on the SSP2 baseline. For agricultural lands projected to be abandoned in this scenario, it is assumed that they return to their natural vegetation (regrowth).

Bioenergy Production (BP): Starting in 2015, natural vegetation or abandoned agricultural lands are replaced by biofuel crops. The only constraint applied is that yields should be more than negligible. Above ground carbon content of biofuel crops is ignored since it is assumed that all produced biofuels are combusted, and below ground carbon rebalances according to the new conditions. Climate feedbacks from land clearing are ignored, but climate follows the RCP2.6 or RCP6.0 trajectory described above (i.e. climate is assumed identical to the NV case). The BP case is repeated for the three primary crop types included in this study: grass, wood and sugarcane.

Land-use change emissions

As mentioned above, the method accounts for both initial LUC emissions and gradual changes in carbon stocks throughout the projection period. These are called *Type1* and *Type2* emissions respectively. Figure 3.5 shows the difference in total carbon stocks between the NV and BP cases for six of the implied land-use changes. Panel (a) shows that in the NV case, carbon stocks of abandoned agricultural land increase due to the assumed re-growth in natural vegetation. For the BP case, above ground biomass is assumed to be zero since the crops are assumed to be constantly harvested and combusted as biofuels. Furthermore, all natural lands show a prolonged loss in soil carbon stocks after initial clearing (compounded annual depreciation rate of approximately 1% per year over the entire period).

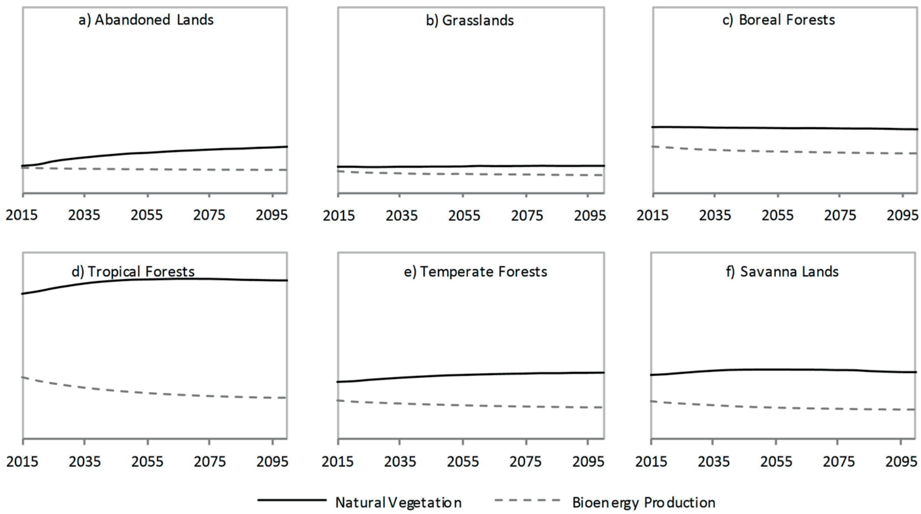

Figure 3.5. Indication of how total carbon stock change through the projection period, per biome (a-f) for the NV and BP cases. All graphs at the same scale. Note, these figures indicative based on aggregate carbon stocks per biome for grassy feedstock production. There is significant variation across gird cells and for different bioenergy crops.

Type1 emissions are the initial (2015) loss in carbon stock due to LUC, and are calculated according to equation (3.1). Note that this includes only carbon embedded in *living* biomass, i.e. above and below ground biomass.

$$Type1_i = \left[CC_{NV,i,AGB} + CC_{NV,i,BGB}\right]_{2015} \tag{3.1}$$

Where:
Type1: Instantaneous (2015) emissions due to land clearing ($kgCO_{2\text{-}eq}$)
CC: Grid cell carbon content ($kgCO_{2\text{-}eq}$)
NV: Natural Vegetation case
BP: Bioenergy Production case
i: Grid cell identifier
AGB and BGB: Above and below ground biomass respectively
Changes in carbon content of grid cells over the projection period (Type2) are calculated according to equation (3.2). The first and second elements of equation (3.2) determine cumulative changes in the NV and BP cases respectively.

$$Type2_i = \left(CC_{NV,i,t_{horizon}} - CC_{NV,i,t_{2016}}\right) - \left(CC_{BP,i,t_{horizon}} - CC_{BP,i,t_{2016}}\right) \quad \textbf{(3.2)}$$

Where the carbon contents include all carbon pools: above ground, below ground, soil litter and soil carbon. The carbon fluxes are calculated over the entire time horizon ($t_{horizon}$), which is 2035 and 2100 for the short (EF_{20}) and long-term (EF_{85}) emission factors respectively.

Other emissions

Besides those of land-use change, this study also includes emissions from nitrogen application, on-farm operations and conversion of biomass to biofuels. These are expressed in $kgCO_2$-eq/GJ_{Sec}, (i.e. per unit biofuel production) according to equation (3.3). The data used it shown in Table 3.1.

$$OtherEmis_i = \left(\frac{N2O_i + NREU_i}{ConvEff}\right) + \left(ConvElec \times CCElec_i\right) \quad \textbf{(3.3)}$$

Where:
OtherEmis: Non land-use change emissions for biofuel production ($kgCO_2$-eq/ GJ_{Sec})
N2O: N_2O emissions from crop production due to fertiliser and manure application ($kgCO_2$-eq/GJ_{Prim})
NREU: Emissions from non-renewable energy use for biomass production ($kgCO_2$-eq/GJ_{Prim})
ConvEff: Conversion efficiency of biomass (GJ_{Sec}/GJ_{Prim})
ConvElec: Electricity requirement for biomass conversion ($GJ_{Electricity}$/GJ_{Sec})
CCElec: Emission factor of electricity, regional ($kgCO_2$-eq/$GJ_{Electricity}$)

Emission Factor and Payback Period

By dividing the LUC emissions by the cumulative biofuel production of the corresponding time horizon, we get the EF due to land-use change. The final emission factor is calculated using equation (3.4).

$$EF_i = \frac{Type1_i + Type2_i}{\sum_{2015}^{t_{horizon}} BiofuelPotential_i} + OtherEmis_i \tag{3.4}$$

The supply curves are plotted for annual bioenergy potential, thus the (cumulative) potential calculated in the denominator of equation (3.4) is divided by the time horizon in order to get the average annual bioenergy production.

Since the method described above takes into account cumulative emissions and biofuel production, once the $EF_{Biofuel}$ of each grid cell falls below $EF_{Gasoline}$, the total emissions mitigated due to gasoline replacement start becoming greater than the emission due to biofuel production. Thus the time required to reach EF parity is the PBP (see Figure 3.6). The time horizon is up to 2100, thus the maximum calculable PBP is 85 years. The algorithm checks for possible increases in $EF_{Biofuel}$ (up to 2100) due to regrowth of natural vegetation in the *NV* case. We implicitly assume that biofuels and gasoline are homogenous and exactly substitutable.

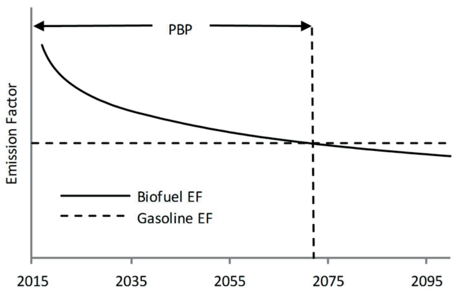

Figure 3.6. Method used to determine PBP_{GHG}.

3.8.4. Sensitivity scenarios

The method was repeated in order to test the results across a number of uncertainties. These are done in order to highlight specific aspects of the methodology as well as the importance of certain assumptions. All scenarios are run independently of each other in order to isolate for specific effects.

- *Const. yield:* Bioenergy crop yields are assumed constant from the base year (2015) onwards, thus the projected improvements in yields shown in Figure 3.4 are ignored.
- *Low tech.*: This case uses pessimistic figures for the conversion efficiencies of biofuel production technologies, as shown in Table 3.1.
- *Low ag. land:* Land use scenario based on the SSP1 baseline(van Vuuren et al., 2014; IIASA, 2015). It assumes reduced agricultural demand and increased in-

tensification. This leads to increased availability of abandoned lands for biofuel production.

- *6.0 Climate:* Use climate projections (and thus different CO_2 fertilisation rates) assuming climate change consistent with an RCP 6.0 projection (Moss et al., 2010; Collins et al., 2013).

The method presented here assumes that the original natural vegetation releases all of its carbon content without any energy production, as other studies do as well. An extra calculation is done in order to estimate the effect on the EF_{85} of using the original natural vegetation for biofuel production. The same calculation described by equation (3.4) above is used, except that an extra volume of biofuel is added to the cumulative biofuel potential. This extra biofuel production is calculated by equation (3.5):

$$ExtraBiofuel_i = \frac{\left[CC_{NV,i,AGB}\right]_{2015}}{CC_{Wood}} \times HHV \times ConvEff \qquad \textbf{(3.5)}$$

Where:

$CC_{NV,i,AGB}$: Is the above ground carbon content per grid cell (excluding leaves) (tC)
HHV: The higher heating value of wood (19.5 $GJ_{Biomass}/t_{Wood}$) (ECN, 2012)
CC_{wood}: Carbon content of wood (0.5 tC/t_{Wood}) (Thomas & Martin, 2012)

3.9. Appendix II: Supplementary results

Table 3.2. Emission factor supply curves for EF_{20} and EF_{85} for grass methanol, wood methanol and sugarcane ethanol. Also shown are the mean and the standard deviation of the EF. Note: biofuel potentials are averaged over 2016-2100. The supply curves of different chains cannot be added.

Emission Factor ($kgCO_{2-eq}/GJ_{Sec}$)	**Cumulative biofuel potential (EJ_{Sec}/yr) assuming a 20-year horizon**			**Cumulative biofuel potential (EJ_{Sec}/yr) assuming a 85-year horizon**		
	Grass Methanol	Wood Methanol	Sugarcane Ethanol	Grass Methanol	Wood Methanol	Sugarcane Ethanol
<0	0	0	0	0	0	0
<5	0	0	0	0	0	0
<10	0	0	0	0	0	0
<15	0	0	0	1	0	0
<20	0	0	0	4	2	1
<25	0	0	0	12	5	3
<30	0	0	0	24	10	6
<35	1	0	0	42	18	10
<40	2	0	1	60	29	20
<45	3	1	1	132	65	30
<50	4	1	2	249	110	66
<55	5	2	3	345	164	119
<60	7	3	4	408	226	162
<65	10	4	5	456	286	218
<70	13	5	7	476	320	247
<75	18	7	9	485	357	263
<80	23	9	12	492	373	276
<85	29	10	15	499	387	281
<90	34	12	17	505	399	283
<95	40	14	19	511	407	286
<100	44	17	21	516	412	288
>100	550	423	295	550	423	295
Mean EF	328	312	257	76	67	61
Standard deviation	225	135	162	45	21	29

Table 3.3. Greenhouse gas payback period supply curves for grass methanol, wood methanol and sugarcane ethanol. The supply curves of different chains cannot be added.

GHG Payback Period (years)	**Cumulative biofuel potential (EJ_{Sec}/yr)**		
	Grass Methanol	Wood Methanol	Sugarcane Ethanol
<1	0	0	0
<5	8	2	4
<10	13	3	7
<15	21	6	11
<20	31	11	16
<25	45	15	21
<30	56	24	24
<35	68	32	27
<40	85	41	31
<45	148	58	36
<50	249	95	56
<55	338	141	105
<60	401	196	147
<65	449	267	195
<70	475	303	243
<75	484	347	261
<80	491	369	277
<85	499	388	281
>85	550	423	295

Table 3.4. 85-year emission factor supply curves for primary biomass from grass, wood and sugarcane feedstocks. The supply curves of different chains cannot be added.

Emission Factor (kg$CO_{2\text{-}eq}$/GJ_{Prim})	**Cumulative biomass potential (EJ_{Prim}/yr)**		
	Grass Methanol	Wood Methanol	Sugarcane Ethanol
<0	0	0	0
<5	3	1	3
<10	19	9	15
<15	57	25	41
<20	115	57	90
<25	403	177	329
<30	647	347	527
<35	779	492	573
<40	807	587	587
<45	827	635	594
<50	843	668	598
<55	859	686	601
<60	870	697	602
<65	879	701	603
<70	886	704	604
<75	893	705	604
<80	898	705	605
<85	902	706	605
<90	905	706	605
<95	907	706	606
<100	909	706	606
>100	917	706	607

Table 3.5. Emission factor supply curves for (EF_{85}) grass methanol, wood methanol and sugarcane ethanol, for all sensitivity scenarios. Note: biofuel potentials are averaged over 2016-2100. The supply curves of different chains cannot be added.

	Grass Methanol				**Wood Methanol**				**Sugarcane Ethanol**			
	Const. Yields	**Low Tech.**	**High Land.**	**6.0 Climate**	**Const. Yields**	**Low Tech.**	**High Land.**	**6.0 Climate**	**Const. Yields**	**Low Tech.**	**High Land.**	**6.0 Climate**
Emission Factor ($kgCO_{2\text{-}eq}/GJ_{Sec}$)	Cumulative biofuel potential (EJ_{Sec}/yr) assuming a 85-year horizon											
<0	0	0	0	0	0	0	0	0	0	0	0	0
<5	0	0	0	0	0	0	0	0	0	0	0	0
<10	0	0	0	0	0	0	0	0	0	0	0	0
<15	0	0	1	1	0	0	0	0	0	0	0	0
<20	1	1	5	4	0	0	2	1	0	1	1	1
<25	3	3	19	12	1	1	9	3	1	2	3	4
<30	5	7	45	26	2	3	18	8	2	5	6	8
<35	11	15	80	44	3	6	32	25	3	9	12	13
<40	16	23	120	85	7	10	48	72	6	15	24	24
<45	24	36	212	194	10	15	95	145	9	23	44	51
<50	34	48	342	337	14	22	153	227	12	33	88	116
<55	42	81	445	431	21	41	217	278	15	72	147	185
<60	67	161	513	455	40	71	285	324	19	115	196	231
<65	123	234	563	467	69	106	350	353	25	154	255	259
<70	185	292	584	475	104	140	389	373	43	206	285	271
<75	239	335	593	482	141	182	427	394	69	234	303	278
<80	285	366	600	488	170	222	445	410	90	249	319	282
<85	311	391	607	495	203	251	460	423	109	258	324	286
<90	319	398	613	502	218	274	472	434	137	262	328	289
<95	323	404	620	510	227	297	481	443	147	265	332	291
<100	326	409	624	516	235	308	487	451	155	267	334	292
>100	374	459	659	570	292	353	499	474	195	276	343	300

4

Energy demand and emissions of the non-energy sector

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Abstract

The demand of fossil fuels for non-energy purposes, such as the production of bulk chemicals, is poorly understood. In this study we analyse data on non-energy demand and disaggregate it across key services or products. We construct a simulation model for the main products of non-energy use and project the global demand of primary fuels used as feedstocks and the resulting carbon emissions until 2100. The model is then applied to estimate the potential emission reductions by increased use of biomass, more ambitious climate policy and advanced post-consumer waste management. We project that the global gross demand of feedstocks more than triples from 30 EJ_{Prim}/yr in 2010 to over 100 EJ_{Prim}/yr in 2100, mainly due to increased demand of high value chemicals such as ethylene. Carbon emissions increase disproportionately (from 160 MtC/yr in 2010 to over 650 MtC/yr in 2100) due to greater use of coal, especially in ammonia and methanol production. If biomass is used, it can supply a large portion of the required primary energy and reduce carbon emissions by up to 20% in 2100 compared to the reference development. Climate policy can further reduce emissions by over 30%. Post-consumer waste options such as recycling or incineration with energy recovery do not necessarily reduce energy demand or carbon emissions.

4.1. Introduction

In the analysis of mitigation strategies, most attention is currently paid to the anthropogenic carbon dioxide (CO_2) emissions associated with the use of fossil fuels for energy purposes. Still, around 10% of the total primary fossil energy supplied worldwide is used for non-energy purposes. Non-energy use of energy carriers is defined as "*fuels that are used as raw materials […] and are not consumed as a fuel or transformed into another fuel*" (IEA, 2016). Main uses include (i) feedstock for the production of chemicals such as ethylene, methanol, ammonia in the chemical and petrochemical sector and (ii) coke oven and oil refinery products such as waxes, lubricants, aromatics and bitumen in the energy transformation sector. The share of non-energy use relative to total energy requirements has been increasing (IEA, 2012) and, on a global scale, non-energy is responsible for up to 7% of global CO_2 emissions and 15% of industrial emissions (Olivier & Peters, 2005; IEA, 2010b).

By far, the main energy carrier used for non-energy purposes is oil (75% globally, >90% in the OECD countries). However, also coal and gas are increasingly used (IEA, 2010c; IEA, 2012). An option to reduce the fossil fuel use for non-energy purposes, and the related CO_2 emissions, is fuel switching (including renewable feedstocks). Recent advances in technology have allowed biomass-based routes to substitute production processes starting from fossil fuels via the production of bio-based ethylene, methanol and ammonia next to other widely used compounds as well as novel chemicals that may replace fossil-based chemicals (Dornburg et al., 2008; Ren et al., 2009a; Shen et al., 2010; Chen & Patel, 2011). The Special Report on Renewable Energy Sources of the Intergovernmental Panel on Climate Change (IPCC) highlighted the lack of global studies focusing on the emission reduction potential of biomass for such industrial processes (Chum et al., 2011). Further possibilities to reduce the energy demand and emissions are increased efficiency of material use (Saygin et al., 2011) or recycling of chemicals and energy cascading where embedded energy in non-energy products can be retrieved (Dornburg & Faaij, 2005; Dornburg et al., 2008; IEA, 2009a; Shen et al., 2010).

In order to assess the potential to reduce non-energy emissions, projections are needed of non-energy demand and feedstock use. Unfortunately, most current projections of global non-energy use are based on aggregate and opaque model descriptions (Gielen et al., 2002; IEA, 2009b; IEA, 2014). These studies, therefore, provide little insight in the potential to reduce emissions. Complications in assessing this sector arise due to complex material flows, numerous products and different end products being the raw material for other production processes (Patel et al., 2005; Weiss et al., 2008; Saygin et al., 2011). Difficulties also arise because of ambiguities in non-energy data sets and uncertainties concerning emission accounting.

This study presents a global model (Non-Energy Demand and Emissions model, NEDE) in which the final demand of the non-energy sector is disaggregated over several key products. Feedstock substitution is determined by the associated costs for the final product. The energy and mass flows of representative non-energy processes are calibrated across a consistent global database. The future projections of the non-energy products are driven by exogenous economic, population and fuel price developments. The model is used in order to investigate the emission reduction possibilities of the non-energy sector via substitution (in particular the use of bio-based feedstocks), climate policy and increased material use efficiency (including recycling and incineration with energy recovery of post-consumer waste). The model is designed as part of the IMAGE/TIMER integrated assessment model which provides a description of global environmental change, including the use and production of bioenergy (Hoogwijk et al., 2003; Stehfest et al., 2014).

This chapter is structured as follows. Section 4.2 gives an overview of non-energy use and introduces the data set used to construct the model. Furthermore, a comparison between the data set and the IEA energy balances is provided. Section 4.3 introduces the model outlining the demand functions, processes involved, substitution dynamics as well as the method used to account emissions. Also a description of the scenarios projected with the model is given. Section 4.4 presents the primary non-energy demand and emission projections for the scenarios. Section 4.5 offers a discussion on the model's sensitivities and uncertainties. Section 4.6 summarises the results and draws conclusions.

4.2. Non-energy use

4.2.1. Overview

Primary energy can either be used as a *feedstock* (i.e. converted to a product in which part of it is embodied) or as *process energy* (i.e. consumed in the conversion process). *Net* energy use for non-energy purposes is the primary energy used as a feedstock without the required process energy. *Gross* energy for non-energy purposes is the total (feedstock + process) primary energy used to produce *final products* of the non-energy sector. Throughout this chapter, unless otherwise stated, the term *non-energy use* is synonymous to gross energy use. The products of the non-energy sector are used as materials and therefore the output is mostly quantified in mass terms (tonnes). Since this chapter deals with the integration of non-energy use in an energy model (TIMER) we choose to express the production volumes of final products and the raw material inputs in energy terms, i.e. gigajoule (GJ) primary, final, feedstock or process. Primary energy is converted to final products at a given conversion efficiency

(GJ_{Final}/GJ_{Prim}). The primary energy carriers included in this study are: coal, oil, natural gas, and biomass. Electricity can be used for process energy.

In the model, the final products of non-energy have been aggregated into four distinct classes (products) whose definitions are broad enough to capture the diversity of non-energy use while maintaining a simplified representation[10].

- **Steam cracking**: This process produces the building blocks of the organic petrochemical industry, namely ethylene, propylene, butadiene and aromatics (benzene, toluene and xylene). In this thesis these products are referred to as **High Value Chemicals (HVC)** according to the definition in Ren *et al.* (2006).
- **Ammonia production**: Ammonia is used as the raw material for fertiliser production (90%) or a feedstock for further chemical production (10%) (Ullmann, 2007). Ammonia is produced by the Haber-Bosch process where hydrogen is reacted with nitrogen at high pressure over a catalyst. The hydrogen can be derived from natural gas or oil (via steam reforming), coal or biomass (gasification). Currently, natural gas is used as the main feedstock in most countries with the exception of China, which uses significant amounts of coal (IEA, 2009a).
- **Methanol production**: Methanol is primarily used for the production of various chemicals (e.g. formaldehyde) or it is used directly as a solvent (MI, 2013). Syngas produced from natural gas, petroleum products or coal is reacted with hydrogen over a catalyst to produce methanol (Chauvel & Lefebvre, 1989).
- **Refinery products**: These are the heavier refinery products obtained from the distillation of crude oil and consumed for non-energy purposes. The main products are lubricants, aromatics (BTX - benzene, toluene, xylene) and bitumen.

4.2.2. Historic non-energy use

We have assessed the historic non-energy use for the above products for each of the 26 regions of the IMAGE/TIMER model. Non-energy use of each product is estimated as the multiplication of production volumes and the so-called specific non-energy use[11]. Production capacities of steam cracking and refinery products are available from the Oil and Gas Journal, of ammonia from the US Geological Survey and of methanol from the Methanol Institute (USGS, 1996-2012; OGJ, 1997-2012a; OGJ, 1997-2012b; MI, 1999-2003). Production volumes are subsequently estimated by assuming a capacity utilisa-

[10] Non-energy products, which are not accounted for are soda ash, anodes for aluminium production, carbon black and carbides. They account for a minor part of non-energy use (<5%) (IEA, 2009a).

[11] Specific non-energy useis defined as the factory gate-to-factory gate final energy use required to produce one unit (e.g., one tonne or GJ_{Final}) of chemical. It excludes the energy use of processes outside the chemical production processes such as mining and extraction of fuels. For steam cracking, it excludes backflows to refineries.

tion rate of 90% (Weiss et al., 2008). As mentioned above we use the *gross* non-energy which includes the related process energy used for the production of these products. We choose to do so due to limitations in the IEA data. The IEA questionnaires request from all countries to report their non-energy use based on net definition of non-energy use, but studies have shown that most countries do not report their non-energy use by following these questionnaires (Patel et al., 2005; Weiss et al., 2008). Specific non-energy use and process energy use data originate from the study by Weiss *et al.* (Weiss et al., 2008) and they refer to the global average situation in 2000.

Figure 4.1 shows the energy use for the non-energy sector estimated according to the bottom-up methodology described above (aggregating the contribution by product) for some key regions as well as at a global level. Also shown is the total net non-energy use as reported in IEA energy statistics (IEA, 1971-2005). Globally, the shares of the categories mentioned above were 41%, 25%, 5% and 28% for HVC, ammonia, methanol and refinery products, respectively, in 2007. Western Europe and the USA account

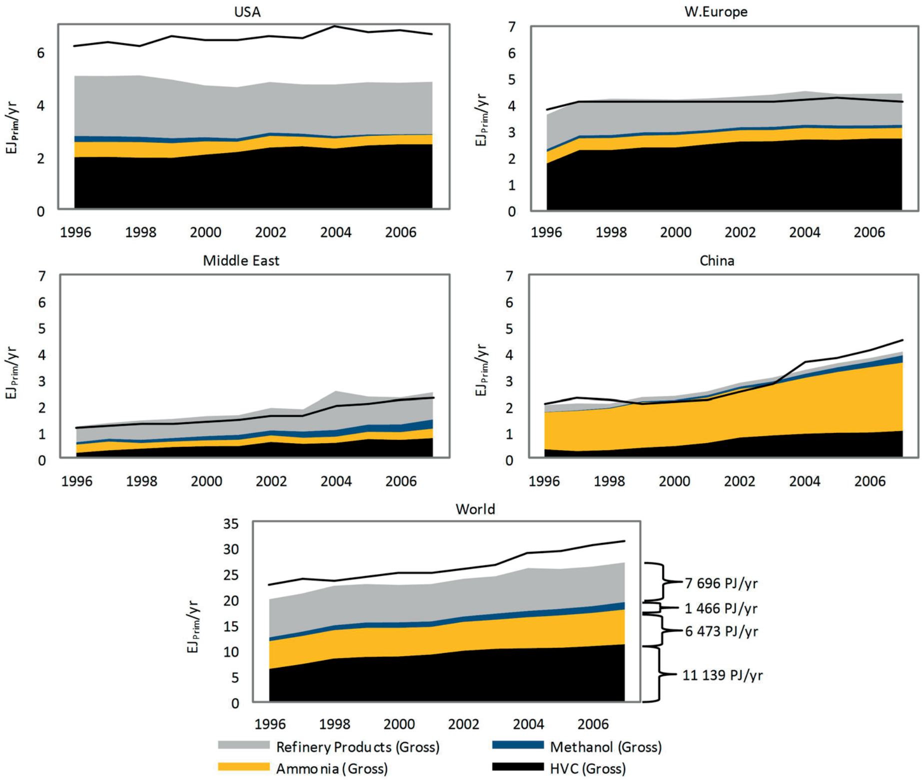

Figure 4.1. Gross consumption of non-energy (EJ_{Prim}/yr) for four key regions (accounting for over half of global capacity) and world total, disaggregated over 4 non-energy products. Also included is the total non-energy use as reported by the IEA.

for almost half of the global non-energy use (primarily for HVC and refinery products). However, their total volume has not increased during the investigated period. In other regions, where growth rates are significant, ammonia and methanol production take a larger share of non-energy use. A discrepancy between the bottom-up data and the IEA non-energy estimates for total non-energy use is clearly visible. Though the two approaches show similar trends, the difference in volume of non-energy use between the two approaches for the 1996-2007 period confirms the earlier findings of Weiss *et al.* (2008) regarding the inconsistencies in 2000.

4.3. Non-Energy Demand and Emissions (NEDE) model

The NEDE model is a global long-term simulation model designed to get insight in trends of primary energy use for non-energy purposes up to the year 2100 and the potential mitigation strategies in this sector. The model describes the non-energy use for the 26 IMAGE/TIMER regions. The long-term focus of the model implies that it needs to aggregate detailed bottom-up data. It does so by linking the non-energy sector's energy demand to the non-energy use products outlined in section 4.2.1 and representative production processes in order to maintain both relevance and functionality. An outline of the model's key steps is shown in Figure 4.2.

4.3.1. Demand functions

In the model, demand of primary energy (GJ_{Prim}) is driven by the demand for each final product (HVC, ammonia, methanol, refinery products) (GJ_{Final}). The regional historic demand outlined in section 4.2.2 was analysed in order to determine the relationship between per capita demand of each product (GJ_{Final}/cap) and economic growth (GDP/cap). Consequently, regional non-energy intensity per product is modelled as a logistic growth relationship between GJ_{Final} demand per capita and GDP per capita according to equation (4.1) (van Vuuren et al., 1999; Groenenberg et al., 2005). The model does not include trade of final products between regions. In the NEDE model, regional historic intensity is used which converges to the global per capita demand for non-energy products by 2050. The regional data and *global* best-fit relationship are shown in Figure 4.3.

$$Intensity_{R,P} = \left(\alpha_P \cdot e^{-\frac{\beta_P}{GDP_R}}\right) \times \min_{1}\left(\gamma_P^{(GDP_R - 20000)}\right) \quad \textbf{(4.1)}$$

Where:
Intensity = GJ_{Final}/cap demand of each non-energy product
GDP = Exogenous projection of per capita GDP ($\$_{2005}$/cap).
α, β, γ = Constants per product

The subscripts *R* and *P* refer to regions and non-energy products respectively. All coefficients and respective regression coefficients are listed in Table 4.1.

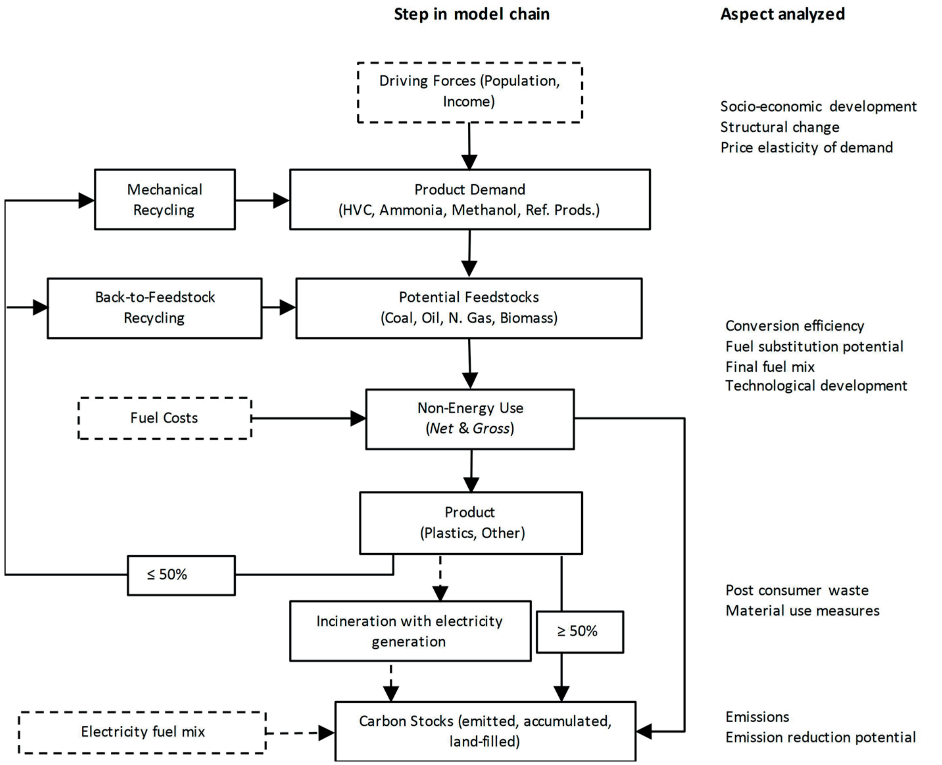

Figure 4.2. Overview of NEDE model. Explicit steps of the model indicated on the left and relevant issues indicated on the right. Dashed boxes show inputs from IMAGE/TIMER and dashed lines show optional calculations (not included as a competing option).

Table 4.1. Coefficients used in calculating intensity of demand of each non-energy product.

	Steam Cracking	Ammonia	Methanol	Refinery Products
α	4.08	1.02	0.48	5.86
β	9457	679	4330	8525
γ	1	1.028	1	0.995
R^2	0.78	0.39	0.20	0.75

We assume that the final demand is also sensitive to increases in energy prices by introducing a price elasticity of demand (PED) (van Vuuren et al., 1999; de Vries et al., 2001). This simulates decreases in demand (either by behavioural changes or increased efficiency measures) with increasing energy prices. Thus, final demand (in GJ_{Final}) is driven by economic growth, population as well as price of energy carriers:

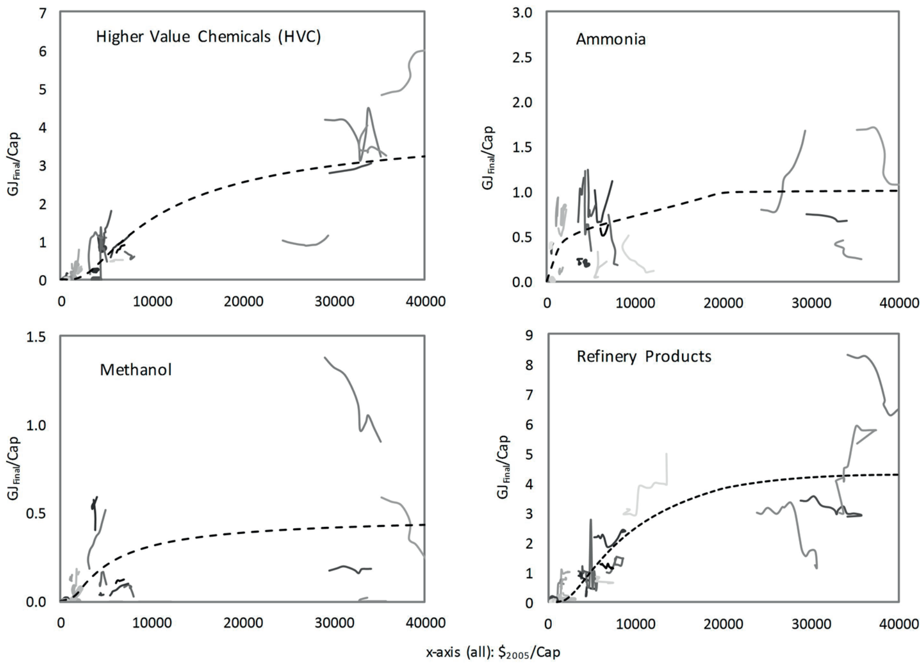

Figure 4.3. Intensity of demand of non-energy products, GJ_{Final}/cap vs. GDP$\$_{2005}$/cap. 1996-2007 IMAGE/TIMER region data (thin lines) and NEDE formulation (dashed line).

$$Final\ Demand_{R,P} = Intensity_{R,P} \times Population_R \times PED_R \quad \textbf{(4.2)}$$

This final demand can be met by a supply (of gross primary energy) of coal, oil, natural gas or biomass. Primary energy demand is calculated from the conversion efficiencies of each feedstock to final products according to representative processes (section 4.3.2) as well as the market shares each process achieves (section 4.3.3).

4.3.2. Processes

High Value Chemicals

Worldwide, the products of steam cracking (i.e. HVC) represent the largest share of the non-energy sector and also offer a substantial potential for emission reduction (Ren & Patel, 2009b). The representation of this product group is therefore relatively detailed in NEDE. Primary fuels are converted to *intermediates* (e.g. naphtha, ethanol), which are in turn converted to HVC. The routes to HVC from primary fuels included in the NEDE model are shown in Figure 4.4. Each step (primary-to-intermediate and intermediate-to-product) has its own conversion efficiency, cost (capital and operation and maintenance (O&M)) and energy requirement based on an analysis of possible petrochemical production processes (Ren et al., 2006; Ren & Patel, 2009b; Gerssen-Gondelach et al., 2014). Figure 4.4 also shows the potential recycling options for post-consumer waste of synthetic organic products as described below.

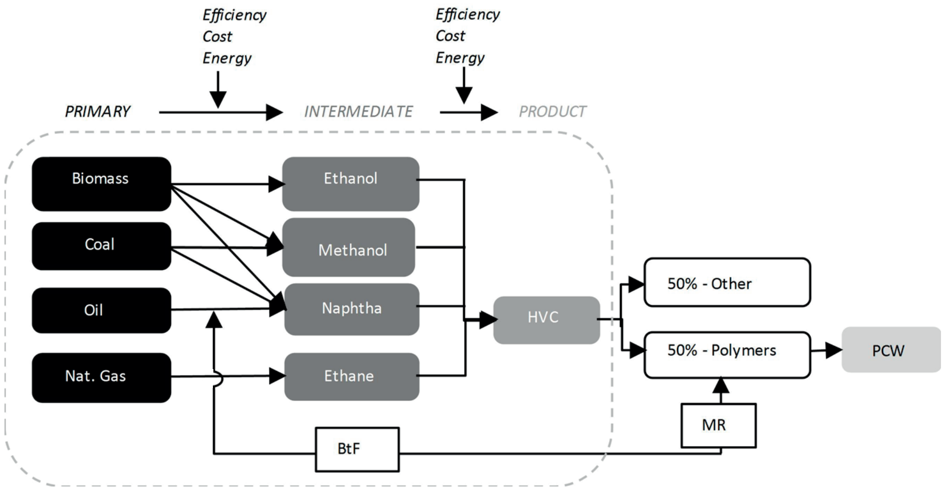

Figure 4.4. Material flows for the production of HVCs. Also shown is the downstream production of post-consumer waste (PCW) and recycling possibilities (described below).

The technical data used for the various potential HVC processes, as well as assumed future improvements, are shown in Table 4.2. Most of the data is taken from Ren *et al.* (Ren et al., 2006; Ren et al., 2009a) while for the production of first and second generation biofuels, data comes from more state of the art databases (Hamelinck & Hoogwijk, 2007; Gerssen-Gondelach et al., 2014). The variable costs due to energy requirement (total of feedstock energy and process energy) depend on the cost projection of the relevant energy carriers. In some cases the production of HVC also includes net co-production of electricity which may act as a source of revenue. All energy costs (or revenues from co-produced electricity) depend on the projections of the price of the relevant energy carrier according the IMAGE/TIMER model.

Ammonia

In ammonia production, natural gas is currently the main feedstock while other possibilities also exist (coal, oil, gas and lignocellulosic biomass). All other potential feedstocks are introduced based on an *energy ratio* compared to natural gas, indicating how much of the primary fuel would be required to replace 1 GJ of natural gas for the production of ammonia. The gross energy requirement for ammonia production from fossil fuels is taken from Neelis *et al.* (2005) while for lignocellulosic biomass, the relative efficiency of hydrogen production from biomass compared to natural gas is used (van Ruijven et al., 2007). The energy ratio of coal, oil and biomass are 1.47, 1.21 and 1.50 $GJ_{prim}/GJ_{NGas\text{-}eq}$, respectively.

Table 4.2. Technical and cost parameters used for each HVC production route. Future (2050) values shown in brackets. Conversion efficiencies for production of intermediate and final HVC shown.

Feedstock - Intermediate	**Efficiency Step 1**[12] **(GJ_{Int}/GJ_{Prim})**	**Efficiency Step 2**[13] **(GJ_{HVC}/GJ_{Int})**	**Fossil Energy**[14] **(GJ_{Prim}/GJ_{HVC})**	**Electricity**[15] **(GJ_{Elec}/GJ_{HVC})**	**Fixed costs**[16] **($\$_{2005}/GJ_{HVC}$)**
	Gross Efficiency		*For steps 1 & 2*		
1. Coal - Methanol	0.57	0.97	0.99	-0.01	6.8
2. Coal - Naphtha[17]	0.59	0.55	1.71	0.00	7.4
3. Oil – Naphtha	1.00	0.60 (0.70)	0.44 (0.23)	0.00	1.9
4. Plastic Waste - Naphtha[18]	0.45	0.70	0.39	0.00	10.4
5. Natural Gas - Ethane	1.00	0.79 (0.80)	0.43 (0.25)	0.00	2.5
6. Lignocellulosic - Naphtha	0.33	0.75	3.75	-0.36	10.1
7. Lignocellulosic - Ethanol	0.41 (0.49)	1.10[19]	0.21	0.00	4.0 (2.6)
8. Maize - Ethanol	0.53 (0.59)	1.10	0.71	0.02	4.3 (4.1)
9. Sugar Cane- Ethanol	0.37 (0.43)	1.10	0.21	0.00 (-0.01)	3.6
10. Lignocellulosic - Methanol	0.60 (0.57)	1.01[20]	0.11	0.06 (0.00)	5.9 (3.3)

References: (Ren et al., 2006; Hamelinck & Hoogwijk, 2007; Ren & Patel, 2009b; Liptow & Tillman, 2012; Gerssen-Gondelach et al., 2014)

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12 Conversion efficiency of primary fuels to intermediate product for specific route. Routes 1-6 based on Lower Heating Value (LHV). Routes 7 – 10 based on higher heating value (HHV). Other possible products of each route are ignored. Future values based on current best available technology. Routes 3 and 5 have a 1st step efficiency of 1 since the intermediate is a necessary product of oil or gas distillation respectively.

13 Conversion efficiency of route intermediate to HVC. All conversion based on LHV basis. For routes 1-6 LHV_{HVC} = 45 GJ/t. For routes 7 to 10 it is assumed that HVC is ethylene, and thus LHV_{HVC} = 47GJ/t. For routes 7 to 10 see relevant footnotes.

14 Does not include feedstock energy for the HVC. In the case of multiple products, energy use is allocated on the basis of their economic values as in Ren *et al.* (2006) and Ren *et al.* (2009).

15 Electricity requirement for conversion of primary fuels to HVC. In case there is a net production of electricity, the value is negative.

16 Includes annualized capital costs and O&M costs for steps 1 & 2. A capital recovery factor of 13% and a capacity utilization rate of 90% are assumed. Biomass processes have significant cost reductions due to learning-by-doing in the production of the intermediates according to projections of the IMAGE/TIMER model (Bio case, see section 4.3.5).

17 This route is the liquefaction of coal to produce naphtha. Fischer-Tropsch naphtha via coal gasification is ignored due to extensive energy and gas cleanup needs.

18 BASF process. Naphtha production from polyolefins via liquefaction, pyrolysis and separation. Also called Back-to-Feedstock (BtF) recycling in this chapter.

19 For routes 7-9, mass yield is $0.61t_{HVC}$ per $t_{Ethanol}$ and $LHV_{Ethanol}$ = 26GJ/t. Energetic efficiency is greater than 1 (routes 7-10) due to endothermicity with energy derived from fossil energy requirement (column 4).

20 Mass yield is $0.43t_{HVC}$ per $t_{Methanol}$ and $LHV_{methanol}$ = 20GJ/t (Ren, 2009).

Methanol

The efficiencies of methanol production from fossil fuels are derived from Neelis *et al.* (2005) and the production from lignocellulosic biomass from Gerssen-Gondelach *et al.* (2014). The efficiencies for coal, oil, natural gas and biomass are 0.52, 0.52, 0.63 and 0.60 $GJ_{Methanol}/GJ_{Prim}$ respectively.

Refinery products

Refinery products are a diverse set of chemicals including aromatics, bitumen and lubricants, which remain after atmospheric distillation of oil. Substituting the feedstock (currently oil) with other energy carriers is not straightforward since the chemical properties of the product may vary. Other feedstocks (especially biomass) may produce products with a higher added value (such as terephthalic acid, derived from para-xylene), which may also perform the services provided by refinery products. Due to the complexities of substituting refinery products with their possible replacements and the significant uncertainties which arise, they are treated in an aggregate matter.

We assume that under all circumstances oil retains 30% of the refinery products market share since it is unlikely that bitumen (asphalt) will be produced from other feedstocks. We make this assumption for a number of reasons. Bitumen is an unavoidable product of the refining industry, and, as petroleum sources increasingly move towards heavy oil, the availability of bitumen will increase. Furthermore, it is most likely that biomass would be used for products with higher added value and so bio-based asphalt is unlikely. Coal, natural gas and biomass compete with oil for the remaining market share (70%). This competition is based on the relative price of refinery products from coal, natural gas and biomass to the price of equivalent products from oil (price ratio). In the initial conditions of the model, the price ratio of coal, natural gas and biomass is set to three. During the simulation period, the price ratio for coal and natural gas decreases as the relative price of oil increases. For biomass it is assumed that it approaches unity by 2050 since it is already observed in Europe that bio-based lubricants are dynamically entering the market (Saygin et al., 2014).

Post-consumer plastic waste

In order to assess possibilities of material efficiency improvement throughout the lifecycle of non-energy products (such as recycling and incineration with electricity generation), we also account for possible routes of post-consumer plastic waste (PCW). PCW represents the total amount of plastics which reached the end of their lifetimes. The availability of PCW is determined by assuming a certain fraction of the downstream products of *HVC*, *methanol* and *refinery products* of the previous year are available as PCW, while the rest is considered accumulated in plastics or used for non-plastic products. More specifically, 50% of HVC, 20% of methanol and 30%

of refinery products become plastics (DOE, 2000; MMSA, 2013; Saygin et al., 2014). It is assumed that 50% of plastic production can be recycled since not all plastics can be collected as PCW. In this study, PCW can contribute to HVC production after being processed in two different recycling processes, namely mechanical Recycling (MR) or Back-to-Feedstock recycling (BtF). The MR route reduces the demand of HVC, while BtF acts as an alternative route for HVC production (as shown in Figure 4.4) (Al-Salem et al., 2009; Shen et al., 2010; Lazarevic et al., 2010; Shen et al., 2012b).

It is assumed that the price of PCW is 4.4 $\$_{2005}/GJ_{Final}$ in 2010 representing the US and Western Europe (Ren & Patel, 2009b). The future price of PCW is linked to the price of fossil fuels. The volume of PCW undergoing MR is capped at 30% in order to account for decreased material properties (downcycling) (DOE, 2000; Al-Salem et al., 2009; MMSA, 2013; Saygin et al., 2014). It is assumed this process requires 0.7 GJ_{Sec} of fossil-based heat and 0.7 GJ_{Sec} of electricity for the production of 1 GJ_{Final} of HVC equivalent (Perugini et al., 2005). The remaining PCW can undergo the BtF process (see Plastic Waste Naphtha in Table 4.2). Both recycling routes compete for a market share of HVC production with other production routes.

In addition to recycling processes, PCW incineration with energy recovery can also contribute to emission reductions relative to electricity generation from separate power plants (section 4.3.5) (Lazarevic et al., 2010). This option is also included in our model, but we exclude any competition with the two recycling options. Thermal efficiency of waste-to-electricity is set at 30% with a future projection to 40%. This assumes that power plants are optimised for waste electricity generation (Dornburg et al., 2006; Ragossnig et al., 2008). Electric efficiency and emission factors of the displaced electricity generation are taken from the baseline of the IMAGE/TIMER model.

4.3.3. Fuel allocation

Allocation of primary energy carriers to each production process depends on the competitiveness of each carrier at producing the final product. Each possible route competes based on their relative costs according to a multinomial logit function shown in equation (4.3). This function allows to model market heterogeneity by assigning the largest market share to the cheapest route, with the remaining market share being shared amongst the remaining routes based on their relative costs.

$$MS_{R,P,EC} = \frac{e^{-\lambda c_{R,P,EC}}}{\sum_{EC} e^{-\lambda c_{R,P,EC}}} \tag{4.3}$$

Where *MS* is the market share each feedstock gets for each product, *c* is the cost of each product and λ is the logit parameter which acts as an elasticity between relative prices. The subscripts *R*, *P* and *EC* stand for region, product and energy carrier, respectively. As shown in equation (4.4), cost depends on the price of the energy carrier as well as its conversion efficiency, the annualised fixed costs and any potential taxes on carbon content of fuels (in the scenario where climate policies are accounted for, see section 4.3.5). Fixed and variable costs are only included for HVC production since data for all of the other production routes are scarce and fuel prices are the main cost component (Broeren et al., 2014). The *Fuel Price* is measured in $\$_{2005}/GJ_{Prim}$ and the efficiency of conversion (*Eff*)[21] is GJ_{Final}/GJ_{Prim}. Thus *Cost* is measured in $\$_{2005}/GJ_{Final}$.

$$Cost_{R,P,EC} = \frac{Fuel\ Price_{R,P,EC} + Ctax_{EC}}{Eff_{P,EC}} + Fixed\ Costs_{P,EC} + Variable\ Costs_{P,EC} \quad \textbf{(4.4)}$$

4.3.4. Emission accounting

The model tracks the carbon flows from the primary energy carrier to the final product, as well as emissions from heat production required for the conversion process. Only CO_2 emissions are accounted, while potential methane emissions, which may be important in HVC and methanol production, are ignored due to lack of data. The accounting of the emissions is in line with the *Good Practice* methods outlined by the IPCC Guidelines for emission inventories (IPCC, 2006). All emissions are measured in MtC.

- **HVC production:** The model simulates the flow of both process and feedstock energy carriers. Consequently the carbon content of the fuel combusted during the production process is included in the emissions. This includes emissions from any electricity use. The carbon content of the feedstock fuels is assumed indefinitely accumulated (sequestered) unless it is incinerated for energy recovery (see post-consumer waste in section 4.3.2). This is in line with the IPCC good practice guidelines for tier 2 emission accounting method.
- **Ammonia:** In this process fossil fuels are a source of hydrogen and so all of the carbon is emitted as CO_2. Downstream urea production, which would reduce these emissions, is ignored due to lack of global urea production data and projections and because a substantial share of global urea production is used as fertiliser which releases CO_2 when decomposing. This is in line with the IPCC good practice guidelines for tier 1 emission accounting method.
- **Methanol:** Emission factors for methanol production from different feedstocks are taken from Neelis *et al.* (2005). These factors assume emissions due to fuel combustion while the carbon embedded in the final product is assumed sequestered and are in line with IPCC tier 1 emission factors.

[21] For the Refinery Products, "*Eff*" is the inverse of the "price ratio" and for ammonia it is the inverse of the "energy ratio" (described in the respective parts of section 4.3.2).

- **Refinery products:** Most refinery products end up as materials that are used for the long-term such as bitumen or aromatics, which are assumed to sequester their embedded carbon. About 10% of refinery products are lubricants of which 20% are oxidised during use (ODU) according to IPCC tier 1 emissions accounting.

Carbon not emitted according to the above rules is assumed to be accumulated in the products. Thus, PCW has a certain carbon content, which is conserved (in the resultant) HVC if recycled and emitted if incinerated for electricity production. Further simplifying assumptions are made in order to keep the modelling manageable: Many derivatives of the HVCs (particularly ethylene derivatives) may emit CO_2 in the form of ODU (Weiss et al., 2007). Knowledge of specific flows of chemicals and uses per region would be required in order to properly assess this. Since our analysis is on global and long-term scales, it is too uncertain to make such assumptions and therefore these ODU emissions are ignored. An emission factor is attached to biomass production (5-7 kgC/GJ_{Prim}, varies across regions) which accounts for non-renewable energy use during production as well as net emissions due to the displacement of natural vegetation. This is in agreement with estimates of the International Food Policy Research Institute (IFPRI) (Al-Riffai et al., 2010). The carbon content of biomass itself is zero since it is assumed to come from perfectly renewable resources (plantations and residues).

4.3.5. Scenarios

In this study, we apply different scenarios to assess effects on energy use and emission reduction potential by biomass, climate policy and PCW policies. In all cases, the population, GDP and energy prices are based on the OECD Environmental Outlook (OECD, 2012). Exogenous global GDP and population growth, as well as energy carrier prices as projected by the IMAGE/TIMER model are shown in Table 4.3. The prices of energy carriers are governed by resource depletion dynamics (price increases) and learning by doing in technology conversion (price decreases).

Table 4.3. Key indicators (global average) of the OECD Environmental Outlook baseline.

Year	GDP/Cap ($_{2005}$/ Cap)	Price of Oil ($_{2005}$/GJ$_{Prim}$)	Price of Coal ($_{2005}$/GJ$_{Prim}$)	Price of Gas ($_{2005}$/GJ$_{Prim}$)	Price of Biomass ($_{2005}$/GJ$_{Prim}$)
2010	7 148	8.3	2.7	3.5	6.0
2020	9 155	9.5	2.4	4.0	6.0
2030	11 738	10.5	2.6	5.6	6.1
2040	15 159	12.1	2.6	7.0	7.0
2050	19 360	13.8	2.6	7.5	7.1
2060	24 653	15.7	2.5	8.4	8.2
2070	31 096	18.7	2.5	8.7	8.3
2080	38 912	22.8	2.5	9.5	9.1
2090	47 968	25.7	2.5	11.0	9.6
2100	58 058	26.8	2.5	11.9	9.6

The baseline projection is made in order to determine the future demand of non-energy products. This final demand is then met by primary energy carriers whose market shares are based on equation (4.3). We simulate two separate cases for the baseline projections: 1) Non-energy products are produced from fossil fuel energy carriers only, and 2) in addition to fossil fuels, biomass can also be used as a feedstock, competing with fossil fuels. By doing so, we assess the total emissions, demand of primary energy carriers and the mitigating effect of the use of biomass. These two cases will be referred to as the *NoBio* and *Bio* cases respectively.

Climate policy scenarios are performed for the two base cases. Carbon taxes of 20, 50 and 100$_{2005}$/tC are applied to the price of primary fossil fuels in order to determine the reaction of the energy mix (and associated emissions) of non-energy use to energy prices and how the availability of biomass affects the fuel substitution possibilities. It is assumed that the tax is applied in 2015 globally and remains constant throughout the simulation period.

Finally, two PCW policy scenarios are developed in order to investigate the effects of 1) Increased recycling rates, and 2) Incineration with electricity generation. In the first case, the full potential of PCW available for either MR or BtF recycling is used (something which does not happen in the base cases where it competes with other options). In the second scenario, 30% of the PCW potential is used by the power production sector replacing the projected use of fossil-based fuels in the baseline[22]. Regional demand for electricity and fuel use is based on projections of the IMAGE/TIMER model for the OECD Environmental Outlook scenario. The carbon content of the PCW is assumed emitted, and the total power sector emissions are compared

[22] The European Union (EU) currently incinerates 20% of its PCW (Lazarevic et al., 2010). This is ignored in our base cases since the effects of different routes are assessed, not the *business as usual*.

with the baseline emissions. These two scenarios are called the *full recycle* and *incineration* scenarios respectively.

4.4. Results

The following sections outline the projections of the NEDE model for future demand for non-energy use and its associated emissions under the different scenarios described in section 3.5. Detailed numerical results concerning primary energy use and carbon flows under all scenarios are available in the Appendix.

4.4.1. Baseline projections

Figure 4.5 shows the projected global non-energy demand up until 2100 (EJ_{Final}/yr) in the baseline with a breakdown by final products (left) or region (right). The respective (global) primary energy demand is shown in Table 4.6 in the Appendix. The final demand is identical for the *NoBio* and *Bio* cases. Total final demand increases from 19 EJ_{Final}/yr in 2010 to 47 EJ_{Final}/yr in 2050 and 72 EJ_{Final}/yr in 2100, as a consequence of volume growth for all products. The increase is asymmetric across products, with the greatest increase coming from HVC and refinery product demand since these products have the highest intensity of demand at high incomes. Between 2010 and 2100, HVC increases its share from 30% to 38% while the share of ammonia falls from 21% to 12%. The shares of methanol and refinery products are constant at 4% and 46%, respectively. The growth is driven by developing economies, with Europe, North America and the Former Soviet Union (FSU) not contributing to non-energy demand growth. These regions already have high intensity levels which have been declining the past years, and further economic growth does not increase their non-energy demand (see Figure 4.3). On the other hand the Asia-Pacific, South Asia and Africa regions have both growing economies and populations, leading to a large growth in demand.

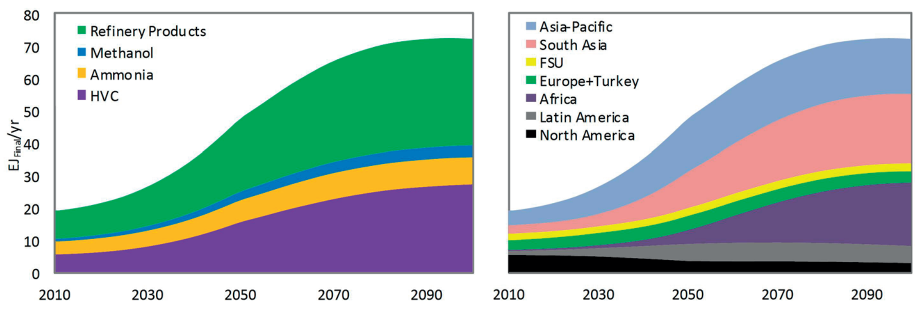

Figure 4.5. Total global final non-energy demand (EJ_{Final}/yr). Per product, (left), per region (right). Identical for Nobio and Bio cases.

It is important to consider changes in product and regional demand when assessing substitutability of different energy carriers and thus primary energy demand and emissions. This is because different products have different fuel switching possibilities (and efficiencies) and energy costs vary across regions. Primary energy demand and emissions will be the focus of the rest of this section.

Figure 4.6 shows the primary energy demand per energy carrier (including PCW) for the *NoBio* and *Bio* cases. The shares of primary energy carrier use per product are shown in Table 4.7 in the Appendix. One may note the rapid reduction in oil demand between 2010 and 2020. Pre-2010 the model is forced to reproduce the total fuel use reported in the IEA energy statistics while the shares of each final product are based on the data outlined in section 4.2.2. The difference in total demand between the data and IEA statistics is obvious in Figure 4.1 and may come from erroneous reporting in the IEA statistics. Both the total demand and the fuel use are re-adjusted to the bottom-up data between 2010 and 2020. The projections show that the global demand of primary energy carriers for non-energy increases from approximately 30 EJ_{Prim}/yr in 2010 to 100 EJ_{Prim}/yr (and 10 EJ_{Prim}/yr of PCW, most of which is recycled via MR) in 2100. This is equivalent to a compound annual growth rate of primary energy of 2% per year from 2010 to 2050 and 1.5% per year for the entire period analysed. Gas becomes increasingly important in the short term, mainly due to fuel switching in HVC production in developed regions, while developing regions continue using oil. Natural gas is also used heavily in ammonia and methanol production. In the longer term, increases in the price of oil lead to further increase in use of natural gas and eventually a shift to coal based chemistry. The increase in coal in the long-term is largely due to its requirement for process heat generation associated with switching to coal-based HVC. Furthermore, coal is increasingly used for methanol and ammonia production towards the end of the century.

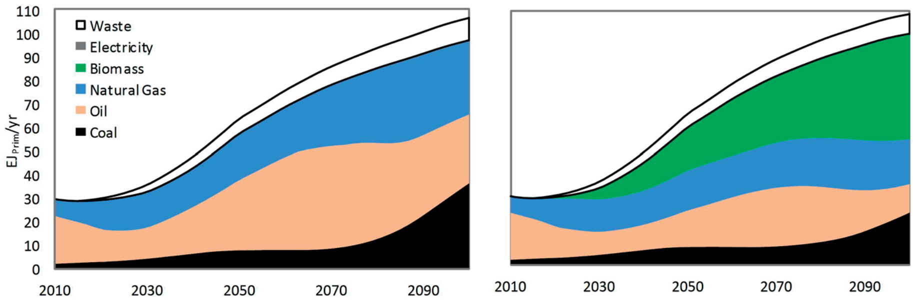

Figure 4.6. Total gross primary Non-energy demand (EJ_{Prim}) per energy carrier. NoBio (left) and Bio (right).

If biomass is also used as a feedstock (Figure 4.6, right), it is projected to become a significant non-energy feedstock supplying 19 EJ_{Prim}/yr in 2050 and 45 EJ_{Prim}/yr in 2100. Biomass becomes competitive due to disproportionate price increases in fossil fuels as well as cost reductions in biobased methanol production due to learning. By 2100, most of the biomass (50%) demand replaces oil which is used for refinery products production. 43% of the biomass is used to produce HVC, replacing all fossil fuels but primarily coal, which is the marginal fuel in the *NoBio* case and about 7% is used for ammonia production. Biomass accounts for 65% refinery product production 46% of HVC and 21% of ammonia in 2100.

Since feedstocks for HVC account for more than a third of non-energy use according to the projections (Table 4.7) and this product is the most interesting concerning renewable feedstocks and PCW recycling, it is worth looking at it in more detail. Figure 4.7 shows the primary energy carriers used as feedstocks for HVC production only. The model projects that all of the waste available for mechanical recycling is used, while back-to-feedstock recycling is minor. This is due to its high costs and energy requirement. Also the continued importance of oil (especially outside North America) in the medium term is shown. Biomass becomes important after 2030 due to cost reductions in HVC production from bio-based methanol. Primary energy demand, excluding waste, in 2100 increases from 30 EJ_{Prim}/yr in the *NoBio* case to 34 EJ_{Prim}/yr in the *Bio* case due to the lower conversion efficiency of biomass to HVC compared to fossil fuels.

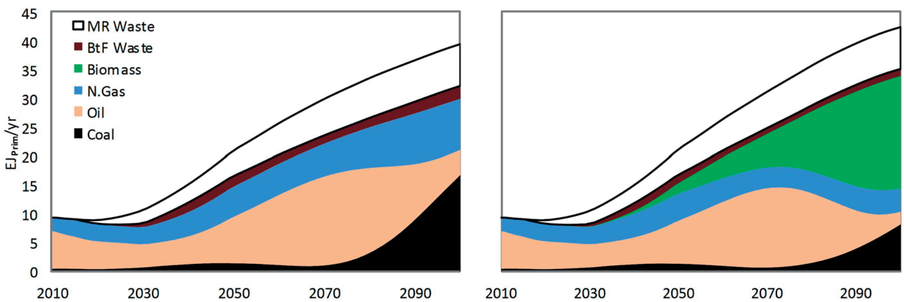

Figure 4.7. Net primary energy demand (EJ_{Prim}) for HVC, including recycled fractions. NoBio (left) and Bio (right).

As the demand for non-energy products increases, emissions of this sector also increase. Figure 4.8 shows for 2010, 2050 and 2100 the distribution of the global annual carbon flows between emitted, accumulated and recycled. The use of biomass can overall significantly limit the total amount of carbon within the sector in the long run, especially the carbon accumulated in products. It can reduce annual emissions in

2100 from 677 MtC/yr to 544 MtC/yr (20% reduction) by replacing a large portion of fossil fuels by biomass in ammonia and reduction in coal-based HVC.

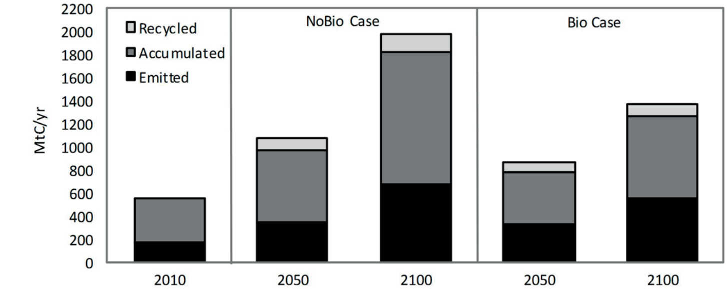

Figure 4.8. Carbon flows in 2010, 2050 and 2100 for the NoBio and Bio cases.

4.4.2. Climate policy

In the climate policy scenarios we tax the carbon content of primary energy carriers at 20, 50 and 100 $/tC. The effect of climate policy in 2100 on total primary energy demand and the sectors' annual emissions for both *NoBio* and *Bio* cases are shown in Figure 4.9 (see Table 4.8 in the Appendix for the developments in fuel mix). In the *NoBio* case, climate policy leads to coal being replaced by natural gas and to a lesser extent oil. This reduces the energy use for coal-based HVC and lowers the overall emissions (36% at 100 $\$_{2005}$/tC). In the Bio case, biomass becomes increasingly important further reducing emissions (33% at 100 $\$_{2005}$/tC), but as previously mentioned this also reduces the conversion efficiency. Thus, climate policy has a smaller effect on primary energy demand in the *Bio* case than in the *NoBio* case. Decreases in total primary energy demand (and consequently emissions) are also driven by reduced final demand due to the price elasticity of demand.

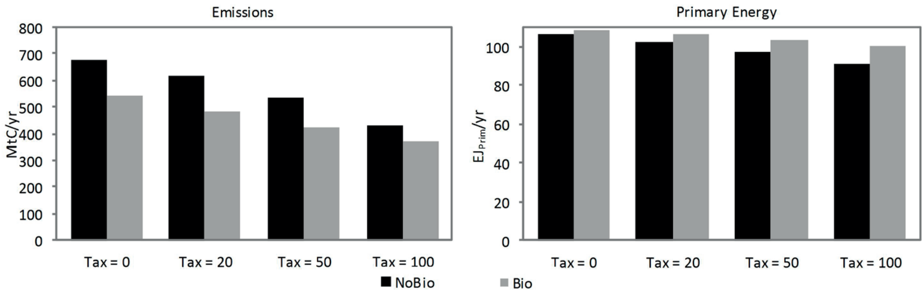

Figure 4.9. Left: Total emitted carbon (MtC/yr), Right: Total non-energy demand (EJ/yr) for NoBio and Bio cases per tax level for 2100.

4.4.3. Post-consumer waste policies

In the base case projections (*NoBio* and *Bio*), NEDE indicated that the waste available for mechanical recycling is utilised; back-to-feedstock recycling is not a competitive HVC production option and only used marginally. We discuss now the results of alternative PCW scenarios. The first PCW policy scenario assumes the Bio case with the BtF route forced on 70% of the PCW (the other 30% undergoing MR). The results show that forced BtF does not reduce the demand of primary energy carriers and emissions with respect to the base Bio case (Table 4.8 in the Appendix, *Full Recycle* scenario), a conclusion other studies have also come to (Lazarevic et al., 2010). The reason being BtF's low efficiency and high process energy (Table 4.2).

The second PCW scenario assumes that the quantity of PCW not used for recycling in the base case can be incinerated with subsequent electricity generation. This is repeated for both *NoBio* and *Bio* cases since the carbon content, and thus emitted carbon, of PCW changes. In the power sector, PCW replaces an aggregate mix of the fossil primary energy carriers, whose use in baseline projections according to the IMAGE/TIMER model is shown in Table 4.9 in the Appendix. Globally, coal is projected to become the dominant primary fuel for electricity generation, but the carbon content (CC) of electricity decreases due to improvements in the thermodynamic efficiency of electricity generation.

Table 4.4 shows the primary fuel demand and carbon content per GJ fuel use of the electricity generation sector in the base case. The carbon content of electricity is 464 gCO_2/kWh and 453 gCO_2/kWh for 2050 and 2100 respectively. Also shown are the CC and volume of PCW the *NoBio* and *Bio* cases in 2050 and 2100. It is assumed that waste-to-electricity efficiency is 30%, increasing to 40% in 2100 (Dornburg et al., 2006; Ragossnig et al., 2008). Efficiency of fossil based electricity generation, globally increasing from 42% to 55% in 2050 and 62% in 2100, is based on the projections of the IMAGE/TIMER model and regional electricity fuel mix. Consequently, each GJ of PCW replaces <1 GJ of primary fossil fuels for electricity generation (fossil replacement rate).

The incineration of PCW with electricity production overall does decrease the demand of primary fuels. However, due to the low fossil replacement rate, PCW can lead to a reduction in electricity emissions only if CC-PCW is much lower than CC-Elec. As shown in Table 4.4, this is not the case in any of the scenarios with incineration with electricity generation leads to net increases in emissions (up to 466 gC/kWh), with higher emissions in the *Nobio* case due to the higher carbon content of PCW. PCW cascading can lead to emissions reductions if the fossil replacement rate can be improved by increasing the efficiency of waste-to electricity or if the carbon content of PCW is further reduced (Ragossnig et al., 2008; Lazarevic et al., 2010).

Table 4.4. Details of baseline electricity generation, availabiltiy and carbon content (CC) of PCW, and emission effects of PCW incineration with electricity generation. NoBio and Bio cases in 2050 and 2100. Note: Table may contain rounding errors.

	2050		2100	
	NoBio	Bio	NoBio	Bio
Electricity Base Case				
CC-Elec (kgC/GJ_{Prim})	19.4		21.2	
Electricity Fuel (EJ_{Prim})	384		628	
Electricity Emission (MtC)	7429		13293	
Electricity Emission Factor (gCO_2/kWh)	*465*		*452*	
PCW Parameters				
CC-PCW (kgC/GJ_{PCW})	20.4	19.5	22.3	16.5
PCW availability (EJ)	2.9		4.9	
Fossil Replacement Rate (GJ_{Prim}/GJ_{PCW})	0.55		0.62	
PCW Incineration Results				
Electricity Fuel (EJ_{Prim})	381		624	
Electricity Emissions-fuel (MtC/yr)	7398		13226	
Electricity Emissions-PCW (MtC/yr)	59	57	108	80
Total Emissions (MtC/yr)	7457	7455	13335	13306
Electricity Emission Factor (gCO_2/kWh)	*466*	*466*	*454*	*453*
Emission Change (MtC/yr)	+29	+26	+42	+13

4.5. Discussion

The main purpose of the model is to project non-energy use and to study the possibilities for this sector to reduce its CO_2 emissions. An emphasis has been placed on the potential use of biomass as well as various post-consumer plastic waste treatment options. A key outcome is the potentially significant contribution of biomass in this sector, leading to large emission reductions. In order to investigate the robustness of these results and to investigate the effect of important parameters on our findings, we have performed a sensitivity analysis. Furthermore, the results have also been compared to the outcomes of other relevant studies.

In the NEDE model, non-energy final demand is driven by per-capita economic growth and the model allocates market shares of primary fuels per final product based on relative costs. Figure 4.10 shows a sensitivity analysis performed on the use of biomass as well as the carbon emissions by 2100 when varying the projections for GDP/cap and energy prices (see Table 4.3) by ±25% for the *Bio* scenario. As shown in Figure 4.3, it is hypothesized that demand of non-energy products flattens out with increasing affluence, thus the final demand and resultant biomass use and emissions become less sensitive to changes in GDP/cap. Since the model allocates market shares of primary fuels based on relative costs, the results heavily depend on the competitiveness of primary energy carriers. According to the model results, as fossil fuels become more expensive, biomass use increases as it is the marginal fuel. Consequently, the competitiveness of biomass is very sensitive to its price. As the price of individual fossil fuels changes, biomass use is affected to a lesser degree since other fossil fuels can also have marginal gains.

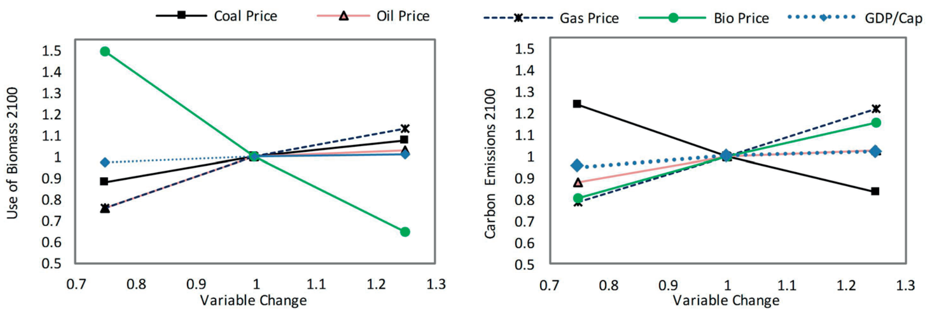

Figure 4.10. Results of sensitivity analysis on use of biomass (left) and emissions (right) for 2100. Effect of energy carrier prices and per capita GDP (Bio case).

Emissions in 2100 are driven by coal use (especially in ammonia production), and consequently by its competitiveness with gas and biomass which are the marginal fuels. It is important to note that even in the case where the biomass price is 25% higher, the total emissions are still lower than in the *NoBio* case.

The model projects that all of the PCW available for mechanical recycling is used since it is considered a cheap method to reduce HVC demand. In order to assess how this may affect the conclusions of the model, Table 4.5 shows how the fossil and biomass energy requirement of the Bio scenario are affected when recycling routes are ignored. As expected the total primary energy demand increases. This increase comes from both biomass and fossil fuel use, which leads to an emission increase when recycling is ignored.

Table 4.5. Change in the non-energy sector's total biomass and fossil energy demand and its emissions when recycling is excluded (results shown for Bio case, 2100).

	Bio case	No Recycling	%
Total Biomass (EJ_{Prim}/yr)	45	52	+14%
Total Fossil Energy (EJ_{Prim}/yr)	54	64	+18%
Total Primary Energy (EJ_{Prim}/yr)	100	116	+15%
Emission (MtC/yr)	544	593	+9%

An inherent uncertainty of the NEDE model concerns the future projections of non-energy demand and the overall market structure. Demand has been modelled as a function of observed intensities of demand for non-energy products with respect to economic development. Earlier studies found meaningful relationships to support this hypothesis for bulk materials such as steel, cement, paper and aluminium (van Vuuren et al., 1999; Groenenberg et al., 2005; Lysen et al., 2006). Besides economic growth, the availability of cheap feedstocks and newly installed large refinery capacities (Middle East and more recently shale gas in the USA), or the existence of innovative high value added sectors in (e.g. in Japan and Europe) are also factors determining non-energy demand. This explains why the fits are somewhat worse when compared to other sectors. Furthermore, trade of non-energy products is not explicitly modelled. An attempt has been made to incorporate these dynamics in the NEDE model as regional demand of each product depends both on economic development and energy prices (through a price-induced multiplier). Consequently, at any given GDP, regions with lower energy costs are going to have a relatively higher (production) demand. Institutional aspects of the non-energy sector and its intimate relation to oil and gas extraction capital are ignored, especially concerning the refinery products. Our methodology assumes that there is a given demand for these products, which should be met irrespective of oil and gas extraction and refining trends. Given the assumed relationship with economic development, a study highlighting how per capita demand developed since 2007 would provide valuable insight on the robustness of our method. Due to the *price ratio* assumptions of bio-based refinery products, biomass use for this product is projected to be very high. The development of this price ratio is highly uncertain and based on limited current observations.

The results highlight a very high use of biomass in the non-energy sector. This result is optimistic since it is assumed that no other competitive use of biomass for energy purposes exist. This high use reflects only the projected techno-economic potential of biomass in the non-energy sector; Chapter 5 investigates how this potential may be limited due to other biomass uses.

Though the model investigates carbon flows per non-energy product, the representation of emissions is simplified in order to maintain relevance and simplicity. Emissions of the non-energy sector are difficult to model due to complex material and energy flows, with huge uncertainties in future projections. Furthermore, it is assumed that whatever carbon is not emitted during feedstock conversion or incineration is accumulated indefinitely in non-energy products (and land-fills). Plastic waste degradation has been estimated at 1-5% during a 100 year period (Lazarevic et al., 2010). Thus this assumed accumulated carbon may have significant effects if the time period of the analysis were to be expanded, increasing the emissions of the *NoBio* case and improving the performance of the incineration scenarios.

Despite the uncertainties, the model compares well with other studies. Allwood *et al.* (2010) estimate carbon emissions from plastics production in 2006 at 136MtC, while for the same year NEDE calculates the emissions at 139MtC. Though the non-energy use estimates between the NEDE model and the IEA statistics differ (see section 4.2.2), the annual growth rate for global non-energy demand between 2010 and 2050 according to NEDE is 1.98%, while the IEA-Energy Technology Perspectives baseline is 1.93% (IEA, 2010b). The same IEA study also projects that carbon emissions related to non-energy use will more than double between 2007 and 2050, in agreement with our results. Concerning the ability of biomass to penetrate into this sector, Gielen *et al.* (2002) estimate that biomass can account for 22% of the petrochemical sector in 2050, which is in line with our 28% projection for the Bio scenario.

4.6. Conclusions

This chapter presented an analysis and possible future trajectories of non-energy demand and the associated emissions. Available data has been assessed and used to construct a simulation model able to project final demand, primary energy demand of different energy carriers and the magnitude of the carbon flows.

Analysis of bottom-up data has highlighted inconsistencies in the IEA energy statistics concerning non-energy use; a conclusion which other studies have also drawn (Weiss et al., 2008). The bottom-up data has been used to develop the NEDE model, a top-down simulation model for global long-term projections of the non-energy sector. The model assumes that the non-energy sector demand can be represented by a limited number of products which can be produced from primary fuels. Each fuel competes for a market share of the final product based on its fuel costs, conversion costs and conversion efficiency.

The model is a significant step forward concerning the future assessment of the non-energy sector. The NEDE model can assess the dynamics of the non-energy sector and how its structure changes with time and economic development. Following, it provides projections of overall primary demand for non-energy as well as the potential of fuel switching as representative pathways for each product and fuel are included. In addition to explicit energy flows, carbon flows are also modelled, accounting for emitted, recycled and accumulated carbon. The model can be used to assess how different scenarios such as climate policy and waste incineration with energy recovery affect non-energy demand and its emissions. Finally, the NEDE model is fully integrated in the IMAGE/TIMER integrated assessment model framework. Integrated assessment models usually model non-energy in secondary energy terms (as opposed to Final Energy in NEDE) thus ignoring effects of energy carrier conversion efficiency and have little detail due to complexities in different flows in the energy system. Important progress has been made with the NEDE model since the level of description is detailed enough to be relevant while also aggregate enough to be included in an integrated assessment model.

The model projects that global demand of non-energy will increase significantly from 30 EJ_{Prim}/yr today to over 100 EJ_{Prim}/yr by 2100. HVC is projected to be the most important non-energy product, followed by refinery products and ammonia. Assuming only fossil fuel use, oil and natural gas are the main feedstocks for HVC up until 2050. Subsequent oil price increases lead to replacement by coal and natural gas. Coal becomes increasingly important in the production of methanol and ammonia, replacing natural gas.

The use of biomass for non-energy purposes can significantly reduce fossil energy demand and emissions. Assuming only the use of fossil fuels, the annual emissions of non-energy increase from 163 MtC/yr in 2010 to 677 MtC/yr in 2100. However, biomass can eventually supply over 40% of the total required primary energy, reducing emissions to 544 MtC/yr. The sensitivity analysis has shown that this result is robust since even if the price of biomass were 25% higher, the emissions would still be significantly lower than the *NoBio* case. However, it is important to keep in mind that in this study, biomass does not compete for other energy services (biofuels, residential heating, etc.). Thus, this chapter does not study the optimal use or the competition of biomass across various options in the energy system, but rather its techno-economic potential in the non-energy sector alone.

Emissions can be further reduced by promoting fuel switching via climate policy. At a carbon tax rate of 100 $\$_{2005}$/tC, the sector's emissions are projected to reduce to 423 MtC/yr and 367 MtC/yr by 2100 in the NoBio and Bio cases, respectively. This re-emphasizes the importance of biomass at reducing emission abatement costs since *BioCase* at no tax offers similar emission levels with the the *NoBio* case at a 50 $\$_{2005}$/tC tax (534 MtC/yr).

Cascading uses of post-consumer waste do not necessarily reduce the total primary energy demand and emissions of non-energy use. The model projects that when competing freely, all of the waste available for mechanical recycling is used. Back-to-feedstock recycling is marginal due to its high costs and energy requirements. The full recycle scenario showed that forcing back-to-feedstock recycling does not reduce energy demand and emissions compared to the Bio case. Mechanical recycling reduces total primary energy demand for feedstocks by 15%, but has a smaller effect on emissions since it has emissions of its own. If 30% of PCW is used as a feedstock for electricity production, though reducing the demand for primary energy carriers, it may increase the emissions of the power sector. This happens despite projections that coal becomes a significant primary fuel for electricity generation. The emission increase is due to the reduced efficiency of electricity generation from PCW with respect to fossil fuels, while also emitting the carbon content of PCW. Emission reductions via this measure are possible with efficient waste to-electricity technologies and avoiding the use of carbon intensive non-energy feedstocks.

In conclusion, the NEDE model indicates that energy and emissions reduction in the non-energy sector can profit most from fuel switching to biomass and avoiding the use of coal feedstocks. This may reduce the annual emissions by up to 20% in 2100. Post-consumer waste measures may reduce emissions only if recycling and cascading processes become more efficient. A similar analysis of other possible uses of biomass in the energy system is required in order to determine if biomass for non-energy use is the optimal option for reducing emissions.

4.7. Appendix

Table 4.6. Primary energy demand (including PCW) for non-energy products and HVC-heat as well as total demand for NoBio and Bio cases.

	NoBio			Bio		
	2010	2050	2100	2010	2050	2100
HVC-Net	32%	33%	37%	32%	32%	39%
HVC-Heat	9%	6%	12%	9%	6%	8%
Ammonia	24%	18%	14%	24%	19%	15%
Methanol	5%	7%	6%	5%	7%	6%
Refinery Products	30%	35%	31%	30%	36%	32%
Total EJ_{Prim}/yr	29	63	107	29	65	109

Table 4.7. Shares of primary energy carrier and total primary energy demand (including waste) per final product and HVC-heat. For NoBio/Bio cases and Recycling scenario in 2050 and 2100.

			Coal	Oil	Natural Gas	Biomass	Waste	Electricity	Total $EJ_{Prim/yr}$ [23]
2050	NoBio	HVC-Net	7%	38%	25%	0%	30%	0%	21
		HVC-Heat	20%	32%	41%	0%	0%	8%	4
		Ammonia	29%	1%	70%	0%	0%	0%	11
		Methanol	47%	0%	53%	0%	0%	0%	5
		Ref. Prods	0%	90%	10%	0%	0%	0%	22
									63
	Bio	HVC-Net	6%	35%	22%	9%	28%	0%	21
		HVC-Heat	18%	31%	42%	0%	0%	8%	4
		Ammonia	27%	1%	62%	10%	0%	0%	12
		Methanol	47%	0%	53%	0%	0%	0%	5
		Ref. Prods	0%	30%	5%	65%	0%	0%	24
									65
	Full Recycle	HVC-Net	4%	23%	15%	6%	52%	0%	25
		HVC-Heat	14%	23%	56%	0%	0%	8%	4
		Ammonia	27%	1%	62%	10%	0%	0%	12
		Methanol	47%	0%	53%	0%	0%	0%	5
		Ref. Prods	0%	30%	5%	65%	0%	0%	24
									70
2100	NoBio	HVC-Net	43%	11%	23%	0%	23%	0%	39
		HVC-Heat	71%	5%	20%	0%	0%	4%	13
		Ammonia	40%	0%	60%	0%	0%	0%	15
		Methanol	70%	0%	30%	0%	0%	0%	7
		Ref. Prods	0%	73%	27%	0%	0%	0%	33
									106
	Bio	HVC-Net	19%	5%	10%	46%	20%	0%	42
		HVC-Heat	52%	4%	38%	0%	0%	6%	9
		Ammonia	32%	0%	47%	21%	0%	0%	16
		Methanol	69%	0%	31%	0%	0%	0%	7
		Ref. Prods	0%	28%	7%	65%	0%	0%	35
									109
	Full Recycle	HVC-Net	12%	4%	7%	33%	44%	0%	48
		HVC-Heat	39%	3%	52%	0%	0%	6%	8
		Ammonia	32%	0%	47%	20%	0%	0%	16
		Methanol	68%	0%	32%	0%	0%	0%	7
		Ref. Prods	0%	28%	7%	65%	0%	0%	35
									114

[23] Including the use of waste.

Table 4.8. Shares of each primary fuel for total non-energy use, total primary energy (including waste) and total emissions. With and without availability of biomass, carbon taxes and recycling of HVC.

Scenario	Tax	Year	Energy Carrier						Total	
			Coal	Oil	N.Gas	Bio	Waste	Elec	Primary Energy ($EJ_{Prim/yr}$)[24]	Emissions (MtC)
NoBio	0	2010	6%	69%	24%	0%	0%	0%	30	163
		2050	12%	47%	31%	0%	10%	0%	63	339
		2100	34%	27%	29%	0%	9%	0%	107	677
	50	2010	6%	69%	24%	0%	0%	0%	30	163
		2050	9%	47%	33%	0%	10%	0%	61	308
		2100	21%	33%	36%	0%	10%	1%	97	534
	100	2010	6%	69%	24%	0%	0%	0%	30	162
		2050	7%	46%	36%	0%	10%	0%	59	282
		2100	12%	35%	42%	0%	10%	1%	91	433
Bio	0	2010	6%	69%	24%	0%	0%	0%	30	163
		2050	11%	24%	26%	28%	9%	0%	65	329
		2100	21%	11%	18%	42%	8%	0%	109	544
	50	2010	6%	69%	24%	0%	0%	0%	30	163
		2050	8%	23%	28%	32%	9%	0%	63	296
		2100	10%	12%	19%	50%	8%	0%	103	423
	100	2010	6%	69%	24%	0%	0%	0%	30	162
		2050	6%	20%	29%	35%	9%	0%	62	269
		2100	7%	11%	19%	54%	8%	0%	100	367
Full Recycle[25]	0	2010	6%	69%	24%	0%	0%	0%	30	163
		2050	10%	20%	25%	26%	19%	0%	70	331
		2100	17%	10%	17%	36%	19%	0%	114	528

Table 4.9. Baseline (OECD Environmental Outlook) projections of shares of primary fuel for electricity generation according to the IMAGE/TIMER model.

	2010	2050	2100
Coal	44%	53%	72%
Oil	5%	0%	0%
N. Gas	16%	16%	2%
Biomass	3%	0%	0%
Nuclear	13%	8%	7%
Solar/Wind	3%	14%	13%
Hydro	16%	9%	7%
Total (EJ_{Elec}/yr)	72	211	387

[24] Including use of waste.

[25] This experiment is based on the Bio case at a 0 tax level.

Table 4.10. Annual and cumulative carbon flows for NoBio, Bio, Full-Recycle, Incineration and No-Recycle scenarios.

Flow Type	Scenario	Annual Flows		Cumulative Flows	
		MtC/yr		MtC	
		2050	2100	2050	2100
Emitted	NoBio	339	677	8 586	32 105
	Bio	329	544	8 459	29 662
	Full Recycle	331	528	8 471	29 704
	Incineration[26]	356	557	8 925	31 306
	No Recycle	338	593	8 637	30 611
Recycled	NoBio	102	162	1 984	8 812
	Bio	91	101	1 817	7 087
	Full Recycle	202	242	3 452	16 192
	Incineration	91	101	1 817	7 087
	No Recycle	0	0	0	0
Accumulated	NoBio	634	1 142	14 638	61 340
	Bio	449	728	11 991	43 945
	Full Recycle	282	491	9 567	30 114
	Incineration	392	648	10 915	39 072
	No Recycle	655	1 015	16 014	60 911

[26] Changes in power sector emissions due to cascading are allocated to the non-energy sector. System emissions increase due to lower aggregate efficiency in the power sector.

5

Competing uses of biomass for energy and chemicals: Implications for long-term global CO_2 mitigation potential

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Abstract

Biomass is considered a low carbon source for various energy or chemical options. This chapter assesses it´s different possible uses, the competition between these uses, and the implications for long-term global energy demand and energy-system emissions. A scenario analysis is performed using the TIMER energy system model. Under baseline conditions, 170 EJ_{Sec}/yr of secondary biomass is consumed in 2100 (approximately 18% of total secondary energy demand), used primarily in the transport, buildings and non-energy (chemical production) sectors. This leads to a reduction of 9% of CO_2 emissions compared to a counterfactual scenario where no bioenergy is used. Bioenergy and biochemicals can contribute up to a further 40% reduction of emissions at carbon taxes greater than 500$\$_{2005}$/tC. As higher CO_2 taxes are applied, bioenergy is increasingly diverted towards electricity generation. Results are more sensitive to assumptions about resource availability than about technological parameters. To estimate the effectiveness of bioenergy in specific sectors, experiments are performed in which bioenergy is only allowed in one sector at the time. The results show that cross-sectoral leakage and emissions from biomass conversion limit the total emission reduction possible in each sector. In terms of reducing emissions per unit of bioenergy use, we show that the use of bioelectricity is the most effective, especially when used with carbon capture and storage. However, this technology only penetrates at a high carbon price (>100$\$_{2005}$/tC) and competition with transport fuels may limit its adoption.

5.1. Introduction

The use of biomass as a renewable source for energy and chemical purposes and as an emission mitigation measure has received much attention (Chum et al., 2011; GEA, 2012; IEA, 2013). From an energy perspective, the use of biomass is attractive given its potentially low greenhouse gas (GHG) emissions and the ability to relatively easily replace fossil fuels in many parts of the energy system. Biomass-based energy carriers (bioenergy) can be used in transport, as heating or cooking fuels in households, or for conversion to electricity. Biomass can also replace fossil fuels in non-energy purposes as a feedstock for the production of bulk chemicals (biochemicals) (Dornburg et al., 2008). Analyses using integrated assessment models (IAMs) have highlighted the importance of biomass use in the energy system to meet emission reduction targets (van Vuuren et al., 2007; van Vliet et al., 2009; Luckow et al., 2010; van Vuuren et al., 2010b; Calvin et al., 2013; Rose et al., 2014). At the same time, however, there are considerable questions with regard to the potential of biomass given the competition for land, the cost of conversion of biomass to bioenergy or biochemicals and the possible direct and indirect greenhouse gas emissions during the production of biomass and its conversion (Searchinger et al., 2008; van Vuuren et al., 2009b; Dornburg et al., 2010; Haberl et al., 2010; Beringer et al., 2011).

The effectiveness of bioenergy at reducing emissions depends, amongst others, on which fuel it replaces. Several studies have looked at specific uses of biomass in energy systems and associated emission reductions (Dornburg & Faaij, 2005; Azar et al., 2010; Klein et al., 2011; Schmidt et al., 2011; Taibi et al., 2012; Daioglou et al., 2014). However, the implications for the remaining energy system are important. Displacing fossil fuels from one use makes them available for use elsewhere, potentially leading to cross-sectoral leakage. The study of leakage has focused on economic equilibrium models with a weak representation of physical parameters such as demand functions and technologies. Furthermore there is a wide range and uncertainty on the elasticities used in most of these studies (Rajagopal et al., 2011; W. Thompson et al., 2011). A more descriptive explanation of leakage may indicate that several dynamic factors play a role, for instance, related to sectors responding differently to different emission taxes and available fuels. Also time-dependent impacts (e.g. related to learning) could further complicate the matter. In other words, a detailed description of the energy system is needed for a better understanding of the share and location of final energy, which can be substituted by bioenergy.

Given the uncertainties and the potentially important role assigned to bioenergy for emission mitigation, a key question is what its best use in the energy system is. It is also important to investigate how competition between different biomass uses may limit its deployment to uses which would provide greater emission reductions. Recently Creutzig *et al.* (2012) argued that existing assessments are insufficient owing to limitations of system representation, ignoring market factors or narrow exploration of solution space in IAMs.

This study seeks to address some of the above issues by investigating how biomass may contribute to long-term energy and chemical demands and its effect on energy system emissions under different circumstances. We use the TIMER energy system simulation model whose projections of bioenergy and biochemical use and the associated emission reductions are assessed for a number of scenarios. First, total and sectoral (industry, transport, etc.) bioenergy use is projected under a baseline, and the effect of uncertainties on land availability and biomass-to-bioenergy/biochemicals conversion technologies are investigated. Following, in order to gain insight into the competing applications of biomass and their emission implications, scenario projections where the conversion of biomass is limited to a specific end-use sector are made. This provides insight into how different biomass uses may displace fossil fuels and thus lead to overall emission changes including second order effects such as cross-sectoral leakage. Finally, the marginal emission reduction of biomass, per end use, is investigated by looking into impacts of increasing a tax on the carbon content of energy carriers. By comparing the results of specific biomass uses with the case where it is allowed to be used freely in the energy system, we get insights into the effectiveness of different biomass strategies at reducing emissions, as well as the effect of competition for this limited resource. This analysis is done on a global scale and with a long-term time horizon (2100). Thus, the study takes into account long-term energy use projections as energy demand and supply evolve.

The rest of the chapter is structured as follows. In section 5.2 definitions and the system description are outlined followed by a description of the scenarios and indicators used to present the results. Also presented are the energy and emission projections of the baseline scenario. The results section (5.3) presents the results of the study. Finally section 5.4 outlines the uncertainties of the model and the projections, compares the results to existing literature and highlights the main conclusions of the study.

5.2. Materials and methods

5.2.1. Definitions

Throughout this Chapter, unless otherwise stated, *biomass* is defined as a primary energy source. *Bioenergy* is the use of biomass based energy carriers (solid or liquid) produced from crops or residues in order to provide energy services of the end-use sectors. The use of these energy carriers as feedstocks for the production of *biochemicals* are also referred to as *non-energy* uses, the terms being used interchangeably.

According to the TIMER model, the energy system is disaggregated into different end use sectors: industry, transport, buildings, non-energy and rest. Non-energy incorporates the non-energetic use of energy carriers (as feedstocks) for the production bulk chemicals (ethylene, ammonia, methanol, etc.) while a small fraction of energy carrier also used as a process fuel. *Rest* includes non-specified uses as defined by the IEA (excluding residential, commercial and public services). Besides these *final demand* sectors, we also account for biomass use in the *electricity* sector, and thus account for its possible conversion to that energy carrier. Note that *electricity* is not a final demand sector but rather a conversion sector which supplies the final demand. Unless stated otherwise, energy demand is presented in secondary energy terms (i.e. GJ_{sec}) and energy carriers included are coal, oil, gas, bioenergy, electricity and other (includes traditional biomass use in poor households, hydrogen, nuclear, solar, wind, hydropower and waste). Note that the use of traditional biomass, though included in the model, is not analysed in this study as it is assigned to the *other* energy carrier.

CO_2 emissions are accounted by assuming that the carbon content of a fossil-based secondary energy carrier is released upon combustion. Thus, given the secondary energy demand of each end-use sector, we can determine each sector's emissions. In the non-energy sector, fuels are not necessarily combusted and carbon may be *sequestered* in the form of plastics and chemicals. A detailed description of how the TIMER model deals with this can be found in Chapter 4. For the end-use sectors (industry, transport, buildings, non-energy and rest) we only look at direct emissions and thus exclude electricity, which is presented separately in order to avoid double counting.

In order to get a complete picture of the emission effects of increased bioenergy/biochemical use, it is interesting to investigate how emissions from the supply of secondary energy may be affected. Thus, we include an additional emission sector called *energy supply*. The TIMER model includes an *own energy use* in order to produce fossil fuels which leads to certain emissions. Concerning biomass, the model takes into account emissions from non-renewable fuel use in bioenergy production (as presented in Table 5.1) as well as net emissions due to the displacement of natural vegetation. For the latter, it assumes emissions to be 5-7kgC/GJ_{Prim}, varying across regions. The emission factor has been determined using the IMAGE model as described by Otto *et al.* (2015). This is done by comparing two extreme runs: in which (i) no biomass is grown, and (ii) biomass is grown on all the available land. The difference in the land-based carbon stocks over the projection period, together with the yield of biomass leads to an emission factor in kgC/GJ_{prim}. Indirect land-use change is not accounted for and the interaction of biomass growth with agriculture is beyond the scope of this Chapter.

5.2.2. System description

The TIMER model is a system-dynamics, recursive simulation model of the energy system. Results depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states (van Vuuren, van Ruijven et al., 2014). The model projects the development of the energy system and its emissions and has been used to assess possible future energy system emission pathways (van Vuuren et al., 2007; Rose et al., 2014). Energy demand is determined for specific energy functions on the basis of assumptions on population and economic growth, and is met by investments in energy consuming technologies. The model includes key dynamics such as autonomous and price-induced energy efficiency improvements which lower the demand, accounting of capital stocks and turnover rates, trade of energy carriers, and learning by doing which leads to cost reductions in technologies. The model has been calibrated in order to reproduce the IEA energy balances for the period 1971-2005 (IEA).

Energy supply is based on the cost supply curves of different primary energy carriers (Rogner, 1997; Mulders et al., 2006). For non-renewable sources, these are formulated in terms of cumulative extraction; for renewable sources, these are formulated in terms of annual production. Subsequent equations describe how primary resources are converted to secondary energy carriers at a given efficiency and cost (including capital and operation and maintenance costs). If multiple secondary energy carriers can be used for a given energy function, they compete based on their relative costs (and preference levels), where the cheapest fuel gets the largest market share based on a multinomial-logit model. Electricity demand is met by the power generation sector, which in turn has a demand for energy carriers. Climate policy is modelled by introducing a carbon tax based on the carbon content of the fuels, thus changing their relative costs.

For the production of bioenergy (or biochemicals), the entire supply chain from land availability, biomass production and conversion to energy carriers and chemicals is modelled. The yields of energy-crops and land availability are taken from the IMAGE model and are based on the methodology used by Hoogwijk *et al.* (2005). Biomass can be grown on *abandoned agricultural land* or *other natural lands* which excludes land used by urban developments, agriculture, natural forests and unsuitable lands. Land availability and crop yields on different land types determine the available biomass resource. As more biofuels are used, energy crops are expanded onto less productive lands, increasing production costs and creating a cost-supply curve. Primary biomass can also be supplied by residues whose potential is exogenously set based on a literature review (Berndes et al., 2003).

Biomass can be converted into solid or liquid secondary energy carriers. Potential bioenergy carriers include Fischer-Tropsch (FT) diesel, wood-based ethanol or methanol, maize ethanol, wheat ethanol, sugar ethanol or oil crop biodiesel. The final makeup of liquid biofuels is determined based on the relative cost of each of the above routes, where the cheapest route gets the largest market share. Solid biofuels can be produced from dedicated energy crops as well as residues. The techno-economic parameters for biomass conversion technologies used in the TIMER model are shown in Table 5.1. Literature sources indicate a large range in techno-economic parameters, especially for future values of conversion efficiency and investment costs. Pessimistic values reported in literature are investigated in the scenario analysis and shown in brackets in Table 5.1.

For a more detailed description of how the TIMER model represents the energy system, see van Vuuren *et al.* (2014). For a detailed description of the energy demand functions, see Daioglou *et al.* (2012), Girod *et al.* (2012), Daioglou *et al.* (2014) and van Ruijven *et al.* (2016).

5.2.3. Scenarios

In this study we use the TIMER model in order to do a detailed investigation on the contribution of bioenergy or biochemicals to long-term emission reductions of the energy system. We assess how much they can contribute to total demand, where they are used and how their use is affected by assumptions on primary availability and techno-economic parameters of biomass conversion. Following, we look into how competing uses may affect its overall effectiveness in reducing emissions.

The role of biomass in the energy system is context dependent: For instance, the question of how effective biofuels are in transport depends on alternative fuel options and technologies, total transport energy demand, and the cost and efficiency of conversion technologies to produce the biofuels. These factors further depend on key interrelationships within the energy system, but also on uncertain developments in each demand sector regarding future energy demand and the costs of different technologies. Our analysis, therefore, needs to be done in the context of a baseline scenario. Based on this baseline, we run a number of scenarios to investigate the effect of key uncertainties concerning biomass availability and its conversion (*System Bioenergy Scenarios)*. In order to assess the effectivness of different biomass uses and how competition may limit this, we run a set of scenarios where bioenergy is limited to a specific end-use, including biochemicals (*BioSector scenarios*). We compare all projections to a *counterfactual* scenario that assumes no use of biomass at all. The complete list of scenarios is:

1. **Baseline:** All end use sectors compete for biomass. Economic and demographic projections are based on the OECD Environmental Outlook baseline (OECD, 2012).

The main assumptions and projections of this scenario are described in section 5.2.5.

2. **System bioenergy scenarios**
   I. *BioLowPot:* Same as *Baseline* but with half land and residue availability.
   II. *BioLowTech:* Same as *Baseline* but with pessimistic parameters for biomass-to-bioenergy conversion technologies (Table 5.1).
3. **Sectoral bioenergy scenarios:** Potential and techno-economic assumptions same as *Baseline* scenario. Collectively referred to as *BioSector* scenarios.
   I. *BioBuildings:* Bioenergy is only used in the buildings sector. This includes the residential and service sectors, where it may be used as a heating or cooking fuel.
   II. *BioNon-energy:* Biomass is only used as a feedstock or process fuel for the production of bulk chemicals such as ethylene, ammonia, methanol, waxes and lubricants (Biochemicals).
   III. *BioElectricity:* Biomass is used for electricity production (which may then be used in energy consuming sectors). This option also allows for bioelectricity with carbon capture and storage (BECCS).
   IV. *BioIndustry:* Bioenergy is only allowed in the industry sector. This option also allows for BECCS – as part of cement, steel and heavy industry production processes.
   V. *BioTransport:* Bioenergy is only allowed in the transport sector (biofuels).
4. **NoBio:** This is a counterfactual to the baseline where bioenergy is not allowed in the energy system. It acts as the reference case to which all other scenarios are compared in order to investigate the effect of bioenergy use.

We run all cases described above with carbon taxes ranging from 0 to 700 US$$_{2005}$/tC, applied to the carbon content of all energy carriers used within the entire system. As these taxes increase, the competitiveness of bioenergy changes in different sectors as each sector has varying emission abatement or fuel substitution possibilities. The experiments thus provide insight into the marginal energy choices and emission reduction potential of each sector for different tax levels. It is assumed that the carbon tax is applied instantaneously in 2015 and remains constant for the entire simulation period. The model outcomes induced by these taxes are presented in cumulative terms for the period 2015 to 2100.

The *BioSector* scenarios (and all tax scenarios) are stylised scenarios in the sense that they are not intended to show expected developments of the energy system, but rather to highlight potentials and feedbacks under specific circumstances. Instead of looking at the *optimal mix* of bioenergy use, we conduct a systematic analysis of bioenergy and its specific uses.

Table 5.1. Technical and cost parameters of the TIMER model for different biofuel production routes[27,28]. Pessimistic data used in scenario analysis shown in brackets.

	Year	FT Diesel	Wood Ethanol	Wood Methanol	Maize Ethanol	Wheat Ethanol	Sugar Ethanol	Oilcrop Biodiesel
					%			
Conversion efficiency[29]	*Present*	40.5	40.7 (34.9)	60.0 (48.0)	53.1	51.1 (48.8)	45.4[30]	45.2 (33.8)
	2050	48 (40.5)	49.0 (34.9)	57.0 (48.0)	59.0 (53.1)	54.3 (48.8)	54.9 (45.4)	47.6 (33.8)
	2100	51 (40.5)	52.0 (34.9)	57.0 (48.0)	64.2 (53.1)	58.4 (48.8)	65.3 (45.4)	47.6 (33.8)
					$\$_{2005}/kW_{biofuel}$			
Investment costs[31]	*Present*	1961 (2199)	1683 (2536)	1024 (1490)	551 (755)	662 (739)	535 (804)	689 (1299)
	2050	1931 (2160)	1655 (2527)	487 (742)	537 (737)	651 (732)	435 (592)	683 (1295)
	2100	1895 (2146)	1597 (2527)	386 (576)	537 (737)	651 (732)	398 (589)	683 (1294)
					% Of Investment Cost			
O&M costs	*Constant*	1.8	2.3	2.4	3.6	3.2	5.5	4.8
					$GJ/GJ_{biofuel}$			
Electricity demand[32]	*Present*	-	0.12	0.07	0.02	-	-0.01	-
	2050		0.08	0.002			-0.06	
Heat demand	*Present*	-	-	-	0.55	0.37	-	0.04
	2050					0.3		
					$\$_{2005}/GJ_{biofuel}$			
Co-product benefits[33]	*Constant*	0.9	1.6	-	3.0	3.4	0.4	1.3

Table 5.1. Technical and cost parameters of the TIMER model for different biofuel production routes[27,28]. Pessimistic data used in scenario analysis shown in brackets. (continued)

	Year	FT Diesel	Wood Ethanol	Wood Methanol	Maize Ethanol	Wheat Ethanol	Sugar Ethanol	Oilcrop Biodiesel
				***kgC/GJ**$_{biofuel}$*				
Process emission[34] factor	*Present*	-	5.4	3.2	7.5	4.4	-	0.5
	2050		2.4	0.1	6.0	2.9		0.4

References: (Hamelinck & Hoogwijk, 2007; Macedo et al., 2008; Chum et al., 2011; Seabra & Macedo, 2011; Gerssen-Gondelach et al., 2014).[33,34]

27 Data shows that installations with high capacities have lowest costs and highest efficiencies, and vice-versa for small capacity installations (Gerssen-Gondelach, 2014). Unless otherwise stated, default values of table are based on average capacities, pessimistic values based on small capacities.

28 For *Investment Costs*, and *Process Emission Factor*, parameters may vary across regions. Global averages are presented.

29 Based on Higher Heating Value. Future improvements largely based on increased capacity.

30 Studies for autonomous distilleries producing only ethanol shows current ethanol yields at 86.3 $l_{ehtanol}/t_{cane,wet}$ and future yields at 91 $l_{ethanol}/t_{cane,wet}$. We convert to energy terms assuming a sugarcane HHV of 4.5 $MJ/_{kgcane,wet}$.

31 Projections are based on endogenous learning-by-doing. According to the projections, wood-methanol has the largest cost reductions since it is the preferred technology.

32 Electricity and heat demand is allocated to production of fuel, i.e. no allocation to possible by-products and based on values from Hamelinck *et al.* (2007). No values for electricity or heat requirement quoted for FT diesel. Sugarcane ethanol co-generates electricity from surplus bagasse.

33 Based on sale of co-products such as glycerin, animal feed and co-generated electricity in the case of sugarcane ethanol. Price of electricity based in TIMER projections.

34 Emission of conversion process only, no land use emissions included. Based on electricity and heat demand multiplied by emission factors of electricity and heat as projected by the TIMER model.

5.2.4. Indicators

For each scenario, we calculate the differences in sectoral or total (sum of all sectors) emissions with respect to the *NoBio* scenario. The *Total Cumulative Emission Change (TCEC)* indicates the sectoral and total emission changes due to different uses of biofuels. It is calculated via equation (5.1).

$$TCEC_S = \sum_{2015}^{2100} Emis_{S,Scen} - \sum_{2015}^{2100} Emis_{S,NoBio} \tag{5.1}$$

Where *Emis* is the annual CO_2 emissions, *S* denotes the emitting sector (including total) and *Scen* refers to the specific scenario. The marginal effects of the carbon tax are captured by the *Marginal Cumulative Emissions Change (MCEC)*. This is the value for the TCEC by running the sectoral scenarios for different carbon taxes. It is described by equation (5.2).

$$MCEC_{Scen,S,tax} = \left[\sum_{2015}^{2100} Emis_{S,Scen}\right]_{tax} - \sum_{2015}^{2100} Emis_{S,NoBio} \tag{5.2}$$

The MCEC shows emission reductions due to changes in the energy system as a whole. Thus, in addition to an increase in biomass use, it also includes emission reduction methods such as fuel switching to clean(er) fuels and structural changes leading to reduced demand. In order to correct for this and to be able to isolate the contribution of biomass, the *Bioenergy Marginal Cumulative Emissions Change (BMCEC)* is also calculated. This compares the cumulative emission change of each scenario at different carbon taxes with respect to the *NoBio* case with the same tax. BMCEC is described by equation (5.3).

$$BMCEC_{Scen,S,tax} = \sum_{2015}^{2100} Emis_{S,Scen,tax} - \sum_{2015}^{2100} Emis_{S,NoBio,tax} \tag{5.3}$$

Note that at a 0 tax level, *TCEC = MCEC = BMCEC*. Finally, in order to determine the effectiveness of bioenergy at reducing total emissions, we determine total emission reductions (due to bioenergy) per unit bioenergy use. This effectiveness changes across carbon taxes as bioenergy/biochemicals substitute different marginal fuels or as abatement technologies such as BECCS become cost-effective:

$$BioEff_{Scen,total,tax} = \frac{-BMCEC_{Scen,total,tax}}{Cumulative\ Bioenergy\ Use_{Scen,total,tax}} \tag{5.4}$$

5.2.5. Baseline projections

The baseline assumptions (population, economic growth and primary potential of energy sources) are based on the OECD Environmental Outlook (OECD, 2012). In this baseline, the total potential of primary woody biomass and residues in 2050 is projected to be 174 EJ_{prim}/yr and 72 EJ_{prim}/yr, respectively. By 2100 these increase to 299 EJ_{prim}/yr and 81 EJ_{prim}/yr. These increases in primary potential are driven by increased yields of woody and food crops, changes in land availability and assumed increases in residue availability (Berndes et al., 2003; Hamelinck & Hoogwijk, 2007; van Vuuren et al., 2009a).

Key projections of this baseline are shown in Table 5.2. The ten-fold increase in economic activity coupled with an increasing population leads a secondary energy demand of approximately 920 EJ_{Sec}/yr in 2100. The overall increase in energy demand coupled with resource scarcity drives up the projected energy prices as seen by the increase in the price of oil, gas and, to a lesser extent, coal and primary biomass. Note that all these prices are determined endogenously (see section 5.2.2). The relatively constant price of coal is due to its large resource base.

Table 5.2. Key indicators of the baseline. Prices of primary energy carriers based on projections of TIMER.

Year	Gross World Product (Trillions $\$_{2005}$)	World Population (Millions)	Price of Oil ($\$_{2005}/GJ_{Prim}$)	Price of Coal ($\$_{2005}/GJ_{Prim}$)	Price of Gas ($\$_{2005}/GJ_{Prim}$)	Price of Biomass ($\$_{2005}/GJ_{Prim}$)
2010	50	6 927	8.2	1.6	3.4	4.5
2020	72	7 691	9.9	1.8	3.8	4.3
2030	100	8 321	11.0	2.1	5.4	4.5
2040	137	8 810	11.4	2.2	6.2	5.0
2050	182	9 154	11.9	2.2	6.4	5.3
2060	240	9 502	14.5	2.2	6.9	5.5
2070	308	9 683	16.7	2.2	7.7	5.8
2080	387	9 725	18.3	2.3	8.5	6.1
2090	473	9 661	18.9	2.3	9.9	6.5
2100	565	9 555	19.6	2.3	10.5	6.6

Figure 5.1 shows the development of secondary energy demand (a) and emissions (b) per sector for the baseline. We also show the total electricity produced in order to highlight its important role in future energy systems. Secondary energy demand is driven by large increases in the buildings and transport sectors, which together account for almost two-thirds of the total demand. The baseline projection shows that both non-energy and industry see modest growth, which flattens out towards the end of the century.

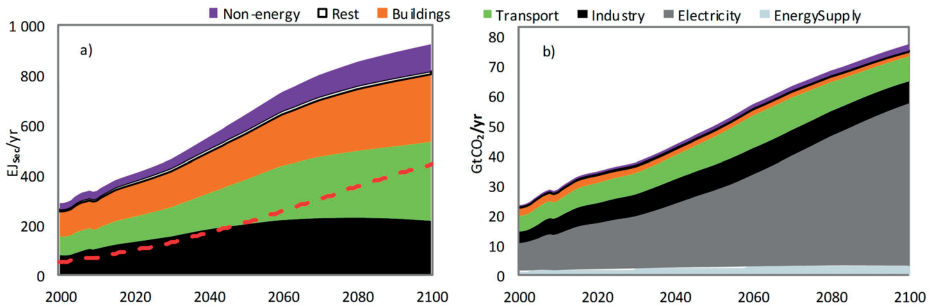

Figure 5.1. Baseline scenario. (a) Global secondary energy demand per sector and total electricity demand (dashed red line). (b) Energy-system emissions per end-use sector and electricity generation.

The results show that in the baseline oil loses its dominant position in the second half of the century, making up only 19% of total secondary energy use (detailed results shown in Table 5.6 in the Appendix, baseline scenario). However, it is still widely used in transport and industry. Gas, bioenergy and coal represent 12%, 18% and 6% of all secondary energy use. Bioenergy use is driven by its competitiveness with oil and gas, leading to significant use in the transport, buildings and non-energy (biochemicals) sectors, which have many oil and gas-based energy functions. By 2100 it is projected that over 40% of the secondary energy demand is due to electricity demand used significantly in buildings, industry and transport. Electricity is increasingly generated by coal which makes up almost 70% of the fuel share by 2100.

Total emissions are projected to increase from approximately 31 $GtCO_2$/yr today to 77 $GtCO_2$/yr in 2100. Most of the emission increase is projected to come from coal-based electricity which by 2100 is responsible for almost 54 $GtCO_2$/yr. The transport sector, being the major energy demand sector, is the second main contributor to emissions at 8 $GtCO_2$/yr, or 11% of total emissions in 2100. In the latter part of the century, a shift towards electric transport (driven by the rapid increase in oil prices) means that despite an increase in energy demand for transport, the annual emissions (at point of consumption) stabilise and decrease slightly towards the end of the century. Heavy industry is the third largest emitter (7 $GtCO_2$/yr in 2100) due to its large size and significant use of coal. Fuel use in the non-energy, buildings and 'rest' sectors contribute very little to global emissions either because they are projected to depend mainly on electricity, the energy use of the sectors is small or, in the case of non-energy, not all fuel use leads to emissions. Due to increased electrification as well as bioenergy use, the buildings sector is projected to reduce its direct emissions.

5.3. Results

In the following sections, we outline the results of the scenario analysis. Quantitative results for all scenarios are summarised in the Appendix.

5.3.1. Baseline and uncertainty scenarios

In the *NoBio* scenario, total cumulative CO_2 emissions are 5099 $GtCO_2$ while in the *Baseline* scenario these are lower at 4652 $GtCO_2$, representing a 9% decrease in emissions due to bioenergy. This difference mainly comes from the transport and buildings sectors; here emissions are projected to be 26% and 50% lower, respectively due to bioenergy use. This is an absolute reduction of 267 GtCO2 and 170 $GtCO_2$ for transport and buildings, respectively. Emissions from the energy supply sector increase from 174 $GtCO_2$ (*NoBio*) to 237 $GtCO_2$ (*Baseline*) due to the production of bioenergy.

In the *Baseline* scenario, the use of bioenergy is projected to be 74 EJ_{Sec}/yr in 2050 and 170 EJ_{Sec}/yr in 2100, or 18% of total secondary energy demand. This is approximately 46% and 70% of the primary potential in 2050 and 2100, respectively. Energy crops (mostly woody) account for 71% and 79% of primary biomass in 2050 and 2100, respectively, the rest coming from residues. This leads to a land requirement of 209 Mha in 2050 and 462 Mha in 2100. From the total bioenergy use, 69% is used in the transport sector, 19% in buildings, non-energy accounts for 11% and 1% is used for electricity production.

As shown in Figure 5.2 (more details are provided in Table 5.6 in the Appendix), in the *BioLowPot* scenario where biomass potential is halved, total bioenergy use is limited to 118 EJ_{Sec}/yr. This affects energy use and emissions of transport, with negligible changes in buildings and non-energy. Total cumulative emissions with respect to *NoBio* decrease by 7% (Table 5.3). For the *BioLowTech* scenario, the changes are similar but less pronounced, which shows that the baseline projections are more sensitive to the overall biomass availability than the techno-economic parameters. In this case, total cumulative emissions with respect to *NoBio* decrease by 8%.

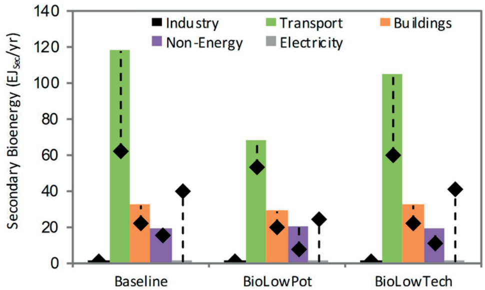

Figure 5.2. Sectoral bioenergy use in 2100 for the Baseline, BioLowPot and BioLowTech scenarios. The dashed black lines show the effect of a 700$\$_{2005}$/tC tax.

Table 5.3. Sectoral and Total cumulative emission (2015-2100) as well as BMCEC for NoBio, Baseline, BioLowPot and BioLowTech scenarios, with and without a 700 $\$_{2005}$/tC tax. Note: Table does not contain energy supply emissions (see footnote 35).

	Industry	Transport	Buildings	Non-energy	Electricity	Rest	Total
				Cumulative Emissions ($GtCO_2$)			
NoBio	696	1021	340	118	2707	43	5099[35]
Baseline	680	754	170	108	2661	43	4652
BioLowPot	681	873	179	108	2676	43	4766
BioLowTech	680	803	168	108	2668	43	4699
With tax:							
NoBio + tax	335	662	251	52	267	24	1713
Baseline + tax	324	581	142	38	-313	20	1019
BioLowPot + tax	326	585	139	44	-108	22	1189
BioLowTech + tax	324	574	141	41	-343	23	991
				BMCEC ($GtCO_2$)			
Baseline	-16	-267	-170	-11	-46	0	-447
BioLowPot	-14	-148	-161	-10	-31	0	-332
BioLowTech	-16	-218	-172	-10	-39	0	-400
With tax:							
Baseline + tax	-11	-81	-109	-15	-580	-4	-694
BioLowPot + tax	-9	-77	-112	-8	-375	-2	-524
BioLowTech + tax	-11	-88	-110	-11	-610	-1	-722

To simulate significant emission mitigation efforts, we apply a 700$\$_{2005}$/tC tax on the cost of energy carriers. The energy system reduces emissions via fuel switching, reduced demand, or adoption of technologies such as carbon capture and storage. Cumulative emissions for the *NoBio+tax* case reduce to 1737 $GtCO_2$. The *Baseline+tax* scenario can further reduce emissions to 1019 $GtCO_2$ via the increased use of bioenergy. While all sectors reduce emissions due to bioenergy and biochemical use, there is a huge change in the electricity production sector. At high tax levels, BECCS becomes an important mitigation technology leading to large emission reductions in this sector. Similar dynamics but to a lesser extent are seen in the *BioLowPot+tax* scenario whose cumulative emissions are 1189 $GtCO_2$. Interestingly, in the *BioLowTech+tax* scenario, the cumulative emissions are lower than the *Baseline+tax* scenario (991 $GtCO_2$) as more negative emissions due to electricity with BECCS are achieved. Reduced possibilities to produce liquid biofuels increase the availability of biomass for electricity

[35] Included in the Total but not shown in this table are the emission changes in the energy supply sector. These are 174 $GtCO_2$ *(NoBio),* 237 $GtCO_2$ *(Baseline),* 206 $GtCO_2$ *(BioLowPot)* and 229 $GtCO_2$ *(BioLowTech)*.

generation. The effectiveness of bioenergy and biochemical uses under competing possibilities is the focus of the remainder of this chapter.

5.3.2. BioSector scenarios

By systematically limiting bioenergy use to a specific end-use sector, we can investigate the indirect effect of fossil fuel leakage between different end-use sectors. Figure 5.3 shows the TCEC for the *Baseline* and each of the cases when bioenergy use is limited to a single sector (*BioSector*). In *BioIndustry* and *BioTransport*, much of the expensive oil in these sectors is easily replaced by bioenergy. As the displaced oil is still too expensive to be used in the remaining sectors, leakage is limited. Furthermore, bioenergy in transport also reduces total electricity demand leading to a small reduction in the electricity sector as well, while the large production of liquid biofuels leads to a significant increase in energy supply emissions. For the *BioBuildings* case oil and gas are replaced leading to leakage towards electricity and transport. For *BioNon-energy* bioenergy primarily replaces gas (and smaller amounts of coal and oil). This leads to more oil use in transport (increasing its emissions), and more gas use in electricity (decreasing its emissions by replacing coal). Also, the large decrease in overall gas demand leads to significant reduction in energy supply emissions. The overall reduction of the non-energy sector is low because of its small size, and specifically for this sector the carbon contained in fossil fuels is not necessarily emitted and may be stored in the form of plastics and chemicals (see section 5.2.1). In the *BioElectricity* case, there is some leakage of oil towards transport and coal towards industry. These however only partially counteract the large emission reduction in the electricity sector.

In almost all scenarios, the transport sector shows emission increases due to leakage of fossil fuels induced by bioenergy use elsewhere. This sector is quite large and depends heavily on oil and to a lesser extent on gas, which tend to be the marginal fuels replaced in the rest of the energy system. In the cases where coal or gas are replaced, the electricity or industry sectors accept the leaked fuel.

When looking at the emissions of specific sectors, Figure 5.3 also shows how the sectoral emission reduction potential may be affected by competing uses of bioenergy. As expected, for any given sector, its emission reductions are greater in the *BioSector* than in the *Baseline* scenarios (as the availability of bioenergy is not shared with the rest of the energy system or it does not accept leaked fossil fuels). This can be seen best for the electricity sector where bioenergy availability actually decreases the cumulative emissions by 46 $GtCO_2$ in the *Baseline* case (with respect to *NoBio*), while in *BioElectricity* it reduces by 217 $GtCO_2$. Total emissions reduction, however, is largest in the *Baseline* case where both transport and buildings can mitigate emissions significantly.

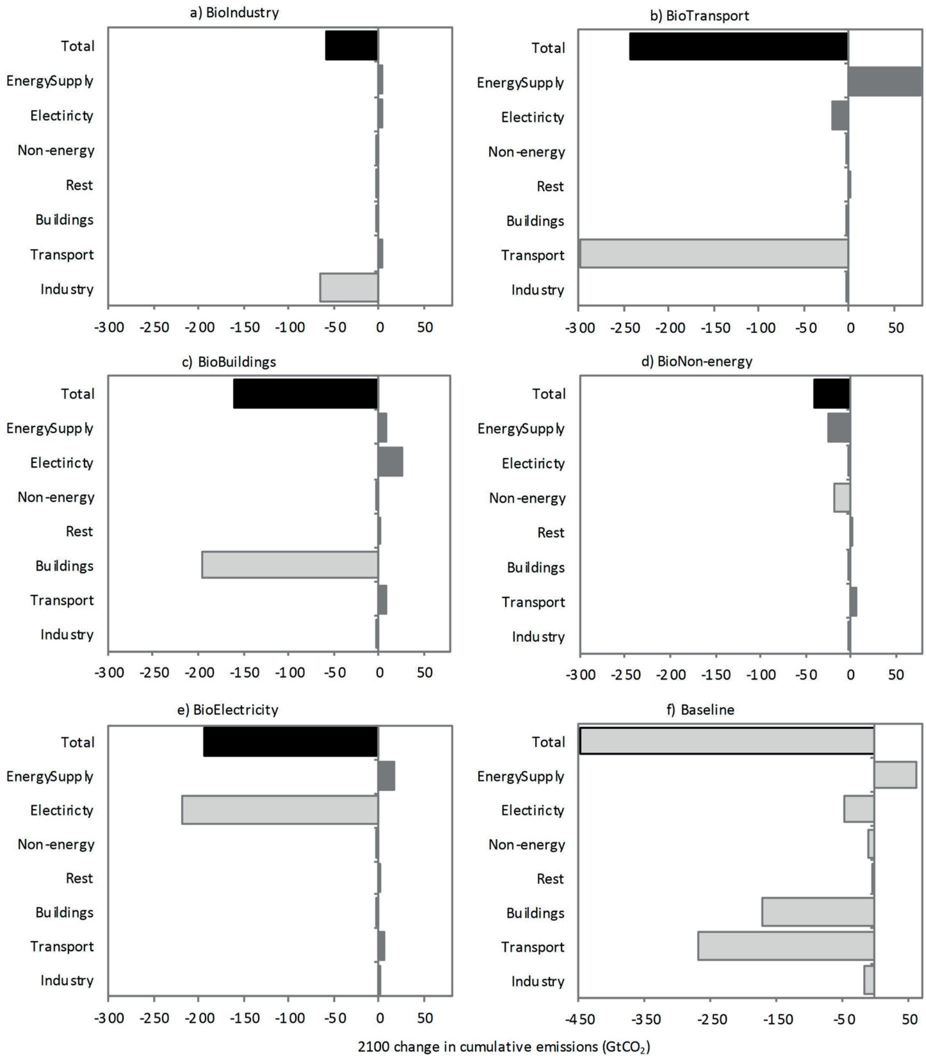

Figure 5.3. TCEC in GtCO2 per sector and total. Results for scenarios (a) BioIndustry, (b) BioTransport, (c) BioBuildings, (d) BioNon-energy, (e) Bioelectricity, (f) Baseline. A negative value means an emissions reduction. Note different scale for (f).

5.3.3. Marginal emission changes

Figure 5.4 shows the marginal sectoral emission changes (MCEC and BMCEC) between *NoBio* and *Baseline* as the carbon tax increases. Detailed results on energy use for the baseline at all tax levels are shown in Table 5.7 the Appendix. The MCEC shows that as carbon tax increases, a very large contribution eventually comes from the power sector. This is in contrast with low tax levels where emission reductions come from transport and buildings. The power sector has the largest abatement potential for three reasons; (i) it has the largest demand for energy and thus largest potential for substitution, (ii) it is the largest emitter due to the heavy use of coal, and (iii) it can adopt carbon capture and storage (CCS) technologies at high carbon prices (greater than 100$\$_{2005}$/tC). While at high tax levels, transport, buildings and industry also contribute to the mitigation potential, their contribution to total mitigation is much smaller than the power sector.

The BMCEC (bottom panel, Figure 5.4) shows that bioenergy contributes to the marginal emission reduction in buildings and transport, however this decreases with increasing taxes. As the tax level increases, the share of bioenergy use increases in non-energy, electricity and to a lesser extent industry (see Table 5.7 in the Appendix). Increased use of bioenergy in these sectors means that its use decreases in buildings and transport. The main reason is that bioenergy is an attractive substitute (especially in combination with CCS) for coal in the electricity, industry and non-energy sectors. Buildings and transport instead shift towards other energy carriers (gas and electricity respectively) and also reduce total demand at high carbon prices.

Figure 5.4. Marginal cumulative emission reductions per sector with increasing carbon taxes on the baseline scenario. Panel (a) shows the MCEC as calculated by Eqn (5.2). Panel (b) shows the BMCEC as calculated by Eqn (5.3). MCEC includes emission reductions due to all fuel switching operations including bioenergy, efficiency improvements, reduced demand, and fossil fuel use with carbon capture and storage. BMCEC shows the contribution of bioenergy to the MCEC.

At tax levels above 100 $\$_{2005}$/tC, biomass use with carbon capture and storage (BECCS) in industry and electricity starts becoming increasingly important. This leads to the possibility of negative emissions (see Table 5.8). Overall, as the carbon tax increases to 700 $\$_{2005}$/tC), secondary energy demand decreases to 640 EJ_{Sec}/yr in 2100. The fraction of bioenergy for non-electric uses decreases from 18% to 16%. At high taxes (greater than 500 $\$_{2005}$/tC), biomass and other non-fossil energy sources make up over 80% of electricity sources.

Table 5.4 shows the change in the energy system cumulative emission (MCEC) due to taxes for the *NoBio, Baseline* and *BioSector* scenarios. As expected, the *NoBio* scenario has the lowest emission reductions. At low tax levels the emission reduction is greatest for the *Baseline.* However, at taxes greater than ≈200 $\$_{2005}$/tC, limiting biomass availability to the electricity sector leads to overall greater emission reductions. Since biomass is not shared with transport (as in the *Baseline* case), the electricity sector can further substitute coal and apply CCS technology. It should be noted that TIMER is a simulation model and therefore does not fully optimise bioenergy use. This makes it a useful tool to identify such situations of sub-optimal use.

Table 5.4. Energy System MCEC ($GtCO_2$) under Baseline and BioSector scenarios with increasing taxes.

Scenario	Tax Level				
	0	100	200	500	700
NoBio	0	-1 520	-2 608	-3 254	-3 386
Baseline	-447	-1 915	-3 049	-3 951	-4 080
BioBuildings	-159	-1 648	-2 731	-3 386	-3 518
BioNon-energy	-40	-1 554	-2 638	-3 291	-3 428
BioElectricity	-194	-1 726	-3 246	-4 380	-4 520
BioIndustry	-58	-1 599	-2 677	-3 329	-3 468
BioTransport	-242	-1 720	-2 756	-3 352	-3 477

5.3.4. Emission reduction effectiveness of bioenergy

Table 5.5 shows the effectiveness of bioenergy and biochemicals at reducing emissions, according to equation (5.4), for the *BioSector* and *Baseline* scenarios with increasing taxes. Without carbon taxes, bioenergy is most effective in reducing emissions when its use is limited to electricity production. As shown above, this does not necessarily mean that the emissions are reduced more than in the unconstrained case, but rather that less bioenergy is used for the given reduction. This finding is thus important for scenarios with stringent constraints on biomass supply. *BioNon-energy* has the lowest effectiveness due to cross-sectoral leakage of fossil fuels and low emission reduction potential of that sector. At higher taxes, limiting the use to electricity production provides the greatest emission reduction per unit bioenergy due to the use of BECCS.

The same holds true but to a lesser extent for the *Baseline* case. For *BioTransport* and *BioIndustry*, at higher taxes bioenergy increasingly replaces electricity thus not contributing to direct emission reductions. For this reason the effectiveness of *Bio-Transport* and *BioIndustry* decrease as taxes increase, with *BioIndustry* increasing its effectiveness eventually due to the adoption of BECCS. Interestingly, *BioLowTech* has a more effective use of bioenergy with respect to the *Baseline* at high taxes since pessimistic assumptions on techno-economic parameters reduce the competition between the transport and electricity sectors for bioenergy use.

Table 5.5. Total emission reductions per unit of bioenergy use in all scenarios for carbon tax levels of 0, 300 and 700 $\$_{2005}$/tC.

Tax:	**0**	**300**	**700**
Scenario		$cumMtCO_2/cumEJ_{Bioenergy}$	
Baseline	57	75	90
BioLowPot	57	69	90
BioLowTech	57	54	99
BioBuildings	61	61	62
BioNon-energy	26	23	23
BioElectricity	143	211	211
BioIndustry	82	55	69
BioTransport	51	39	27

5.4. Discussion

This study compares a number of model-based projections in order to assess the possibilities of biomass use for emission mitigation. We have used a long-term global simulation model with detailed representation of the energy system to systematically analyse the implications of bioenergy and biochemicals. Endogenous dynamic projections of demand from an energy function perspective and depletion of energy sources makes the model suitable to assess scenarios of fuel substitution measures. The TIMER model, being a simulation (as opposed to optimisation) model, is well suited to investigate how competing uses may influence the effectiveness of bioenergy use. However, in order to get insights into the robustness of these results under different system representations, such a detailed scenario analysis investigating the uncertainties and trade-offs between different bioenergy uses should be repeated with other energy system models (including optimisation or general equilibrium models).

The GCAM model, an integrated assessment model, has been used to determine the potential biomass uses under stringent climate targets (Luckow et al., 2010). Their baseline runs are very similar in terms of emissions (80 $GtCO_2$/yr compared to 77 $GtCO_2$/yr in this study). Both models show that bioenergy is used in the baseline and become more important in mitigation scenarios. Concerning emissions reduction, Luckow *et al.* (2010) agree that heavy industry and buildings have a limited contribution to emission reductions, which are mainly driven by fuel switching in transport and electricity generation, and if possible, CCS. Even though the models agree on the importance of BECCS at reducing emissions, according to Luckow *et al.* (2010) at tax levels greater than 700 $\$_{2005}$/tC, almost all of the bioenergy is used with CCS. In this study, even at high taxes bioenergy is still used without CCS as a transport fuel, in the *Baseline* scenario. A key difference is that in GCAM the production of liquid biofuels (for transport) with CCS is included as an option, while in TIMER CCS is limited to electricity production and part of the industry sector. Inter-model comparisons have shown that the production of liquid fuels with CCS is also used in other models which allow for this technology (Calvin et al., 2013). Given the possibilities of biorefining (fuels and chemicals) with CCS, the potential of BECCS may be significant over the entire energy system. Given the importance of liquid fuels for transport it is important for further research to focus on the competition between different options which include CCS.

A comprehensive review of studies on leakage of oil due to biofuels has found that depending on assumptions and modelling technique a range between -20% (1 GJ biofuel replaces 1.2 GJ of oil) and 120% (1 GJ biofuel increases oil use by 0.2GJ). However most of the values fall within 30% and 60% (1 GJ biofuel replaces 0.3-0.6 GJ oil) (Smeets et al., 2014). One of the main uncertainties across all studies (including this one) is the elasticity of substitution of different fuels. The study of leakage has focused on economic equilibrium models with a weak representation of physical parameters (demand functions and technologies). This study seeks to offer a descriptive assessment given a technologically detailed energy system simulation model and also accounting for all fossil fuels, as opposed to just oil, and our results are in the range stated above. Our results are in agreement with previous studies stating that a unit of bioenergy does not replace one unit of fossil fuels. This is true for any alternative energy supply option and thus outcomes on net mitigation impacts depend on overall mitigation targets for the entire economy.

A number of aspects of the model have to be highlighted in order to put the results of this chapter in context. Land-use change (LUC) emissions have been included by attaching an emissions factor to crop based primary biomass. Due to the complex and uncertain nature of land-use change, there is a large variance in the related emission factors across studies (Wicke et al., 2012). Our method does not reflect that increasing use of biomass may lead to marginal increases in LUC since we use a constant land emission factor. Coupling this study with detailed land allocation modelling would allow studying the land-based carbon fluxes and emission mitigation (Gillingham et al., 2008; Wise et al., 2009; Havlik et al., 2011; Rose et al., 2012). This would provide an overall picture of the emission implications of bioenergy use when used together with energy system emission studies such as this one. A similar approach could also be made for the effects on water or biodiversity for a better overall assessment of large-scale use of biomass for energy and chemical purposes. Another area of significant uncertainty concerns the availability of residues as a resource for bioenergy. In this study, primary residue potential is based on a literature review and set at 72 EJ_{Prim}/yr in 2050 and 81EJ_{Prim}/yr in 2100. Furthermore, it is assumed that it is available at low price and has no emission effects or feedbacks on agricultural and forestry systems. Due to the important role that residues play in bioenergy and biochemical production (according to our projections 21% in 2100 come from residues), it is important to consistently assess the availability, costs and limits of the large scale use of this resource.

This study investigates the potentials and uncertainties of biomass as a renewable source for energy and chemical purposes, and highlights the sensitivities and dynamics of its emission mitigation possibilities. The following important observations are made:

Bioenergy is likely to play an important role in future energy systems. Under the baseline projections 170 EJ_{Sec}/yr is projected to be used in 2100. Much of this is used in the transport sector where it can easily replace expensive oil. The buildings and non-energy sectors also replace fossil fuels, but to a much lesser extent. Overall, bioenergy use helps reduce baseline cumulative emissions by 9% to 4.7 $TtCO_2$ when compared to a counterfactual baseline with no bioenergy. The results are shown to be sensitive to assumptions for both bioenergy potential and bioenergy production technologies, with the former having a stronger impact on results. Halving the bioenergy potential reduces bioenergy production to around 118 EJ_{Sec}/yr and cumulative emissions increase to 4.8 $TtCO_2$ while adopting pessimistic conversion technologies results in bioenergy production of 156 EJ_{Sec}/yr and cumulative emissions of 4.7 TCO_2.

In the TIMER model, emission reductions from bioenergy use come mostly from the transport and electricity sectors. At taxes greater than 100 $\$_{2005}$/tC, bioelectricity with CCS leads to significant emissions reductions. At a tax level of 700 $\$_{2005}$/tC, overall emissions are projected to be 1 $TtCO_2$. Assuming no bioenergy use, emissions would stand at 1.7 $TtCO_2$ implying that bioenergy can contribute to a further reduction of emissions by up to 40% at high emission taxes. This emission reduction potential is affected if biomass potential is halved (1.2 $TtCO_2$ in 2100). The *LowTech* case with high tax yields emissions slightly lower than the base case due to increased used of bioelectricity with CCS.

Cross-sectoral leakage can reduce the emission reduction potential and depends on what energy carriers biomass substitutes. Any policies aiming at specific biomass uses have to account for the possibility of cross-sectoral leakage. This is driven by the volume and competitiveness of displaced fuels at providing alternate energy services.

This in turn depends on how elastic sectors are at making fuel choices. Non-energy and buildings have the highest leakage rates since displaced coal, gas and oil from these relatively small sectors are easily absorbed in the large electricity and transport sectors. When bioenergy is limited to the transport sector it replaces oil and electricity use. The expensive oil is not readily consumed elsewhere and the electricity sector also reduces its emissions. Bioenergy use in the electricity sector displaces large volumes of coal which cannot be fully absorbed by the remaining sectors. Thus the large reduction in emissions in the electricity sector counteracts any leakage.

Competing uses of bioenergy potentially limit its effectiveness at reducing emissions. The most effective use of bioenergy for emission reduction is in the electricity sector. This is because this sector is projected to increase its share in total emissions due to its large size and use of coal. Furthermore, bioenergy use with carbon capture and storage at high carbon taxes leads to sharp emission reductions. Non-energy uses of biomass do not offer significant emission reductions due to leakage and the fact that part of the carbon content of feedstocks is sequestered in the form of chemicals (for both fossil and biomass feestocks). With increasing carbon taxation, additional emission reductions due to the use of bioenergy mainly come from changes in the electricity generation mix and to a lesser extent from transport, buildings and heavy industry. As carbon taxes increase, transport demands large volumes of bioenergy since it is the most cost-effective substitute for oil. However, this limits its use in the electricity sector where the use of BECCS can lead to greater emission reductions. Further research is needed in order to assess how BECCS in liquid fuel production influences the effectiveness of different bioenergy CO_2 mitigation options.

5.5. Appendix

Table 5.6. Secondary energy carrier share for the NoBio, Baseline, BioLowPot and BioLowTech scenarios, per sector and total in 2100.

		Sector						
		Industry	Transport	Buildings	Non-energy	Electricity	Rest	Total
NoBio	Coal	12%	0%	0%	31%	70%	0%	7%
	Oil	26%	53%	6%	15%	0%	0%	28%
	Gas	8%	22%	18%	45%	4%	56%	21%
	Bioenergy	0%	0%	0%	0%	0%	0%	0%
	Electricity[36]	49%	25%	74%	0%	0%	41%	42%
	Other	3%	0%	1%	9%	26%	3%	2%
	Total (EJ_{sec}/yr)	217	308	273	113	442	12	**924**[37]
Baseline	Coal	12%	0%	0%	25%	68%	0%	6%
	Oil	26%	30%	2%	13%	0%	0%	19%
	Gas	8%	9%	7%	34%	5%	56%	12%
	Bioenergy	0%	37%	12%	18%	0%	0%	18%
	Electricity	49%	23%	76%	1%	0%	41%	42%
	Other	3%	0%	2%	9%	26%	3%	2%
	Total (EJ_{Sec}/yr)	216	315	270	108	442	12	**923**
BioLowPot	Coal	12%	0%	0%	26%	69%	0%	6%
	Oil	26%	38%	2%	12%	0%	0%	21%
	Gas	8%	16%	8%	33%	5%	55%	14%
	Bioenergy	0%	22%	11%	19%	0%	0%	13%
	Electricity	49%	24%	76%	1%	0%	41%	42%
	Other	3%	0%	2%	9%	26%	3%	2%
	Total (EJ_{Sec}/yr)	216	315	270	109	444	12	**923**
BioLowTech	Coal	12%	0%	0%	26%	68%	0%	6%
	Oil	26%	30%	2%	13%	0%	0%	19%
	Gas	8%	13%	7%	34%	5%	56%	13%
	Bioenergy	0%	33%	12%	18%	0%	0%	17%
	Electricity	49%	24%	76%	1%	0%	41%	43%
	Other	3%	0%	2%	9%	26%	3%	2%
	Total (EJ_{Sec}/yr)	216	316	269	109	444	12	**923**

[36] These are in terms of $EJ_{electricity}$, thus represents proportion of electricity produced from each source, not the share of primary energy for electricity production which depends on conversion efficiencies.

[37] This is the sum of all secondary energy use. Electricity is an energy conversion sector and its consumption is listed in individual sectors. Thus the electricity sector is not included in this sum.

Table 5.7. Shares of secondary energy use, total secondary energy use, annual and cumulative emissions in 2100. Baseline scenario.[41]

Sector	Carbon Tax	Share of Secondary Energy Carrier						Total[38]	Annual emissions[39]	Cumulative Emissions
	$\$_{2005}$/tC	%						$EJ_{sec/yr}$	$GtCO_2$	
		Coal	Oil	Gas	BioEnergy	Electricity	Other			
Industry	0	12%	26%	8%	0%	49%	3%	216	7.4	680
	100	14%	25%	8%	0%	49%	3%	192	6.1	518
	200	14%	24%	8%	1%	49%	2%	178	5.0	420
	500	11%	24%	11%	1%	49%	2%	149	3.7	338
	700	9%	24%	12%	1%	50%	2%	146	3.5	324
Transport	0	0%	30%	9%	37%	23%	0%	315	8.4	754
	100	0%	34%	7%	36%	24%	0%	303	8.4	731
	200	0%	38%	7%	31%	24%	0%	294	9.0	724
	500	0%	35%	5%	30%	30%	0%	264	7.3	641
	700	0%	37%	2%	26%	35%	0%	244	6.7	581
Buildings	0	0%	2%	7%	12%	76%	2%	270	1.5	170
	100	0%	3%	6%	12%	75%	2%	246	1.4	155
	200	0%	3%	6%	13%	75%	2%	234	1.2	152
	500	0%	3%	7%	11%	75%	2%	202	1.2	152
	700	0%	3%	7%	12%	75%	3%	188	1.1	142
Non-energy	0	25%	13%	34%	18%	1%	9%	108	2.2	108
	100	8%	16%	43%	22%	1%	10%	86	1.3	78
	200	3%	15%	48%	23%	1%	10%	75	1.0	62
	500	0%	14%	53%	22%	1%	11%	59	0.7	44
	700	0%	13%	45%	31%	1%	10%	53	0.6	38
Electricity[40]	0	68%	0%	5%	0%	0%	26%	442	54.2	2661
	100	35%	0%	12%	1%	0%	51%	403	23.8	1442
	200	19%	0%	12%	2%	0%	67%	384	5.3	446
	500	11%	0%	8%	9%	0%	72%	348	-6.2	-289
	700	11%	0%	9%	12%	0%	69%	343	-8.1	-313

38 This is the sum of all secondary energy use. Electricity is an energy conversion sector and its consumption is listed in individual sectors. Thus the electricity sector is not included in this sum.

39 Only direct emission shown. Emissions due to sectoral electricity use in "Electricity" sector.

40 These are in terms of $EJ_{electricity}$, thus represents proportion of electricity produced from each source, not the share of primary energy for electricity production which depends on conversion efficiencies.

41 This is the share of energy carriers in all non-electric uses and share of electricity in entire energy system.

Rest	0	0%	0%	56%	0%	41%	3%	12	0.4	43
	100	0%	0%	55%	0%	42%	3%	10	0.3	35
	200	0%	0%	54%	0%	42%	3%	9	0.3	31
	500	0%	0%	54%	0%	42%	3%	7	0.2	22
	700	0%	0%	51%	2%	43%	3%	7	0.2	20
Total[41]	0	6%	19%	12%	18%	42%	2%	923	77.2	4652
	100	4%	21%	11%	19%	43%	2%	837	44.3	3184
	200	3%	22%	12%	18%	43%	2%	790	24.7	2050
	500	2%	21%	11%	17%	45%	2%	682	10.0	1148
	700	2%	21%	10%	16%	47%	2%	640	7.0	1019

Table 5.8. Sectoral and Total cumulative emissions ($GtCO_2$), total energy use, and sectoral fraction of bioenergy. For all scenarios and carbon taxes.

	Tax	Cumulative $GtCO_2$									Energy Use	
		Sector										
Scenario	$\$_{2005}$/tC	Industry	Transport	Buildings	Rest	Non-energy	Electricity	Energy Supply	BECCS[42]	Total	Total EJ_{Sec}/yr	Bioenergy, %
NoBio	0	696	1021	340	43	118	2707	174	0	5099	924	0%
	100	546	964	312	35	87	1470	164	0	3579	832	0%
	200	443	911	296	32	70	591	149	0	2491	782	0%
	500	353	750	263	25	54	273	128	0	1845	664	0%
	700	335	662	251	24	52	267	121	0	1713	631	0%
Baseline	0	680	754	170	43	108	2661	237	0	4652	923	18%
	100	518	731	155	35	78	1442	225	0	3184	837	19%
	200	420	724	152	31	62	446	216	166	2050	790	18%
	500	338	641	152	22	44	-289	239	559	1148	682	17%
	700	324	581	142	20	38	-313	227	574	1019	640	16%
BioBuildings	0	692	1028	144	43	115	2733	183	0	4939	272	16%
	100	546	971	135	35	86	1505	173	0	3451	248	16%
	200	444	917	124	32	70	623	157	0	2367	234	17%
	500	356	759	107	25	54	277	136	0	1713	204	17%
	700	338	668	100	24	52	270	130	0	1581	191	18%
BioNon-Energy	0	695	1027	339	43	100	2705	150	0	5059	108	29%
	100	546	970	311	35	66	1476	139	0	3545	81	39%
	200	444	917	294	32	48	602	124	0	2461	70	45%
	500	357	759	262	25	30	275	101	0	1808	52	60%
	700	341	669	249	24	26	268	93	0	1671	50	64%
Bio-Electricity	0	697	1027	339	43	117	2490	191	0	4905	440	5%
	100	545	970	312	35	86	1234	190	19	3372	403	10%
	200	446	920	295	32	69	-103	194	628	1852	385	14%
	500	357	771	264	25	52	-959	208	1199	719	352	26%
	700	342	680	253	24	51	-971	201	1204	579	346	27%
BioIndustry	0	631	1023	338	43	118	2711	177	0	5041	216	7%
	100	442	968	311	35	87	1487	169	12	3500	192	9%
	200	355	914	294	32	70	601	156	19	2421	177	10%
	500	270	755	262	25	53	272	133	25	1770	151	11%
	700	248	666	250	24	52	265	125	32	1631	150	10%

[42] BECCS are negative emissions since they sequester atmospheric carbon captured by biomass. BECCS is not included in the *Total* since it is accounted in either *Electricity* or *Industry.*

Bio-Transport	0	695	723	339	43	116	2687	252	0	4857	315	40%
	100	546	706	312	35	87	1459	234	0	3379	304	37%
	200	444	701	295	32	70	593	208	0	2342	293	33%
	500	355	599	263	25	54	273	178	0	1747	264	33%
	700	336	521	251	24	53	267	171	0	1622	252	33%

6

The role of biomass and bioenergy in the mitigation strategies of two different integrated assessment modelling frameworks

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Abstract

Integrated assessment models (IAMs) have highlighted the importance of biomass and bioenergy for mitigation scenarios. These models, however, supply and use bio-energy in different ways, based on the diverse representations of the energy and land systems they adopt. This chapter attempts to assess how the differences in structure and scope of the IAMs MESSAGE-GLOBIOM and IMAGE affect the biomass strategies selected in baseline and mitigation scenarios. For this, we first describe how the land and energy systems are represented in each modelling framework. Next, we prescribe similar scenarios in both IAMs in order to investigate the energy, land and greenhouse gas emission effects of bioenergy use. The two systems show striking similarities and differences related to their key assumptions. The models agree on the deployment rates of lignocellulosic biomass of 104-123 EJ_{sec}/yr by 2100 in the mitigation scenarios, largely used as second generation biofuels, with an important role for bioenergy combined with carbon capture and storage. Yet, clear differences are observed in the production routes and final uses of bioenergy. Particularly important are the ability of each model to take advantage of trade-offs in land use patterns, the availability of low carbon technologies and efficiency measures, and the speed at which these technologies can be deployed. This comparison highlights that though different IAMs may agree on an aggregate level, comparing their specific decisions is crucial in order to better understand the potential role and policy implications of bioenergy in climate mitigation.

6.1. Introduction

Bioenergy is often mentioned as a potential substitute of fossil fuels, particularly if stringent climate targets are to be met (Chum et al., 2011; Clarke et al., 2014). When assessing its use and emission mitigation potential it is important to account for multiple supply and final use possibilities which affect both the energy and land use systems. Primary sources include purpose-grown energy crops, biomass from forests and residues from various economic activities (agriculture, forestry, waste streams). Purpose-grown biomass requires land for the production of crops or feedstock, which alters the current and future land-based carbon stocks via direct or indirect land-use change (LUC/iLUC) and competes with other activities such as food, feed and fibre production, biodiversity protection or land preservation. From an energy system perspective, bioenergy can replace fossil fuels either directly or in the provision of final uses (transport, heat, electricity or as a feedstock for chemicals). Its emission mitigation potential depends on its competitiveness in each sector, the fossil fuels it replaces, the speed at which it can be scaled up and its potential use with carbon capture and storage (BECCS).

A useful tool to assess the interactions and the trade-offs between different bioenergy strategies are the so-called Integrated Assessment Models (IAMs). These models generally describe both the land and energy systems and their dynamic changes over time. Previous IAM studies have quantified the global long-term potential of bioenergy and the effect of its increased use on emissions by assessing its impact on energy and/or land systems (van Vuuren et al., 2007; Gillingham et al., 2008; van Vuuren et al., 2009a; Luckow et al., 2010; van Vuuren et al., 2010a; Havlik et al., 2011; Klein et al., 2011; Popp et al., 2012; Rose et al., 2012; Calvin et al., 2013; Popp et al., 2014; Rose et al., 2014).

Recent efforts have improved the representation and interaction between human and natural systems in IAMs, providing increased insight into the processes of global environmental change and the impacts of response strategies. As IAMs have used various approaches to deal with this, they differ with respect to the scope, the theoretical framework (i.e. process, economic, etc.) and the level of detail at which different systems are represented. Model comparisons have focused on understanding how IAMs deploy and use bioenergy, especially in mitigation scenarios, looking into the implications for mitigation costs and land-use (Rose et al., 2012; Luderer et al., 2014; Kriegler et al., 2014; Popp et al., 2014). Though these studies give a useful overview of the differences in IAM projections and highlight the importance of certain technologies in order to make climate targets feasible, they generally do not explain the different constraints and dynamics within which each IAM operates. As a result they provide limited understanding of the strategies –and inherent assumptions– of different IAMs, thus offering few insights concerning the practical aspects of biomass deployment.

This study seeks to further improve the understanding of biomass and bioenergy systems and their relation to climate policy by conducting a more detailed comparison of the structures and results of two selected IAMs. We review the representation of bioenergy supply and demand and compare the model projections for baseline scenarios using a set of harmonised assumptions (population and GDP development, as well as a storyline guiding the scenario framing). Following, we investigate the land and energy system choices each model makes in order to meet a 2°C climate target. We aim to highlight how differences in the IAMs may affect their results and help point out directions for further model development and evaluation.

6.2. Models investigated

In this study we compare the MESSAGE-GLOBIOM (Messner & Strubegger, 1995; Riahi et al., 2012; Havlik, 2015) and IMAGE (Stehfest et al., 2014) models. Both models describe the energy and land-use systems while adopting different formulations, technology portfolios and mitigation measures; making a comparison of their results and insights relevant. We first review how each IAM deals with different land-use options followed by a description of the energy-system representation and the associated bioenergy routes. The overall model structures and an overview of the key aspects concerning bioenergy for each framework are shown in the Appendix.

6.2.1. MESSAGE-GLOBIOM

The MESSAGE-GLOBIOM framework consists of two model components: (i) an agriculture-forestry-bioenergy partial equilibrium model (GLOBIOM), and (ii) an energy system optimisation model (MESSAGE[43]).

Agriculture-forestry-biomass

The Global Biosphere Management Model (GLOBIOM) is a global recursive dynamic partial equilibrium model of the agricultural and forestry sectors, including bioenergy (Havlik et al., 2011; Lauri et al., 2014; IIASA, 2014; Havlik et al., 2014). The model simulates demand quantities, prices and bilateral trade flows for agricultural and forestry products in perfectly competitive markets at a 30 world region aggregation. The spatial resolution of the supply side relies on the concept of simulation units, which are aggregates of 5 to 30 minute pixels belonging to the same altitude, slope, and soil class and country (Skalský et al., 2008).

[43] Further information on MESSAGE can be found at: https://wiki.ucl.ac.uk/display/ADVIAM/MESSAGE

The model includes six land cover types: cropland, grassland, other natural vegetation land, managed forests, unmanaged forests, and plantations. The model switches from one land cover type to another depending on the relative profitability of primary, by-, and final products. For crops, grass, and forest products alternative production systems are calibrated based on biophysical models such as EPIC (Williams, 1995) while a detailed representation of the livestock sector is also included (Havlik et al., 2014). Forest harvest is divided into commercial and non-commercial roundwood as well as harvest losses. For spatially explicit projections of afforestation, deforestation and forest management change, and the related CO_2 emissions, GLOBIOM is coupled with the G4M model (Kindermann et al., 2006; Gusti, 2010; Kindermann et al., 2011; Gusti & Kindermann, 2011)

Productivity increase occurs both exogenously by technological change assumptions, and endogenously through switching among alternative production systems. GLOBIOM deals with agriculture, forestry and bioenergy simultaneously and consequently different types of land use compete for scarce land resources. The model makes these decisions on land cover and management depending on the relative profitability of each choice with market equilibrium solved by maximising the sum of producer and consumer surplus subject to resource, technological and political constraints.

GLOBIOM is used to project biomass supply curves (incl. forest and short rotation plantation biomass, and forestry residues) conditional on the carbon price, and agriculture, forestry and other land use (AFOLU) marginal abatement cost curves (Havlik, 2015). Consequently the energy system model (described below) emulates decisions based on these possible land configurations.

Energy system

MESSAGE is a systems engineering optimisation model used for medium to long-term energy system planning (Riahi et al., 2012). The model makes choices among a number of energy supply and conversion technologies in order to meet final energy demand while accounting for resource extraction, imports and exports, conversion, transport and distribution. The choices are made in order to meet optimisation criteria (minimisation of costs) while fulfilling exogenously determined final energy demand based on a macroeconomic equilibrium framework (MESSAGE-MACRO) (Messner & Schrattenholzer, 2000). Energy-demand sectors included are industry, feedstocks, residential-commercial and transport. As an optimisation model, MESSAGE has perfect foresight, allows for stranded investments (capital phased out before end of technical/economic lifetime) and when allocating fuels it follows a *winner takes all* principle.

Biomass and bioenergy routes

The biomass potentials and costs are described by GLOBIOM for conventional food crops, short rotation plantations, forest harvest, and forest industry residues. The latter two are determined together with decisions about timber logging and sawmill operations, thus are directly related to forest management. In MESSAGE, bioenergy is subsequently represented by either direct use of solid biomass for heat, or converted to 2nd generation liquid fuels, gaseous fuel, electricity or hydrogen. If competitive, carbon capture and storage technologies (CCS) can be applied on the liquid, electricity and hydrogen production routes.

6.2.2. IMAGE

The Integrated Model to Assess the Global Environment (IMAGE) model has three main components: (i) An agricultural economy equilibrium model, (ii) A biophysical crop growth and land-allocation model, and (iii) a system dynamic energy system model. A detailed description of the model and all its components can be found in Stehfest *et al.* (2014) and at www.pbl.nl/IMAGE.

Agricultural economy

The agricultural economy is represented using the agro-economic computable general equilibrium model MAGNET (Hertel, 1997; Woltjer et al., 2011; Woltjer et al., 2014). The model is driven by exogenous demographic and economic projections which lead to changes in volume and structure of demand for agricultural and livestock commodities. The model also calculates changes in prices, production factors and technological progress[44]. MAGNET uses information from IMAGE concerning land availability, suitability and changes in yields due to climate change or expansion into less productive lands. It is important to note that, when used within IMAGE, the agricultural trade model does not include energy crops, which are modelled separately in IMAGE (described below).

Land allocation and bioenergy potential

The land cover model and terrestrial biosphere model[45] of IMAGE are used to determine spatially explicit (5×5 minute) crop yields, carbon fluxes and nutrient dynamics. Thus, the agricultural and livestock demand from MAGNET lead to spatially explicit land-use change and consequent impacts of carbon, nutrient and water cycles. Once agricultural and pasture lands have been allocated and urban, bio-reserves (forests)

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[44] This includes changes in crop yields due to economic pressures, i.e. intensification.

[45] The terrestrial biosphere in IMAGE is represented by the Lund-Potsdam-Jena model with Managed Lands (LPJmL) model (Gerten et al., 2004; Bondeau et al., 2007).

and unsuitable lands have been excluded, the remaining land can in principle be used for biomass growth.

The land-use maps are used to construct supply curves for primary biomass (energy crops), based on the spatially explicit crop yields together with regional labour and capital costs (Hoogwijk et al., 2009). The availability of residues are linked to the production and intensity of the agriculture and forestry sectors, with ecological and competing uses (traditional fuel use, livestock feed) accounted for. Residues supply curves are constructed by taking into account spatially explicit residue productivity together with labour, operation and transport costs (see Chapter 2).

Energy system

The energy system is represented via a dynamic recursive simulation model, TIMER. Energy demand functions are disaggregated for specific economic sectors (industry, transport, buildings, feedstocks and other) and are driven by increases in welfare. Final energy carriers compete for market shares based on their relative costs while primary energy supply is based on supply curves. For non-renewable fuels, this implies that fuel costs are calculated based on cumulative production, while for renewable energy costs depend on actual production levels. On the demand side, efficiency improvements are based on assumed technology trends (autonomous) as well as changes in fuel prices (price-induced). The model includes dynamics such as learning-by-doing, capital stock inertia (based on capital lifetimes) and bilateral trade of homogenous energy carriers. Being a dynamic recursive simulation model, results are not optimised inter-temporally.

Bioenergy routes

In IMAGE, biomass can be provided from energy crops and residues where the former can only be produced on *abandoned agricultural lands* and *other natural lands*, which exclude forests and unproductive locations. Biomass can be converted to pellets, a portfolio of liquid fuels (ethanol, methanol and diesel), or converted to electricity or hydrogen. BECCS can only be applied with electricity and hydrogen production. Biomass can also be used for non-energy purposes such as bulk chemicals as described in Chapter 4.

6.2.3. Boundary conditions and definitions

In this study bioenergy includes all secondary energy carriers (including electricity and heat) and chemical feedstocks produced from biomass. Energy carriers are aggregated as: solids, liquids, gasses, hydrogen, heat and electricity. Energy use and emissions are reported for: industry, transport, buildings, energy conversion and land use. CH_4 and N_2O emissions from land and energy use are converted to CO_2-equivalents using 100 year global warming potentials (Myhre et al., 2013). The sum of CO_2, CH_4 and N_2O are reported in equivalent CO_2 and collectively called GHG emissions.

6.3. Biomass supply and land-use change

MESSAGE-GLOBIOM and IMAGE differ concerning bioenergy sources and the competition of land options. Figure 6.1 shows the biomass supply curves for both model frameworks for 2050 and 2100 including all available primary resources. For IMAGE, which has a biophysical representation and a given amount of available land for biomass, the supply curve depends on marginal yields of energy crops and residues. In contrast, the direct competition between land choices in GLOBIOM implies that with increased biomass profitability, food and feed production can be intensified or even reduced and agricultural land can be converted for biomass production. Managed forests represent another source of biomass which does not directly compete for land with agriculture and is mobilised at higher prices. The different methods adopted to determine resource potentials and costs lead to largely similar supply curves. In both frameworks almost all of the primary resource (approximately 230-250 EJ_{Prim}/yr by 2100) is available for less than 15 $\$_{2005}/GJ_{Prim}$, and the resource base increases between 2050 and 2100.

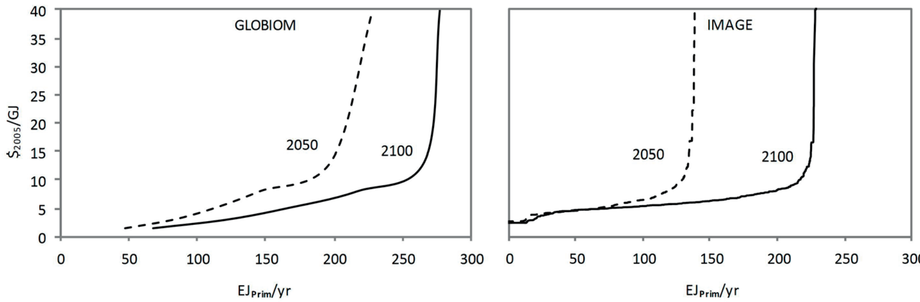

Figure 6.1. Biomass supply curves for GLOBIOM (left) and IMAGE (right), for 2050 and 2100 without other mitigation policies.

Both frameworks assess the GHG emission consequences of increased biomass production depending on additional land use and the underlying carbon stock models. In addition, in GLOBIOM the required changes in forest management due to increased demand for energy wood will have consequences on the carbon stock in existing forests and competition with the agricultural sector may indirectly lead to reduced emissions from crop and livestock production. A snapshot in 2100 for AFOLU emissions with increasing biomass supply and carbon taxes is shown in Figure 6.2. Assuming no climate policy, the emission levels are comparable between the models with both showing increases in AFOLU as biomass demand increases. With the application of carbon taxes IMAGE increases its protected lands and reduces non-CO_2 emissions (Lucas et al., 2007), while GLOBIOM accounts for forest management, which acts as a carbon sink at low biomass demand levels, but overall land becomes a source of emissions at high demand levels. Overall, GLOBIOM AFOLU emissions are more sensitive to the carbon price as well as to the bioenergy demand level than in IMAGE.

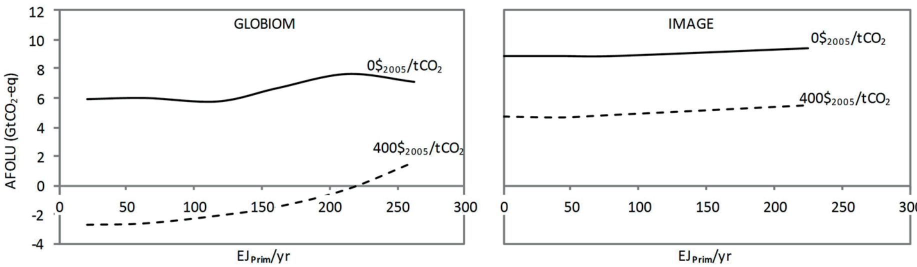

Figure 6.2. AFOLU emissions for GLOBIOM (left) and IMAGE (right) in 2100 with increasing biomass supply. With and without climate policy.

6.4. Scenario projections

6.4.1. Scenarios

First we run a *baseline* scenario which projects the development of the energy and land systems in the 21st century assuming no climate policy. This is based on socio-economic developments as described by the SSP2 scenario (van Vuuren et al., 2014; O'Neill et al., 2014). It is an extrapolation of current trends and assumes intermediate challenges to climate adaptation and mitigation. Socio-economic indicators of the scenarios are available in Table 6.2 the Appendix. Following, a *mitigation* scenario is projected in which the models apply carbon taxes and change land and energy choices in order to reduce emissions consistent with a 2.6W/m^2 radiative forcing target.

The *sensitivity* scenario investigates the changes in energy and land use emissions assuming a complete phase out of commercial bioenergy while maintaining the carbon tax projections of the *mitigation* scenario. It aims to identify how much bioenergy contributes to reducing emissions by comparing emission mitigation between the *mitigation* and *sensitivity* scenarios; the difference being called *the mitigation gap*. Furthermore, this scenario also gives insights on how biomass production may hinder land-based mitigation options.

6.4.2. Energy demand and emissions

As shown in Figure 6.3, both models project an increase in secondary energy, mostly in the form of electricity with smaller gains for gasses and liquids. Despite identical socio-economic conditions, MESSAGE-GLOBIOM projects a higher energy demand than IMAGE by 2100, at 978 EJ_{Sec}/yr and 837 EJ/yr respectively. This implies a compounded annual growth rate (2010-2100) of approximately 1% for both models. In the mitigation scenario, both models reduce energy demand, but IMAGE displays significant gains in efficiency driven by the carbon tax (Figure 6.4). In IMAGE the energy demand reduces by 40% in 2100 with respect to the baseline, while in MESSAGE-GLOBIOM the reduction is 11%.

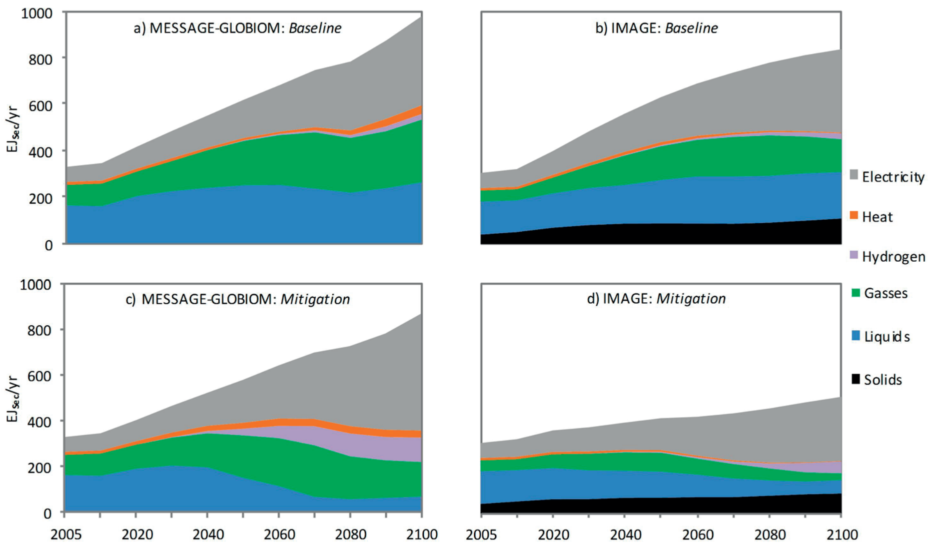

Figure 6.3. Secondary energy demand per energy carrier for each model framework for the baseline (top) and mitigation (bottom) scenarios.

In order to meet the mitigation target, the models project that by 2100 the carbon tax should be 995 $\$_{2005}/tCO_2$ and 677 $\$_{2005}/tCO_2$ for MESSAGE-GLOBIOM and IMAGE respectively. IMAGE has to reduce emissions early on in order to make the mitigation target feasible, thus the carbon tax surpasses 300 $\$_{2005}/tCO_2$ by 2050, with MESSAGE-GLOBIOM standing at 90 $\$_{2005}/tCO_2$ at the same time period.This is because, unlike MESSAGE-GLOBIOM, it lacks perfect foresight and all investments have to remain in operation throughout their technical/economic lifetime (i.e. stranded assets are not allowed).

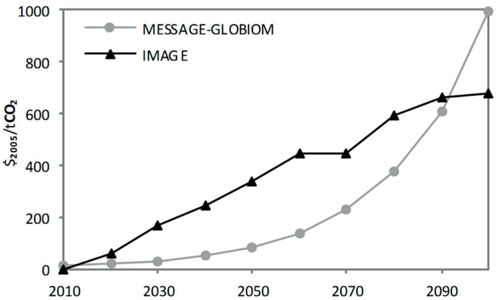

Figure 6.4. Carbon price projections for the mitigation scenario.

Figure 6.5 shows total emissions and their breakdown for the baseline and mitigation scenarios. Due to efficiency improvements and changes in the energy mix in both models, the rate of growth of emissions in the *baseline* is lower than that of energy use, with annual growth rate limited to approximately 0.8%. Interestingly, the total emissions for both models are very similar across the scenarios, showing storyline consistency. However when looking at the emission breakdown, some differences arise concerning the relative importance of different energy demand sectors and land use.

Energy conversion (mostly power generation) is the largest emitter in both models, followed by the transport and industry sectors. Land use emissions are projected to decrease significantly in the baseline, with MESSAGE-GLOBIOM achieving negative land use emissions (sequestration) by 2100. In the *mitigation* scenario, IMAGE ramps-up carbon taxes and reduces emissions early on, while the perfect foresight of MESSAGE-GLOBIOM allows it to apply emission cuts in such a way that allows slower carbon tax increase and delayed emission reductions. Short term mitigation is achieved through LU and forest uptake and by combining cheap fossil fuels with CCS. In the long-term bioenergy production increases, with some increase in LU emissions, as it becomes more competitive with higher eventual fossil fuel prices.

6.4.3. The application of bioenergy

Figure 6.6 shows the volume and structure of bioenergy use in both models for the *baseline* and *mitigation* scenarios. For IMAGE, bioenergy plays a very important role in the *baseline*, providing up to 100 EJ_{Sec}/yr in 2100 (or 13% of total secondary energy) used in both solid and liquid forms. MESSAGE-GLOBIOM on the other hand only deploys 22 EJ_{Sec}/yr by 2100 (2% of total).

As highlighted above, energy conversion (mostly from electricity) and energy use for transport are the main GHG emitters for both models. In the mitigation scenario, MESSAGE-GLOBIOM reduces GHG emissions from electricity production via the use of non-biomass renewables, while producing liquid fuels for transport with BECCS technologies. In IMAGE the penetration of non-biomass renewables is more restricted while liquid BECCS technologies are not available in the model. Thus in the mitigation scenario IMAGE uses liquid bioenergy (without CCS) in the transport sector to replace oil, solid bioenergy in industry and some BECCS in electricity generation. Thus the deep emission reductions MESSAGE-GLOBIOM achieved in the latter half of the century are largely dependent on the availability of liquid BECCS as well as competitive non-biomass renewable electricity.

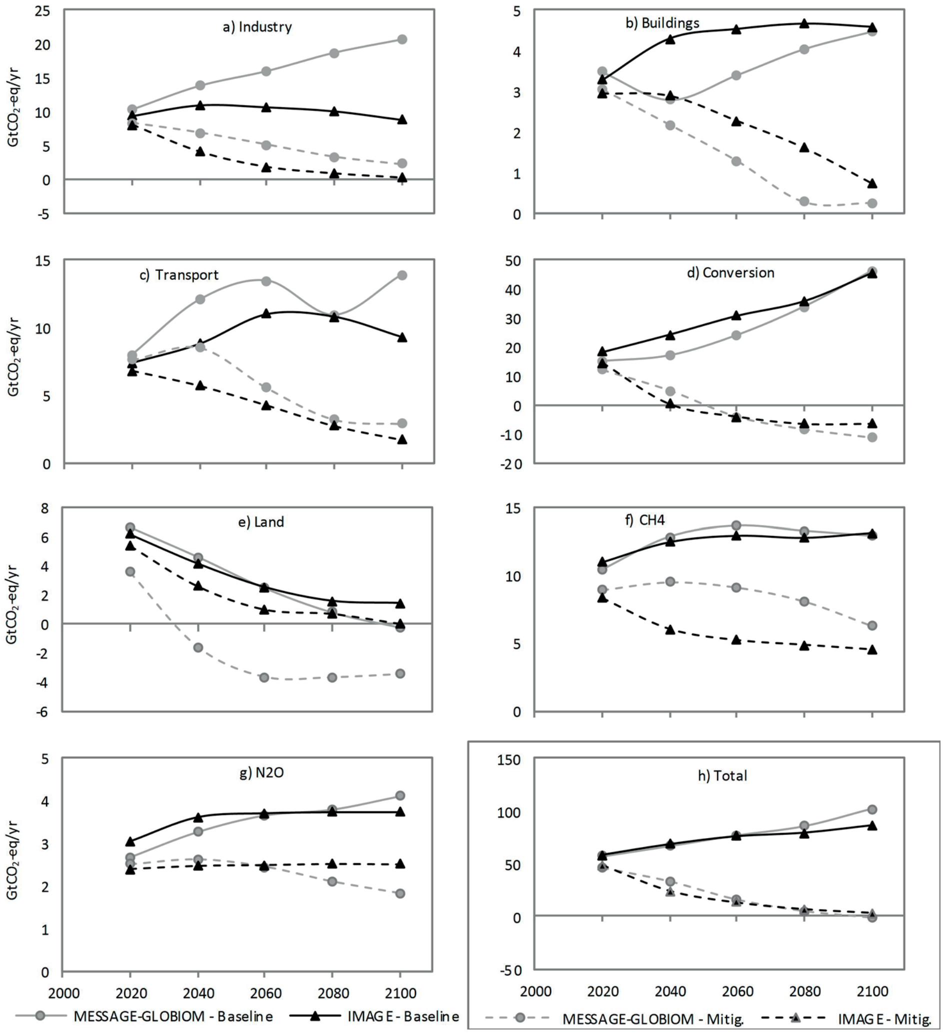

Figure 6.5. GHG emissions per emitting sector (a)-(g) and Total (h). Results shown for each model framework for the baseline and mitigation scenarios.

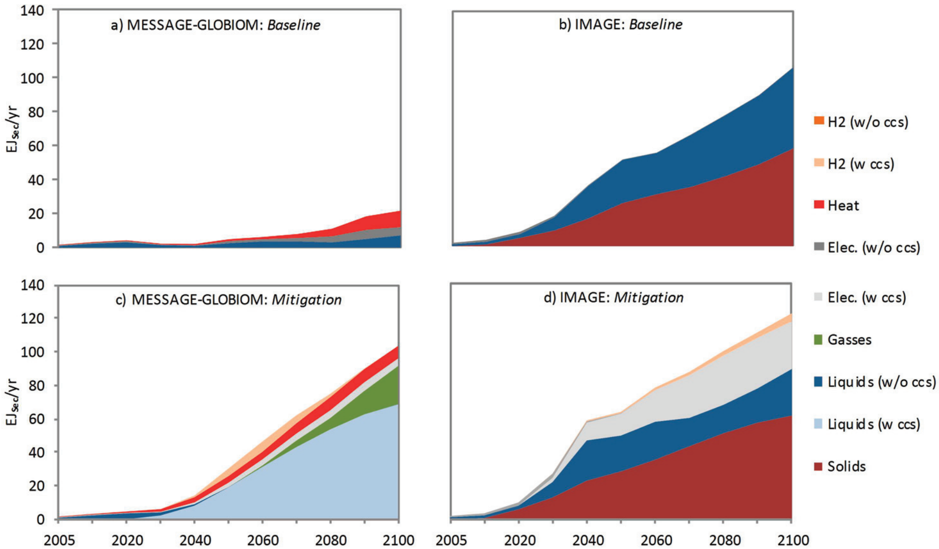

Figure 6.6. Secondary bioenergy consumption per category according to MESSAGE-GLOBIOM (left) and IMAGE (right). Baseline (top) and mitigation scenario (bottom).

Even though bioenergy demand in the *mitigation* scenario is similar for the models, the land demand is very different. For MESSAGE-GLOBIOM residues (from forestry) account for less than 10% and bioenergy supply requires almost 700Mha for short rotation bioenergy production by 2100. The very high profitability of bioenergy in the *mitigation* scenario, leads to severe displacement of food and feed production in MESSAGE-GLOBIOM, and an overall decrease in food production. In IMAGE almost half of the bioenergy supply comes from agricultural and forestry residues and despite having lower aggregate crop yields land requirement is limited to 325Mha coming from abandoned agricultural and *other* (non-forest) lands. Numerical results on land use for both models and all scenarios can be found in Table 6.3 in the Appendix.

6.4.4. Sensitivity scenario

Figure 6.7 shows the emission mitigation contribution of each emission source for the m*itigation* and s*ensitivity* scenarios. Both models achieve more than 75% of total emission reduction from the energy system, with (BE)CCS accounting for a third of this reduction, and the rest coming from fuel switching and efficiency gains in different end use sectors. For the sensitivity scenario, where bioenergy is phased out, the emission reductions with respect to the baseline for MESSAGE-GLOBIOM and IMAGE in 2100 are 90 and 74 $GtCO_2$/yr respectively. This is less than the 103 and 83 $GtCO_2$/yr in the *mitigation* scenario, indicating a mitigation gap of approximately 10% for both models.

In the *sensitivity* scenario MESSAGE-GLOBIOM adopts more (fossil) CCS technologies, and also afforestation of lands which would have otherwise been dedicated to biomass production, as well as less intensive forest management. In IMAGE, there are small mitigation contributions from energy supply (due to avoided emissions from biofuel conversion) and land use due to regrowth of natural vegetation on abandoned lands. As expected, constraints on biomass supply lead to a reduction in the emission mitigation potential of industry, buildings and transportation. The results of this scenario indicate that though there is a trade-off between biomass production and land-based mitigation, the latter cannot meet the overall mitigation potential that bioenergy and the use of BECCS provide.

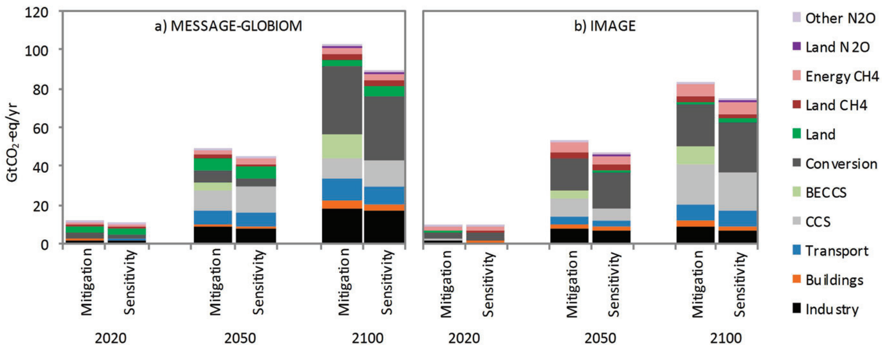

Figure 6.7. Emission reductions per sector in the mitigation and sensitivity scenarios. Note that "Conversion" only accounts for GHG reduction due to fuel switching, not the application of (BE)CCS which is accounted separately.

6.5. Discussion and conclusions

Explaining the differences in the projections of IAMs is inherently difficult as variations may arise due to a number of model specific elements. These include model formulation, solution method, linkage of different sub-models, technological portfolio, macroeconomic dynamics (trade, learning, substitution, etc.), geographic resolution, biophysical and economic representation and parameterisation of all the above. Here we compare the results of two IAMs in more detail than previous studies and explain some of the results by investigating the underlying structures and dynamics present in each IAM.

The two IAMs looked into here are very different in terms of methods and system coverage. Despite this, on a more aggregated level certain results and insights (the overall bioenergy use, the importance of CCS and the *sensitivity* scenario mitigation gap) are similar. This leads to the question of whether underlying assumptions and calibrations lead to these similarities or whether this is a coincidence. For example, the biomass supply curves shown in Figure 6.1 are similar despite the different representations of land and biomass resources. Common elements include the calibration of current land use against FAO data and that both models (and IAMs in general) assume that biomass resources can easily be brought into production. This means that the shape of the supply curve is driven by the maximum potential (i.e. the location of the asymptote) and cost levels. The former depends mostly on yield assumptions for bioenergy crops, availability assumptions for different land use types and expected trends in future agriculture production. While the first two factors are uncertain, future projections for agricultural production are somewhat constrained (see earlier comparisons by Smith *et al.* (2010)).

Still, comparing different models offers important insights reflecting both robust versus specific results as well multiple dynamics that may influence future bioenergy production. For instance, while total emissions in both the baseline and mitigation scenarios (bottom right panel of Figure 6.5) are largely the same, the sectoral emission trajectories show that there could be very different reasons for this. The mitigation strategies depend on the technology portfolio and the elasticities in the energy system in IMAGE and key responses in land use in MESSAGE-GLOBIOM. Furthermore, the carbon tax and emission projections indicate that IMAGE chooses to reduce its energy system emissions early on compared to MESSAGE-GLOBIOM. This highlights the importance of model features such as foresight, capital stock life-times and the availability of technologies that can reduce emissions at a low cost.

This comparison reveals that (the selected) IAMs are still not comprehensive in their representation of different technologies e.g. agricultural residues missing in the MESSAGE-GLOBIOM framework and certain bioenergy routes missing in the IMAGE model. Augmenting each individual IAM by the already parameterized options implemented by the other models would likely lead to improved mitigation potentials/costs and more realistic representation of climate change mitigation impacts. Yet, it is nearly impossible to indicate what dynamics are most important to build a model that would capture *everything*. A detailed comparison can offer additional insights in possible dynamics compared to single model use, this however requires model comparison exercises to go beyond the more common approach of simply comparing results and describing differences. It is important to explain the different strategies deployed and how they are related to the underlying model structure. Further work could also investigate the extent to which the results are driven by the competitiveness of different technologies, the prices of which have not been harmonised between the models for this assessment. Understanding common assumptions and diverging dynamics provides important insights for policy and model development.

This exercise has highlighted a number of important aspects concerning biomass and bioenergy and mitigation strategies. Availability and use of bioenergy is an important element in meeting climate goals, and preferred over setting land aside for carbon sequestration. Secondary bioenergy deployment is projected to reach 104-123 EJ_{Sec}/yr by 2100, largely used as a transport fuel. If electricity production cannot be de-carbonised enough with other renewable sources, bioenergy has an important role to play there too. As CCS is an important mitigation technology, accounting for 23-30% of all emission reductions, providing this technology for both power and fuel production is important. In order to supply the required volumes of bioenergy, the availability of low LUC resources (i.e. residues and forest biomass) and the intensification of agriculture, are requirements.

Acknowledgments

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6.6. Appendix

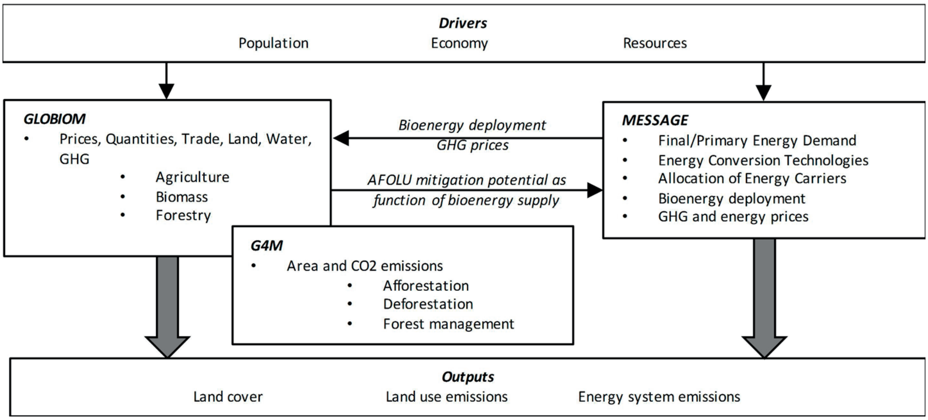

Figure 6.8. Structure of model the MESSAGE-GLOBIOM model framework. Data flows in italic.

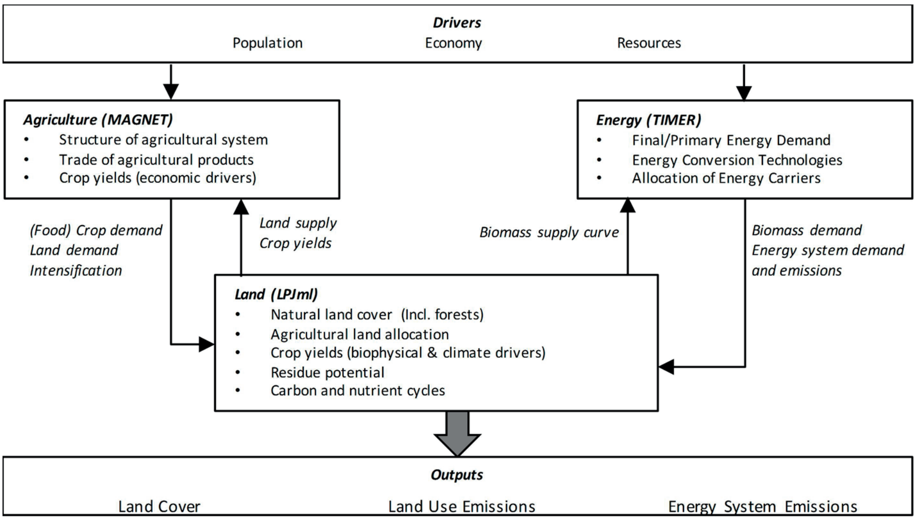

Figure 6.9. Structure of model the IMAGE model framework. Data flows in italic. Note the "Biomass Supply Curve" is determined after the "Land Demand" from MAGNET has been computed.

Table 6.1. Overview of model characteristics and representation of the land and energy systems concerning bioenergy for MESSAGE-GLOBIOM and IMAGE.

	IMAGE	MESSAGE-GLOBIOM
	Land System	
Land Representation	• Agricultural economy represented through a general equilibrium model (MAGNET) • Agricultural demand allocated in land-use model (LPJml) based on biophysical indicators • Land for bioenergy determined once agriculture and bio-reserves are excluded	• Recursive dynamic partial equilibrium • Competition between agriculture, forestry and bioenergy • Land cover decisions based on relative profitability of primary, by- and final products • Afforestation/deforestation decisions based on comparison of net present values of forestry and agriculture (G4M)
Land-Energy Link	• Biomass supply curves based on spatially explicit crop and residue yields, labour and capital costs • Once energy model determined bioenergy demand, land use model allocates spatially specific biomass production based on a set of rules (productivity, proximity to roads, etc.)	• GLOBIOM provides a set of land use pathways which incorporate biomass supply curves based on carbon and biomass prices • MESSAGE emulates land use decisions based on this set of land use pathways. This corresponds to a statistical model describing the relationship between potential bioenergy deployment and GHG/ bioenergy prices.
	Energy System	
Energy Representation	• Simulation • Endogenous final energy demand • Price induced energy efficiency improvements • No foresight • Investments in operation throughout technological lifetime	• Systems engineering optimisation • Exogenous final energy demand • Perfect foresight • Investments can be abandoned before end of technical/economic lifetime
Primary Feedstocks	• Conventional food crops • Short rotation (lignocellulosic) plantations • Agricultural residues • Forestry residues	• Conventional food crops • Short rotation (lignocellulosic) plantations • Forest harvest • Forest industry residues
Bioenergy Routes	• Liquid fuels • Electricity (with and without CCS) • Hydrogen (with and without CCS) • Heat • Solid fuels	• Liquid fuels (with and without CCS) • Gaseous fuels • Electricity (with and without CCS) • Hydrogen (with and without CCS) • Heat • Solid fuels
End Use Sectors (bioenergy)	• Industry • Transport • Residential • Services • Feedstocks	• Industry • Transport • Residential-commercial

Table 6.2. Projections of socio-economic parameters for each model. Note: Global GDP and population are common exogenous drivers for both IAMs.

		2020	**2050**	**2070**	**2100**
Global GDP	Trillion US$$_{2005}$	104	240	347	551
Population	Billion	7.7	9.2	9.5	9.1
Baseline Price Projections: MESSAGE-GLOBIOM[46]					
Solid fuels	$\$_{2005}$/GJ$_{Prim.}$	2.3	2.8	3.7	7.0
Liquid Fuels	$\$_{2005}$/GJ$_{Prim.}$	3.8	6.2	7.7	9.7
Gasseous Fuels	$\$_{2005}$/GJ$_{Prim.}$	4.1	6.3	7.5	13.0
Food Crops and Livestock	(2010=1)	1.04	1.11	1.14	1.08
In mitigation scenario		1.07	1.18	1.35	1.77
Baseline Price Projections: IMAGE					
Solid fuels	$\$_{2005}$/GJ$_{Prim.}$	1.5	2.1	2.2	2.3
Liquid Fuels	$\$_{2005}$/GJ$_{Prim.}$	10.5	11.9	13.0	19.2
Gasseous Fuels	$\$_{2005}$/GJ$_{Prim.}$	3.2	5.6	6.5	11.4
Food Crops and Livestock	(2010=1)	1.09	0.97	0.92	0.85
In mitigation scenario		1.10	1.07	1.09	1.11

[46] In MESSAGE the prices reflect the shadow price. If there is slack, meaning that there is too much capacity in the system, this can cause a low price until this capacity is used and then expanded leading to a higher shadow price. This explains the low starting price for liquid fuels.

Table 6.3. Land balance for baseline, mitigation and sensitivity projections of both model frameworks. 2050 and 2100.

		Baseline		Mitigation		Sensitivity	
		2050	2100	2050	2100	2050	2100
		Land Use (Mha)					
MESSAGE-GLOBIOM	Cropland	1 680	1 728	1 565	1 342	1 577.0	1 423.9
	Biomass	74	203	199	699	0.0	0.0
	Pasture	3 625	3 709	3 266	2 636	3 166.2	2 609.5
	Forest	3 827	3 882	4 143	4 518	4 228.7	4 738.6
	Other	3 271	2 956	3 303	3 281	3 504.7	3 704.6
		Percentage change with respect to *baseline*					
	Cropland			-6.8%	-22.3%	-6.1%	-17.6%
	Biomass			168.9%	245.1%	-100.0%	-100.0%
	Pasture			-9.9%	-28.9%	-12.7%	-29.6%
	Forest			8.3%	16.4%	10.5%	22.1%
	Other			1.0%	11.0%	7.2%	25.3%
		Land Use (Mha)					
IMAGE	Cropland	1 697	1 718	1 684	1 807	1 691.0	1 776.0
	Biomass	101	156	147	325	9.3	0.0
	Pasture	3 342	3 345	3 279	3 302	3 279.0	3 298.0
	Forest	3 667	3 665	3 816	3 839	3 855.0	3 943.0
	Other	4 256	4 180	4 136	3 791	3 898.0	3 923.0
		Percentage change with respect to *baseline*					
	Cropland			-0.7%	5.2%	-0.3%	3.4%
	Biomass			45.8%	108.7%	-90.8%	-100.0%
	Pasture			-1.9%	-1.3%	-1.9%	-1.4%
	Forest			4.1%	4.7%	5.1%	7.6%
	Other			-2.8%	-9.3%	-8.4%	-6.1%

7

Integrated assessment of biomass supply and demand in climate change mitigation scenarios

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7.1. Introduction

Biomass can be an important primary resource of future energy systems (Clarke et al., 2014). From a policy perspective, the use of biomass can be an attractive option to reduce greenhouse gas (GHG) emissions, improve energy security and promote socio-economic development (IEA, 2011). Still, several problems exist with large-scale bioenergy use, including competition with other forms of land use and (in)direct greenhouse gas emissions. Also, given the multiple biomass end-uses, it is unclear how the overall reduction of GHGs depends on different supply and demand possibilities. This means that when setting up policies to mitigate climate change through the use of biomass, it is important to understand the interactions and trade-offs within and between the energy and land systems (Hoogwijk et al., 2005; Smeets et al., 2007a; Dornburg et al., 2010; Slade et al., 2014). The overall potential for biomass and its possible contribution to mitigation efforts depends on the entire supply chain, including factors such as land-use dynamics, the volume and type of replaced fossil fuels and potential feedbacks in the energy system.

These interactions and their long-term development are influenced by a large number of uncertainties including population dynamics, economic development, demand for food, fodder, fibre and energy services, changes in production intensity of agriculture and forestry, decisions concerning land conservation, and the availability and costs of advanced energy conversion technologies. Different scenarios can display plausible and consistent descriptions for how these may unfold (Nakicenovic et al., 2000). Using models to project these *storylines* provides us with a broad set of potential outcomes which is key to understanding the possibilities, requirements, ranges and sensitivities of biomass supply and demand (Kriegler et al., 2012; van Vuuren et al., 2014; Clarke et al., 2014).

The aim of this thesis, set out in Chapter 1, was to investigate the role of biomass as a climate change mitigation option in an integrated manner using the IMAGE 3.0 IAM model (including the modules developed in this thesis). This is done by assessing biomass supply and demand, and the associated GHG emissions. Chapter 2 and Chapter 3 looked into the potential of biomass from residues and crops for modern energy and chemical applications and the associated emissions. Subsequently, Chapter 4 and Chapter 5 investigated the emission consequences of different energy and chemical uses of biomass. Finally, Chapter 6 showed how the representations of the land and energy systems in different models can lead to different possibilities and insights. This final chapter presents an integrated analysis of different possible biomass supply and demand futures using the model improvements and insights from the preceding chapters. The impact of uncertainties in the development of future land and energy systems are investigated by presenting integrated scenarios exploring different socio-economic and climate policy settings.

This chapter is structured as follows. In section 7.2, the main model and scenario assumptions are outlined. Section 7.3 presents the land use and energy system projections of the baseline and mitigation scenarios. Section 7.4 uses the insights of this thesis and the integrated projections of biomass supply and demand in the baseline and mitigation scenarios in order to answer the research questions posed in Chapter 1. Finally, section 7.4 and section 7.5 conclude this thesis by listing policy recommendations for ensuring effective use of biomass for energy and chemicals as mitigation measures, and propose future research avenues.

7.2. Method

This chapter uses the IMAGE 3.0 model (see model description in Chapter 1), including the newly developed modules described in this thesis. The model is used in order to investigate different supply and demand possibilities of biomass and how they affect the GHG balances of the land and energy systems. The study is done in the context of diverging socio-economic scenarios and their respective mitigation pathways.

7.2.1. Biomass and bioenergy in IMAGE

In IMAGE primary biomass can be supplied by abandoned agricultural lands, other natural lands (grasslands, shrubland, savannah and tundra) and residues (Stehfest et al., 2014). An accessibility factor for each land type is used in order to represent constraints to land accessibility such as biodiversity protection and alternative land use. The accessibility factor is set to zero for urban areas, forests, agricultural lands and nature reserves. This means that a *food-first* principle is explicitly set out in the model, where biomass supply cannot directly displace agricultural production. For other natural lands the accessibility factor is set at 20%-50% and for abandoned agricultural lands it is set at 70%. These values are clearly arbitrary, with the numbers used in this study being based on the ranges proposed by de Vries *et al.* (2007). Potential energy crops are sugarcane, maize and lignocellulosic crops which consist of perennial grasses (miscanthus) and woody crops (willow and eucalyptus). As described in Chapter 2, biomass supply from residues is based on production volumes and intensity in agriculture and forestry. The supply is constrained by environmental concerns and competing demand options such as livestock feed and traditional fuel use in poor households. Supply costs for both energy crops and residues are based on capital, labour and transport costs as well as the intensity of production.

The energy system is represented in IMAGE by a dynamic simulation model (TIMER). This model assumes primary biomass can be converted to a number of secondary and final energy carriers: solid fuel, liquid fuel, electricity and hydrogen. Both first and second generation liquid fuels are included (technologies are listed in Table 5.1.

in Chapter 5). Potential bio-electricity production routes include steam turbine, combined cycle, combined heat and power and combinations with CCS. Hydrogen production is based on gasification and can be combined with CCS. Besides energy carriers, biomass can also be used as a feedstock for chemical production (non-energy uses) as described in Chapter 4. The potential non-energy options are higher value chemicals (represented by ethylene and aromatics), ammonia, methanol and heavy refinery products (lubricants and bitumen). Biomass based energy carriers and chemicals compete with other secondary and final energy carriers in order to supply the energy demand. The final market shares of possible technologies are based on their relative costs.

7.2.2. Scenario description

The model is used to project three different reference baselines and their respective mitigation scenarios[47]. These are based on the *Shared Socio-economic Pathways* (SSPs) which describe plausible alternative trends in the evolution of society and ecosystems over a century timescale (O'Neill et al., 2014; Riahi, 2016). These pathways explore the different socio-economic development possibilities, characterised by their challenges to climate mitigation and adaptation, which lead to varying land and energy use, and resultant GHG emissions. Below we describe the main qualitative elements of the baselines and how they are applied in IMAGE. Relevant socio-economic indicators for each baseline are shown in Table 7.1.

The *SSP1* baseline describes a world with low challenges to adaptation and mitigation. Population reaches a maximum by mid-century, decreasing thereafter, while global GDP per capita increases significantly. There are notable efforts towards conserving natural lands and behavioural changes lead to diets with a reduced demand for meat, and fewer energy services. Meanwhile, there are sustained improvements in crop and livestock yields, investments in research and development allow for significant improvements in efficiency and costs of energy technologies, and a reduction in energy intensity. *SSP2* assumes a middle of the road development, based on the extrapolation of current trends. Population continues to increase, stabilising towards the end of the century. Some efforts are made to conserve natural lands and there are some improvements in agricultural production and energy technologies and intensity. Finally, *SSP3* projects a world with high challenges to both adaptation and mitigation. It assumes a regionalised world with very high population growth and only small increases in GDP per capita. Behavioural choices follow an inefficient use of mostly fossil based energy while diets increasingly shift towards meat consumption.

47 Scenarios which assume no action on climate change are called *baseline* scenarios, while those which implement policies in order to meet a climate goal are called *mitigation* scenarios.

This baseline assumes that there is fragmentation between regions, few restrictions on land use, and minor improvements in technologies and energy efficiency.

Mitigation scenarios are projected by simulating the application of climate policies through the adoption of a carbon tax. This in turn promotes the adoption of behaviour and technologies which lead to lower greenhouse gas emissions. Furthermore, stricter constraints for land conversion are placed on areas with high carbon stocks, the threshold being set at 10, 15 and 20 ktC/km^2 for SSP1, 2 and 3 respectively. These thresholds are based on opportunity costs of avoided deforestation as determined by the IMAGE model and explained in Overmars *et al.* (2014). Note that these constraints are quite strict, for instance Greenpeace (2013) defines *"High Carbon Stock"* forest in the tropics as those having at least 60t/km^2. The carbon taxes are endogenously determined so as to meet a radiative forcing target corresponding to 2.6-3.4 W/m^2. The application of this tax affects the volume and structure of both agricultural and energy demand, driven by the increased competitiveness of technologies or management options with a low carbon intensity. Non-CO_2 GHGs from energy, land and agricultural sources are also curtailed through the application of the carbon tax through the use of marginal abatement cost curves described by Lucas *et al.* (2007). The overall process through which the mitigation scenarios are constructed in IMAGE is described in van Vuuren *et al.* (2007).

Table 7.1. Socio-economic indicators for the baseline scenarios. Population and GDP per capita are exogenous drivers, while agriculture and livestock production are endogenous projections of IMAGE 3.0.

		Population (Billions)		
	2030	2050	2070	2100
SSP1	8.1	8.5	8.3	7.0
SSP2	8.3	9.2	9.5	9.1
SSP3	8.6	10.0	11.2	12.8
		GDP per Capita ($\$_{2005}$/cap)		
SSP1	19 844	35 027	51 745	83 104
SSP2	17 844	25 987	36 423	60 486
SSP3	16 238	18 442	19 653	22 366
		Agriculture and livestock production index (1 = 2010)		
SSP1	1.29	1.50	1.49	1.49
SSP2	1.38	1.62	1.69	1.79
SSP3	1.38	1.60	1.73	1.91

7.2.3. Scope and definitions

All results presented below are for a global and long-term basis. Throughout this chapter, biomass is defined as the primary resource for bioenergy and biochemicals.

Unless otherwise stated, the term is used interchangeably for lignocellulosic, sugar and starch crops, as well as agricultural and forestry residues. Bioenergy consists of secondary energy carriers and final energy uses supplied from biomass such as solids (for heat production in buildings and industry), liquids (biofuels used in transport) electricity and hydrogen. In this definition we exclude low quality traditional uses such as heating or cooking in poor households. Non-energy uses of biomass include biochemicals such as ethylene, ammonia, methanol, waxes and lubricants as described in Chapter 4.

GHG emissions are presented for energy supply, energy demand, land, CH_4 and N_2O. Energy supply includes emissions from supply chains and conversion to secondary energy carriers, while energy demand emissions arise due to combustion of energy carriers at end use. Land use emissions are changes in land based carbon-stocks. CH_4 and N_2O emissions from land and energy use are converted to CO_2-equivalents (CO_2-eq) using 100 year global warming potentials (Myhre et al., 2013) and the sum of CO_2, CH_4 and N_2O are collectively called greenhouse gas (GHG) emissions.

7.3. Land use and energy system projections

Before exploring the ranges and routes of biomass supply and demand we will first discuss how the different SSP assumptions (and their mitigation scenarios) lead to different developments for land use and the energy system[48]. These in turn affect the future potential of biomass and its emission mitigation possibilities.

7.3.1. Land use trends

Population and welfare growth in all three baselines lead to an increase in the demand of agriculture and livestock (Table 7.1). These increases, combined with changes in production intensity lead to the different land-cover projections (Figure 7.1). SSP1 has the lowest overall demand for crop and livestock production. Combined with a strong increase in production intensity, this leads to a net abandonment of agricultural lands and an increase in forest cover and other natural lands. From these, abandoned and a portion of other natural lands are in principle available for biomass production. In 2010, land use for food crops and pasture was approximately 4800 MHa (FAO, 2013). In the SSP1 scenario, this decreases by almost 400 MHa and 1000 MHa by 2050 and 2100, respectively. This leads to a land use for food production in 2100 of 78% of current use. SSP3 forms the other extreme. Here, the slow improvements in yields and the increase in global population lead to a growing demand for agriculture and pasture, increasing land use by 300 MHa by 2050. By 2100, total land use in the SSP3

[48] All results presented in this chapter are based on version 13 of the SSP database (https://tntcat.iiasa.ac.at/SspDb/).

baseline stands at over 5300 MHa, putting further pressure on forests and other natural lands.

Forests and other natural lands account for approximately 62% of land cover in 2010. For SSP1, the trends discussed above lead to an increase to 69% by the end of the century. Conversely, for SSP2 and SSP3 there is a continuing loss of natural lands whose coverage decreases to 59% and 57% of land cover respectively in 2100. An overview of the land balance for all baselines and mitigation scenarios is available in Table 7.3 in the Appendix.

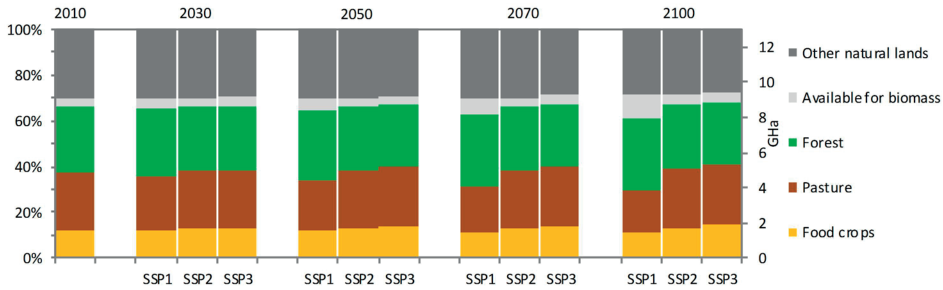

Figure 7.1. Land balance projections across all baselines. *Other natural lands* include natural grasslands and (non-forest) protected areas. Total land area accounted for is 13GHa.

7.3.2. Energy demand and use

Each SSP baseline scenario leads to different developments in the energy system. Both primary and final energy demand are lowest in SSP1 and largest in SSP2. The lower welfare levels of SSP3 and the resultant lower per capita energy demands mean that despite its larger population, this scenario has a lower overall energy demand than SSP2. SSP1 sees a significant de-carbonisation of primary energy with coal and oil largely phased out by the end of the century with increasing importance of natural gas, modern biomass and other renewables. Furthermore, high welfare levels mean that traditional biomass is completely phased out by the end of the century. The high energy demand of SSP2 and SSP3 require increased use of fossil fuels, especially coal which becomes increasingly competitive as oil and gas prices increase (see Table 7.4 in the Appendix). Preferences and technological improvements also affect the supply of primary energy, especially the contribution of renewable energy. The projections of primary and final energy demand across all scenarios are available in Table 7.5 in the Appendix.

Primary energy demand increases from approximately 500 EJ_{prim}/yr in 2010 to 757, 853 and 835 EJ_{prim}/yr in 2050 for SSP1, 2 and 3 respectively. For SSP1 this decreases to 720 EJ_{prim}/yr by 2100 and increases to over 1000 EJ_{prim}/yr for SSP2 and SSP3. The lower projection of SSP1 is a result of population decline towards the end of the century and rapid improvements in energy intensity. In SSP1, fossil fuels account for more than 70% of primary energy supply in 2050, while for SSP2 and SSP3 fossil fuels account for approximately 80%. By 2100, these shares change to 48%, 73% and 78% for SSP1, 2 and 3 respectively with the latter two seeing coal use surpassing 400 EJ_{prim}/yr.

For all baselines, growth in electricity demand drives the changes in the final energy. This is caused by increased access to electricity and an electrification of energy functions (appliances in households, transport, etc.) as oil and gas prices increase. However, a significant volume of liquid fuels (from fossil and biomass sources) continue to exist due to demand from the transport sector. A detailed account of energy system projections for the IMAGE SSP scenarios is available in van Vuuren *et al.* (2016) and for the total set of SSP scenarios in Bauer *et al.* (2016).

7.3.3. Mitigation projections

The GHG emissions of the baselines lead to an increase in the radiative forcing[49] from approximately 2 W/m^2 currently to 3.9-4.2 W/m^2 in 2050 and 4.8-6.5 W/m^2 in 2100. This leads to global mean temperatures increasing by 3-4°C towards the end of the century compared to pre-industrial levels. The upper limit refers to the SSP2 and SSP3 scenarios where GHG emissions from LUC and energy use remain or increase. In the mitigation scenarios a carbon tax is introduced (applied to energy sources and non-CO_2 gasses) in order to meet the radiative forcing targets of 2.6 and 3.4 W/m^2 (The 2.6 W/m^2 target is unfeasible for the SSP3 baseline in the IMAGE model given the socio-economic trends and assumptions on possible technologies). Figure 7.2 shows the projected carbon taxes and radiative forcing for each scenario.

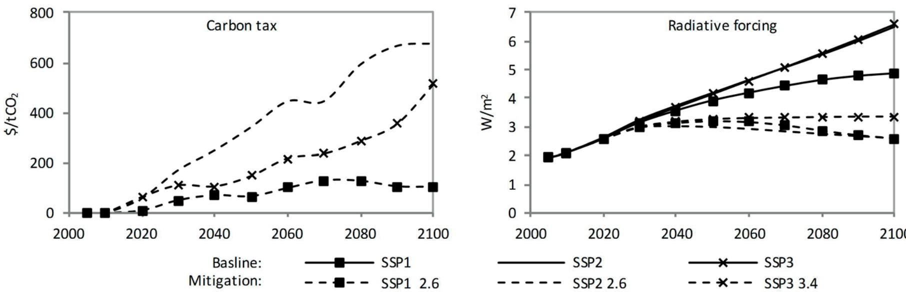

Figure 7.2. Projections of carbon tax and radiative forcing across relevant scenarios.

The projections of baseline and mitigation emissions and their sources are shown in the lower panel of Figure 7.3 (numerical results are presented in Table 7.6 in the Appendix). Due to its lower overall population and energy intensity, the baseline

49 In this chapter radiative forcing is defined as the forcing from all greenhouse gasses and forcing agents, including contributions from albedo, nitrate and mineral dust.

emissions of SSP1 are projected to decline after 2050. Consequently, the carbon tax also peaks at 130$_{2005}$/tCO$_2$ in 2070 and declines thereafter, reaching 100$_{2005}$/tCO$_2$ in 2100. For SSP2 and SSP3, higher baseline emissions lead to carbon taxes reaching 680$_{2005}$/tCO$_2$ and 513$_{2005}$/tCO$_2$ respectively, the latter being lower since its climate target is more lenient.

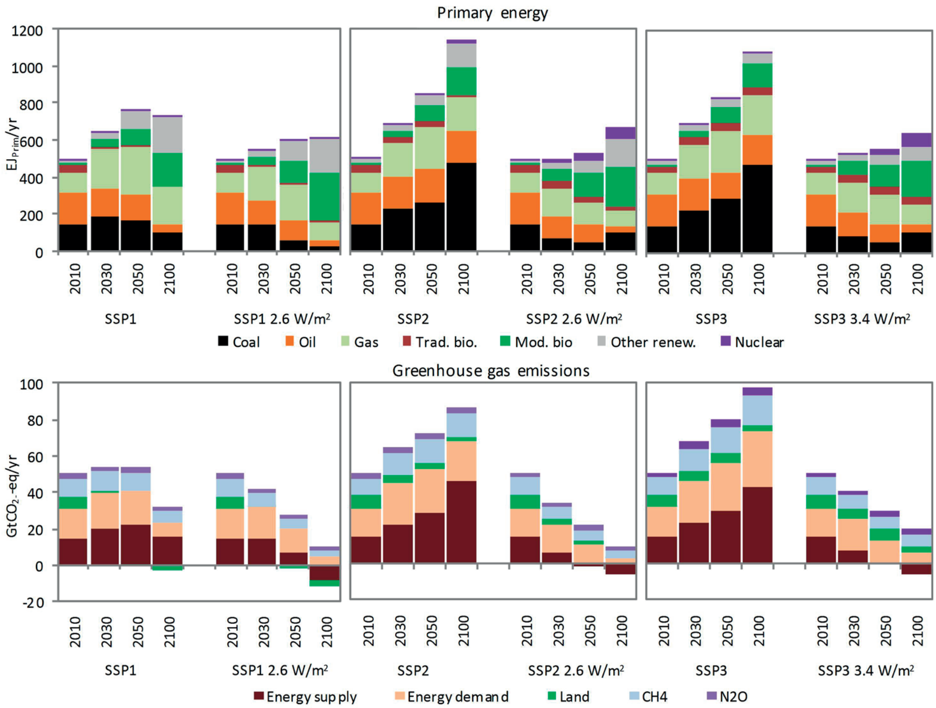

Figure 7.3. Projections of primary energy (top) and greenhouse gas emissions (bottom) in the baseline and mitigation scenarios. Disaggregated per energy source and emission source. Note SSP3 has a more lenient forcing target as the 2.6 W/m^2 target is infeasible (as described in the text).

The mitigation scenarios, which have specific constraints on loss of natural lands based on protecting carbon stocks, project an increase of forest land in SSP1 and SSP2. Although LUC CO_2 emissions are projected to decrease from today's level in all the baselines, this decrease is more pronounced in the mitigation scenarios (Figure 7.3). The associated increased biomass production adds pressure to land use emissions, while the constraints on land with high carbon contents partially mitigate this effect. In the SSP1 mitigation scenario, anthropogenic land-based emissions become negative -while still providing biomass- towards the end of the century. For the SSP3 mitigation scenario, the lenient carbon stock constraints combined with biomass demand and decreased carbon fertilisation lead to similar LUC emissions as the baseline. These dynamics are discussed further in section 7.4.3.

In all mitigation scenarios, energy-related greenhouse gas emissions are reduced significantly compared to the baseline. These arise from reduced demand due to efficiency increases, fuel switching towards cleaner sources and an increased use of CCS and BECCS, the latter of which leads to negative emissions. Interestingly, in SSP2 and 3, there is a slight resurgence in coal consumption by the end of the century. This is due to the high energy demand of these scenarios and the availability of CCS technologies, which in turn are made possible by the high carbon tax. Total primary energy demand in 2050 is projected to be 595, 528 and 561 EJ/yr for the mitigation scenarios of SSP1, 2 and 3, respectively. These imply a 21%, 38% and 33% decrease compared to the respective baselines. By 2100, the required decrease in primary energy with respect to the baseline is 16%, 41% and 40%, further highlighting the relative ease of SSP1 and difficulty of SSP2 and SSP3 at meeting the climate targets.

7.4. The role of biomass in climate change mitigation

In this section we discuss the role of biomass, bioenergy and biochemicals in climate change mitigation. For this we use the main findings of chapters 2 to 6 to bring forward the underlying dynamics, uncertainties and sensitivities of biomass supply and demand and the potential contribution to climate change mitigation. Furthermore, these findings are discussed in the context of the SSP scenarios described above. This section is structured according to the research questions posed in Chapter 1. Thus, sections 7.4.1 to 7.4.3 investigate specific dynamics of the land and energy systems which affect the mitigation potential of biomass. These help explain the overall ranges of biomass supply and demand for the SSP scenarios shown in section 7.4.4.

7.4.1. Drivers and constraints of biomass supply

Research Question 1: What is the potential future supply of modern biomass from residues and energy crops when accounting for the drivers and constraints in a spatially explicit manner?

Residues

The availability of residues depends on the production and intensity of agricultural and forestry operations, ecological constraints and competing uses such as feed for livestock or traditional fuel use in poor households (see Chapter 2). The theoretical potential (i.e. maximum possible given agriculture and forestry production) of residues is projected to increase driven by the growth in the demand of agricultural products. Increasing crop yields have a smaller effect as yield gains tend to benefit the *merchantable* component of the crop (in terms of its primary use). The projections show the theoretical potential reaching 130, 136 and 145 EJ_{Prim}/yr in 2050 for SSP1, 2 and 3 respectively, not increasing much thereafter. However, the calculations show that approximately two-thirds of this potential cannot be used for bioenergy due to competing uses and ecological constraints.

Here, it should be noted that the ecological functions of residues, of which erosion control is the limiting factor, is first of all a function of total land use. Since the ecological constraint requires a constant volume of residues per hectare (as opposed to a fraction of total production), marginal improvements in residue production per hectare are in principle available for bioenergy purposes once this constraint is met. Residue supply is also limited by other uses, the most common of which are as feed for livestock or as a heating and/or cooking fuel in poor households. The volume of residues demanded for these uses depends on livestock production systems and the access of poor households to modern energy carriers. Residue supply costs depend on the collection costs (which in turn depend on the residue availability per hectare) and transport distance. Consequently, extensive production increases the cost of both these components by decreasing residue availability per hectare (lower yields and more constricting ecological constraints) and increasing the transport distance.

Interestingly, the supply of residues (available potential) as calculated in IMAGE does not depend strongly on baseline assumptions. In the SSP1[50] baseline, overall agricultural and forestry production is relatively low, but the intensive nature of agriculture and the limited demand of residues for competing uses led to an availability of approximately 40% of the theoretical potential. In contrast, in the SSP3 baseline, where high population growth drives up the theoretical potential, extensive agricultural production and increased dependence of livestock feed and traditional fuel use on residues limits the availability to 30%. These counteracting effects lead to similar residue supply across the three baselines, with SSP1 having slightly lower costs due to geographical concentration of the supply (available potential for all scenarios shown in Table 7.2).

Energy crops

The methods developed by Hoogwijk *et al.* (2005; 2009), are used to assess the potential of energy crops, thus we assume that lands used for agricultural production and other protected areas are not available. Figure 7.4 shows IMAGE maps of land availability for future energy crop production, highlighting lands classified as abandoned agricultural or other natural lands. Numerical results of the land availability per category are available in Table 7.3 in the Appendix. In SSP1, the decrease in demand of land for agricultural production allows for significant volumes of aban-

50 In Chapter 2 the SSP1, SSP2 and SSP3 baselines are called *Optimistic, Medium* and *Pessimistic,* respectively.

doned lands, while the stricter environmental constraints limit the volume of other natural lands. The SSP3 baseline shows the opposite behaviour, with SSP2 occupying a middle ground. The type of land which is available is very important for the overall biomass potential. Abandoned agricultural lands tend to have the highest yields since these are the most biophysically attractive locations, while moving into unused lands (which tend to be of lower quality according to the allocation rules of IMAGE) results in reduced marginal yields.

In IMAGE, primary biomass can be supplied by maize, sugarcane and lignocellulosic crops (including miscanthus, willow and eucalyptus). Lignocellulosic crops are preferred in all projections due to the higher yields they attain. Their aggregate yields are projected to increase from approximately 250 GJ_{Prim}/Ha today to 306, 262 and 257 GJ_{Prim}/Ha for SSP1, 2 and 3 respectively by 2050. By 2100, further increases lead to yields of 426, 401 and 395 GJ_{Prim}/Ha. The differences across the scenarios arise due to the varying land quality available in each case as well as improvements in management. The figures imply aggregate energy crop yields increasing by 0.5-0.6% per year (2010-2100)[51]. This is slightly lower than observed growth rates in food crop yields which have been shown to range between 0.7-1.6% per year between 1961 and 2010 (Gerssen-Gondelach et al., 2015). These improvements over time allow for the required land sparing and also contribute to lowering bioenergy prices in IMAGE.

Specifically, for abandoned agricultural lands yields approach 400 GJ_{Prim}/Ha by 2050 and 500 GJ/yr by 2100. For other natural lands aggregate yields are 350 GJ_{Prim}/Ha and 370 GJ_{Prim}/Ha in 2050 and 2100 respectively. These yields are within the current and projected productivity ranges for perennial grasses and short rotation lignocellulosic crops (Boehmel et al., 2008; Gerssen-Gondelach et al., 2014). The availability of high quality land is important when considering the productivity of marginal or degraded lands. Nijsen *et al.* (2012) used the IMAGE model to estimate the yields of lignocellulosic crops in degraded lands at 200 GJ_{Prim}/Ha. Wicke *et al.* (2011) determined the yields in salt affected soils to be, on average, 60 GJ_{Prim}/Ha. Degraded lands, however, may offer GHG benefits via carbon sequestration.

Figure 7.5 shows the cost-supply curves in 2050 and 2100 for primary biomass from each of the considered sources and the total across all baselines as projected by IMAGE. The availability of abandoned agricultural lands with high yields lead to SSP1 having the highest biomass potential, despite the stricter constraints on natural lands. For SSP2 and SSP3 baselines, despite the more lenient constraints on land use, the high demand for agriculture limits biomass production to lower quality lands reducing the overall potential. Primary biomass potential is projected to increase to 140-220

[51] These vary depending on crop and location. These are global aggregate improvement rates for perennial grasses as projected by IMAGE. Woody crops growth rates are 0.4%-0.5% and for sugarcane crops they are 0.6%-0.8%.

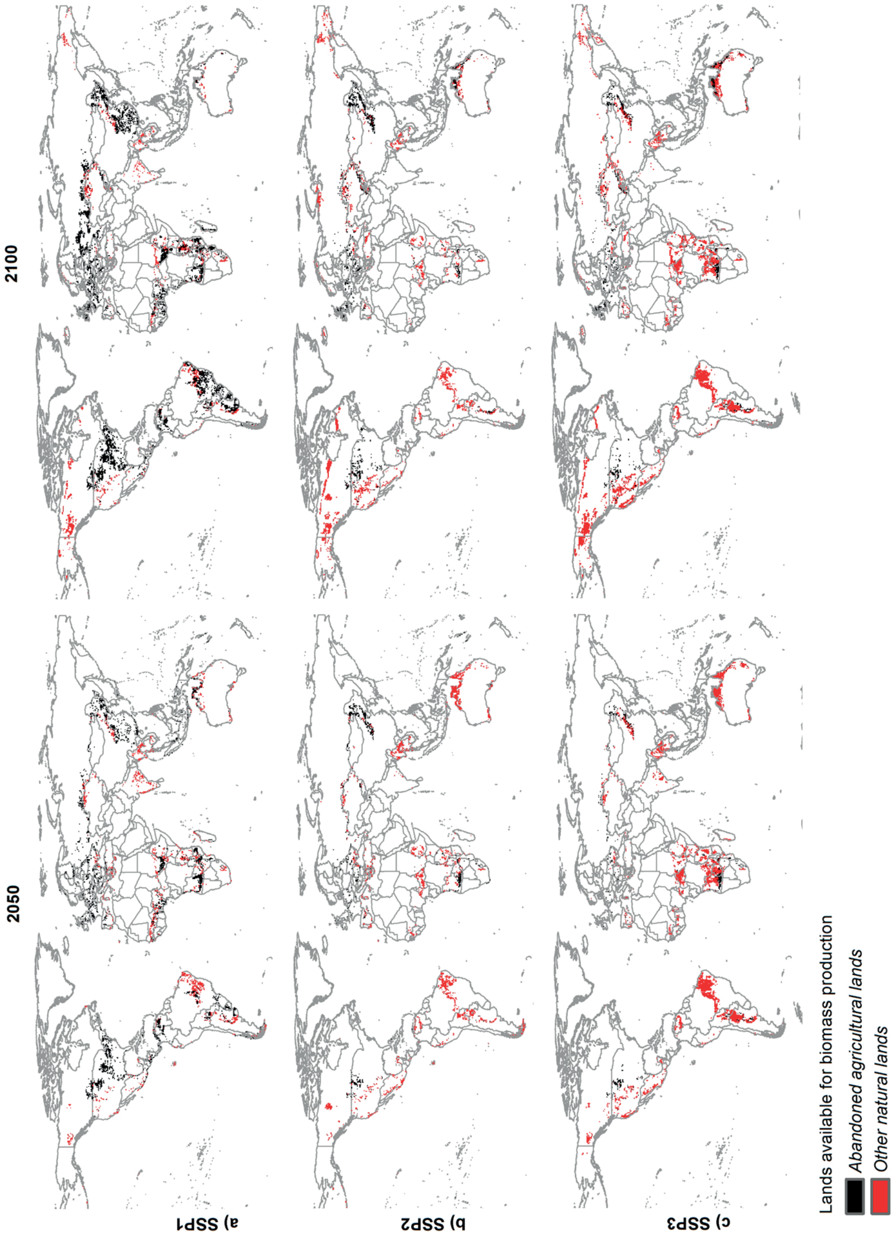

Figure 7.4. Abandoned agricultural (black) and other natural lands (red) available for biomass production in 2050 (left) and 2100 (right) for all baselines.

EJ_{Prim}/yr in 2050 and 200-590 EJ_{Prim}/yr in 2100 for the baselines (a summary of biomass potentials and production are shown in Table 7.2). As described above, the supply from residues is relatively constant across the scenarios with availability and quality of land for energy crops forming the major uncertainty. The maps and supply curves shown in Figure 7.4 and Figure 7.5 are based on the baseline projections. In the mitigation scenarios, due to the carbon-stock constraints and changes in agricultural production, the maps and supply curves have small differences but the same overall patterns.

7.4.2. Demand of bioenergy and biochemicals

Research Question 2: What is the demand for biomass for different energy and chemical purposes in a dynamic energy system model?

Biochemicals

Non-energy use of primary energy carriers (i.e. feedstocks for chemicals) is often poorly described in IAMs. In IMAGE, a significant step forward has been made in order to include this sector and explore its long term fuel switching and material efficiency possibilities (Chapter 4). The model determines the demand of primary energy carriers in order to produce non-energy products, represented by higher value chemicals (ethylene and aromatics), ammonia, methanol and heavy refinery products (waxes and lubricants).

The new non-energy model projects that for all the SSPs primary energy demand for non-energy products increases from 26 EJ_{Prim}/yr in 2010 to 44 EJ_{Prim}/yr in 2050. By 2100 this further increases to 58, 92 and 77 EJ_{Prim}/yr for SSP1, 2 and 3 respectively. As shown in Chapter 4, in a counterfactual scenario where biomass is assumed unavailable, coal-based feedstocks become increasingly important by the end of the century, driven by the increase in final demand and price increases of oil and natural gas. If biomass is allowed as a feedstock, it can contribute to over 30% of the primary feedstock supply by 2050 and over 35-50% by 2100. Besides the increase of fossil fuel prices, increased competitiveness of biomass is also due to learning in the production of bio-based intermediate chemicals (ethanol and methanol).

Bioenergy in the energy system

In addition to the non-energy uses outlined above, biomass can be used in the energy system to meet a number of different functions. Assessing its potential future contribution to final energy demand must take into account a number of dynamics such as the competition with other energy sources, the potential future development of energy supply and demand –including changes, breakthroughs and cost reductions in technologies– and any possible rebound and/or leakage effects. The energy model of IMAGE is an appropriate tool for investigating such systemic changes in a dynamic fashion.

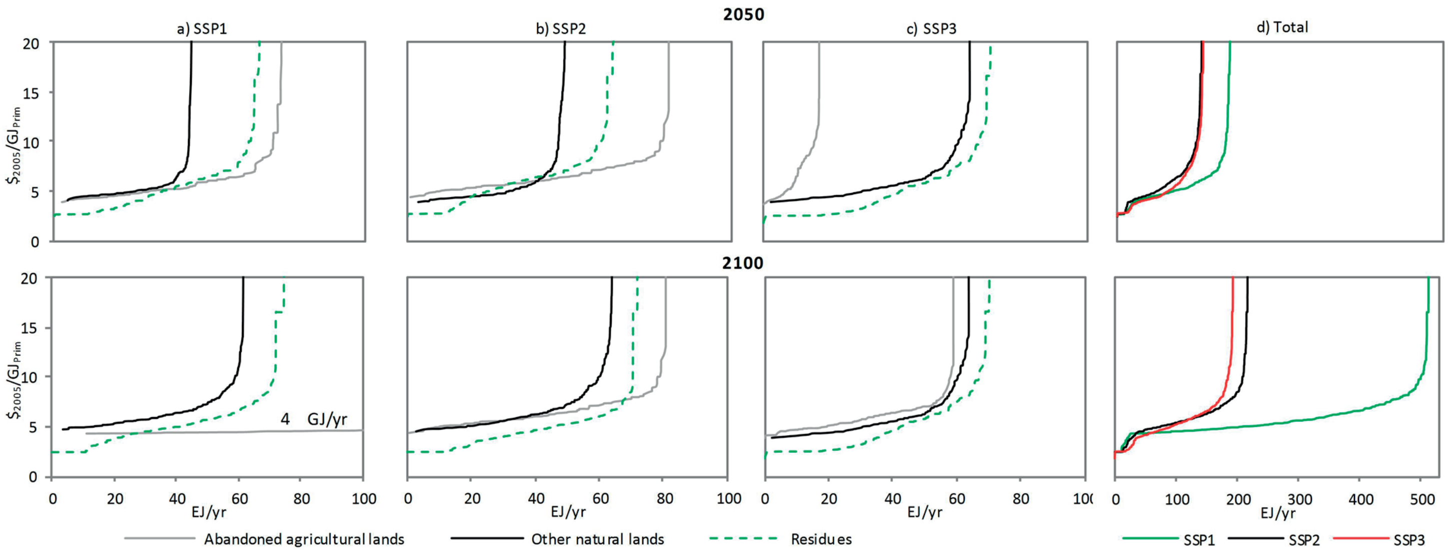

Figure 7.5. Global biomass supply curves (<20$_{2005}$/GJ$_{Prim}$) in 2050 (top) and 2100 (bottom) for the three baselines (a)-(c) disaggregated between abandoned lands (grey), other natural lands (black) and residues (green-dashed). Also shown are the total biomass supply curves (d) for SSP1 (green), SSP2 (black) and SSP3 (red).

Figure 7.6 shows the projections of bioenergy and biochemical use for the baseline and mitigation scenarios. All cases show an increase in overall use throughout the projection period. Long-term use increases in the mitigation scenarios, prompted by the application of carbon taxes which increase the competitiveness of bioenergy technologies. The favourable technological assumptions and biomass supply curves of SSP1 lead to this scenario having the highest rates of biomass based final energy, despite the fact that SSP1 has the overall lowest demand for primary and final energy (see section 7.3.2 and Table 7.5 in the Appendix). By 2050, bioenergy and biochemicals account for 12% of the total final consumption for SSP1, and 8% for SSP2 and 3. These increase to 24%, 13% and 11% respectively by 2100. In the mitigation scenarios these fractions are even higher at 35%, 25% and 21% (2100), respectively.

The primary use of biomass in the baselines is for liquid fuels. As explained in Chapter 5, this is due demand from the transport sector amid increasing oil prices. Other important uses include chemicals (non-energy) as described above and solid bioenergy as a heating fuel in buildings and industry. The importance of solid fuels increases in SSP2 and SSP3 scenarios due to the pessimistic assumptions on the improvement of 2nd generation biofuel technologies (ranges of conversion efficiencies are shown in Table 5.1 in Chapter 5) as well as increased demand for heat in buildings and industry. In SSP1, the availability of improved technologies also allows for small amounts of hydrogen to be produced.

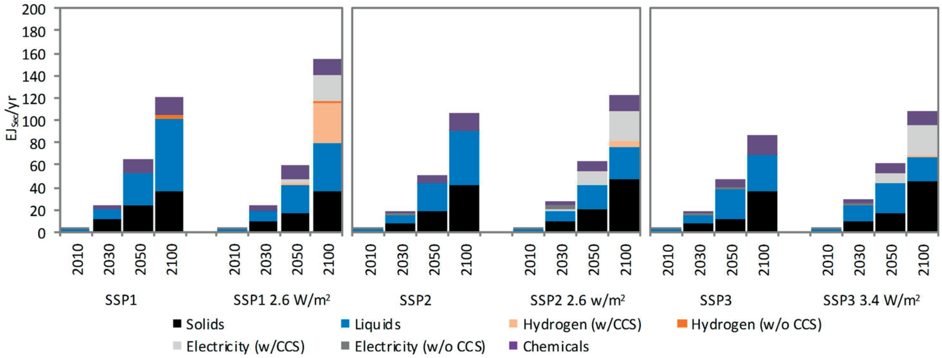

Figure 7.6. Final energy and non-energy (chemicals) consumption of biomass in the baseline and mitigation scenarios.

In the mitigation scenarios, BECCS technologies become more competitive as a result of the carbon taxes. These include both electricity and hydrogen production, the latter of which is most visible again in SSP1. However, production of liquid fuels persists for use in transport where bioenergy is the only cost-effective substitute for oil in several subsectors such as aviation and freight. For similar reasons, the use of solids is also maintained in the mitigation scenarios. It is important to note that these dynamics represent the most competitive uses of bioenergy in the TIMER model.

However, the allocation of final biomass uses is crucial for the overall mitigation potential, as shown in the next section.

7.4.3. Contribution to emission mitigation

Research Question 3: What is the overall greenhouse gas impact of biomass deployment for bioenergy and biochemicals, taking the potential dynamics of future land use and the energy system into account?

The overall contribution of bioenergy and biochemicals to climate mitigation depends on the net impact on the land and energy system emissions. In this thesis, these were assessed in Chapter 3 (LUC), Chapter 4 (non-energy) and Chapter 5 (energy system). Here, we use the SSP senarios to discuss the key findings from these chapters. The answer to this research question is structured in four components: i) land-use change emissions associated with biomass production, ii) changes in energy-system emissions due to biomass use in various sectors, iii) impact of cascading biochemicals on energy related emissions and iv) overall emission reduction due to biomass use.

Land-use change emissions due to biomass production

The effect of biomass production on LUC emissions depends on the quality of available land for biomass (section 7.4.1) and the demand for biomass from energy crops (section 7.4.2). The carbon stock constraints applied in the mitigation scenarios also affect the allocation of biomass production and the associated LUC emissions. This can be seen in Figure 7.7, which displays the projections of energy crop production and overall LUC emissions (including agriculture, pasture, afforestation/deforestation, etc.) for all scenarios. Although SSP1 projects the highest biomass demand, it has the lowest LUC emissions due to the availability of high quality abandoned agricultural lands. This is opposed to the other baselines where biomass production largely depends on natural lands.

Furthermore, despite the fact that the long-term demand for energy crops in SSP1 2.6 increases by 65% with respect to its baseline, the resultant land emissions are only 6% higher than the baseline in 2100 and land continues to act as a net carbon sink by mid-century. This is due to the carbon stock constraints applied in the mitigation scenario as well as the fact that biomass is mostly produced on abandoned agricultural lands, benefiting from the improved yields there. Thus the overall disturbance of carbon-stocks is low. In contrast, for SSP3 3.4, a small increase in energy crop demand (with respect to the baseline) leads to land emission increases in the order of 20% in 2100, as the carbon stocks of unprotected natural lands are affected. The carbon stock constraints are most effective when comparing the SSP2 baseline with its mitigation scenario. This baseline sees increasing demand of agriculture throughout the projection period, and although LUC emissions decrease, they are always positive. In this case the application of the carbon stock constraint in the mitigation scenario leads to an almost complete elimination of land use emissions, despite maintaining agricultural production and almost doubling the demand of energy crops.

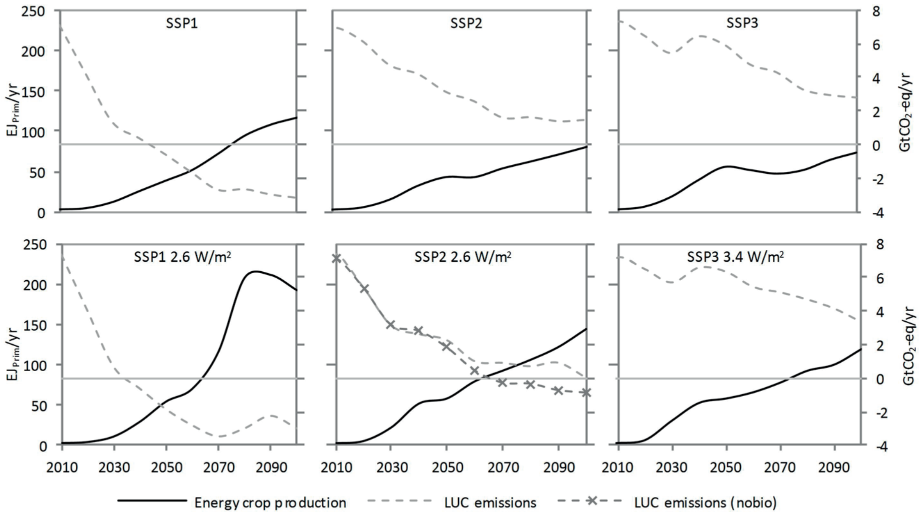

Figure 7.7. Energy crop production (solid line, left axis) and total land-use change emissions (dashed line, right axis) for all baselines and mitigation scenarios. Also shown are LUC emissions assuming no biomass production for the SSP2 2.6 W/m^2 scenario (dashed crossed line) as projected in Chapter 6. Note: LUC emissions include all land-based sources and sinks including agriculture, pasture, afforestation/deforestation, etc.

For the SSP2 2.6 land-use scenario, an extra projection has been done in order to demonstrate the trade-off between biomass production and LUC emissions, as shown in Figure 7.7 in the SSP2 2.6 panel (nobio). This is based on the sensitivity scenario of Chapter 6 which assumes the land-use scenarios of SSP2 2.6 with no biomass production. In 2010, LUC emissions stand at 7 $GtCO_2$-eq/yr, reducing to almost 0 by the end of the century in the SSP2 mitigation scenario. Assuming no biomass production, LUC emissions would have further reduced to almost -1 $GtCO_2$/eq. Although similar experiments have not been performed for the SSP1 and SSP3 scenarios, one would expect the '*gap'* to be relatively smaller *per unit biomass production* for SSP1 and larger for SSP3. This is because crop yields tend to be higher for SSP1 leading to lower land use. Furthermore in SSP1, biomass is produced mostly on abandoned agricultural lands and lands with high carbon stocks are protected. On the contrary, SSP3 has lower yields, production tends to be on natural lands and carbon stock constraints are more lenient, leading to biomass having a greater effect on carbon stocks.

Chapter 3 uses a novel method to investigate the spatially explicit effect of biofuel production on land-based carbon stocks. IMAGE maps of projected carbon stocks and crop productivity are used to calculate the ratio of cumulative changes in land-based carbon stocks to cumulative biofuel production over the period 2015-2100, defined as the 85-year emission factor (EF_{85}). This indicator shows a high variation across different locations, with the 10^{th}-90^{th} percentile range of the biofuel emission factors being 37-138 $kgCO_2/GJ_{Sec}$ for grass based methanol, 42-94 $kgCO_2$-eq/GJ_{Sec} for wood based methanol and 35-85 $kgCO_2/GJ_{Sec}$ for sugarcane ethanol. Besides the high spatial variability, the study also highlights a number of important elements that should be taken into account when estimating the emission reduction potential of biomass from energy crops. Land clearing only accounts for about a third of the emissions of biofuel supply, with non-renewable energy use accounting for another third. The remaining emissions come from long-term changes in carbon stocks and how they compare with a counterfactual with (re)growth of natural vegetation. However these proportions vary significantly. Furthermore, the emission-supply curves generated in Chapter 3 imply that at high biomass production levels, overall GHG benefits are achieved with time horizons above 30-40 years.

Energy system emissions and effect of different bioenergy uses

Biomass can potentially reduce emissions in a number of end uses (section 7.4.2). It is against this backdrop that long-term effectiveness of bioenergy and biochemical use has to be determined. Chapter 5 investigates how cross-sectoral leakage of displaced fossil fuels and the competition of multiple end uses for this resource affect its overall emission mitigation. The experiments conducted assume biomass availability is limited to a specific end use sector (buildings, non-energy, industry, transport and electricity production) as well as a *default* case where all sectors compete with each other for this resource. The emission mitigation potential is calculated by comparing overall energy system emissions of different biomass uses to a counterfactual with no biomass use. Figure 7.8 shows the biomass use and its contribution to emission reductions for each of the experiments[52].

The default scenario -where each sector competes for the resource- shows the highest biomass use and overall emission reductions, at 9% with respect to the no-biomass counterfactual. When investigating specific uses, biomass use for electricity production is shown to be the most attractive option in terms of total emission reduction per unit secondary bioenergy. This value stands at 143 $kgCO_2/GJ_{Sec}$ for bio-electricity, 51 $kgCO_2/GJ_{Sec}$ for bio-transport and 57 $kgCO_2/GJ_{Sec}$ for the default case (for details on all sectors and how this indicator is measured see Chapter 5). As mentioned in section 7.3.2,

[52] Chapter 5 was based on the OECD Environmental Outlook baseline which is similar in terms of parameterization as the SSP2 baseline described in this chapter.

electricity becomes the main final energy carrier in the baseline; with coal as a major feedstock for electricity generation. Thus producing electricity from biomass offers higher emission reductions than replacing oil or natural gas in other sectors.

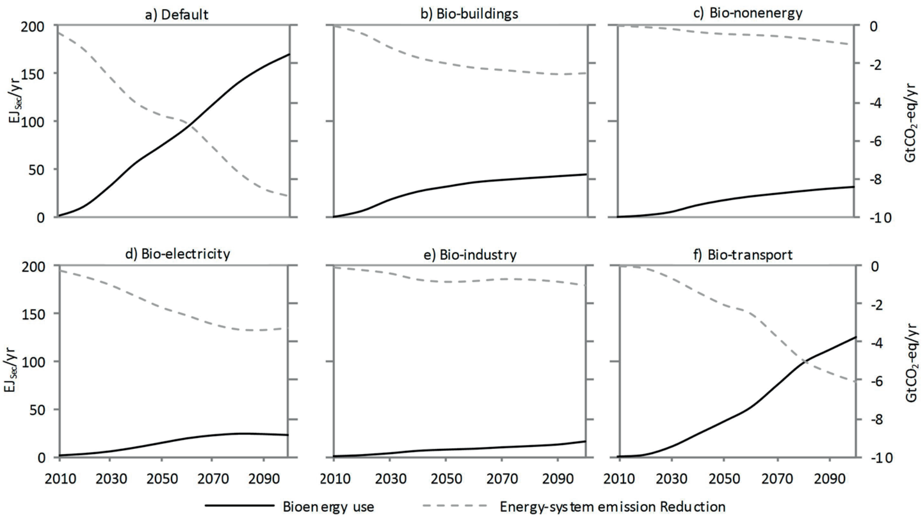

Figure 7.8. Bioenergy use (solid line, left axis) and energy system emission reduction with respect to a no-bioenergy case (dashed line, right axis). The scenarios and naming convention are described in Chapter 5. Bioenergy is measured in secondary terms. For non-energy this is bio-ethanol/methanol or heating fuel demand, for electricity this is EJ of electricity produced from biomass.

With high carbon taxes and free competition across sectors, biomass can contribute to a further 40% emission reduction. As explained in section 7.4.2, this is done by adopting BECCS technologies in electricity production, substituting oil in transport and as a heating fuel in buildings and industry. Use of bioenergy in transport and heating constricts its more effective use in the electricity sector, where if limited there, it could contribute to further emission reductions of up to 60%. Consequently, reducing heat demand in buildings and industry, as well as reducing the dependence of the transport sector on liquid fuels could contribute to deeper emission reductions by allowing for more effective use of bioenergy.

The sensitivity scenario of Chapter 5 tested how the competitiveness and effectiveness of bioenergy in the energy system are affected by assumptions on technological improvement and resource availability. The latter was shown to be more important since projected increases in fossil fuel prices make bioenergy competitive even with modest improvements in technology. Yet, the importance of technology development is highlighted in the sensitivity analysis of Chapter 3 where it was shown that improvements are a requirement in order to ensure that the emissions from biomass production are not prohibitively high.

It should be noted that these results are sensitive to the way the energy system is represented and timing of technology availability. As mentioned, IMAGE projects significant use of coal for power production whose displacement is an effective way for biomass to mitigate emissions, especially if implemented early on. However, if the electricity sector could be decarbonised early enough with other renewables, then more biomass could be directed towards transport where it is most competitive. This behaviour is displayed by the MESSAGE-GLOBIOM IAM (see Chapter 6) which has more optimistic assumptions on the availability and costs of other renewables.

Impact of cascading biochemicals

In Chapter 4 cascading uses of biochemicals through recycling and incineration with power generation are investigated. The analysis shows that the carbon emissions benefit accrued in either case are limited, and may be counter-productive. Concerning recycling, energy required for chemical recycling outweighs some of the benefits of reduced non-energy demand with overall emissions reducing by only 3%. For cascading, the relatively less efficient waste-to-electricity power-plants (compared to conventional ones) imply a low fossil fuel replacement rate (GJ of fossil fuels replaced per GJ post-consumer waste). Furthermore, unless the chemicals cascaded are exclusively bio-based (i.e. contain only *renewable-carbon*), the low fossil replacement rates, may lead to overall emission increases. This is because waste retains its carbon for long time periods while waste incineration releases it. The current low efficiency waste-to-power implies a small volume of electricity production per unit of carbon released, while otherwise the carbon would have been sequestered. Thus, it is important to ensure that cascading chains have high enough efficiencies and are managed so as to only include renewable carbon.

Overall emission reduction due to biomass, bioenergy and biochemicals

As described above, biomass use leads to changes in carbon balances of both the energy and the land-use systems. The trade-off between potential land-based mitigation (i.e. through afforestation) and biomass production is investigated in Chapter 6. As shown in Figure 7.9, while biomass production does increase LUC emissions with respect to a counterfactual with no biomass, the emission mitigation of the energy system leads to overall GHG benefits. The foregone emission reduction by avoiding biomass use can be seen as a *mitigation gap*. As shown in panel (a) of Figure 7.9, by 2100 total emissions fall from 86 $GtCO_2$-eq/yr in the baseline to 3 $GtCO_2$-eq/yr for the SSP2 2.6 scenario (i.e. a mitigation of 83 $GtCO_2$-eq/yr). For the *nobio* case the mitigation is 74 $GtCO_2$-eq/yr, leading to a *mitigation gap* of 9 $GtCO_2$-eq/yr with respect to the normal SSP2 2.6.

The components of this mitigation gap (Figure 7.9, panel (b)) highlight the contribution biomass has to overall mitigation. For the SSP2 mitigation scenario, biomass contributes to emission reductions by decarbonising energy supply (primarily the power sector, in combination with BECCS) and by substituting fossil fuels in energy demand end uses described in section 7.4.2. By 2050 this contribution is 4 and 2 $GtCO_2$-eq/yr respectively, increasing to 7 and 3 $GtCO_2$-eq/yr by 2100. Production of biomass leads to increased LUC and N_2O emissions by approximately 1 $GtCO_2$-eq/yr .

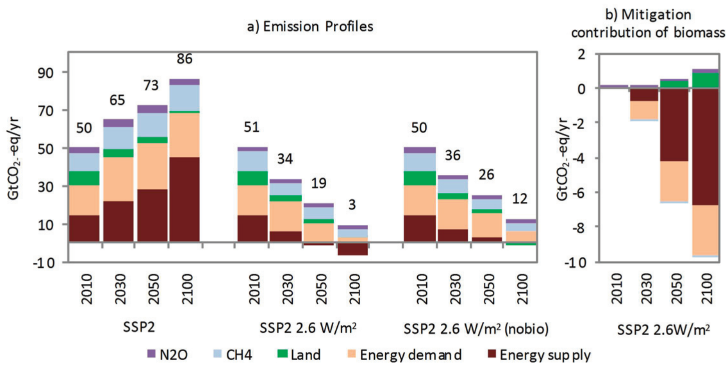

Figure 7.9. (a) GHG emissions for SSP2 baseline, mitigation and mitigation with constrained biomass. Numbers refer to the total GHG emissions. (b) Contribution of biomass to overall mitigation in SSP2 2.6 W/m2.

7.4.4. Ranges and robustness

Research Question 4: What is the future role of biomass, bioenergy and biochemicals in various climate change mitigation scenarios when accounting for the land and energy systems in an integrated manner?

Supply

Table 7.2 summarises key indicators for biomass supply and demand across all of the scenarios. As shown, primary biomass production is projected to increase to 80-87 EJ_{Prim}/yr in 2050 and 132-177 EJ_{Prim}/yr in 2100 for the baselines. In the mitigation scenarios, these numbers increase significantly to 118-126 EJ_{Prim}/yr in 2050 and 197-266 EJ_{Prim}/yr in 2100. The potential supply from residues is relatively constant across the scenarios with availability and quality of land being the major uncertainty. For all cases, residues make up most of the short term supply of primary biomass in the IMAGE projections as they generally are the cheapest resource at volumes less than 30 EJ_{Prim}/yr (see supply curves in Figure 7.5). This finding is consistent with several other IAM models (Rose et al., 2014; Popp et al., 2014). Furthermore, the long-term use of residues remains fairly constant across scenarios. While residues dominate biomass supply in the short term, eventual depletion of low cost residues and improvements

Table 7.2. Projections of key indicators for biomass and bioenergy across all scenarios.

		Baseline			Mitigation		
		SSP1	SSP2	SSP3	SSP1 2.6	SSP2 2.6	SSP3 3.4
					Primary Potential (EJ_{Prim}/yr)		
2050	Residues	72	70	65	70	68	64
	Energy Crops	149	74	81	135	72	96
	Total	221	143	146	206	140	161
					Primary Production (EJ_{Prim}/yr)		
	Residues	48	37	27	64	68	63
	Energy Crops	38	43	55	54	58	58
	Total	87	80	82	118	126	121
					Land Use (MHa)		
		126	165	215	178	222	226
					Secondary Bioenergy (EJ_{Sec}/yr)		
	w/o CCS	65	52	48	55	50	52
	w CCS	0	0	0	4	14	9
					% Total Final Consumption		
		12%	8%	8%	13%	15%	14%
					Primary Potential (EJ_{Prim}/yr)		
2100	Residues	80	79	77	78	77	76
	Energy Crops	507	155	123	452	157	153
	Total	587	234	200	530	234	229
					Primary Production (EJ_{Prim}/yr)		
	Residues	60	71	59	74	75	76
	Energy Crops	117	81	73	192	144	119
	Total	177	152	132	266	220	197
					Land Use (MHa)		
		274	201	185	451	359	302
					Secondary Bioenergy (EJ_{Sec}/yr)		
	w/o CCS	121	107	86	94	90	80
	w CCS	0	0	0	61	33	29
					% Total Final Consumption		
		24%	13%	11%	35%	25%	21%

in yields of energy crops means that after mid-century energy crops become the dominant primary source of biomass.

Figure 7.10 shows the projected production of residues and energy crops across all scenarios for five different world regions. Asia and OECD are the most important supply regions for residues since, as shown in Chapter 2, they produce crops with high residue potential (maize, rice and oilcrops) and enjoy lower competing uses. For energy crops, in SSP1, Latin America is projected to become increasingly important (40%

of total supply by 2100), while in SSP3 Asia and OECD regions (which are the main consumers) increase their relative production due to trade barriers in this baseline. In the mitigation scenarios, the relative importance of the Asia and OECD regions increases, accounting for approximately 30% each of the total supply. This is due to the limiting effect of the carbon stock restriction on Latin America (although this region remains important), as well as their above mentioned importance as supply regions of residues. For all scenarios, Africa accounts for 10-17% while the former Soviet Union is projected to supply less than 10% of the global demand.

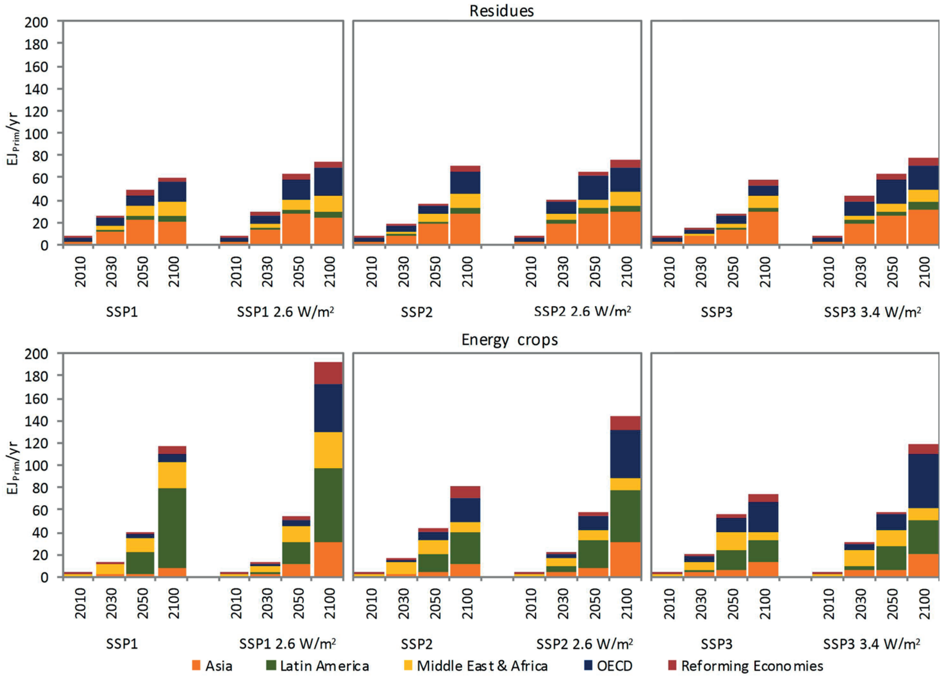

Figure 7.10. Primary biomass production from residues (top) and energy crops (bottom) disaggregated across production regions for all scenarios.

According to IMAGE, lignocellulosic crops (such as miscanthus and to a lesser extent woody biomass such as willow and eucalyptus) are the dominant energy crop. These are preferred over 1st generation sources due to their higher yields and ability to be grown in diverse locations. Realising the biomass production projected in the mitigation scenarios implies compounded annual growth rates of total production of the order of 4%. This requires significant changes in the production chains and international trade capacity. Furthermore, as highlighted in section 7.4.3, ensuring that this supply does not lead to adverse land use emissions requires the application of strict land use constraints.

Demand

As discussed in section 7.4.2, (modern) bioenergy and biochemicals play an increasingly important role across all scenarios (specific uses are shown in Table 7.7 in the Appendix). Across all baselines, the predominant uses are in the form of biochemicals, solids for heat in buildings and industry, or as second generation biofuels used in transport (Figure 7.6 above). This is driven by increases in the price of oil, which is projected to increase from 10 $\$_{2005}$/GJ to 13-14 $\$_{2005}$/GJ (80-85$\$_{2005}$ per barrel) by 2050 and 16-19 $\$_{2005}$/GJ (100-117$\$_{2005}$ per barrel) by 2100. Furthermore, technological learning and increases in crop yields drive down the price of biofuels. In the SSP1 baseline technological improvements lead to a small amount being converted to hydrogen towards the end of the century (4 EJ/yr).

In the mitigation scenarios bioenergy and biochemicals are projected to account for up to a third of the total final consumption of secondary energy, and about 10% of the overall mitigation. This figure is specific to SSP2 2.6 as discussed in section 7.4.3 with the specific contribution shown in Figure 7.9. The achieved mitigation is largely driven by ramping up BECCS which is projected to become competitive in the latter half of the century, promoted by technological improvements and high enough carbon taxes which make negative emissions very attractive. Biomass used with BECCS technologies is crucial in IMAGE for meeting strict climate targets, something reflected across a number of IAMs (Kriegler et al., 2014; Luderer et al., 2014). The contribution to mitigation is limited to 10%, despite the fact that bioenergy makes up 25% of TFC, for a number of reasons. Additional mitigation efforts such as the adoption of efficiency measures and the increased use of renewable energy leads to decreases in the carbon intensity of different end uses. Consequently, biomass has decreasing marginal emission reductions. This effect can be mitigated by focusing biomass use to the most effective end uses such as BECCS (Chapter 5). Additionally, LUC emissions due to biomass production further limit the mitigated emissions. For these reasons the potential contribution of biomass to mitigation efforts is higher in the SSP1 case where there is a lower displacement of carbon stocks and increased use of BECCS technologies. Conversely, the unfavourable developments of the SSP3 case would further limit the overall benefits of biomass use.

Box 7.1. Matching land-use emissions and energy-system reductions

The methods developed in this thesis allow us to assess the trade-off between emissions associated with biomass supply and avoided emissions as a result of bioenergy use. The emission-supply curves developed in Chapter 3 show the potential supply of different biofuels with increasing marginal EF_{85}[1]. Conversely, Chapter 5 calculates the ratio of cumulative (2015-2100) energy system emission reductions of different bioenergy options to the cumulative bioenergy use for the same period (see Table 5.5 in Chapter 5). This can be described as a *Reduction factor*, or RF_{85}.

In order to attain overall emission reductions over this 85 year period, it is necessary for $RF_{85} > EF_{85}$. In the case of limiting biomass to the transport sector (*BioTransport* scenario of Chapter 5), the RF_{85} is 51 $kgCO_2/GJ_{sec}$. Using the supply curves of Chapter 3, about 250 EJ_{sec}/yr of biofuels from non-woody feedstocks[2] are available that would still lead to an overall emission reduction. For the *BioElectricity* scenario the RF_{85} is 143 $kgCO_2/GJ_{Sec}$. Again, using the EF_{85} supply curves of primary biomass and assuming a (pessimistic) conversion efficiency of 30% for biomass power plants, about 250 EJ_{sec}/yr of bioelectricity can be generated from non-woody feedstocks[3] while achieving emission reductions in the given time frame[4].

In either case, further increases in biomass supply would lead to GHG payback times above 85 years.

1 EF_{85} is the emission factor of biofuels accounted over an 85 year period (2015-2100).

2 For woody and sugarcane feedstocks the potential reduces to approximately 110 and 60 EJ_{Sec}/yr.

3 For woody feedstocks the potential is 180 EJ_{sec}/yr. Sugarcane based electricity is only possible during the production of ethanol in TIMER.

4 Note that the above calculations assume that biomass is planted on the best available lands (from an emission perspective).

Comparison with the MESSAGE-GLOBIOM IAM

The above results were all calculated using the IMAGE model. In order to show the impact of using different models, Chapter 6 compares the projections of the SSP2 baseline and mitigation scenarios of IMAGE and MESSAGE-GLOBIOM[53]. Both models agree that biomass and bioenergy play an important role in mitigation scenarios. They project similar deployment rates -and the application of CCS- by the end of the century and highlight the importance of land uses in order to balance food production, biomass production and land-based emissions. However, due to the different methods through which the land and energy systems are represented, the specific supply routes, land use and overall mitigation strategies differ significantly.

53 MESSAGE-GLOBIOM is an IAM developed by the International Institute for Applied Systems Analysis.

Unlike IMAGE which follows a *food first* principle, MESSAGE-GLOBIOM allows different land options (agriculture, forestry and biomass production) to compete based on their relative profitability. Furthermore, the representation of residues in GLOBIOM is restricted to the forestry sector which has limited potential, as in IMAGE (see Chapter 2). For the mitigation scenario, while IMAGE projects a large portion of primary biomass to come from residues, in MESSAGE-GLOBIOM the carbon taxes lead to a very high profitability of biomass for energy purposes and afforestation (carbon plantations) which drives displacement of food and feed and an overall decrease in food production.

Both models agree on the importance of decarbonisation of the power sector including the use of BECCS. The bioenergy strategies employed, however, are very different. MESSAGE-GLOBIOM opts for short term mitigation through different land use strategies and delaying the use of bioenergy towards the latter part of the century focusing on biofuel use in transport combined with CCS. This difference in strategies is due to some crucial aspects of MESSAGE-GLOBIOM: the land use system is more elastic offering significant land-based mitigation, (more) optimistic assumptions of non-biomass renewables for power production, the prospect of having stranded assets (low capital stock inertia), perfect foresight, and the possibility of biofuels combined with BECCS.

The comparison highlights that, while IAMs can improve the understanding of the dynamics, trade-offs and possibilities of biomass supply and demand, the specific insights and mitigation strategies adopted by different models may vary. These depend on how the relevant systems are represented and how comprehensive they are concerning the availability of different supply and use possibilities, e.g. agricultural residues missing in the MESSAGE-GLOBIOM framework, and biofuel production with CCS routes missing in the IMAGE model.

7.5. Policy recommendations

The results of this thesis have identified a number of key policy recommendations for the application of biomass, bioenergy and biochemicals in order to reduce GHG emissions. These can be summarised as follows:

Biomass sources: According to the model calculations, perennial grasses are the most attractive feedstock in terms of potential, costs and associated emissions. This is due to their comparatively high yields, their diverse range of applications for energy and chemicals and their short growing cycles. Large scale production and delivery of these resources at high enough yields may be achieved through incentives and stable policies. Additionally, residues can also form a significant low cost and low emission source (>50 EJ_{prim}/yr), as long as ecological constraints and other current uses are managed effectively. The former could benefit from reduced-till and plastic mulching (Qin et al., 2015; Batidzirai et al., 2016), and the latter by avoiding residues as livestock feed and increasing the access of poor households to modern energy carriers.

Minimise supply emissions: The land-use emissions associated with biomass supply have been shown to vary significantly across locations. Ensuring energy crop supply with low GHG effects requires increases in productivity of energy and food crops and livestock. Minimising land required for food production (especially pasture) and increasing land quality would allow for the availability of large volumes of productive land. In such cases the availability of biomass with low emission (<20 $kgCO_2$-eq/GJ_{prim}) effects could be greater than 100 EJ_{Prim}/yr. In this light, the modernization of food production systems and adoption of approaches such as integrated crop-livestock farming may offer an opportunity to increase the productivity, decrease emissions and restore degraded lands (Gil et al., 2016; Bennetzen et al., 2016). Improved crop yields would also increase the supply of residues while lowering their costs. Furthermore, it is important to ensure the protection of lands with high carbon stocks and other ecosystem services, ideally through international mechanisms and agreements in order to avoid leakage (Overmars et al., 2014).

Conversion and use: Mitigation scenarios depend on the availability of affordable lignocellulosic (2nd generation) biofuels, biomass feedstocks in power production, and their combination with carbon capture and storage. More research on these technologies is needed for effective use of biomass in GHG mitigation. Additionally, there are important synergies between effective bioenergy use and efficiency gains in the energy system. Bioenergy can meet heat demand in buildings and industry at a low cost and may also become very competitive in transport. However, unless biofuel-CCS technologies are available, the emission reduction per unit bioenergy for these sectors (20-80 $kgCO_2/GJ_{Sec}$) is lower than if it were used for power production (>100 $kgCO_2/GJ_{Sec}$). The latter having a larger reduction potential because biomass can replace large volumes of coal there. This is important if policy aims to reduce emissions substantially. Improvements in energy intensity of buildings and different transport modes can help direct biomass towards the more effective uses. Energy and climate policies could benefit from such *tandem* approaches. Though biochemicals may be an attractive use of biomass (van Dam et al., 2005; Brar et al., 2014), their overall contribution to climate mitigation is limited when compared to other biomass options. In order to maximise benefits of cascading uses, improved recycling and incineration technologies as well as management of what chemicals are cascaded is required.

Policy timeframes: Due to high up-front emissions from land-use change, bioenergy often offers serious mitigation only when used in a long-term context. The short accounting periods used by some policies (e.g. EU RED) limits the potential for biofuel supply below what is required for strict climate targets. Allowing for longer accounting periods (>20 years) would streamline policies with the biomass volumes IAMs suggest are required for strict climate goals. This is particularly true if there are increased pressures on natural lands due to agricultural expansion.

Supply chains: The level of bioenergy demand in the mitigation scenarios will require large-scale production of primary biomass and its international trade. Though the projected growth rates are large (≈4% per year), they are not without precedent as similar (and larger) growth rates in production and international trade of energy, metals and agricultural commodities have been witnessed in the 20th century (Stopford, 2009). In this context important focus areas include the adoption of fully functioning markets for residues and second generation feedstocks, biomass certification schemes, harmonisation of quality standards and scaling up of international maritime trade.

7.6. Further research

The work presented in this thesis has highlighted a number of areas which warrant further research. These include a number of opportunities for improving the representation and evaluation of biomass and bioenergy in models, as well as understanding how model results can be translated into practice.

Exploration of model uncertainty: A Monte-Carlo analysis using probability distribution functions for relevant parameters could provide insight on the uncertainties involved. The analysis could focus on addressing the uncertainty in land use and demand models. Key parameters include, for example, techno-economic parameters of conversion and end-use technologies, crop yields (food and energy) and substitution elasticities.

Potential biomass chains: Chapter 6 highlighted that the possibility of biofuels with CCS may allow for varying bioenergy strategies and improved effectiveness of bioenergy use in mitigation scenarios. Better understanding is needed on how different energy models respond to different sets of technologies such as CCS possibilities, transport options and other renewables. Furthermore, detailed models should assess the potential synergistic effects offered by multiple-output facilities such as biorefineries (Thornley, 2014; Clark & Deswarte, 2015). On the supply side, IAMs contain little to no detail on intercropping, agroforestry, mixed crop-livestock systems as well as the possibility of carbon sequestration due to biomass production on converted agricultural and degraded lands (Tolbert et al., 2002; Garten, 2012). An integrated assessment of the potential production and environmental performance of these systems is needed.

Trade-offs of biomass use and land allocation: The methodology developed in Chapter 3 can be used to better understand the GHG effects of different volumes of bioenergy supply. These emission-supply curves can be compared to similar mitigation-supply curves from bioenergy and biochemical use or afforestation (see Box 7.1). This would allow for a better understanding of the trade-offs of different land and energy uses.

Ecological and competing uses of residues: Based on the results presented in this study, residues may offer an important supply option. However, it is important to further check the supply and demand dynamics of this resource in IAMs with more bottom-up information. Furthermore, a better understanding of the GHG trade-off of different residue uses (bioenergy, livestock feed, left on the soil) is required. In particular, the critical elements affecting this trade-off need to be better understood.

Further impacts: This thesis focused on the GHG emission impacts of biomass on the land and energy systems. Yet, recent publications have indicated the importance of evaluating other possible impacts of bioenergy, including biodiversity, water and nutrient use (Searchinger et al., 2015). Bottom-up and model assessments can further investigate the potential effects and trade-offs of increased biomass production on these issues.

Feasibility of IAM projections: IAM analyses provide perspectives of possible biomass and bioenergy or biochemical uses and their contribution to climate mitigation, amongst a large number of other mitigation routes. Given the projected large-scale deployment of biomass, it is important to identify potential barriers (infrastructure, legal, financial, technological, social, etc.) and highlight the necessary boundary conditions which would ensure that this deployment is achieved without adverse effects.

This thesis has focused on developing, assessing, and projecting scenarios of an integrated assessment model. The statistician George Box wrote "*all models are wrong but some are useful".* This is undoubtedly true, but the usefulness of any model depends on how it is used. Model assessments of biomass and the projected mitigation strategies are inherently uncertain as they are based on conceptual representations of a system with multiple known and unknown interactions. Due to the plethora of potential dynamics, no single model can fully account for all the possibilities, feedbacks and costs of bioenergy use. This is especially true as models tend to follow specific paradigms (economic, optimisation, simulation, etc.), each suited to answering particular questions and offer related insights. While the results of this thesis provide important new insights into the role of biomass as a climate change mitigation option, addressing these questions, and developing new ones, with different models and approaches is required. Comparing the insights from different representations of the involved systems is crucial to understanding their nuances and directing us towards a clearer view of a complex and often veiled environment.

7.7. Appendix

Table 7.3. Land use and available land for bioenergy production (MHa) for all scenarios.

		Baseline Scenarios			Mitigation Scenarios		
		SSP1	**SSP2**	**SSP3**	**SSP1 2.6**	**SSP2 2.6**	**SSP3 3.4**
					MHa		
2050	Food Crop Land	1 537	1 699	1 757	1 498	1 685	1 768
	Pasture	2 941	3 342	3 421	2 864	3 278	3 418
	Forest	3 939	3 668	3 583	4 080	3 815	3 572
	Other Lands[54]	4 646	4 355	4 304	4 621	4 285	4 305
	Total	*13 063*	*13 063*	*13 063*	*13 063*	*13 063*	*13 063*
	Land Available for Biomass:						
	Abandoned	433	152	115	475	163	123
	Other lands	228	272	378.5	143	256	416
2100	Food Crop Land	1 444	1 717	1 922	1 469	1 812	2 024
	Pasture	2 361	3 348	3 460	2 324	3 296	3 462
	Forest	4 217	3 664	3 490	4 344	3 840	3 406
	Other Lands	5 041	4 335	4 191	4 925	4 115	4 170
	Total	*13 063*	*13 063*	*13 063*	*13 063*	*13 063*	*13 063*
	Land Available for Biomass:						
	Abandoned	1 094	322	242.8	1 124	331	253
	Other lands	225	293	386.3	148	295	447

Table 7.4. Price projections of fossil fuel primary energy carriers and electricity for all baselines.

		Baseline Scenarios		
		SSP1	SSP2	SSP3
			$\$_{2005}$/GJ	
2010	Coal		1.5	
	Oil		10.5	
	Natural Gas		3.2	
	Electricity		22.4	
2050	Coal	2.1	2.2	2.2
	Oil	12.9	13.5	13.8
	Natural Gas	7.9	7.3	7.4
	Electricity	20.8	19.6	18.5
2100	Coal	2.2	2.3	2.4
	Oil	16.1	19.2	18.6
	Natural Gas	10.6	11.4	11.0
	Electricity	21.6	19.2	18.0

[54] This includes urban areas and lands which may be used for biomass growth.

Table 7.5. Projections of primary and final energy consumption for all scenarios.

		Baseline				Mitigation			
		2010	2030	2050	2100	2010	2030	2050	2100
		Primary Energy (EJ_{Prim}/yr)							
SSP1	Coal	144	186	166	102	144	140	57	21
	Oil	172	154	133	45	172	136	110	41
	Gas	112	210	260	200	112	178	193	98
	Trad. Bio	41	16	14	3	41	13	11	2
	Mod. Bio	10	38	87	177	10	40	118	266
	Other Renew.	14	31	94	193	14	31	101	175
	Nuclear	10	9	3	0	10	10	3	1
SSP2	Coal	144	230	259	474	144	66	42	96
	Oil	172	169	184	172	172	126	106	37
	Gas	112	185	231	185	112	149	118	87
	Trad. Bio	41	36	30	13	41	25	29	12
	Mod. Bio	10	33	80	152	10	66	126	220
	Other Renew.	14	32	57	130	14	31	68	153
	Nuclear	10	12	12	13	10	22	36	63
SSP3	Coal	144	234	297	472	144	92	56	106
	Oil	172	165	140	163	172	129	100	48
	Gas	112	188	227	220	112	165	158	104
	Trad. Bio	41	41	43	36	41	42	42	46
	Mod. Bio	10	32	82	132	10	74	121	197
	Other Renew.	14	28	38	52	14	28	53	76
	Nuclear	10	11	7	15	10	16	30	72
		Final Energy (EJ_{Final}/yr)							
SSP1	Solids	81	73	78	58	81	67	65	57
	Liquids	134	142	138	97	134	130	117	73
	Gasses	48	90	134	83	48	80	112	57
	Heat	11	12	9	2	11	10	8	2
	Hydrogen	0	1	5	20	0	1	6	43
	Electricity	58	116	179	247	58	105	146	211
SSP2	Solids	81	105	106	120	81	89	92	100
	Liquids	134	159	187	199	134	125	113	58
	Gasses	48	94	145	141	48	72	82	29
	Heat	11	13	12	3	11	9	7	2
	Hydrogen	0	1	4	20	0	1	4	53
	Electricity	58	116	168	322	58	91	121	253
SSP3	Solids	81	118	143	186	81	108	107	149
	Liquids	134	155	146	175	134	142	101	44
	Gasses	48	99	153	180	48	89	106	50
	Heat	11	14	12	4	11	13	7	2
	Hydrogen	0	1	3	5	0	0	3	69
	Electricity	58	112	151	252	58	102	108	200

Table 7.6. Emissions per source (MtCO2-eq/yr) for all scenarios.

		Baseline Scenarios			Mitigation Scenarios		
		SSP1	SSP2	SSP3	SSP1 2.6	SSP2 2.6	SSP3 3.4
		MtCO$_2$-eq/yr					
2050	Energy Supply	21 813	27 886	29 011	6 760	-1 556	95
	Energy Demand	18 521	24 895	26 480	12 952	10 726	12 787
	Land	-581	3 125	5 955	-1 851	2 257	6 333
	CH_4	10 461	12 941	14 054	5 555	5 544	6 970
	N_2O	2 829	3 731	4 310	2 064	2 508	3 029
	Total	53 043	72 577	79 810	25 481	19 480	29 214
2100	Energy Supply	15 923	45 446	42 710	-8 786	-6 466	-5 608
	Energy Demand	7 537	22 662	30 827	4 797	2 693	6 059
	Land	-3 173	1 475	2 797	-2 986	30	3 337
	CH_4	6 135	13 162	16 397	3 285	4 579	6 215
	N_2O	2 225	3 742	5 013	1 820	2 520	3 388
	Total	28 647	86 488	97 744	-1 870	3 356	13 392

Table 7.7. Secondary bioenergy production per energy carrier and total final consumption (EJ/yr) for all scenarios.

		Baseline Scenarios			Mitigation Scenarios		
		SSP1	SSP2	SSP3	SSP1 2.6	SSP2 2.6	SSP3 3.4
		EJ$_{Sec}$/yr					
2050	Solids	24	18	12	18	20	17
	Liquids	28	26	27	25	21	26
	Hydrogen (w/CCS)	-	-	-	2	1	-
	Hydrogen (w/o CCS)	-	-	-	-	-	-
	Electricity (w/CCS)	-	-	-	2	13	9
	Electricity (w/o CCS)	-	-	-	1	-	1
	Chemicals	13	7	8	12	9	8
	Total Final Consumption	542	623	608	454	420	433
2100	Solids	36	42	37	37	48	45
	Liquids	65	48	32	42	28	21
	Hydrogen (w/CCS)	-	-	-	37	5	2
	Hydrogen (w/o CCS)	4	-	-	-	-	-
	Electricity (w/CCS)	-	-	-	24	28	27
	Electricity (w/o CCS)	-	-	-	-	-	-
	Chemicals	16	16	17	14	14	14
	Total Final Consumption[55]	507	804	803	442	495	515

[55] Includes all fossil and renewable energy carriers.

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Summary

Background

The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicated that in order to meet the climate targets discussed in international climate policy, anthropogenic greenhouse gas (GHG) emissions need to be reduced significantly over the next decades. The majority of these emissions come from the combustion of fossil fuels for energy purposes. Emission mitigation will require fundamental changes in energy supply and demand, such as increased energy efficiency and substitution of fossil fuels by alternative sources. The use of biomass as an alternative energy source is attractive as it can be sourced from a number of primary sources (crops, residues, waste streams, etc.) and it can provide multiple services such as heat and power, liquid fuels for transport, and act as a feedstock non-energy uses such as (bio)chemicals. Furthermore, biomass derived energy carriers (bioenergy) can be easily integrated in existing energy infrastructure.

Yet, the large scale use of biomass and bioenergy in climate mitigation is controversial. Significant uncertainties exist concerning the current and projected primary potential: recent assessments estimate that by 2050 this potential may range between 50 and 500 EJ_{Prim}/yr. There also is little agreement on the contribution of biomass and bioenergy to reducing GHG emissions as its effectiveness depends on a number of uncertainties. Biomass production leads to direct and/or indirect land use change (LUC) which may result in losses of land-based carbon stocks. The associated emissions are very difficult to assess given the uncertainties in land-use dynamics. The eventual emission reductions in the energy system depend on the way biomass is used, for instance as a liquid fuel, to produce electricity or as feedstock for biochemicals or the application of novel technologies such as bioenergy with carbon capture and storage (BECCS). Overall, in current literature the avoided GHG emissions from different biomass uses can range from below 0 to greater than 200 $kgCO_2$-eq/GJ_{Sec}.

The large spread in estimates on future biomass availability and GHG emission reduction potentials highlight the important uncertainties involved in its assessment. These uncertainties depend on a number of technical, social, behavioural, political and economic factors which determine how land and energy use may develop in the future.

Aim and research questions

This thesis aims to investigate the role of biomass as a climate change mitigation option by using an integrated assessment model (IAM), the *Integrated Model to Assess the Global Environment* (IMAGE). This allows for an integrated analytical framework which includes spatial details of biomass availability and carbon dynamics as well as a dynamic representation of competing biomass resources and applications. In developing and using the IAM, this thesis addresses the following research questions:

1. What is the potential future supply of modern biomass from residues and energy crops when accounting for the drivers and constraints in a spatially explicit manner?
2. What is the demand for biomass for different energy and chemical purposes in a dynamic energy system model?
3. What is the overall greenhouse gas impact of biomass deployment for bioenergy and biochemicals, taking the potential dynamics of future land use and the energy system into account?
4. What is the future role of biomass, bioenergy and biochemicals in various climate change mitigation scenarios when accounting for the land and energy systems in an integrated manner?

Method

The IMAGE model is designed to investigate the interactions between human and natural systems by using simplified representations of the most relevant processes. These include interactions within and between the land, energy, economic and climate systems. The purpose of the model is to assess global change and the effect of different policies.

This thesis improves specific modules of IMAGE so as to better represent the supply and demand of biomass. Furthermore, IMAGE is used in order to conduct various experiments to answer the research questions, accounting for several uncertainties including socio-economic development and the presence of stringent climate policy. By comparing the results of different scenarios we highlight the ranges, drivers and constraints of biomass, bioenergy and biochemical pathways, and how they vary across different possible futures.

The scenarios used are based on the *Shared Socioeconomic Pathways* (SSP) which explore different socio-economic development possibilities, characterized by their challenges to climate mitigation and adaptation. These consequently lead to varying land and energy use and resultant GHG emissions. The *SSP1* baseline describes a world with low challenges with population reaching a maximum by mid-century, decreasing thereafter, while global GDP per capita increases significantly. Furthermore there are notable efforts towards conserving natural lands, reducing meat consumption, increasing crop and livestock yields and increasing energy efficiency. *SSP2* assumes a middle of the road development based on the extrapolation of current trends, with population stabilizing towards the end of the century and some efforts towards conserving natural land and increasing agricultural and energy efficiency. Finally, SSP3 projects a world with high challenges to adaptation and mitigation, with very high population growth, few restrictions on land use, limited improvements in welfare and persistence of inefficient agriculture and energy systems.

Each baseline has a mitigation scenario which simulates the application of climate policies in order to meet a radiative forcing target corresponding to 2.6-3.4 W/m^2. The mitigation scenarios are called *SSP1 2.6*, *SSP2 2.6* and *SSP3 3.4*.

Outline

In order to develop and apply the methods required to answer these questions, this thesis investigates long term *biomass supply* (Chapters 2 & 3), *biomass demand* (Chapters 3 & 4), and *integrated biomass scenarios* (Chapters 5 & 6). Each of these chapters addresses one or more of the research questions by developing and investigating modelling methods and performing (integrated) scenario analyses.

Chapter 2 outlines the method used in order to determine the long term supply and cost of residues from agriculture and forestry operations. We use the IMAGE model to project the production of these sectors as well as existing demands of residues such as livestock feed and traditional fuel use. Subsequently, we calculate their spatial availability and costs and derive supply curves of this resource in an integrated and geographically explicit manner.

Chapter 3 introduces the concept of emission curves which display LUC emissions as a function of biomass supply. IMAGE projections of land-based carbon stocks and biomass yields are used to calculate spatially specific emission factors and GHG payback periods. Emission supply curves for different 1st and 2nd generation biofuels are presented, paying special attention to the suitability of different biomes and the sensitivity to key assumptions.

Chapter 4 presents the method by which the non-energy uses of energy carriers (feedstocks for chemicals) were included in the TIMER model. The model is used to investigate the long-term potential of biochemicals, the effects of climate policy, and mitigation potential of cascading chemicals through recycling and/or incineration with power production.

Chapter 5 uses the updated TIMER model in order to investigate the long-term use and emission implications of biomass in the energy system by investigating different bioenergy and biochemical uses. Attention is paid to the emission reduction per unit biomass for each end-use, the role of competing possibilities, and the effect of increasingly stringent climate policy. Furthermore, the results are tested for uncertainties in biomass demand and technological development.

Chapter 6 compares the structures and results of two IAM frameworks: IMAGE and MESSAGE-GLOBIOM by describing their representations of the land and energy and systems, focusing on how each IAM determines the supply and demand of biomass and bioenergy. Consistent baseline and mitigation scenarios are projected and a sensitivity scenario investigating the trade-off between biomass production and land-based mitigation is applied.

Chapter 7 uses the improved IMAGE model (including the additions of Chapters 2 & 4) in order to investigate the role of biomass for climate change mitigation in an integrated manner. Finally, this chapter incorporates the individual results from the preceding chapters in order to answer the research questions, give policy recommendations and propose further research avenues.

The role of biomass in climate change mitigation

Drivers and constraints of biomass supply

Residues

The maximum *theoretical potential* of residues depends on overall agriculture and forestry production and the intensity of these operations. The *available potential* is restricted by ecological constraints and competing uses such as feed for livestock or traditional fuel use in poor households. The projections show that the *theoretical potential* increases from approximately 120 EJ_{Prim}/yr today to 130, 136 and 145 EJ_{Prim}/yr by 2050 for SSP1, 2 and 3 respectively. However ecological and competing uses limit the *available* potential to 72, 70 and 65 EJ_{Prim}/yr. This increases to 80, 79 and 77 EJ_{Prim}/yr by 2100, almost all of which is available at less than 10 $\$_{2005}/GJ_{Prim}$.

Interestingly, the available potential does not vary much across different scenarios due to counteracting dynamics. In SSP1, lower agricultural production limits the theoretical potential, but lower livestock production and reduced traditional fuel use also limit the competing demand. In SSP3 the theoretical potential is higher (due to higher production) but the competing uses are also higher. Furthermore, due to the more extensive production, residues in SSP3 are also slightly more expensive due to increased transport costs.

Energy Crops

Energy crops in IMAGE can either be produced on abandoned agricultural lands or on natural lands which are not protected. Typically, in IMAGE calculations it is assumed that forest areas are excluded for biomass production. In SSP1, the decrease in demand of land for agricultural production allows for significant volumes of abandoned lands, while the stricter environmental constraints limit the volume of natural lands. The SSP3 baseline shows the opposite behaviour, with SSP2 occupying a middle ground. The type of land which is available is very important for the overall biomass potential, as abandoned agricultural lands tend to have the highest yields. Unused lands usually have high yields with high emissions (forests) or lower yields (natural grasslands).

Aggregate biomass yields (lignocellulosic crops) are projected to increase from approximately 250 GJ_{Prim}/Ha today to 306, 262 and 257 GJ_{Prim}/Ha for SSP1, 2 and 3 respectively by 2050. By 2100, further increases lead to yields of 426, 401 and 395 GJ_{Prim}/Ha. The differences across the scenarios arise due to the varying land quality available in each case as well as improvements in management. The availability of abandoned agricultural lands with high yields lead to SSP1 having the highest biomass potential, despite the stricter constraints on natural lands. For SSP2 and SSP3 baselines, despite the more lenient constraints on land use, the high demand for agriculture limits biomass production to lower quality lands reducing the overall potential. Energy crop potential is projected to be 149, 74 and 81 EJ_{Prim}/yr in 2050 for SSP1, 2 and 3 respectively, increasing to 507, 155 and 123 EJ_{Prim}/yr by 2100. The available potential for residues and energy crops for all scenarios is shown in Table 1.

Demand for bioenergy and biochemicals

Biochemicals

In the SSPs, total primary energy demand for non-energy products increases from 26 EJ_{Prim}/yr in 2010 to around 45 EJ_{Prim}/yr in 2050 and 58, 92 and 77 EJ_{Prim}/yr for SSP1, 2 and 3 respectively in 2100. As shown in Chapter 4, in a counterfactual scenario where biomass is assumed unavailable, coal-based feedstocks become increasingly important by the end of the century, driven by price increases of oil and natural gas. If biomass is allowed as a feedstock, it can contribute to over 30% of the primary supply by 2050 and over 35-50% by 2100. Besides rising fossil fuel prices, biomass competitiveness is also increased by learning in the production of bio-based intermediate chemicals (ethanol and methanol).

Bioenergy in the energy system

Figure 1 shows the projections of bioenergy and biochemical use for the baseline and mitigation scenarios. All cases show an increase in bioenergy use throughout the projection period. The long-term use further increases in the mitigation scenarios, prompted by the application of carbon taxes. The favourable technological assumptions and biomass availability lead to the highest bioenergy use in the SSP1 scenario. By 2050, bioenergy and biochemicals account for 12% of the total secondary energy

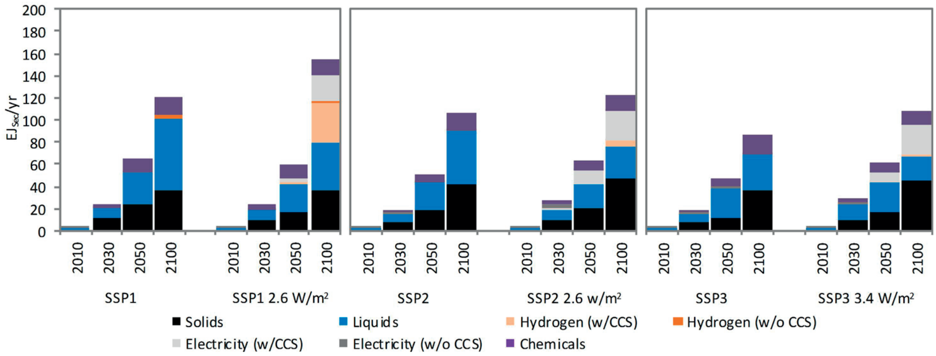


Figure 1. Final energy and non-energy (chemicals) consumption of biomass in the baseline and mitigation scenarios.

for SSP1, and 8% for SSP2 and 3. These shares increase to 24%, 13% and 11% respectively by 2100. In the mitigation scenarios, these fractions are even higher at 35%, 25% and 21% (2100), respectively.

The primary use of biomass in the baselines is for liquid fuels. As explained in Chapter 5, this is due to demand from the transport sector amid increasing oil prices. Other important uses include chemicals (non-energy) as described above and solid bioenergy as a heating fuel in buildings and industry. The importance of solid fuels increases in SSP2 and SSP3 scenarios due to pessimistic assumptions on the improvement of 2nd generation biofuel technologies as well as increased demand for heat in buildings and industry. In SSP1, the availability of improved technologies also allows for small amounts of hydrogen to be produced.

In the mitigation scenarios, BECCS technologies become more competitive as a result of the carbon taxes. These include both electricity and hydrogen production, the latter of which is most visible again in SSP1. However, production of liquid and solid fuels persists in uses where this type of bioenergy is the only cost-effective substitute for fossil fuels.

Contribution to emission mitigation

Land-use change due to biomass production

The emission factors calculated in Chapter 3 show large spatial variation, with the 10th-90th percentile range of the biofuel emission factors being 37-138 $kgCO_2/GJ_{Sec}$ for grass based methanol, 42-94 $kgCO_2$-eq/GJ_{Sec} for wood based methanol and 35-85 $kgCO_2/GJ_{Sec}$ for sugarcane ethanol. When estimating the emission reduction potential of biomass from energy crops a number of important elements should be taken into account. Land clearing only accounts for about a third of the emissions of biofuel supply, with non-renewable energy use accounting for another third. The remaining emissions come from long-term changes in carbon stocks and how they compare with a counterfactual with natural vegetation. However these proportions vary significantly. Furthermore, the emission-supply curves generated in Chapter 3 imply that at high biomass production levels, overall GHG benefits are achieved with time horizons above 30-40 years.

In the scenario analysis, both the quality of available land for biomass and the demand for biomass from energy crops affect the LUC emissions. The availability of high quality (abandoned) land leads to higher yields and thus lower land demand. Consequently, although SSP1 projects the highest biomass demand, it has the lowest LUC emissions. In the other baselines, biomass production largely depends on natural lands, leading to higher LUC emissions. Furthermore, ensuring biomass supply with low LUC emissions can be achieved by applying constraints on land availability based on the carbon stocks of lands. This is done in the mitigation scenarios with the strongest constraints placed on SSP1 and the weakest on SSP3. Consequently, in SSP1 2.6, though the demand for energy crops increases by 65% with respect to its baseline, the resultant land emissions are only 6% higher. In contrast, for SSP3 3.4, a small increase in energy crop demand (with respect to the baseline) leads to land emission increases in the order of 20% in 2100, as the carbon stocks of unprotected natural lands are affected.

Energy system emissions and effect of different bioenergy uses

When biomass competes freely for a number of end uses (buildings, non-energy, transport and electricity production) it can contribute to reducing energy system emissions by 9% with respect to a no-biomass counterfactual. When investigating specific uses, biomass use for electricity production is shown to be the most attractive option in terms of total emission reduction per unit secondary bioenergy use. This is because electricity becomes the main final energy carrier in the baseline; with coal as a major feedstock for electricity generation. Thus, producing electricity from biomass offers higher emission reductions than replacing oil or natural gas in other sectors. With high carbon taxes and free competition across sectors, biomass can contribute to a further 40% emission reduction by adopting BECCS technologies in electricity production, substituting oil in transport and use as a heating fuel in buildings and industry. Use of bioenergy in transport and heating reduces the more effective use in the electricity sector.

Overall emission reduction due to biomass, bioenergy and biochemicals

As described above, biomass use leads to changes in carbon fluxes in both the energy and the land-use systems. Figure 2 shows, the GHG emissions from different sources for the SSP2 baseline, the SSP2 2.6 mitigation scenario and a sensitivity scenario on

SSP2 2.6 with no biomass. The effect that biomass has on each of the emission sectors is shown in panel (b). As shown, while biomass production does increase LUC emissions with respect to a counterfactual with no biomass, the emission mitigation of the energy system leads to an overall GHG reduction. Biomass contributes to emission reductions by decarbonising energy supply (primarily the power sector, in combination with BECCS) and by substituting fossil fuels in energy demand end uses. By 2050 this contribution is 4 and 2 $GtCO_2$-eq/yr respectively, increasing to 7 and 3 $GtCO_2$-eq/yr by 2100. The biomass production leads to increased LUC and N_2O emissions by approximately 1 $GtCO_2$-eq/yr .

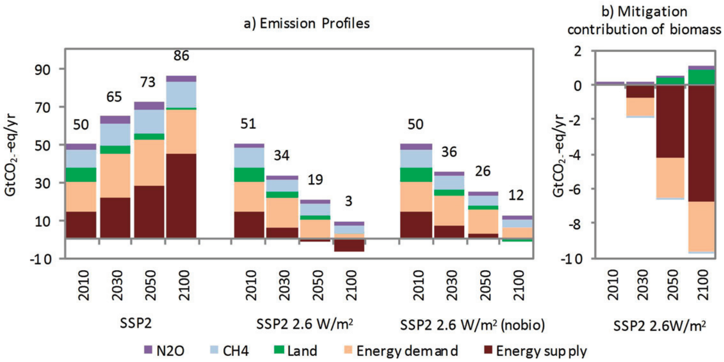


Figure 2. (a) GHG emissions for SSP2 baseline, mitigation and mitigation with constrained biomass. Numbers refer to the total GHG emissions. (b) Contribution of biomass to overall mitigation in SSP2 2.6.

Ranges and robustness

Table 1 summarises key indicators for biomass supply and demand across all of the scenarios. As shown, primary biomass production is projected to increase to 80-87 EJ_{Prim}/yr in 2050 and 132-177 EJ_{Prim}/yr in 2100 for the baselines. In the mitigation scenarios, these numbers increase significantly to 118-126 EJ_{Prim}/yr in 2050 and 197-266 EJ_{Prim}/yr in 2100. The potential supply from residues is relatively constant across the scenarios with availability and quality of land being the major uncertainty. Residues make up most of the short term supply of primary biomass as they generally are the cheapest resource at volumes less than 30 EJ_{Prim}/yr. However, eventual depletion of low cost residues and improvements in yields of energy crops means that after mid-century energy crops become the dominant primary source of biomass.

Land use for biomass production is projected to increase to over 300 MHa by 2100 in the mitigation scenarios. For comparison, in 2010 approximately 4800 MHa were used for food crops and pasture. In the mitigation scenarios bioenergy and biochemicals are projected to account for up to a third of the total final consumption of secondary energy, and contribute to about 10% of the overall mitigation (this number is specific to SSP2 2.6 as shown in Figure 2). The achieved mitigation is largely driven by ramping

Table 1. Projections of key indicators for biomass and bioenergy across all scenarios.

		Baseline			Mitigation		
		SSP1	SSP2	SSP3	SSP1 2.6	SSP2 2.6	SSP3 3.4
				Primary Potential(EJ_{Prim}/yr)			
2050	Residues	72	70	65	70	68	64
	Energy Crops	149	74	81	135	72	96
	Total	221	143	146	206	140	161
				Primary Production (EJ_{Prim}/yr)			
	Residues	48	37	27	64	68	63
	Energy Crops	38	43	55	54	58	58
	Total	87	80	82	118	126	121
				Land Use(MHa)			
		126	165	215	178	222	226
				Secondary Bioenergy (EJ_{Sec}/yr)			
	w/o CCS	65	52	48	55	50	52
	w CCS	0	0	0	4	14	9
				% Total Final Consumption			
		12%	8%	8%	13%	15%	14%
				Primary Potential(EJ_{Prim}/yr)			
2100	Residues	80	79	77	78	77	76
	Energy Crops	507	155	123	452	157	153
	Total	587	234	200	530	234	229
				Primary Production (EJ_{Prim}/yr)			
	Residues	60	71	59	74	75	76
	Energy Crops	117	81	73	192	144	119
	Total	177	152	132	266	220	197
				Land Use(MHa)			
		274	201	185	451	359	302
				Secondary Bioenergy (EJ_{Sec}/yr)			
	w/o CCS	121	107	86	94	90	80
	w CCS	0	0	0	61	33	29
				% Total Final Consumption			
		24%	13%	11%	35%	25%	21%

up BECCS which is projected to become competitive in the latter half of the century, promoted by technological improvements and high enough carbon taxes which make negative emissions very attractive. It should be noted that BECCS technologies are crucial in IMAGE and other IAMs for meeting strict climate targets. The MESSAGE-GLOBIOM model uses BECCS together with liquid fuel production (a technology not available in IMAGE).

The contribution of biomass to overall mitigation is limited to 10%, despite the fact that bioenergy makes up 25% of TFC, for a number of reasons. Additional mitigation efforts such as the adoption of efficiency measures and the increased use of renewable energy leads to decreases in the carbon intensity of different end uses. Consequently, biomass has decreasing marginal emission reductions. This effect can be mitigated by further limiting biomass use to the most effective end uses such as BECCS. Additionally, LUC emissions due to biomass production also restrain the mitigation potential. For these reasons the potential contribution of biomass to mitigation efforts is higher in the SSP1 case where there is a lower displacement of carbon stocks and increased use of BECCS technologies. Conversely, the unfavourable developments of the SSP3 case would further limit the overall benefits of biomass use.

Policy and research recommendations

Biomass sources: According to the model calculations, lignocellulosic feedstocks are the most attractive feedstock in terms of potential, costs and associated emissions. Additionally, residues can also form a significant source (>50 EJ_{prim}/yr) with low costs and emissions, as long as ecological constraints and other current uses are managed effectively. The former could benefit from and reduced-till and plastic mulching and the latter by avoiding residues as livestock feed and increasing the access of poor households to modern energy carriers. It is important to further check the supply and demand dynamics of this resource in IAMs with more bottom-up information.

Supply emissions: The land-use emissions associated with biomass supply have been shown to vary significantly. Ensuring energy crop supply with low GHG effects requires increases in productivity of agricultural system in production of food and energy crops. This would minimise land required for food production (especially pasture), lead to higher quality land available for biomass production. In this case, the availability of biomass with low emission (<20 $kgCO_2$-eq/GJ_{prim}) effects could be greater than 100 EJ_{Prim}/yr. Therefore, the modernization of food production systems and adoption of approaches such as integrated crop-livestock farming may offer an opportunity to increase the productivity, decrease emissions, restore degraded lands and decrease biomass costs. An integrated assessment of these systems is needed. Furthermore, it is important to ensure the protection of lands with high carbon stocks and to investigate the trade-offs between biomass production and CO_2 sequestration through afforestation. Concerning residues, a better understanding of the GHG trade-off of different residue uses (bioenergy, livestock feed, left on the soil) is required.

Conversion and use: Mitigation scenarios depend on the availability of affordable lignocellulosic (2nd generation) biofuels, biomass feedstocks in power production, and their combination with carbon capture and storage. Biomass can meet heat demand in buildings and industry at a low cost and may also become very competitive in transport. However, improvements in energy intensity of buildings and different transport modes can help direct biomass towards the more effective uses. Additionally, a better understanding is needed on how different energy models respond to different sets of technologies such as CCS possibilities, transport options and other renewables.

Feasibility of projections: The level of biomass demand in the mitigation scenarios requires large-scale production of primary biomass and its international trade. It is important to identify potential barriers (infrastructure, legal, financial, technological, social, etc.) and highlight the necessary boundary conditions ensuring that this deployment is achieved without adverse effects. Furthermore, due to the plethora of potential dynamics, no single model can fully account for all the possibilities, feedbacks and costs of biomass and bioenergy use. While the results of this thesis provide important new insights into the role of biomass as a climate change mitigation option, addressing these questions and developing new models and approaches is required.

Samenvatting

Achtergrond

In het 5^e *Assessment Report* van het *Intergovernmental Panel on Climate Change* (IPCC) staat dat de emissie van broeikasgassen als gevolg van menselijke activiteit in de komende decennia fors teruggedrongen dient te worden willen we de internationale klimaatdoelen halen. Het merendeel van deze broeikasgassen komt voort uit de verbranding van fossiele brandstoffen waarmee wij energie opwekken. Emissiemitigatie vraagt om wezenlijke veranderingen in vraag en aanbod van energie, zoals een betere energie-efficiëntie, en vervanging van fossiele brandstoffen door alternatieve bronnen. Het gebruik van biomassa als alternatieve energiebron is aantrekkelijk, aangezien het uit verschillende primaire bronnen (gewassen, residuen, afvalstromen, enz.) kan worden gehaald en op diverse manieren kan worden gebruikt. Zo is het bruikbaar voor de opwekking van warmte en stroom, als grondstof voor vloeibare brandstoffen in het vervoer en als basismateriaal voor niet-energetische toepassingen, zoals chemicaliën en biochemicaliën (non-energy). Daarnaast kunnen van biomassa afgeleide energiedragers (bio-energie) eenvoudig in de bestaande energie-infrastructuur geïntegreerd worden.

Ondanks deze voordelen, is het gebruik van biomassa en bio-energie op grote schaal voor klimaatmitigatie controversieel. Er zijn een aantal onzekere factoren in de berekening van het totale primaire energie potentieel: recente schattingen lopen uiteen van 50 tot 500 EJ/yr in 2050. Ook bestaat er weinig overeenstemming over de bijdrage van biomassa in de terugdringing van de emissie van broeikasgassen, aangezien de effectiviteit afhangt van een aantal onzekere factoren. De productie van biomassa leidt tot een (in)directe landgebruiksveranderingen (LUC) dat gevolgen kan hebben voor de aanwezige koolstofvoorraden. De bijbehorende emissies zijn moeilijk te bepalen, gezien de onzekerheden van landgebruiksverandering. De uiteindelijke vermindering van de emissies in het energiesysteem hangt af van de wijze waarop biomassa wordt gebruikt. Zo kan het gebruikt worden voor vloeibare brandstof, voor de opwekking van stroom, als basismateriaal voor biochemicaliën of voor de toepassing van nieuwe technologieën zoals bio-energie met koolstofafvang en -opslag (BECCS). In de huidige literatuur variëren de emissiereducties van het gebruik van biomassa van 0 tot meer dan 200 $kgCO_2$-eq/GJ_{Sec}.

De grote spreidingen in zowel de schattingen voor het potentieel van biomassa en terugdringing van de emissiereducties leggen de nadruk op de belangrijke gevoeligheden. Deze onzekerheden hangen af van een heel aantal technische maar ook sociaal-economische factoren die bepalen hoe land- en energiegebruik zich in de toekomst gaat ontwikkelen.

Doel en onderzoeksvragen

Het doel van dit proefschrift is om de rol van biomassa om klimaatverandering tegen te gaan nader te onderzoeken. Hiervoor wordt het geïntegreerd analysemodel (IAM), het zgn. *Integrated Model to Assess the Global Environment* (IMAGE). IMAGE biedt een geïntegreerd analytisch en modelmatig raamwerk met ruimtelijke details over de beschikbaarheid van biomassa en koolstofdynamiek. Ook is er een dynamische weergave van concurrerende landgebruiksdoeleinden en toepassingen. Bij de ontwikkeling en het gebruik van het IAM gaat dit proefschrift in op de volgende onderzoeksvragen:

1. Wat is het potentiële toekomstige aanbod van moderne biomassa uit residuen en energiegewassen, waarbij er rekening gehouden wordt met de drijvende en beperkende krachten op een ruimtelijk expliciete wijze?
2. Wat is de vraag naar biomassa voor verschillende toepassingen van energie en chemicaliën in een dynamisch energiesysteemmodel?
3. Wat is de totale invloed op de broeikasgassen bij de inzet van biomassa voor bio-energie en biochemicaliën, rekening houdend met het toekomstig landgebruik het energiesysteem?
4. Wat is de toekomstige rol van biomassa, bio-energie en biochemicaliën in de verschillende scenario's waarin klimaatverandering wordt teruggedrongen, rekening houdend met het landgebruik en het energiesysteem?

Methode

Het IMAGE-model is ontworpen om de interactie tussen menselijke en natuurlijke systemen te onderzoeken, door gebruik te maken van een vereenvoudigde weergave van de meest relevante mondiale processen. Hieronder vallen interacties binnen en tussen de diverse systemen (land, energie, economie en klimaat). Met het model wordt beoogd de mondiale verandering en het effect van diverse soorten beleid te beoordelen.

In dit proefschrift worden specifieke onderdelen van IMAGE verbeterd waarmee een betere voorstelling wordt gegeven van vraag en aanbod van biomassa. Verder wordt IMAGE gebruikt voor diverse experimenten; daarmee kan een antwoord worden gegeven op de onderzoeksvragen, rekening houdend met diverse onzekerheden, waaronder sociaaleconomische ontwikkelingen en de aanwezigheid van streng klimaatbeleid. Door de resultaten van verschillende scenario's met elkaar te vergelijken komen de verscheidenheid, de drijvende en beperkende factoren voor het gebruik van biomassa, bio-energie en biochemische paden naar voren en hoe ze in de diverse toekomstscenario's variëren.

De gebruikte scenario's zijn gebaseerd op de *Shared Socioeconomic Pathways* (SSP) waarmee onderzoek wordt gedaan naar de verschillende mogelijkheden voor sociaaleconomische ontwikkeling. Deze kennen elk hun eigen problemen met klimaatmitigatie en –adaptatie en leiden zodoende tot wisselend gebruik van land en energie en de daarmee gepaard gaande emissie van broeikasgassen. In de SSP1 (basislijn) wordt een wereld beschreven met weinig problemen, waarbij het bevolkingscijfer halverwege de eeuw zijn hoogtepunt bereikt, terwijl het bruto binnenlands product per hoofd van de bevolking overal ter wereld aanzienlijk stijgt. Verder wordt er behoorlijk veel moeite gedaan om natuurgebieden te behouden, de vraag naar vlees te verminderen, de hoeveelheid landbouwproducten en het rendement van dieren te verhogen en de energie-efficiëntie te vergroten. Bij SSP2 wordt uitgegaan van een gemiddelde ontwikkeling op basis van de extrapolatie van huidige trends, met een stabiliserend bevolkingscijfer tegen het einde van de eeuw en een geringe mate van inspanning voor het behoud van natuurgebieden, en vergroting van de efficiëntie van landbouw en energie. Tot slot wordt in SSP3 een wereld voorgesteld met grote problemen op het gebied van adaptatie en mitigatie, met een zeer sterke bevolkingstoename, weinig beperkingen op het gebruik van land, een beperkte verbetering in welzijn en inefficiënte landbouw- en energiesystemen.

Elke basislijn kent zijn eigen mitigatiescenario waarbij de toepassing van klimaatbeleid wordt gesimuleerd, teneinde een stralingsforceringsdoel te bereiken dat overeenkomt met 2,6-3,4 W/m^2. De mitigatiescenario's worden hierna SSP1-2,6, SSP2-2,6 en SSP3-3,4 genoemd.

Overzicht

Om deze vragen te kunnen beantwoorden, zijn er diverse methoden nodig, die moeten worden ontwikkeld en toegepast. Daarom wordt in dit proefschrift het volgende onderzocht: het aanbod van biomassa (Hoofdstuk 2 & 3), de vraag naar biomassa (Hoofdstuk 3 & 4), en de geïntegreerde biomassascenario's (Hoofdstuk 5 & 6). Deze hoofdstukken gaan in op één of meer onderzoeksvragen door methoden voor het maken van modellen te ontwikkelen en te onderzoeken en (geïntegreerde) scenario-analyses te maken.

In **Hoofdstuk 2** wordt een schets gegeven van de methode die is gebruikt om het aanbod en de kosten van residuen uit landbouw en bosbouw op de lange termijn te bepalen. Er wordt gebruik gemaakt van het IMAGE-model voor de projecties van de productie in deze sectoren en van de bestaande vraag naar residuen, bijv. voor het gebruik als diervoeding en als conventionele brandstoffen. Vervolgens worden de ruimtelijke beschikbaarheid en kosten ervan berekend, en worden daaruit aanbodcurves afgeleid, een en ander op een geïntegreerde en geografisch expliciete wijze.

In **Hoofdstuk 3** wordt het concept ‘emissiecurve’ geïntroduceerd, waarin de emissie van LUC als functie van biomassabron wordt getoond. De op basis van het IMAGE-model gemaakte projecties van koolstofvoorraden in de grond en het rendement van biomassa worden gebruikt om ruimtelijke specifieke emissiefactoren en de terugbetaalperiodes voor broeikasgassen te berekenen. Daarbij worden de emissieaanbodcurves voor diverse biobrandstoffen van de 1^{e} en 2^{e} generatie gepresenteerd, met specifieke aandacht voor de geschiktheid van verschillende biomen en de sensitiviteit voor belangrijke aannames.

Hoofdstuk 4 toont een methode waarmee de diverse vormen van non-energy gebruik van energiedragers (basismaterialen voor chemicaliën) in het TIMER-model zijn opgenomen. Dit model wordt gebruikt om te onderzoeken wat op de lange termijn het potentieel is van biochemicaliën, de gevolgen van klimaatbeleid, en het mitigatiepotentieel van neerslaande chemicaliën door recycling en/of verbranding bij de opwekking van stroom.

In **Hoofdstuk 5** worden met bijgewerkte TIMER-model de gevolgen van langdurig gebruik en emissie van biomassa in het energiesysteem bepaald door onderzoek te doen naar de diverse vormen van gebruik van bio-energie en biochemicaliën. Daarbij wordt aandacht besteed aan de emissiereductie per eenheid biomassa voor ieder eindgebruik, de rol van concurrerende mogelijkheden, en het effect van steeds strenger wordend klimaatbeleid. Voorts worden de resultaten getoetst aan de hand van de onzekere factoren in de vraag naar biomassa en technologische ontwikkelingen.

In **Hoofdstuk 6** volgt een vergelijking van de structuren en resultaten van twee IAM kaders: IMAGE en MESSAGE-GLOBIOM door een beschrijving te geven van grond, energie en systemen, met specifieke aandacht voor de wijze waarop iedere IAM vraag en aanbod van biomassa en bio-energie bepaalt. Ook wordt een projectie gegeven van consequente basislijn- en mitigatiescenario’s, evenals een sensitiviteitsscenario waarbij de wisselwerking tussen de productie van biomassa en toepassing van landgebonden mitigatie wordt onderzocht.

In **Hoofdstuk 7** wordt gebruik gemaakt van het verbeterde IMAGE-model (waaronder de toevoegingen uit Hoofdstuk 2 & 4) om op geïntegreerde manier te onderzoeken wat de rol van biomassa voor mitigatie van klimaatverandering is. Tot slot worden in dit hoofdstuk ook de afzonderlijke bevindingen uit de eerdere hoofdstukken uiteengezet, om de onderzoeksvragen te beantwoorden, aanbevelingen voor beleid te geven en verdere onderzoeksmiddelen voor te stellen.

De rol van biomassa in mitigatie van klimaatverandering

Drijvende en beperkende krachten in het aanbod van biomassa

Residuen

Het maximale *theoretische potentieel* van residuen hangt af van de opbrengst uit landbouw en bosbouw en de intensiteit van deze activiteiten. Het *beschikbare potentieel* wordt begrensd door ecologische beperkingen en concurrerende vormen van gebruik, zoals diervoeding of gebruik van conventionele brandstoffen in arme huishoudens. Uit de projecties blijkt dat het *theoretische potentieel* toeneemt van circa 120 EJ_{Prim}/yr (heden) naar 130, 136 en 145 EJ_{Prim}/yr in 2050 voor SSP1, 2 resp. 3. Ecologische en concurrerende vormen van gebruik beperken echter het *beschikbare* potentieel tot 72, 70 resp. 65 EJ_{Prim}/yr. Dit stijgt naar 80, 79 resp. 77 EJ_{Prim}/yr in 2100 en bijna alles daarvan is beschikbaar op minder dan 10 $\$_{2005}$/$GJ_{Prim}$.

Opvallend is dat het beschikbare potentieel voor de afzonderlijke scenario's niet veel verschilt vanwege neutraliserende gevolgen. In SSP1 beperkt de lagere landbouwopbrengst het theoretisch potentieel, maar een lagere vleesopbrengst en lager conventioneel brandstofgebruik beperken ook de concurrerende vraag. In SSP3 is het theoretisch potentieel hoger (vanwege de hogere productie) maar de concurrerende vormen van gebruik zijn ook hoger. Verder zijn in SSP3 de residuen waarschijnlijk iets duurder vanwege de extensievere productie door hogere transportkosten.

Energiegewassen

Energiegewassen kunnen in IMAGE geteeld worden op onbeheerde akkers óf in onbeschermde natuurgebieden. Typisch is dat er in IMAGE-berekeningen vanuit gegaan wordt dat bosgrond niet gebruikt wordt voor de productie van biomassa. In SSP1 laat de afname in de vraag naar grond voor landbouw ruimte voor behoorlijk grote hoeveelheden onbeheerd land, terwijl de strengere milieubeperkingen de oppervlakte aan natuurgebieden beperken. Uit de basislijn van SSP3 blijkt tegenovergesteld gedrag, en SSP2 ligt ergens in het midden. Het type beschikbare grond is heel belangrijk voor het totale biomassapotentieel, aangezien onbeheerde landbouwakkers gewoonlijk de hoogste opbrengst geven. Ongebruikte grond kan ook een hoge opbrengst opleveren, maar ook hoge emissies (bossen) of lagere opbrengsten (natuurlijke graslanden).

De raming is dat de totale opbrengst aan biomassa (lignocellulose gewassen) toeneemt van ongeveer 250 GJ_{Prim}/Ha vandaag naar 306, 262 resp. 257 GJ_{Prim}/Ha voor SSP1, 2 en 3 in 2050. In 2100 leidt een verdere toename tot opbrengsten van 426, 401 en 395 GJ_{Prim}/Ha. De verschillen in de scenario's komen voort uit de verschillende kwaliteit van de beschikbare grond, alsmede verbeteringen in het beheer ervan. De beschikbaarheid van onbeheerde landbouwgronden met een hoge opbrengst zorgt ervoor dat SSP1 het hoogste biomassapotentieel heeft, ondanks de strengere beperkingen voor natuurgebieden. Voor de basislijnen van SSP2 en SSP3 leidt de hoge vraag naar landbouw ertoe dat biomassa op land van een lagere kwaliteit wordt geproduceerd, ondanks de minder strenge beperkingen in het gebruik van de grond; als gevolg daarvan daalt het totale potentieel. Het potentieel voor energiegewassen wordt geraamd op 149, 74 en 81 EJ_{Prim}/yr in 2050 voor SSP1, 2 resp. 3 met een toename naar 507, 155 en 123 EJ_{Prim}/yr in 2100. Tabel 1 geeft het beschikbare potentieel voor residuen en energiegewassen voor alle scenario's.

Vraag naar bio-energie en biochemicaliën

Biochemicaliën

In de SSP's neemt de totale primaire energievraag voor non-energy producten toe van 26 EJ_{Prim}/yr in 2010 tot circa 45 EJ_{Prim}/yr in 2050 en 58, 92 resp. 77 EJ_{Prim}/yr voor SSP1, 2 en 3 in 2100. Zoals Hoofdstuk 4 laat zien worden de koolstofgebaseerde grondstoffen in een contrafeitelijk scenario, waarin biomassa onbeschikbaar wordt verondersteld, tegen het einde van de eeuw steeds belangrijker vanwege de stijgende prijs van olie en aardgas. Indien biomassa als grondstof wordt toegestaan, kan het bijdragen aan meer dan 30% van het primaire aanbod in 2050 en aan meer dan 35-50% in 2100. Naast de stijgende prijs van fossiele brandstoffen neemt ook het concurrentievermogen van biomassa toe doordat er steeds wordt bijgeleerd in de productie van tussenproducten op basis van duurzame materialen (ethanol en methanol).

Bio-energie in het energiesysteem

Afbeelding 1 toont de projecties van het gebruik van bio-energie en biochemicaliën voor de basislijn- en mitigatiescenario's. In alle gevallen is er sprake van een toename in het gebruik van bio-energie over de hele projectieperiode. Het gebruik op de lange termijn neemt nog meer toe in de mitigatiescenario's, aangezet door de toepassing van belasting op koolstoffen. De gunstige technologische aannames en beschikbaarheid van biomassa leiden tot het hoogste gebruik in bio-energie in het scenario van SSP1. In 2050 nemen bio-energie en biochemicaliën 12% van de totale secundaire energie voor hun rekening in SSP1, en 8% in SSP2 en SSP3. Deze stijgen tot 24%, 13% resp. 11% in 2100. In de mitigatiescenario's liggen deze zelfs hoger, nl. op 35%, 25% resp. 21% (2100).

Het primaire gebruik van biomassa in de basislijnen geldt voor vloeibare brandstoffen. Zoals uiteengezet in Hoofdstuk 5 komt dit door de vraag van de vervoerssector tijdens een stijgende olieprijs. Andere belangrijke vormen van gebruik zijn chemicaliën (non-energy) zoals hiervoor beschreven en vaste bio-energie als warmtebron voor gebouwen en de industrie. Het belang van vaste brandstoffen neemt in de scenario's SSP2 en SSP3 verder toe vanwege de pessimistische aannames over de verbetering van de biobrandstoftechnologieën van de 2e generatie en een toegenomen vraag naar warmte in gebouwen en de industrie. In SSP1 is de beschikbaarheid van verbeterde technologieën ook goed voor de productie van een kleine hoeveelheid waterstof.

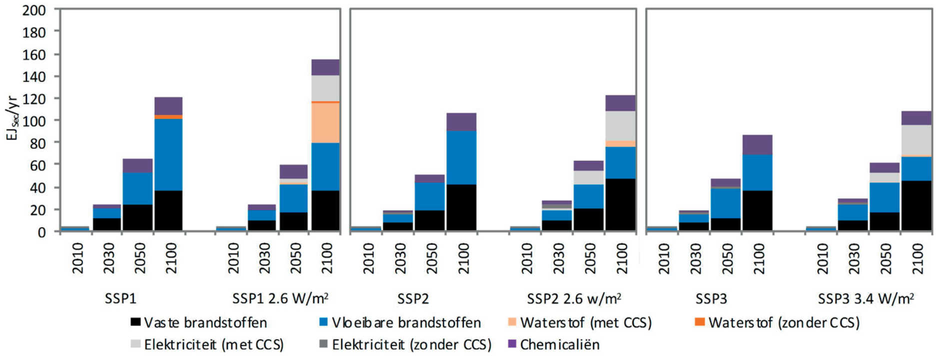
In de mitigatiescenario's worden BECCS-technologieën steeds concurrerender door het heffen van belasting op koolstoffen. Hieronder vallen zowel de opwekking van elektriciteit als de productie van waterstof, waarbij de laatste opnieuw het duidelijkst zichtbaar is in SSP1. De productie van vloeibare en vaste brandstoffen zet echter door in de vormen van gebruik waarin dit type bio-energie de enige rendabele vervanging voor fossiele brandstoffen is.

Bijdrage aan mitigatie van emissies

Gewijzigd gebruik van grond ten gevolge van de productie van biomassa

De in Hoofdstuk 3 berekende emissiefactoren laten een grote ruimtelijke variatie zien, met een bandbreedte van 10-90 percentiel van de emissiefactoren voor biobrandstoffen (37-138 $kgCO_2/GJ_{Sec}$ voor methanol uit gras, 42-94 $kgCO_2$-eq/GJ_{Sec} voor methanol uit hout en 35-85 $kgCO_2/GJ_{Sec}$ voor ethanol uit suikerriet). Bij het ramen van het potentieel voor emissiereductie van biomassa uit energiegewassen dient er met een aantal belangrijke elementen rekening te worden gehouden. Het kappen van bossen om land vrij te maken is goed voor zo'n derde van de emissie uit het aanbod aan biobrandstoffen, terwijl het gebruik van niet-hernieuwbare energie ook goed is voor een derde. De resterende emissie komt uit wijzigingen in de koolstofvoorraad op de lange termijn en hoe die zich verhoudt tot een contrafeitelijk scenario met natuurlijke vegetatie. Echter, deze verhoudingen variëren aanzienlijk. Verder impliceren de in Hoofdstuk 3 gegenereerde emissieaanbodcurves dat het totale voordeel van broeikasgassen bij een hoog niveau aan biomassaproductie pas worden bereikt over meer dan 30-40 jaar.

In de analyse van de scenario's hebben zowel de kwaliteit van beschikbare grond voor biomassa en de vraag naar biomassa uit energiegewassen invloed op de emissie van LUC. De beschikbaarheid van hoogwaardige (onbeheerde) gronden leidt tot hogere opbrengsten en dus tot een lagere vraag naar grond. Hoewel in SSP1 de hoogste vraag naar biomassa wordt geprojecteerd, heeft het de laagste emissie van LUC. In de andere basislijnen hangt de productie van biomassa voornamelijk af van de natuurlijke gronden, hetgeen leidt tot een hogere emissie van LUC. Verder kan men ervoor zorgen dat het aanbod aan biomassa met een lage emissie van LUC wordt bereikt door de beschikbaarheid van grond in te perken aan de hand van de koolstofvoorraad in de grond. Daarvan is sprake in de mitigatiescenario's, waarbij de zwaarste beperkingen in SSP1 en de lichtste in SSP3 voorkomen. Als gevolg daarvan is de daaruit volgende emissie uit grond in SSP1 2.6 maar 6% hoger, hoewel de vraag naar energiegewassen



Afbeelding 1. Definitief gebruik van biomassa voor energie en non-energy (chemicaliën) in de basislijn en mitigatiescenario's.

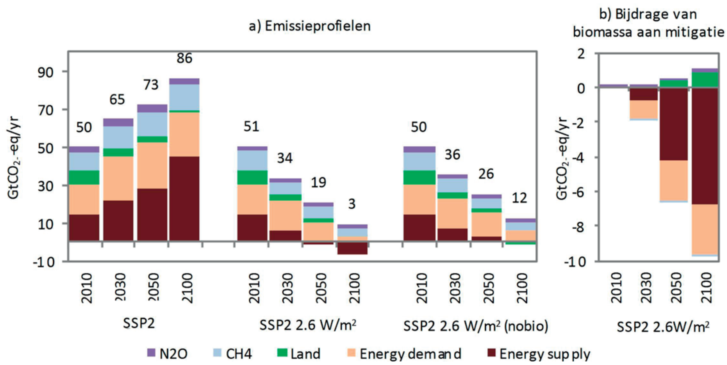
65% stijgt ten opzichte van de basislijn. Daar staat voor SSP3 3.4 tegenover dat een kleine toename in de vraag naar energiegewassen (ten opzichte van de basislijn) leidt tot zo'n 20% toename in de emissie van grond in 2100, aangezien die van invloed is op de koolstofvoorraad van onbeschermde natuurgebieden.

Emissie van energiesystemen en het effect van diverse vormen van gebruik van bio-energie

Bij vrije concurrentie voor een aantal vormen van eindgebruik (verwarming van gebouwen, non-energy, vervoer en de opwekking van elektriciteit) kan biomassa bijdragen aan de terugdringing van emissies door de energiesystemen met 9% ten opzichte van een contrafeitelijk scenario zonder biomassa. Bij het onderzoeken van specifieke vormen van gebruik blijkt het gebruik van biomassa voor de opwekking van elektriciteit de meest aantrekkelijke optie te zijn voor de totale emissiereductie per eenheid secundair gebruik van bio-energie. Dat komt omdat elektriciteit de belangrijkste uiteindelijke energiedrager in de basislijn wordt en kolen de belangrijkste grondstof voor het opwekken van elektriciteit zijn. Dus biedt het opwekken van elektriciteit uit biomassa een grotere reductie in emissie aan dan het vervangen van olie of aardgas in andere sectoren. Met hoge belasting op koolstoffen en vrije concurrentie in alle sectoren kan biomassa bijdragen aan een verdere 40% terugdringing van de emissie door het aannemen van BECCS-technologieën bij het opwekken van elektriciteit, door olie te vervangen in de vervoerssector en door energie te gebruiken als warmtebron voor gebouwen en in de industrie. Met het gebruik van bio-energie ten behoeve van vervoer en verwarming neemt het effectiever gebruik in de elektriciteitssector af.

Totale emissiereductie als gevolg van biomassa, bio-energie en biochemicaliën

Zoals hiervoor beschreven leidt het gebruik van biomassa tot veranderingen in de koolstofstromen in zowel het energiesysteem als landgebruik. Afbeelding 2 geeft



Afbeelding 2. (a) GHG-emissies voor SSP2 basislijn, mitigatie en mitigatie met verplichte biomassa. (b) Bijdrage van biomassa aan totale mitigatie in SSP2 2.6 W/m2. Het SSP2 2.6 W/m2 (geen biomassa) scenario is een sensitiviteitsscenario waarbij het gebruik van grond en energieprojecten gelijk is als dat van SSP2 2.6 W/m2 maar waarbij de vraag naar biomassa en bio-energie wordt uitgesloten. De getallen verwijzen naar de totale GHG-emissies.

de emissie van broeikasgassen uit verschillende bronnen voor de SSP2-basislijn, het SSP2 2.6 mitigatiescenario en een sensitiviteitsscenario op SSP2 2.6 zonder biomassa weer. Het effect dat biomassa op ieder van de emissiesectoren heeft wordt getoond in kolom (b). Zoals de afbeelding laat zien leidt de emissiemitigatie van het energiesysteem tot een totale reductie in broeikasgassen, terwijl de productie van biomassa de emissie van LUC doet toenemen, afgezet tegen een contrafeitelijk scenario zonder biomassa. Biomassa draagt bij aan terugdringing van emissie door het energieaanbod te ontkolen (voornamelijk in de energiesector, in combinatie met BECCS) en door het vervangen van fossiele brandstoffen in de vraag naar en de vormen van gebruik van energie. In 2050 bedraagt deze bijdrage 4 resp. 2 $GtCO_2$-eq/yr, met een verhoging naar 7 resp. 3 $GtCO_2$-eq/yr in 2100. De productie van biomassa leidt tot een hogere emissie van LUC en N_2O met circa 1 $GtCO_2$-eq/yr .

Bereik en robuustheid

In tabel 1 worden de belangrijkste indicatoren voor vraag en aanbod van biomassa door alle scenario's heen samengevat. Zoals wordt getoond is de raming voor de productie van primaire biomassa een toename naar 80-87 EJ_{Prim}/yr in 2050 en 132-177 EJ_{Prim}/yr in 2100 voor de basislijnen. In de mitigatiescenario's stijgen deze getallen fors naar 118-126 EJ_{Prim}/yr in 2050 en 197-266 EJ_{Prim}/yr in 2100. Het potentiële aanbod uit residuen is relatief constant door de scenario's heen, waarbij de beschikbaarheid en kwaliteit van grond de grote onzekere factoren zijn. Residuen zijn goed voor het merendeel van het aanbod van primaire biomassa op de korte termijn, aangezien deze over het algemeen de goedkoopste bron zijn bij volumes onder de 30EJ/yr. Echter, uiteindelijke uitputting van goedkope residuen en een betere opbrengst van

Tabel 1. Projecties van belangrijke indicatoren voor biomassa en bio-energie door alle scenario's heen.

		Basislijn			Mitigatie		
		SSP1	SSP2	SSP3	SSP1 2.6	SSP2 2.6	SSP3 3.4
					Primair Potentieel (EJ_{Prim}/yr)		
2050	Residuen	72	70	65	70	68	64
	Energiegewassen	149	74	81	135	72	96
	Totaal	221	143	146	206	140	161
					Primaire Productie (EJ_{Prim}/yr)		
	Residuen	48	37	27	64	68	63
	Energiegewassen	38	43	55	54	58	58
	Totaal	87	80	82	118	126	121
					Gebruik van Grond (MHa)		
		126	165	215	178	222	226
					Secundaire Bio-energie (EJ_{Sec}/yr)		
	zonder CCS	65	52	48	55	50	52
	met CCS	0	0	0	4	14	9
					% Totaal Definitief Gebruik		
		12%	8%	8%	13%	15%	14%
					Primair Potentieel (EJ_{Prim}/yr)		
2100	Residuen	80	79	77	78	77	76
	Energiegewassen	507	155	123	452	157	153
	Totaal	587	234	200	530	234	229
					Primaire Productie (EJ_{Prim}/yr)		
	Residuen	60	71	59	74	75	76
	Energiegewassen	117	81	73	192	144	119
	Totaal	177	152	132	266	220	197
					Gebruik van Grond (MHa)		
		274	201	185	451	359	302
					Secundaire Bio-energie (EJ_{Sec}/yr)		
	zonder CCS	121	107	86	94	90	80
	met CCS	0	0	0	61	33	29
					% Totaal Definitief Gebruik		
		24%	13%	11%	35%	25%	21%

energiegewassen betekenen dat energiegewassen in de tweede helft van de eeuw de dominante primaire bron van biomassa worden.

De raming in de mitigatiescenario's is dat het gebruik van grond voor het produceren van biomassa stijgt naar meer dan 300 MHa in 2100. Ter vergelijking; in 2010 werd circa 4800 MHa gebruikt voor voedselgewassen en weidegrond. In de mitigatiescenario's is de raming dat bio-energie en biochemicaliën maximaal een derde van het totale definitieve gebruik van secundaire energie voor hun rekening nemen, en circa 10% van de totale mitigatie (dit cijfer is specifiek voor SSP2 2.6, zoals aangegeven in Afbeelding 2). De gerealiseerde mitigatie wordt grotendeels gedreven door het opvoeren van BECCS, dat volgens ramingen in de tweede helft van de eeuw steeds concurrerender wordt, dankzij technologische verbeteringen en voldoende hoge belastingen op koolstoffen waardoor negatieve emissie zeer aantrekkelijk wordt. Er zij opgemerkt dat BECCS-technologieën cruciaal zijn in IMAGE en andere IAM's voor het behalen van de strenge klimaatdoelen. In de MESSAGE-GLOBIOM wordt BECCS gebruikt samen met de productie van vloeibare brandstoffen (een technologie die niet beschikbaar is in IMAGE).

De bijdrage van biomassa aan de totale mitigatie is maar 10%, ondanks het feit dat bio-energie goed is voor 25% van de totale hoeveelheid brandstofgebruik, en wel om een aantal redenen. Extra inspanningen om mitigatie te bereiken, zoals het treffen van efficiëntiemaatregelen en een bredere toepassing van duurzame energie leiden tot afname van de koolstofintensiteit voor de verschillende vormen van eindgebruik. Zodoende draagt biomassa steeds minder bij aan de emissiedaling. Dit effect kan worden gematigd door het gebruik van biomassa verder te beperken tot de meest effectieve vormen van eindgebruik, zoals BECCS. Daarnaast beletten de LUC emissies als gevolg van de productie van biomassa ook het mitigatiepotentieel. Om deze redenen is de potentiële bijdrage van biomassa aan de inspanning tot mitigatie hoger in de situatie van SSP1 waar er sprake is van een lagere verdringing van de koolstofvoorraad en een toegenomen gebruik van BECCS technologieën. Daar staat tegenover dat de ongunstige ontwikkelingen van de situatie in SSP3 de totale voordelen van het gebruik van biomassa zouden beperken.

Beleids- en onderzoeksaanbevelingen

Biomassabronnen: Volgens de modelberekeningen zijn de lignocellulose basismaterialen de meest aantrekkelijke materialen qua potentieel, kosten en de daaraan gekoppelde emissie. Daarnaast kunnen ook residuen een belangrijke bron vormen (>50 EJ_{prim}/yr) met lage kosten en een lage emissie, zolang het beheer van de ecologische beperkingen en andere huidige vormen van gebruik effectief plaatsvindt. Het eerste kan bevorderlijk zijn voor minder intensief ploegen en plastic mulching en het laatste door residuen niet als diervoeder te gebruiken en de toegang van arme huishoudens tot moderne energiedragers te verbeteren. Het is belangrijk om de dynamiek van vraag en aanbod van deze hulpbron verder te controleren in IAM's met meer informatie van onderaf.

Aanbodemissie: Het blijkt dat de emissie door gebruik van grond in verband met het aanbod van biomassa sterk varieert. Om ervoor te zorgen dat het aanbod aan energiegewassen leidt tot een geringe emissie van broeikasgassen is een toename in de productiviteit van landbouwsystemen bij de productie van voedsel en energiegewassen nodig. Hierdoor wordt de voor voedselproductie benodigde grond (voornamelijk weidegronden) sterk teruggebracht en neemt de kwaliteit van de voor de productie van biomassa beschikbare grond toe. In dit geval kan de beschikbaarheid van biomassa met lage emissie-effecten (<20 $kgCO_2$-eq/GJ_{prim}) groter zijn dan 100 EJ_{Prim}/yr. Zo kunnen modernisering van voedselproductiesystemen en de aanname van benaderingen zoals *integrated crop-livestock farming* een kans bieden om de productiviteit te vergroten, emissies te verlagen, verwilderde grond weer bruikbaar te maken en de kosten van biomassa te verlagen. Er is een geïntegreerde analyse van deze systemen nodig. Verder is het belangrijk te zorgen dat grond met grote koolstofvoorraden beschermd wordt en de wisselwerking tussen de productie van biomassa en de opname van CO_2 via nieuwe aanplant wordt onderzocht. Wat betreft residuen is er meer inzicht nodig in de wisselwerking tussen de verschillende vormen van gebruik van de diverse residuen (bio-energie, diervoeding, achterlaten op het land).

Conversie en gebruik: Mitigatiescenario's hangen af van de beschikbaarheid van betaalbare biobrandstoffen op basis van lignocellulose (2^{e} generatie), basismaterialen voor biomassa bij de opwekking van stroom, en hun combinatie met CCS. Met biomassa kan worden voorzien in de vraag naar goedkope verwarming van gebouwen en de industrie en kan dat ook in het vervoer concurrerend worden. Echter, verbeteringen in de energie-intensiteit van gebouwen en verschillende vervoersmodi kunnen helpen om biomassa de weg wijzen naar effectievere vormen van gebruik. Daarnaast is er meer inzicht nodig in hoe de verschillende energiemodellen reageren op verschillende soorten technologie, zoals CCS-mogelijkheden, vervoersopties en andere duurzame energiebronnen.

Haalbaarheid van projecties: Het niveau van vraag naar biomassa in de mitigatiescenario's vereist de productie van primaire biomassa op grote schaal, en de internationale handel daarin. Het is van belang om potentiële drempels (infrastructureel, juridisch, financieel, technologisch, sociaal, enz.) vast te stellen en de benodigde randvoorwaarden naar voren te brengen zodat deze inzet zonder negatieve gevolgen wordt bereikt. Verder kan in geen enkel model, door de veelheid aan potentiële dynamische factoren, volledig rekening worden gehouden met alle mogelijkheden, terugkoppelingen en kosten van het gebruik van biomassa en bio-energie. Al bieden de bevindingen in dit proefschrift belangrijke nieuwe inzichten in de rol van biomassa als mogelijkheid om klimaatverandering terug te dringen, toch moeten deze vragen steeds weer aan de orde worden gesteld, en zijn er nieuwe vragen nodig, met andere modellen en benaderingen.

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Curriculum vitae

Vassilis Daioglou was born on the 14th of August 1985 in Athens, Greece, where he also spent most of his childhood. Between 2003 and 2007 he attended the University of Southampton in the United Kingdom, where he graduated with a 1st Class honours degree in *Mechanical Engineering* (M.Eng.). He then spent a year working in an Athens based engineering consultancy firm. In 2008 he moved to the Netherlands where he pursued an M.Sc. degree in *Sustainable Development – Energy and Resources* at Utrecht University, graduating in December 2010. During this time he did an internship at the Netherlands Environmental Assessment Agency (PBL). There, he helped develop a global residential energy demand model disaggregated between urban and rural areas and investigated the implications of climate policy on energy access of poor households. Between 2011 and 2016 he conducted his PhD research at Utrecht University and PBL, the result of which is the present thesis. In 2013 he spent three months in Laxenburg, Austria as a visiting researcher at the International Institute for Applied Systems Analysis (IIASA) where he compared the bioenergy strategies of the IMAGE and MESSAGE-GLOBIOM models (Chapter 6 of the present thesis). He has also contributed to the *IEA Bioenergy Task 40* (www.bioenergytrade.org) and the *Energy Modeling Forum* project 33 on bioenergy and land use (emf.stanford.edu). As of April 2016 he is a climate policy researcher at PBL.

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